

LABORATORY INVESTIGATION OF INSULATOR CONTAMINATION PROBLEMS

BY

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S Y N O P S I S

This thesis deals with the practical aspect of the laboratory examination of contaminated insulators. A technique which gives a pollution curve for cylindrical insulator models is described. The technique is later extended to apply to practical insulator shapes, giving curves which can be used to assess insulator performance. A method of applying these curves to results obtained in the field is suggested. The method takes into account the effect of insulator shape and weather conditions, on the accumulation of contaminant at a given test site. In addition, a system is described whereby leakage currents from contaminated insulators can be measured and recorded. Typical results obtained are given as examples of system application.

A C K N O W L E D G E M E N T S

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CHAPTER I

INTRODUCTION

The engineer has been aware of the problems caused by the contamination of external insulation since about 1912. Since then, a great deal of information has been contributed towards the solution of these problems. Their solution is still of vital importance today. Unless these problems are solved they will continue to be a stumbling block to the distribution of the large amount of power required for modern-day production and living.

Voltages in excess of 1 MV are being planned for future transmission systems, and as industry expands the pollution problem presents an increasing threat to reliable power transmission. Great progress has been made in controlling effluent output into the atmosphere. At coastal towns and cities these benefits are being offset. This is because urban areas are increasing in size, and due to lack of space, power stations, switchyards, and transmission lines, are being placed nearer the coast. Here the problem of salt pollution will remain, because natural phenomena are more difficult, if not impossible to control.

PREVIOUS WORK AT THE UNIVERSITY OF CAPE TOWN

Work in the field of polluted insulators at the University of Cape Town was started at undergraduate level in 1971. At that time a choice had to be made between the two basically different methods of laboratory pollution tests. These are the salt fog method and the

predeposited method. The salt fog method was rejected, since it requires a special testing chamber and associated spray equipment, due to the highly corrosive effect of the salt. In addition, the two main disadvantages are that the order of merit for insulator types is given as a measure of salinity concentration, and that each test is of very long duration. The salinity is a very difficult variable to relate to insulator performance under service conditions, where the measure is usually conductivity, salt deposit density, or leakage current counts. The predeposited method was thus chosen.

The idea was to develop a simple test for polluted insulators, and initially tests were conducted using cylindrical glass tubes as model insulators. These cylinders are roughly 7 cm in diameter, on which two copper electrodes are attached about 22 cm apart. To achieve a good contact between the copper strips and the glass cylinders, the edges of the electrodes were filled with 'Gun-Gum', which is a slightly conductive compound.

The pollutant used was a standard suspension of 100 gm of Kieselguhr, 10 gm of Aerosil (SiO_2) as an inert water retentive substance, and one litre of distilled water. Different conductances were achieved by adding various amounts of common salt. The model insulators were then sprayed by hand to get a thin, even, but subjective, deposit, and allowed to dry.

The models were then wet to maximum conductivity, using a fine distilled water mist. A steam fog was also used initially, to try to achieve uniform continuous wetting, but was found to be unsuitable.

After wetting was completed, the spray was removed, and a known voltage was applied to the unit. This method is known as the predeposited prewet process. A variation of this method was to achieve

maximum conductivity, and to keep the water mist on the specimen, whilst applying the preset voltage to the unit. This is known as the predeposited continuous wetting process, and was used to try to validate the predeposited prewet method.

The conductivity was determined by applying a 500 V a.c. source to the model, once it had been completely saturated, and measuring the leakage current flowing through the unit. This was converted to surface conductivity σ_s by multiplying the measured surface conductance G_s by the form factor F .

To understand how form factor comes about, and its function, a small digression is necessary.

For a given volume of substance of volume resistivity ρ , or volume conductivity σ , length l , thickness t and width w giving an area A , the resistance R and conductance G are given respectively by :

$$R = \frac{\rho \cdot l}{A} = \frac{\rho \cdot l}{t \cdot w}$$

and

$$G = \frac{\sigma \cdot A}{l} = \frac{\sigma \cdot t \cdot w}{l}$$

For a deposit of constant thickness, the surface conductance G_s can be expressed in terms of surface conductivity σ_s as :

$$G_s = \sigma_s \cdot \frac{w}{l}$$

Thus the surface conductivity is given by :

$$\sigma_s = G_s \cdot \frac{l}{w} = \text{Surface conductance} \times \text{Form factor.}$$

For complicated shapes, such as cones or insulators, the width is given by circumference, which is a function of diameter. However, for these shapes, the diameter is a function of leakage distance, or distance from one electrode, and the form factor can be expressed in general terms as :

$$F = \int_0^{\ell} \frac{ds}{\pi \cdot D(s)}$$

where :

s = leakage distance measured from one electrode

$D(s)$ = diameter at s

ℓ = total leakage distance.

For the simple cylindrical models used, the form factor becomes :

$$F = \int_0^{\ell} \frac{ds}{\pi \cdot D(s)} = \frac{1}{\pi \cdot D} \int_0^{\ell} ds = \frac{\ell}{\pi \cdot D} \text{ , c.f. } \frac{1}{w}$$

Therefore the form factor takes into account the insulator shape, ensuring that all insulators can be evaluated independent of shape. The form factor can be obtained by direct mathematical integration, or by graphical integration.

Throughout this thesis, the measured surface conductance is referred to as conductance. No real distinction has been made in the use of the term conductivity, although volume conductivity, and surface conductivity are different concepts. When the term conductivity occurs, it is clear in which sense it is used, however, in some cases the distinction is made clearer by referring to form factor.

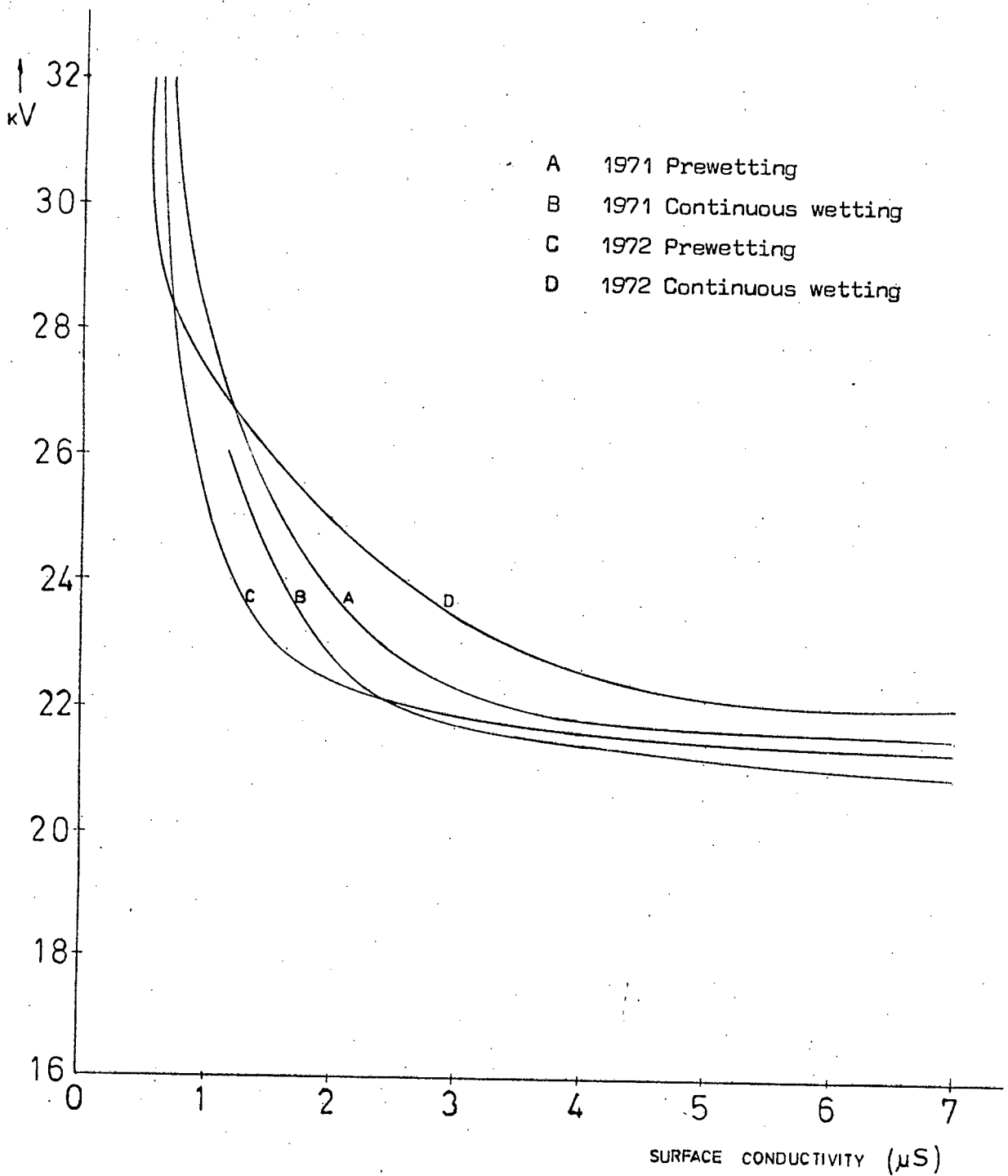


Fig 1 Previous years' results using model insulators.

For each test, the voltage at which a particular model would either flash over, or dry completely and with-stand the applied voltage, was plotted as a function of model conductivity, measured immediately preceding voltage application. The envelope of flashover points gave the curves shown in Fig 1.

It was found in all cases that if a model did not flash over within 30 seconds of voltage application, it would not flash over at all. This occurred regardless of the test method, and even under continuous spray conditions. Attempts to reproduce the flashover phenomenon as it occurs in practice were not successful. After the model had been allowed to dry, it was energised with voltages ranging from a nominal working voltage of 6 kV, to voltages of over 20 kV. It was then sprayed with a mist of distilled water to try to induce a flashover. Regardless of the energising voltage, the model withstood this voltage and remained dry.

CHAPTER II

PRELIMINARIES TO POLLUTED INSULATOR MODEL TESTS

DETERMINING CLEAN MODEL CHARACTERISTICS

Tests were started using the previously described cylindrical insulator models. In previous years, the models had been tested on a wooden frame as suspension which had proved unsatisfactory, due to the configuration used, and severe leakages were present from the models to earth over the surface of the wooden frame. A new metal suspension and a different configuration were used which overcame this problem.

The clean dry flashover voltages of the models were determined by observing ten flashover voltages for each insulator, and obtaining a temperature, pressure and humidity corrected average. The results are given in Appendix B, and the circuit diagram is given in Fig 2.

The averages were plotted against model length, and as a function of model diameter, and are shown in Fig 3. The flashover values obtained were slightly lower than those of previous years. This is due to the different suspension arrangement, and thus a different capacitive field distribution.

The flashover voltage does not alter much with changes in length and diameter, but this was expected, since the distance between electrodes varies from 21,8 cm to 23,2 cm, and diameters vary from 6,3 cm to 7,1 cm. To see whether there was any effect due to a change in surface area, flashover averages were also plotted as a function of length divided by diameter. No fundamental effect was noticed.

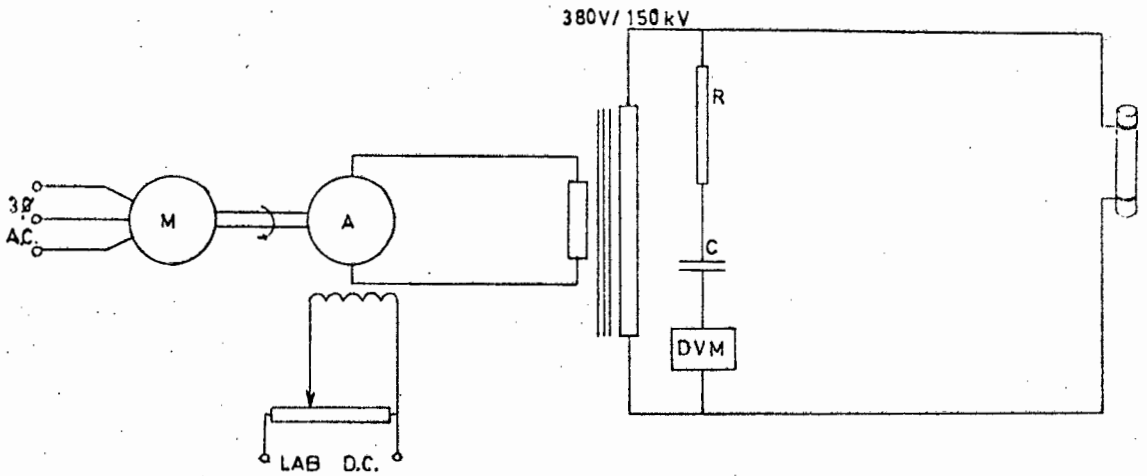


Fig 2 Initial circuit arrangement

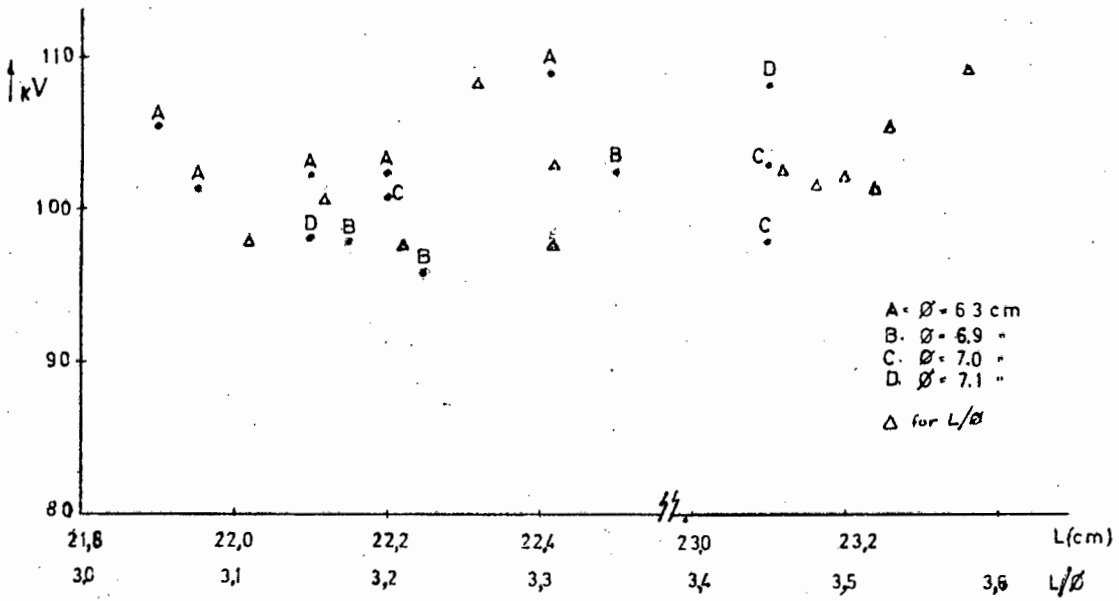


Fig 3 Model flashover voltages

THE CONDUCTIVITY BRIDGE

It was mentioned previously that the conductivity of the wet model insulators was determined by applying a 500 V a.c. source to the unit and measuring the current flowing. This may have resulted in subsequent preferential drying of the unit in certain places. It was felt that equivalent or better results could be obtained by using a low voltage a.c. bridge.

Apart from its simplicity of use, compared to the previous method, it was also used to determine pollutant slurry conductivity before spraying. For this application, a conductivity cell was also constructed, and used in conjunction with the bridge. It was hoped that the measured slurry conductivity could be used as a definite guide to the final sprayed conductance.

The operation of the bridge is quite simple. The complete circuit and an explanation of the way it works is given in Appendix A, and the bridge is shown in Photograph 1. The two bridge arms are operated in antiphase from a 15 V - 0 - 15 V centre tapped transformer, as shown in Fig 4. The same centre tapped winding drives two transistors in phase cross-over to function as switches. Thus at the electrodes a maximum of 15 V R.M.S. is applied to the unit under test. This is considered high enough to overcome slight irregularities in surface pollutant deposit, but low enough to ensure that drying is not due to measurement technique. This was checked by polluting the two model insulators and wetting them to the same measured conductance. The bridge was continuously connected to one of them, and from time to time the leads were removed and connected to the other model to monitor its conductance. It was found that the conductance of the two units kept pace with time,



Photograph 1 The conductivity bridge

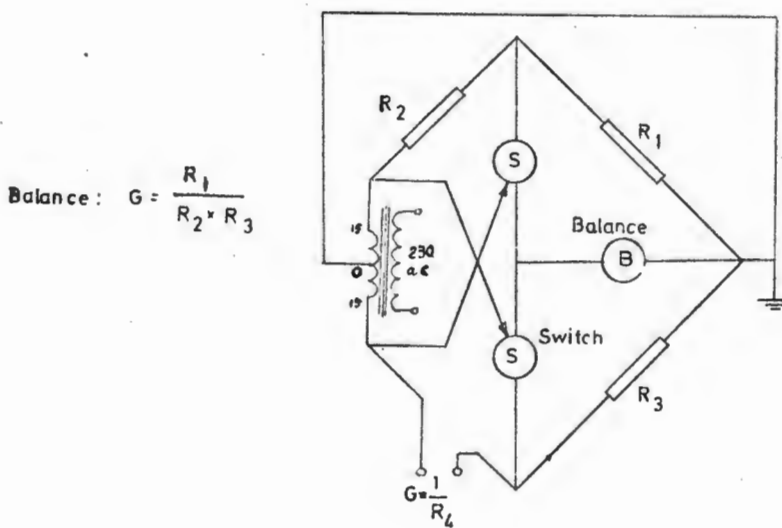
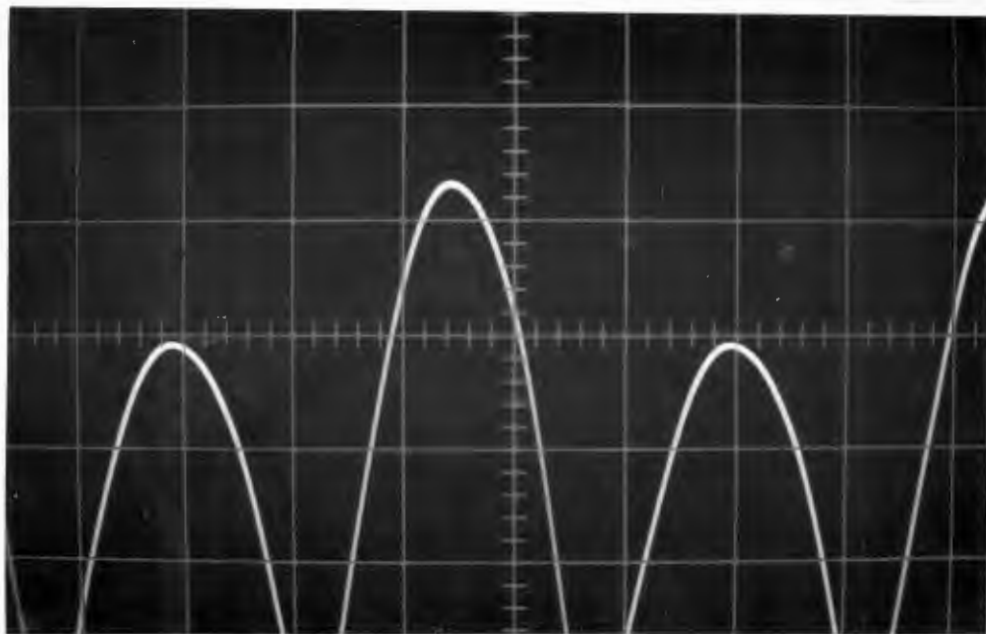
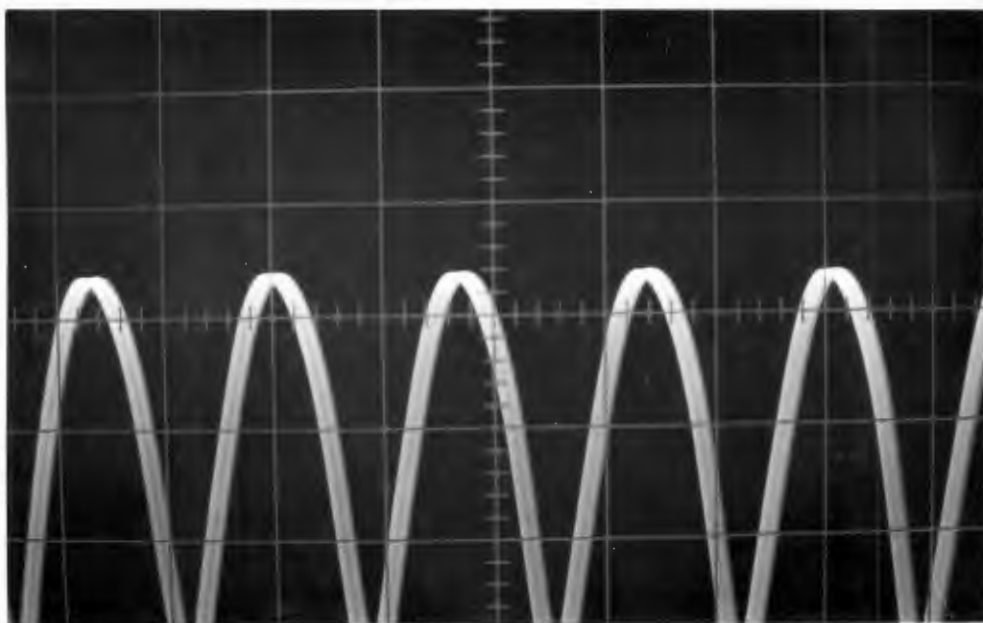


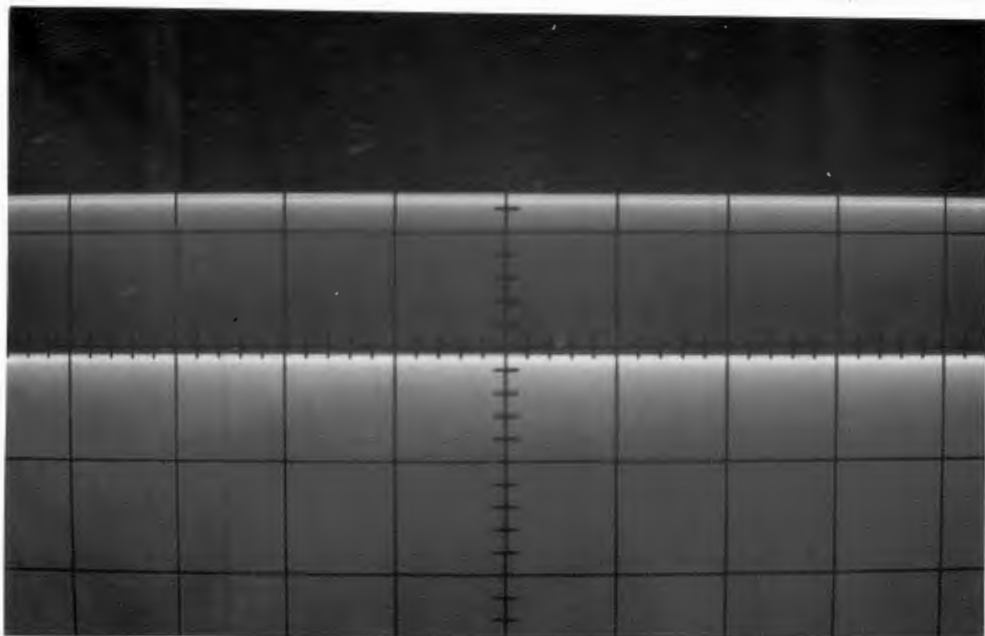
Fig 4 Conductivity bridge operation



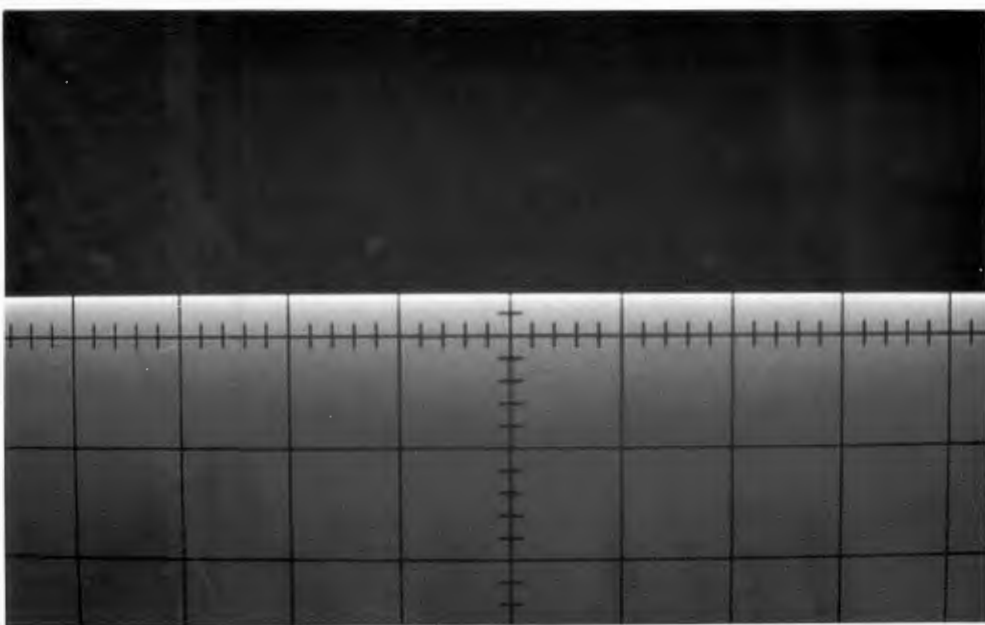
Photograph 2 Unbalanced bridge sinusoidal display



Photograph 3 Balanced bridge sinusoidal display



Photograph 4 Unbalanced bridge raster display



Photograph 5 Balanced bridge raster display.

drying was thus only due to normal atmospheric evaporation and not due to the current flowing. In fact for a pollution surface conductance of $10 \mu\text{S}$ a current of $150 \mu\text{A}$ flows, which is negligible.

The balance indicator used was an oscilloscope, the output being fed to the Y input of the oscilloscope. The time base can be set to lock on the mains frequency, giving an output as shown in Photograph 2, balance being indicated when the half-waves are of equal magnitude as in Photograph 3. An alternative is to use a very fast time base, giving a raster, and since the sinewave spends more time near to its peak value, it gives two sharp bright upper edges, as shown in Photograph 4. Photograph 5 shows the balance condition using the raster. In all cases, increased sensitivity can be achieved by increasing the gain and lowering the Y axis to show only the peaks of the switched output waveform.

The bridge has three ranges, overlapping at the ends, measuring conductance from 1 to $1000 \mu\text{S}$. This is ample range for the type of work involved, and the bridge has the great advantage of not inducing polarisation, since it is an a.c. bridge.

The unit was calibrated by connecting accurate variable resistors into the electrode sockets and marking the balance position of R_1 onto a plastic backing. The unit is accurate to half a division on all the ranges.

It must be noted that the bridge in fact measures conductance in micromhos. The measured conductance is then converted to conductivity by the form factor obtained from the insulator dimensions.

A conductivity cell to measure slurry conductivities was manufactured by the Chemistry Department of the University, to the required specifications, and is shown in Photograph 6.

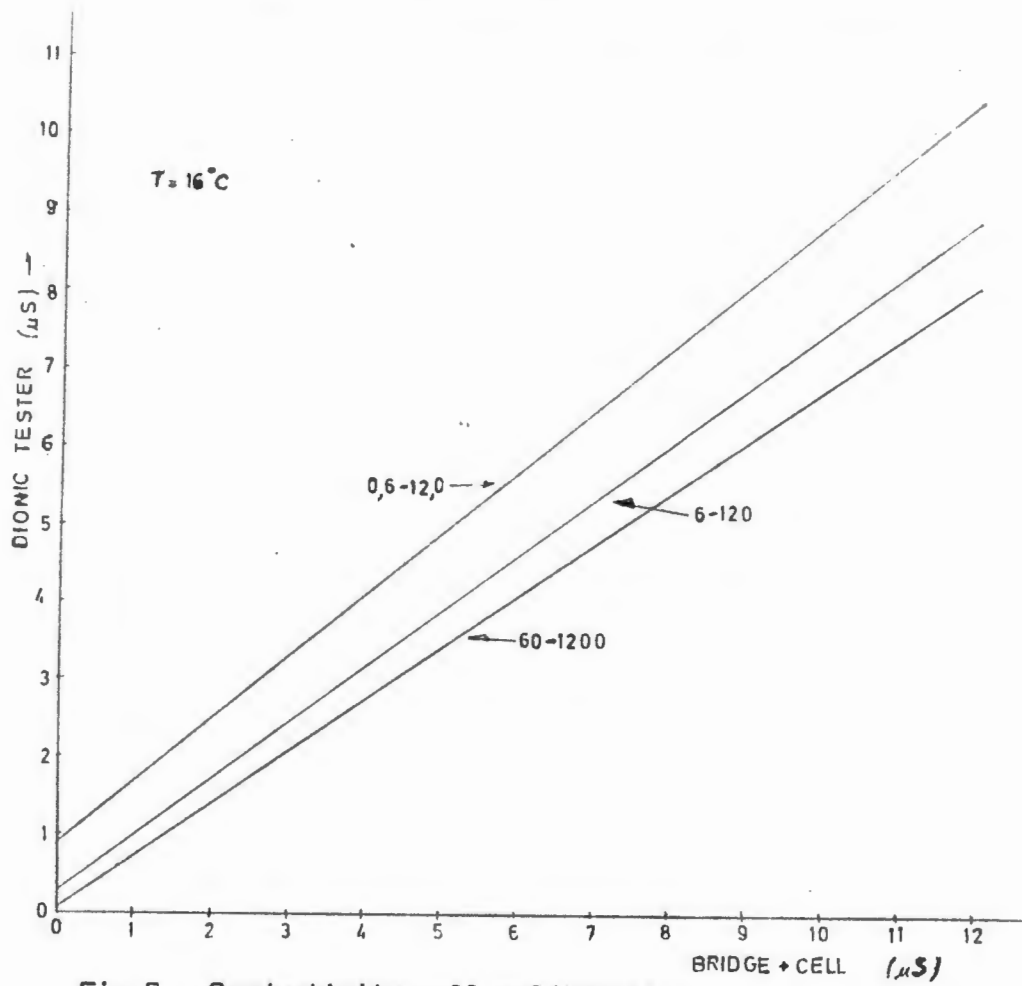


Fig 5 Conductivity cell calibration



Photograph 6
The conductivity cell

It consists of a glass cell with a vent hole, and glass supported platinum electrodes about 1 cm^2 each, set 1 cm apart. The glass covering and support ensures that calibration, once performed, is kept constant, and the cell can be used with thick slurries without damage or change. The cell was calibrated against the laboratory Dionic water tester.

A solution of salt and water was made up and its conductivity determined using the manufactured cell and the Dionic water tester. Various concentrations were used for each range, and best-fit lines were determined. The original calibration was performed with water at 16°C , and for other temperatures, tables must be used when measuring solution conductivity at these temperatures. The relation between the conductivities obtained using the two cells, can be expressed in equation form from Fig 5 as :

Range (μS)	Equation
0,6 - 12	$D = 0,9 + 0,8 T$
6,0 - 120	$D = 5,0 + 7,2 T$
60,0 - 1200	$D = 10,0 + 67,0 T$

Where D = Conductivity given by the Dionic water tester,
and T = Conductivity obtained by using the cell and bridge.

MIST CHARACTERISTICS

A collapsible wooden frame, $3 \text{ m} \times 3 \text{ m} \times 3 \text{ m}$, with a clear plastic cover was built for polluted insulator tests. The laboratory water supply was from a constant head tank, giving a maximum pressure

of 16 p.s.i., and the air supply was from a small compressor capable of delivering 2,5 cu.ft. of air at 25 p.s.i. Two sizes of Fogjet water nozzles were erected diametrically opposite, on the vertical supports of the tent, and were used to create a hollow cone, wide-angle round spray. A diagram of one of the nozzles is shown in Fig 6. By controlling air and water pressures a wide range of mist densities was possible inside the tent.

After initial estimates had been made of the expected air pressures and water flow rates, a 0,3 to 30 l/h flowmeter, and a 0 - 1 bar air pressure gauge were purchased. More accurate readings were then taken at various air pressures and water flow rates. The mist in the tent was collected through a funnel into a measuring cylinder placed at the centre of the tent, and at about the height where an insulator under test would be. After the mist had stabilized for about 10 minutes, timing was started and the volume of water collected after 1 hour and $1\frac{1}{2}$ hours was noted. The results shown in Fig 7 show that for a constant water flow rate, a roughly logarithmic relationship exists between air pressure and volume of water collected. A linear relationship was found between the volume of water collected and flow rates, for constant air pressure settings. The results tend to show that the particle size produced by atomisation has a bearing on the amount and rate of wetting produced on a particular insulator under test in such a tent. At low pressures, larger particle sizes result from incomplete atomisation, and under the influence of gravity these fall to the floor, without having travelled far in a horizontal direction.

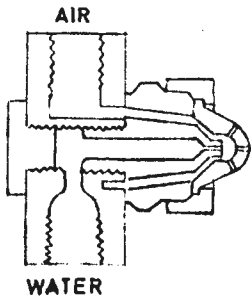


Fig 6 Atomizing nozzle

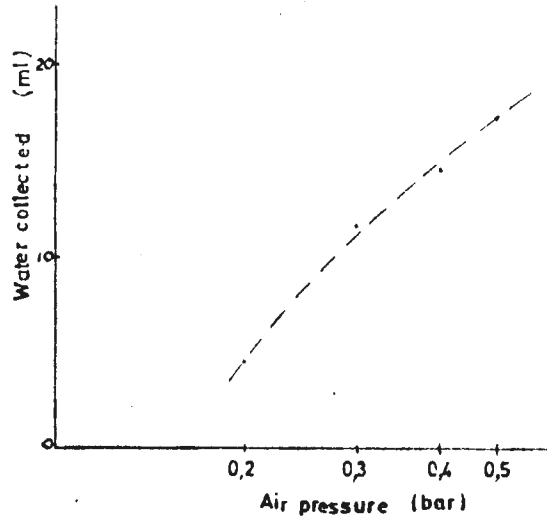


Fig 7 Constant flow rate results

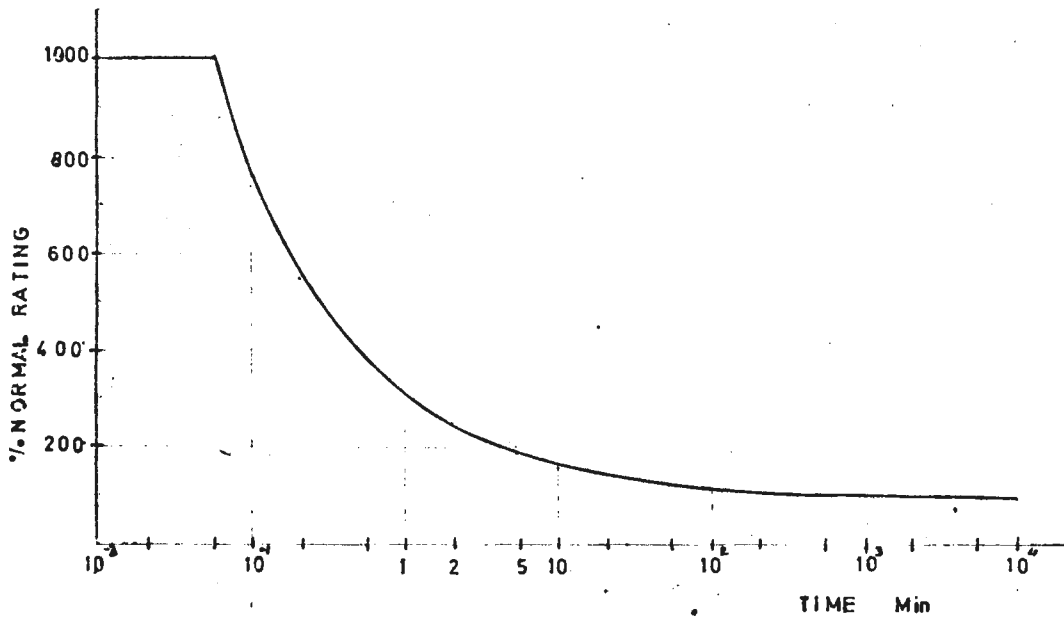


Fig 8 Variac overload limit characteristic

THE REGULATION PROBLEM

The laboratory supply used previously was found to have too high a regulation for testing contaminated insulators. When wet polluted insulators were energised, a voltage drop of half the applied voltage resulted, or a regulation of 50 %. This meant that the current was seriously limited, probably affecting the drying of the insulators and hence the flashover process. The problem persisted when two phases of a Variac were used in parallel instead of the alternator. The trouble was due to high turn-ratio of the laboratory transformer, a high magnetisation current, a low output current of 0,3 A, and that only a small portion (20 %) of the available output voltage was being used. The alternator has a synchronous impedance of 246 k Ω referred to the transformer secondary, whilst the transformer itself has a short-circuit impedance of 62 k Ω referred to the secondary. To overcome this problem a small 18 kVA, 33 kV/220 V-440 V distribution transformer was purchased.

A buck-boost arrangement was used with a 5 kW, 220 V/ 55 V transformer in the buck mode, and two phases of a Variac in parallel were used as the regulator. This ensured that only part of the short circuit current would be supplied by the Variac, while a choke coil eliminated circulating currents between the Variac phases. Fast acting 25 A fuses were used with each phase of the Variac, which invariably operated on flashover. The supply current on flashover, as measured with a galvanometric recorder, was found to be 250 A R.M.S. For a voltage setting of 20 kV to 25 kV, about 100 A is supplied by the Variac, or 50 A per phase. This is 2,5 the rated current, and the Variac characteristics in Fig 8 show that this can be supplied for between one and two minutes. The fuses were then replaced by 13 A fuse

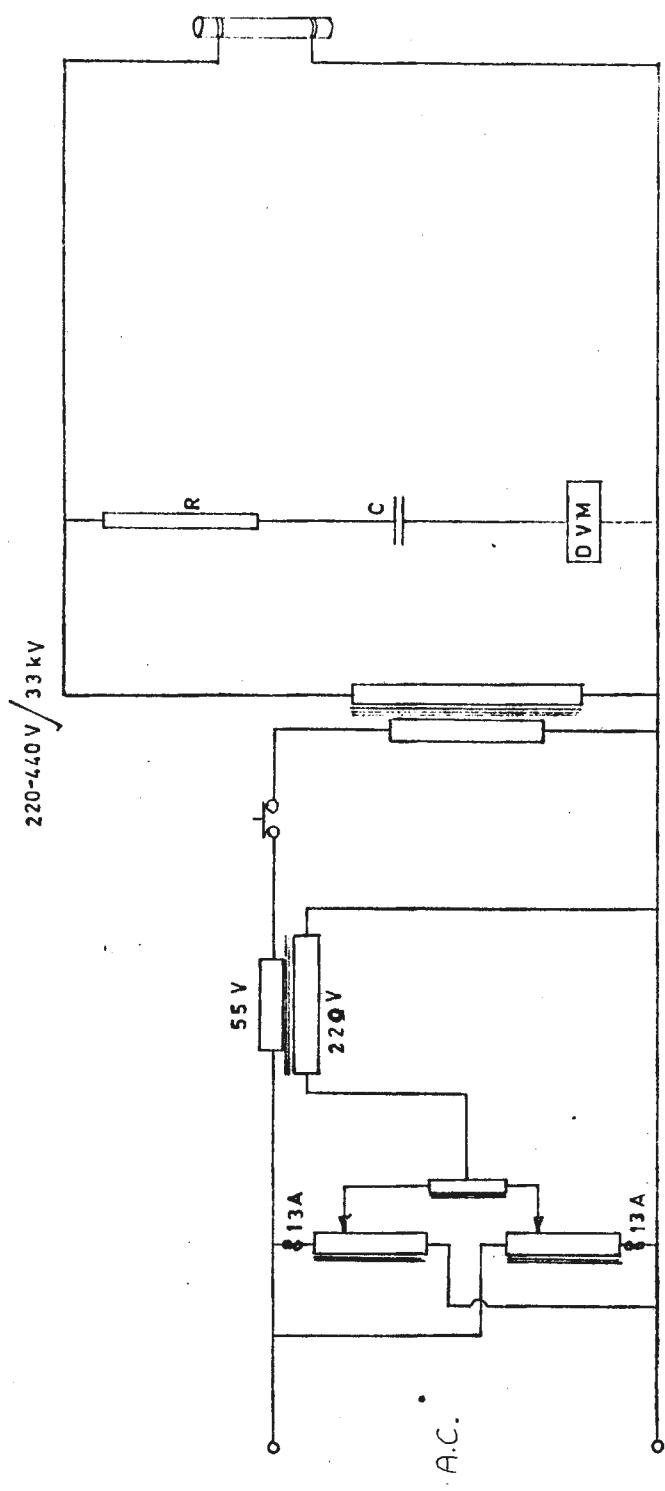


Fig 9 Polluted insulator test circuit

wire, and a hand-operated breaker was used to disconnect power to the transformer on flashover. A U.V. recording of current showed that the breaker was normally operated within 10 cycles of flashover occurring. The 13 A fuses only blew if the supply was left in for about 5 seconds, which is well within the Variac capability. In hundreds of flashovers this arrangement was found to be very satisfactory, no harm having come to the Variac windings or brushes.

The final circuit used for all subsequent testing is shown in Fig 9. The new transformer enabled a voltage range of 12 kV to 33 kV, which was adequate for model testing, or for testing single insulator units. The new arrangement gave less than 1 kV drop on energising a contaminated model, which is about 4 % regulation.

SLURRY CONDUCTIVITY AND MODEL INSULATOR CONDUCTANCE

Using the conductivity bridge, measurements were made of various pollutant slurry conductivities and corresponding insulator model conductance after spraying. Slurries were made of a standard Keiselguhr suspension, composed of 100 gm Keiselguhr, 10 gm Aerosil (S_iO_2), and 1,0 litre of distilled water. Varying amounts of salt were added to alter the conductivity. A suspension of Kaolin and distilled water with varying amounts of salt was also used.

Once the slurry conductivity had been determined, the bridge electrodes were connected to the model insulator electrodes. In this way it was possible to continuously monitor the applied pollutant conductance, and ensured no time lag between application and measurement. This monitoring method was also used on all subsequent spraying occasions, and not only for this portion of the tests.

Results showed that there was no correlation between slurry conductivity and insulator conductance after spraying. This is because the pollutant layer was sprayed onto the model by hand, and is thus a very subjective layer. Both uniformity in cover and thickness of deposit are difficult to achieve and repeat, the visual observation only being an approximation. It was also found that after the first coat had dried, and a second coat was sprayed on, the resultant model conductance did not double. This is due to several factors. One is again the problem of subjective spraying. Another is that the first layer is not wet to the same extent by the new coat, as when it was first applied. A further factor is that some drying occurs whilst spraying, because of the drying effect of the compressed air.

The problem of subjectivity can be alleviated by spraying with a mechanical arrangement of a number of nozzles, evenly spaced around the model, the model being pulled through the resulting ring of spray at a constant speed. Deposit conductivity and deposit density can then be varied, both by changing the amount of salt in the pollutant slurry, and by altering the rate at which the model is pulled through. The problem of wetting the model to the same extent after the second coat of pollutant has been applied, is more difficult. It would require further spraying with distilled water until maximum conductivity is achieved, but this point is very close to when the deposit runs off the surface.

Slurry conductivity can therefore only be used as a rough guide to sprayed pollutant conductivity. If high values of conductivity are required on insulators, a high slurry conductivity is preferable, and vice versa. This generally eliminates the need for thick deposits on the insulators if high values of sprayed conductivity are required, keeping deposit thickness to tolerable values.

CHAPTER III

CONTINUOUS WETTING TESTS ON MODEL INSULATORS

The predeposited prewet method of assessing contaminated insulator behaviour is both very simple to use, and is very quick, compared to the other test methods available for such tests. However, before it can be used for insulator assessment, it should be validated against another method, such as the predeposited continuous spray method, to ensure that the results obtained are the same for both tests. For this reason, continuous wetting tests on model insulators were undertaken.

Tests were conducted on model insulators which had been hand sprayed with a standard Kieselguhr suspension, to which some salt had been added. A varying number of layers was applied to achieve higher conductivities, rather than increasing the salt content and using only one layer. This eliminated making up of a number of solutions, although it resulted in slightly thicker deposits. Because only two or three layers were applied, this was thought justified and possibly gave a more even deposit density. The layers were applied with the conductivity bridge continuously connected to the model electrodes, to continuously monitor conductance. After the models had dried, they were placed in the mist tent, the conductivity bridge still being connected, and a mist was introduced into the tent until the model reached maximum conductance.

However, certain problems were soon experienced. Wetting of the models took between 20 and 40 minutes, at the end of which time, they were only wet on the sides that faced the spray nozzles.

The other two sides remained dry, and it was necessary to rotate the cylinders by 90° to achieve complete wetting. When this was done the measured conductance rose quickly and markedly, confirming incomplete wetting. The wetting in these conditions is thus due mainly to larger drops falling onto the model, because of incomplete atomisation. This was verified by lowering the water flow rate from 15 l/h to 5 l/h. In this case, wetting took over one hour. The longer time required may be attributed to the lower resultant mist density, but the model still had to be rotated, although the observed rise in conductance, was not as great as before. The amount of water being pushed out into the mist tent therefore had little effect, except to determine the rate at which wetting occurs in specimens. An increase in wetting rate is mainly due to the increased mist density that occurs with higher water flow rates. The wetting rate is also affected by the air pressure. Although a higher pressure promotes finer atomisation, the spray is projected further at the same time, and more water falls onto the polluted unit.

When the spray nozzles were pointed away from the insulator models, achieving maximum conductance took even longer, but a more even wetting took place.

It was felt at this stage that the predeposited continuous wetting method is a small variation from the predeposited prewet method. Once maximum conductance has been achieved, and the model is energised, the only difference between the two methods is that a fine fog is enveloping the model in the continuous wet test. Flashover develops normally within 30 seconds of voltage application if it develops at all, otherwise the unit dries out completely and remains dry. In this time, provided the mist is not too heavy, rewetting of

the model is minimal, and almost no difference should be experienced with results from either method. This is dealt with more fully in the next chapter.

During the wetting interval before energisation, it was found that as wetting continued, the measured conductance kept on increasing until the pre-deposited layer washed off. The conductance rose to a value greater than that recorded when the pollutant was first applied, and this occurred in all cases, even when only one layer had been applied. Moreover, the conductance often kept on increasing, even after the pollutant deposit had washed off. The final value was usually half as great again as the measured applied conductance value. This shows that the conductivity of the laboratory water supply was far too high, compared to applied model conductivity.

The conductance reached was thus not only a function of the initial pollutant conductance, but was also a function of the deposit thickness, and hence the water thickness if the specimen is fully saturated. This not only applies to thick layers, but due to the high water conductivity, also applies to the present tests. The flashover process would then be influenced, and possibly governed by the latent heat of evaporation of water when the voltage is applied and drying occurs.

Tests with the mist tent were thus abandoned. This type of test could be resumed, without having to alter the water conductivity, if very high pollutant values are required for tests. It was then decided to validate the prewet method with the aid of results obtained in previous years for the continuously wet method.

CHAPTER IV

PREDEPOSITED PREWET TESTS ON MODEL INSULATORS

Validation of the predeposited prewet method was achieved by comparing results from the predeposited prewet method, with previous years' results from the predeposited continuously wet method. At the same time, the method of using partial but uniform wetting was investigated as a means of insulator assessment. This set of tests was performed using Kieselguhr as pollutant. To determine whether a Kaolin suspension could be used to obtain equivalent results, predeposited prewet tests with full wetting were also conducted.

KIESELGUHR TESTS USING PARTIAL WETTING

The first set of tests using the partial wetting technique was performed using a standard Kieselguhr suspension, only one coat being sprayed onto the insulator models used previously, the conductivity being adjusted by adding salt to the suspension. Photograph 7 shows a polluted and a clean insulator model. During spraying, the wet conductance was measured, and the unit was subsequently allowed to dry. Once dry it was sprayed with distilled water from a hand-held spray gun, but the conductance was not allowed to reach its previously recorded value. The unit was sprayed as evenly as possible from a distance, so that uniform but partial wetting took place. The conductivity bridge was then removed and a known preset voltage was applied. Whether the unit withstood the applied voltage or not was noted, and this voltage was recorded on a graph against the measured conductance, adjusted by form factor to give conductivity.



Photograph 7 Contaminated and clean model insulators

The number of times that individual models were used before re-polluting depended on the condition of the surface after each test, and the models were generally used for three tests before washing.

The up / down method of obtaining the 50 % flashover probability voltage was tried without success. In theory once this probability has been found, a normal Poisson or Binomial distribution is assumed, and any other flashover probability value can be determined. The method consists of applying a known voltage to a polluted specimen of known conductivity. Flashover or withstand is noted for this voltage, the unit is allowed to dry, and is subsequently re-wet to the same conductivity as before. The voltage is lowered or raised respectively by 5 % and the result is again noted. This is repeated until there is a change of result, when the voltage is now raised or lowered respectively by 5 %. The voltage for the 50 % flashover probability is then given by :

$$V_{50 \%} = \frac{\sum (n V)}{\sum n}$$

where n is the number of times the voltage V was used, irrespective of whether a flashover or withstand was recorded. The method relies on at least 20 observations being made for a given conductivity value, with each voltage value recurring three or four times. It was not possible to achieve exactly equal conductivities without performing an unacceptably great number of tests, and since only a few tests were performed for each conductivity value, the resulting curve was very distorted.

However, all the individual results, given in Appendix B, were plotted on a graph, and the envelope of flashovers gave the curve shown in Fig 10.

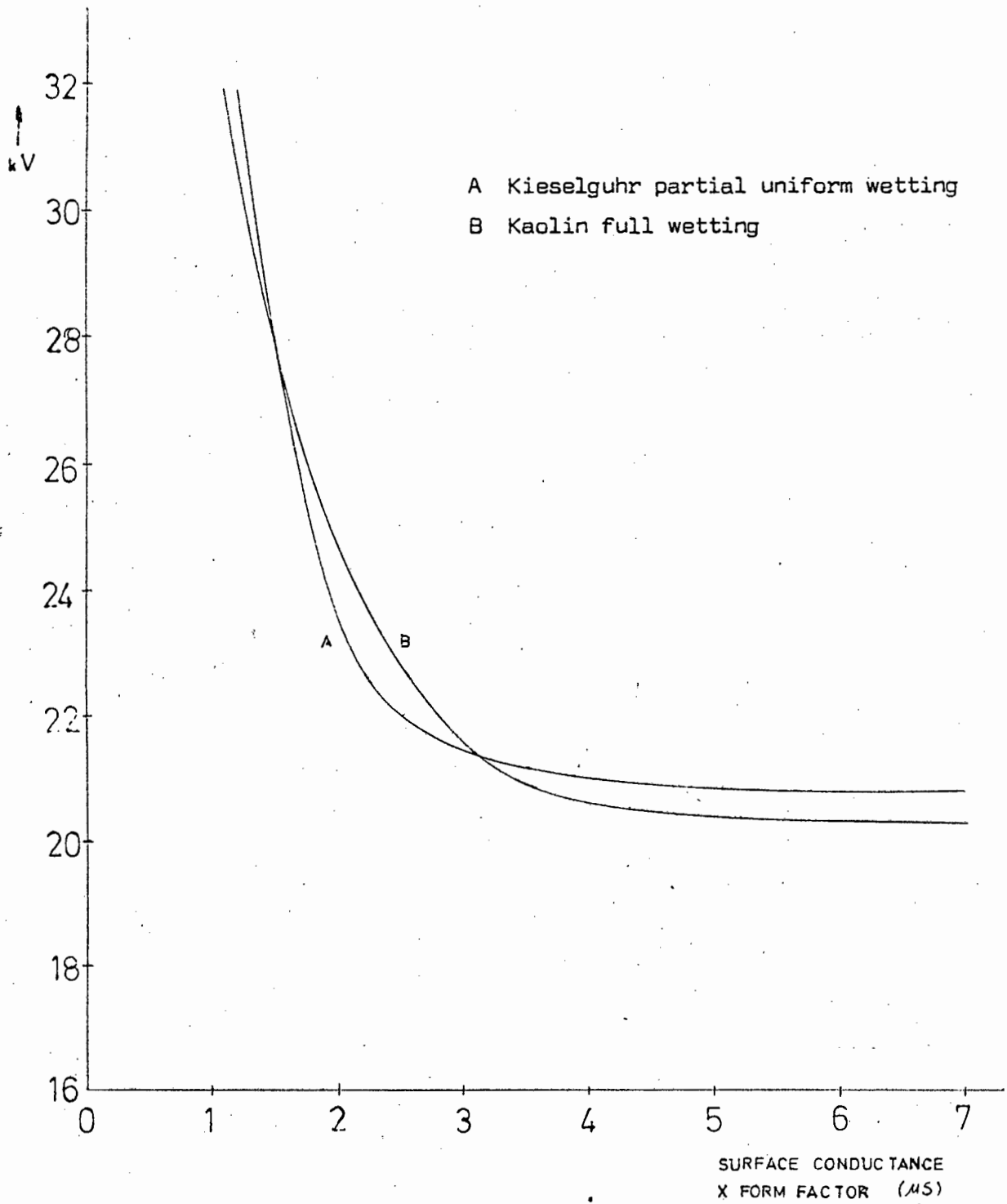


Fig 10 Kieselguhr and Kaolin curves for model insulators

KAOLIN TESTS USING FULL WETTING

The next set of tests was performed using a Kaolin and distilled water suspension. Two types of clay were easily available, a dark grey one and a white one. The dark clay has impurities, including iron and a number of oxides, and is unsuitable. The white clay on the other hand is extremely salt free and inert, this clay having a lower conductivity than Kieselguhr for equal amounts in suspension. It has good binding or adhesive properties provided not too much water is added.

A slurry was made up using this clay and distilled water, of a consistency suitable for spraying. Insulator models were again sprayed with one coat of pollutant, and the conductivity was adjusted by adding salt.

For some tests however, the models, once dry, were sprayed with distilled water to their maximum conductance, and this value was always close to the one measured when the pollutant was first applied. Excessive spraying with water caused pollutant run-off, and a certain amount of care had to be exercised. As before, a pre-set known voltage was applied to the unit under test, and the envelope obtained from the tests is shown in Fig 10. Individual results are given in Appendix B. Again only three tests per model were conducted, each time spraying with distilled water to achieve maximum conductance. If more tests were performed, the flashover voltage tended to become erratic, probably due to ionic salt concentration redistribution.

DISCUSSION OF RESULTS

It can be seen from Fig 10 that the curves obtained by the two different methods are close to one another, whilst the effects of

subjectivity in these tests must still be borne in mind. Both curves were obtained using the predeposited prewet technique. In one case, Kieselguhr was used with uniform, but partial wetting, to achieve any desired conductivity. Although salt is the conducting medium, the amount of distilled water sprayed onto the unit determines the conductivity, before energisation. In the other case, Kaolin was used with uniform full wetting to achieve the maximum possible conductivity, without causing the run-off of the deposit.

The curves obtained in 1971 and 1972 are reproduced in Fig 11, to which has been added the curves from Fig 10. The previous years' results were obtained by two different operators, using a standard Kieselguhr solution, with both continuous and pre-wetting techniques.

Certain observations can now be made, and conclusions drawn from these results.

The end result of the two sets of tests is that the curves obtained by the two techniques are close to the ones obtained in previous years, and that they are also close to one another.

The results of Kieselguhr tests with partial wetting, show that since this curve is close to the continuous wetting curves, the predeposited prewet technique is equivalent to the predeposited continuously wet technique, and the test method is thus validated. Furthermore, partial wetting can be used instead of wetting to maximum conductivity, provided the measured conductance before voltage application is used to plot the curves. This can be concluded, since the Kieselguhr prewet curve using partial wetting is again close to all the other curves.

The results of Kaolin tests with full wetting show that Kaolin may be used in the place of Kieselguhr as pollutant.

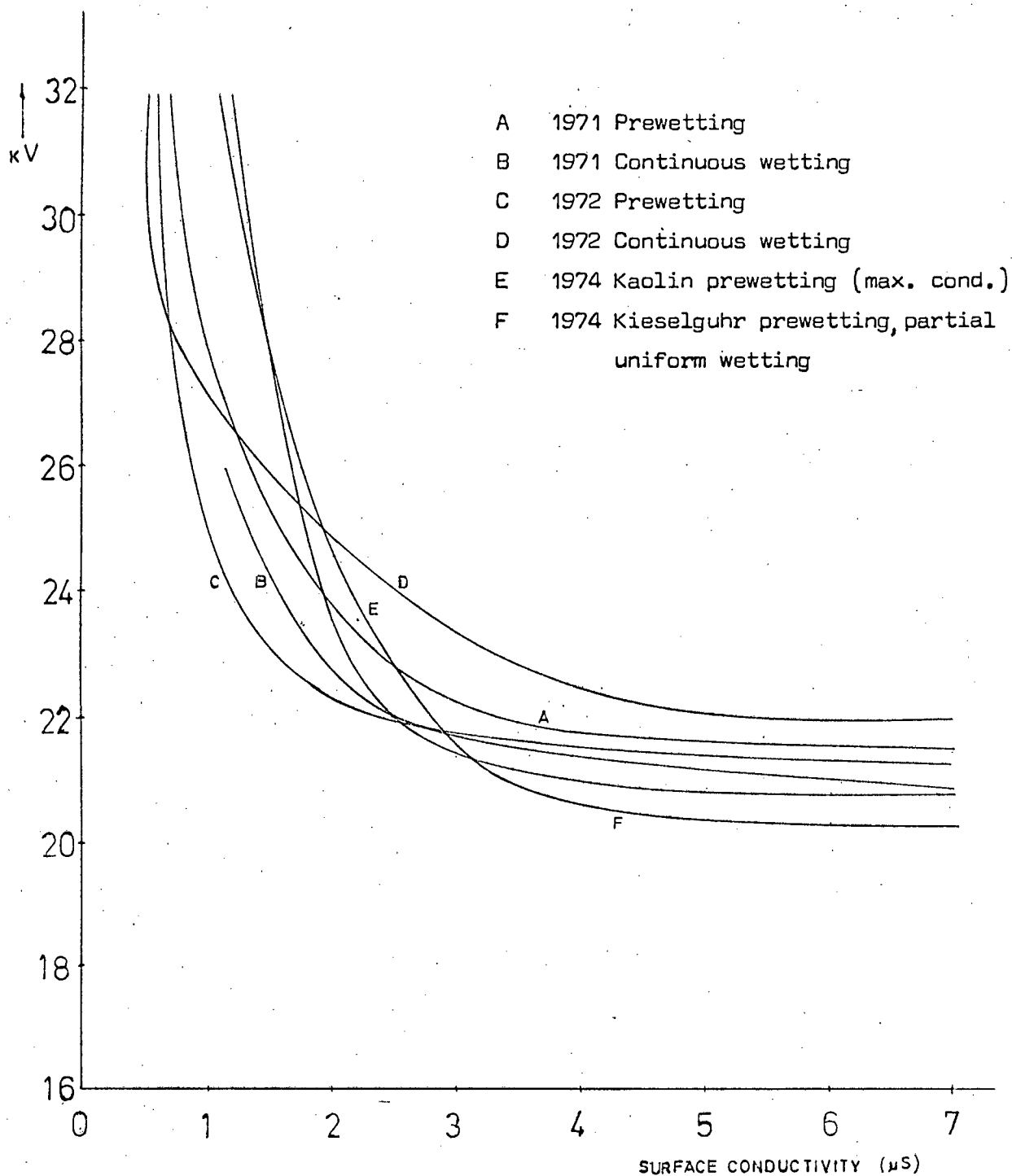


Fig 11 Pollution curves for models, 1971 to 1974

This is because the curve obtained with Kaolin is again close to the prewet curves of previous years, and in both cases, the models were taken to maximum conductivity, ensuring equivalent wetting technique.

The fact that the partially wet curve using the Kieselguhr, and the fully wet using the Kaolin are close to one another, has a further significance. It means that any inert pollutant can be applied to achieve a pollution curve.

The predeposited continuous wetting type of test is therefore only a variation of the predeposited prewet test. If in both tests similar units are sprayed until they reach similar maximum conductivities, and then are subjected to a voltage stress, then the results should be close to one another. This is true of the results above. Any difference that may occur should be due to the fact that in the prewet case there is no enveloping mist, and in the continuous wetting case the unit has mist around it on energisation. This can influence the results in two ways. Firstly, as an arc is inclined to travel more easily in the resulting steam, the continuous wetting case may lead to a slightly easier condition for flashover. Secondly, the enveloping mist will tend to modify the resistance of the unit since it will continue to wet the surface.

It must also be remembered that the application of the pollutant, the method of measurement of conductivity, and the method of wetting the models, were performed by three different operators, working independently of each other.

Fig 12 shows the envelope of boundaries for all six curves of Fig 11 on a voltage scale to the mean, clean dry flashover value for all models. The shaded portion between the full lines is obtained from laboratory tests, whilst the unshaded portion between the dotted lines

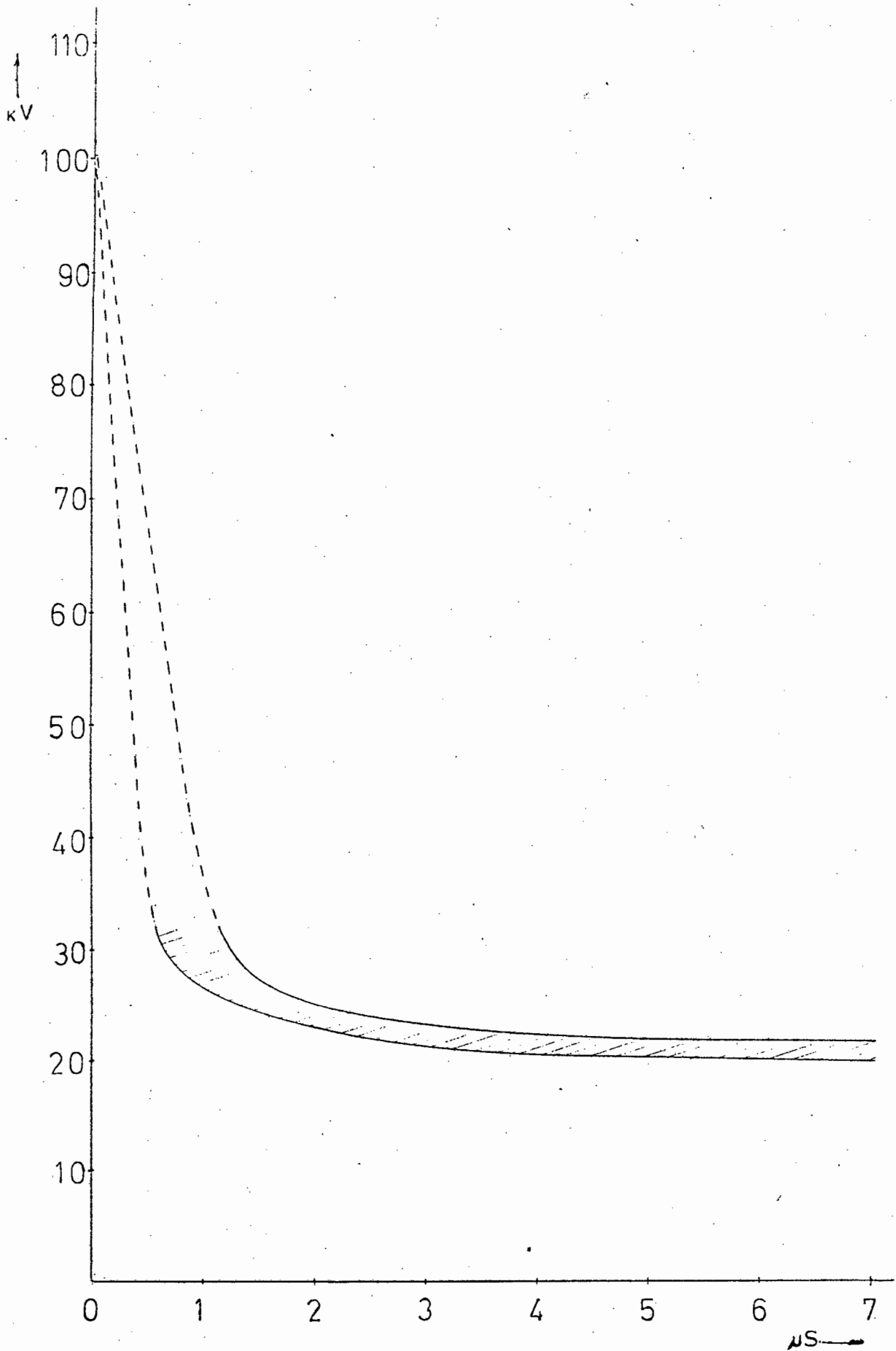


Fig 12 Flashover boundaries for insulator models

is the presumed envelope limits to the clean flashover value.

The average difference of all the curves together, related to the lowest boundary was found to be 7,3 %. This percentage difference is arrived at by noting the voltage difference between the lower and upper curve for a given conductivity from 1 μS to 7 μS , and expressing this value as a percentage of the voltage of the lower curve at the chosen conductivity. These percentages are then arithmetically averaged to give the final percentage difference.

It is necessary to use this method, or a similar one, since the position of the curve for the same insulator varies with conductivity, (or the amount of pollutant deposit), and it is not possible to relate conductivities to a clean, dry flashover voltage value.

The analysis of the difference between continuous and prewetting curves for separate years gives averages of 3,7 % for 1971, and 5,7 % for 1972. This tends to reinforce the view that the two techniques are almost equivalent. The difference between partial prewetting and wetting to maximum conductivity was found to be only 2,5 %, which indicates that either method can be used to obtain a curve for a polluted insulator.

In all cases the observed difference is less than 6 %, whilst the lowest difference is only 2,5 %. These differences may therefore be ignored. This view was supported by Professor Kind, who is the director of the High Voltage Research Institute at Brunswick University. In a conversation he stated that for laboratory tests on insulators under polluted conditions, due to the large number of variables involved, a difference of 5 % in performance or results is not very significant, and that in Europe, a difference of 10 % or greater is regarded as being significant.

Thus either the predeposited prewet method, or the predeposited continuous wetting method can be used to obtain pollution curves for insulators in the laboratory. However, one method should be used throughout to maintain consistency of procedure. It can also be seen that any inert pollutant can be used to give these curves, and that it is possible to use any desired conductivity. It follows that after initial contamination, instead of using distilled water, a salty solution may be sprayed to increase conductivity, without having to make up a number of batches of pollutant with varying amounts of salt. All this greatly facilitates the testing, and the time required for such tests is also considerably shortened.

Some conditions must however be noted to qualify the above statements.

a) The pollution film must not be too thick, since this may influence the flashover process by impeding the escape of steam formed after energisation.

b) Not too much water must be used to bring the insulators to a given conductivity, since the flashover process may be influenced by the large amount of latent heat required to evaporate the water for dry bands to form.

c) It must be ensured that wetting of the pollution layer is uniform. If this is not so, preferential drying takes place at a point which has been wet more thoroughly. Dry band formation may then be governed by this, and the flashover process may again be unjustifiably influenced. Uniform wetting is especially important at low conductivity values. This may be improved by using a low conductivity pollutant in the first place, such as Kaolin, which requires more water than Kieselguhr to achieve an equal conductance for the same deposit density.

It can be argued that the above conclusions and conditions may not apply to practical insulators, especially in the field, where almost invariably, there are uneven pollutant deposits, non-uniform wetting and amounts of water ranging from a fine fog to a heavy shower.

However, the conclusions and conditions apply to tests performed in the laboratory, and specifically to the model insulators tested. No attempt has been made to reproduce surface contaminant distribution that occurs in practice, but an attempt has been made to develop a simple, quick, reliable, and efficient testing technique, to judge polluted insulators in the laboratory. This has been shown to have been achieved, at least with cylindrical model insulators. The next major step, was to see whether this simple technique could be extended to practical insulator shapes.

CHAPTER V

SIMULATION OF FOG TYPE FLASHOVER

Before tests on practical insulators were started, an investigation was conducted into the problem of inducing a flashover under mist conditions, when polluted models were already energised. As mentioned previously, it had been impossible to induce a flashover at any voltage below the clean flashover value, using the continuous wetting technique when the insulator models were already energised.

It was thought that if trouble-prone insulators, as used in practice on lines and substations, were removed and tested for their conductivity using distilled water, they would show fairly high conductivities. The conductivity values determined from leakage current measurements cannot be regarded as true conductivities, due to the dry bands occurring under energised conditions. Even under arcing conditions, when large currents may flow, to leave only a small portion of the conducting surface between various arcs, the remainder of the insulator is non-conducting, due to the dry bands, unless arcs are present there as well. Thus in general, the apparent conductance measured by leakage currents tends to be low, but to produce a flashover, the real conductance of the unit without dry bands should be high.

To test this idea, the same model insulators were used, polluted with one coat of standard Kieselguhr suspension, but a large amount of salt was used to give a measured wet conductance of about 10 times normal, i.e. between 60 μ S and 100 μ S. The test voltage range was from 6 kV to 25 kV and various mist densities were used by adjusting water flow rate into the tent.

The lower voltage value was chosen so as to give about one inch leakage distance per kV_{L-L} . Although models were used, the figure approximates the values found in practice. Starting with a dry energised model in the tent, in all cases the insulator model under test flashed over within 15 minutes of introducing the mist spray. The mist took between 5 and 10 minutes to stabilize in the tent, and flashover occurred earlier with higher energisation voltage and with higher water flow rates. When lower voltages and lower mist densities were used, the flashovers took longer to occur, but again, in all cases, the model flashed over.

The discharge stability criteria proposed by various investigators all try to relate the complex voltage, current, and pollutant resistivity combinations to the simple final result of flashover or withstand. The dry band and flashover processes are easier to understand if treated qualitatively, and Fig 13 shows the processes.

Starting with a wet polluted insulator that is subsequently energised, dry band formation and arc development occur as follows. The current flowing causes preferential drying of the pollutant at one point. For a cylindrical model, the position of this point is normally determined by some slight irregularity, or some point where a thicker surface deposit is present. For practical insulators this point is normally near one of the electrodes, because of the increased current density there due to insulator shape. The current density in the wet region near the dry point is now increased, and further drying takes place. This continues until a thin dry band is formed around the insulator. Since this narrow band cannot support the voltage stress, an arc develops. Further drying takes

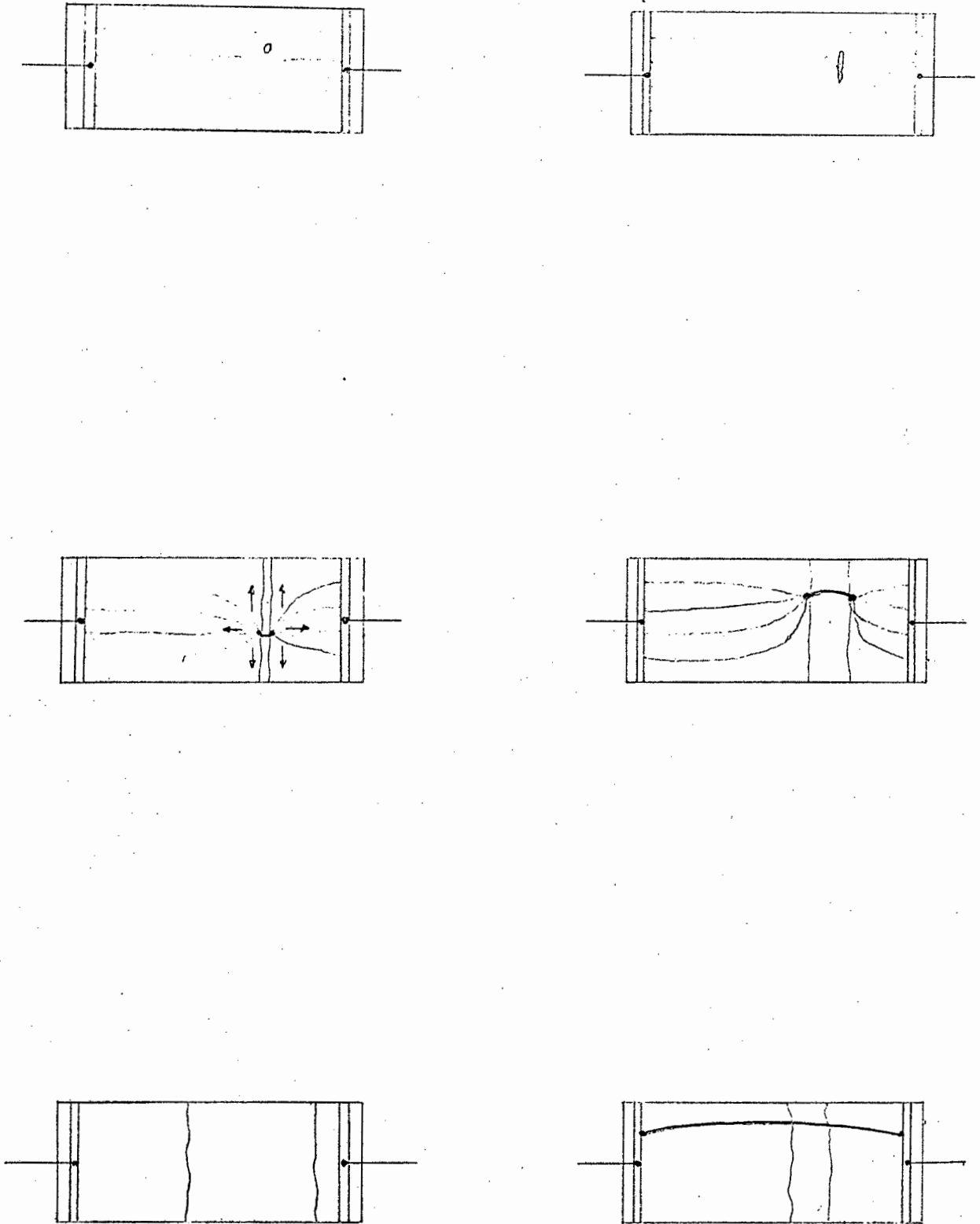


Fig 13 Dry band and arc formation, leading to withstand or flashover

place at the arc roots, and the arc is forced to move. The arc can travel either to the electrodes, or circumferentially around the insulator. In the latter case, the dry band widens, until it can withstand the voltage stress, and the arc is finally extinguished.

The arc can of course, travel to the electrode at any time after dry band formation. If the voltage stress across the arc is lower than the value required to maintain it burning, the arc will extend towards the electrodes. This is achieved if the resistance in series with the arc is decreasing faster than the arc can travel circumferentially around the insulator, or in fact, completely dry the pollutant at the roots. Flashover then results. But this is exactly what was achieved in the laboratory. The models had a high conductivity. When wet by a mist spray, a conducting path was achieved which soon caused a dry band and an arc to develop. However, due to the large amount of salt present, the conductivity of the wet portion fell very fast, and the arc travelled from one electrode to another, following an ever-decreasing resistance path to create flashover. Only a small amount of water was required for this because of the high ionic salt solubility. This is important, since it has direct application to the pollution condition found at the coast, where the pollutant collected by insulators is mainly crystalline salt.

The low values of conductivity chosen for the tests on models in previous years, explains why flashover under energised conditions was never achieved.

A paper presented at a recent Symposium on High Voltage Engineering in South Africa, in Johannesburg, in November 1974, held a possible key to the verification of the idea that the measured conductivities of polluted insulators in service had to be high for flashover to occur. It was reported that a string of insulators which had flashed over in service had been removed, and the flashover had been reproduced in a laboratory when energised at service voltage and sprayed with water mist.

It was suggested that the conductivity of the un-energised insulators when saturated with distilled water, be measured. The six insulators were of the Bullers flat disc type, but unfortunately their resistance was measured with a digital multimeter. The following results were given :

1	5,61 Mohms	4	1,02 Mohms
2	2,00 Mohms	5	3,50 Mohms
3	2,80 Mohms	6	3,60 Mohms

Thus their conductance varied from $0,178 \mu S$ to $0,98 \mu S$. Assuming an insulator form factor of 0,519 the corresponding surface conductivities are $0,09 \mu S$ and $0,51 \mu S$ respectively. The low conductivity values may be explained in the following manner.

Under service conditions the insulators would be subject to deposition, and when moistened, arcing would occur. The dry bands form first at regions of highest current density, namely the cap and pin, and severe arcing would almost always be present. With water evaporation and arc movement, most, if not all of the deposit at the cap and pin would be removed and swept away by the wind.

A digital multimeter is a very low voltage instrument, thus bridging of these gaps would not be possible, and incorrect information would be obtained about surface conductivity. It is still felt that for flashover to be possible at working voltage, the surface conductivity would have to be considerably higher than those quoted.

This is because laboratory tests on model insulators in previous years did not flash over when conductivities used were in the order of $6 \mu\text{S}$, and energisation voltages were about 20 kV. Secondly, flashover occurred at an equivalent service voltage with model insulators only when conductivities were in the order of $50 \mu\text{S}$.

The problem is then one of measurement. For service insulators the gaps between the electrodes and the pollution layer should be eliminated if unenergised values of conductivity are to be measured. This can be done by using a high voltage source for a few seconds to bridge any gaps present with arcs, and then measure the leakage currents. An alternative is to use a conducting paint or paste to short these gaps out.

The problem of measuring the true conductance was again present in the next chapter, where tests were performed on practical insulators.

CHAPTER VI

PRACTICAL INSULATOR TESTS

The simple technique of partial prewetting was extended to practical insulators. If an order of merit could be obtained using different insulator shapes, the technique would be fully validated. The order of merit obtained in the laboratory need not be the same as the one obtained from field tests. This is because with the tests described below, the self-cleaning properties determined by insulator shape are not taken into account.

Two types of insulators were available. One was a Pilkington toughened glass insulator, with a diameter of 10" and a leakage distance of 11". The other type was a Bullers open profile or flat disc type with a 12" diameter to achieve the same 11" leakage distance as the Pilkington type. The insulators are suitable for 11 kV_{L-L} each, giving about one inch leakage distance per kV_{L-L}. Photograph 8 and Photograph 9 show the tops and the undersides of both insulator types.

In spraying the insulators with pollutant it was found that the measured conductance was only in the order of 1 μ S. This was found to be due to the sprayed pollutant not making good contact with the metal cap and pin of the insulator. The problem was overcome by filling the gaps with a semi-conducting compound called 'Gun-Gum'. For laboratory work the gap can be filled with any conducting or non-conducting filler, provided it leaves a smooth finish and is not easily soluble in water. If a non-conducting filler such as cement is used however, the form factor for the unit has to be re-calculated to take into account the increased leakage path.



Photograph 8 Pilkington and Bullers insulators (tops)



Photograph 9 Pilkington and Bullers insulators (undersides)

After the gaps had been filled, the insulators were again sprayed whilst measuring the conductivity, and this time conductivity measurements showed considerable improvement.

To obtain the complete range of conductance values required, different methods were used. One or two layers were sprayed on, with suspensions containing various amounts of salt to achieve the required conductance. For lower values, a Kaolin suspension was used instead of the standard Kieselguhr suspension. Again, one or two coats were sprayed on, with suspensions containing various quantities of salt.

If only one coat of pollutant was used, the wet conductance was recorded, and the insulator disc was energised at a preset voltage. The result was noted and the insulator disc was allowed to dry. When thoroughly dry the insulator was sprayed with distilled water, while the conductance was again measured. The insulator was not necessarily taken to its previously measured conductance value whilst being sprayed, but it was endeavoured to spray as uniformly as possible. The pollutant layer was then allowed to stabilize for a minute or so before voltage application. It was noticed in most cases, that during this period the measured conductance rose slightly, and then remained quite steady until the water evaporated under natural drying. The measured conductance rose because more salt nuclei became ionized as the water permeated the pollutant. The slight increase after spraying was particularly noticeable, if incomplete saturation, and hence incomplete salt ionisation was obtained by partial but uniform wetting.

The drying and wetting process was repeated, obtaining another conductance value. In this way, at least three different values of conductivity were achieved for a particular insulator disc before wash-

ing it, cutting down the amount of time and work required to obtain a pollution curve.

If two layers of pollutant were applied, the unit was allowed to dry before spraying on the second layer. Monitoring of conductance showed similar results to those obtained when polluting models, when more than one layer was applied.

After the second layer had been applied, and its conductance noted, the unit was energised at a preset voltage. The result was noted and the unit was allowed to dry. The wetting and drying process was repeated two or three times, each time testing at a different conductance value.

The reason for allowing the insulators to dry completely between tests was to allow the insulator and pollutant to regain ambient temperature. With the arcing produced from energisation, a lot of steam was produced, raising the insulator surface temperature. By allowing restabilisation of temperature, it ensured that preferential drying of pollutant after energisation was not influenced by temperature inequilibrium.

A separate curve was obtained for each type of insulator. The results which gave the curves shown in Fig 14, are given in Appendix B. The curves are the envelopes of the lowest voltage which caused flashover for a particular measured conductance, and the transition from flashover to withstand was clearly defined for both curves.

It must be noted that the curves were obtained using one insulator disc of each type. It is realized that results obtained by testing single units are often erratic, but the curves obtained from the tests had clearly defined boundaries, and it is not thought.

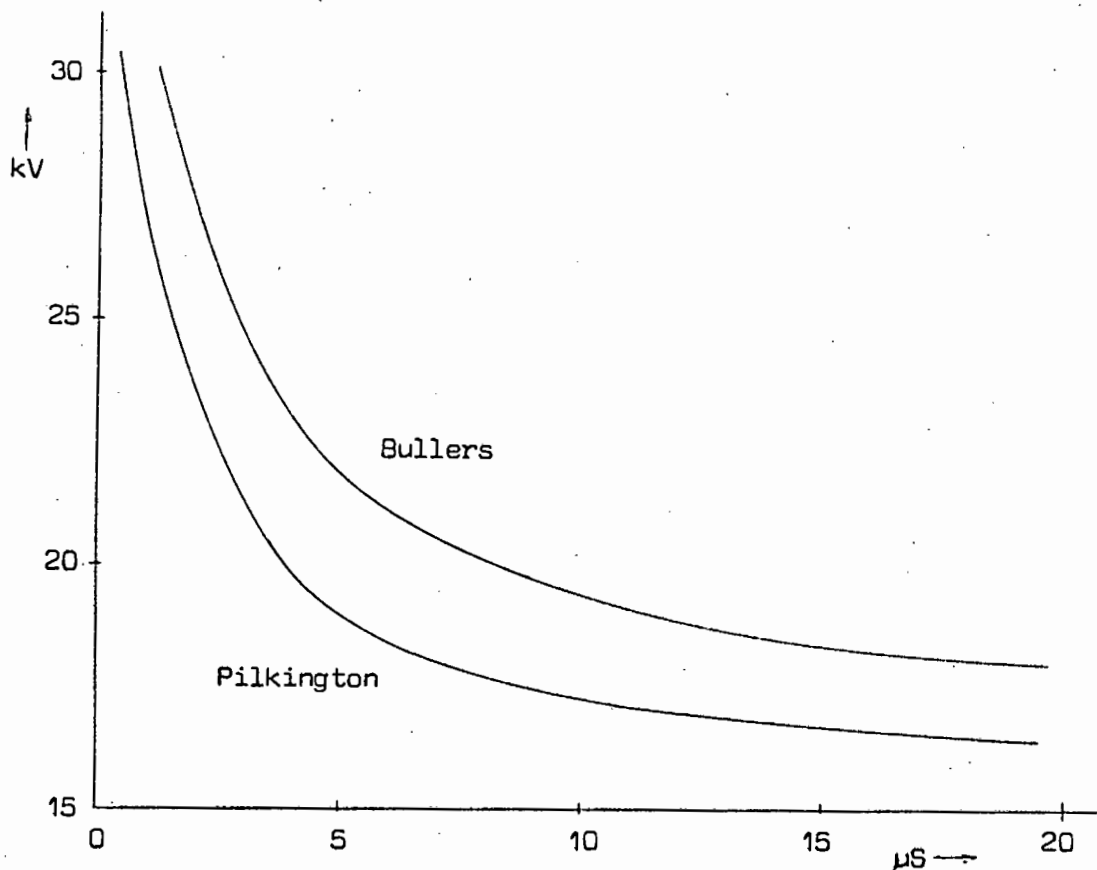


Fig 14 Insulator pre-wet pollution curves without form factor

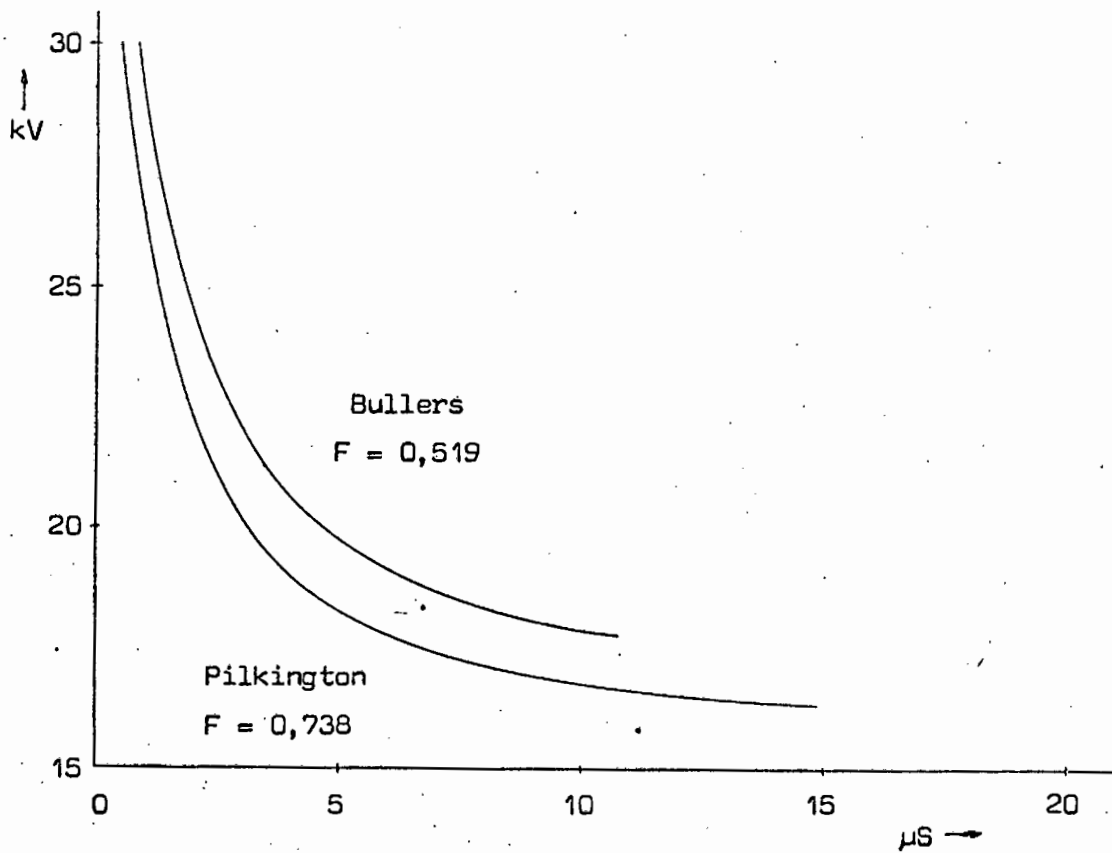


Fig 15 Insulator pre-wet pollution curves with form factor

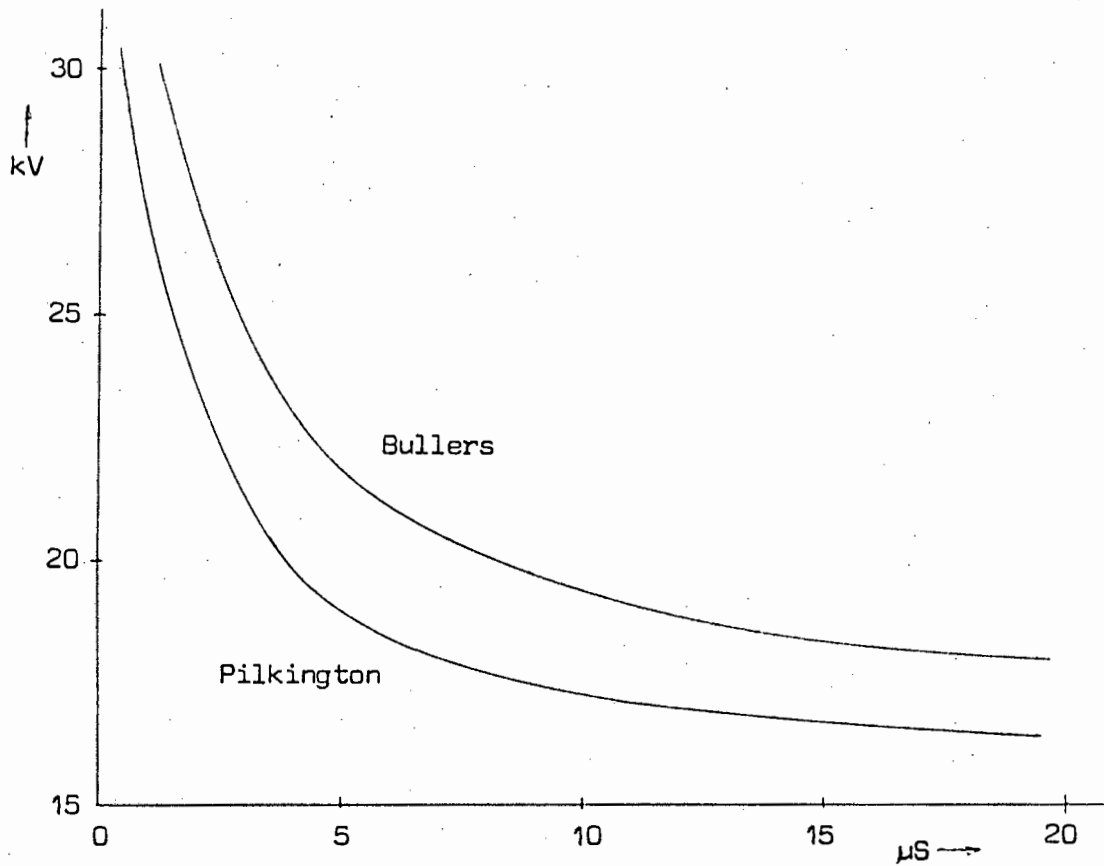


Fig 14 Insulator pre-wet pollution curves without form factor

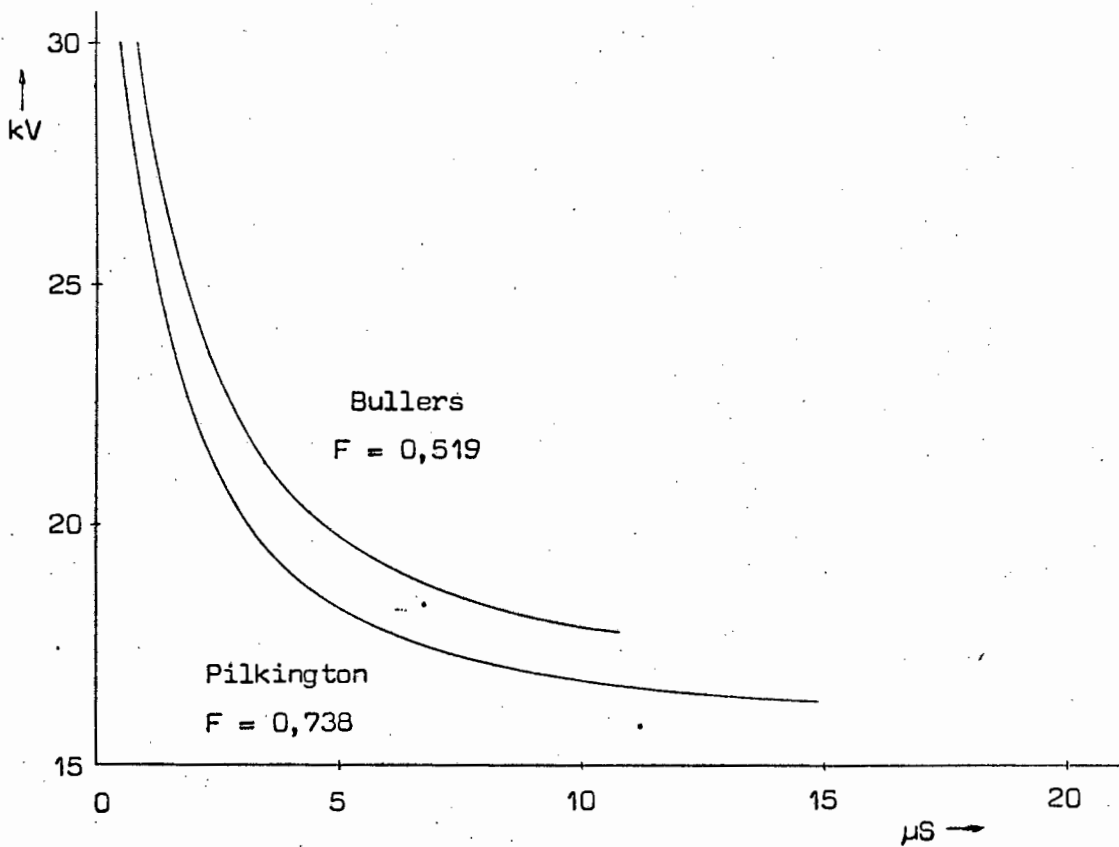


Fig 15 Insulator pre-wet pollution curves with form factor

that distorted results have been obtained.

The tests described rely on plotting a measured conductance, and if two or more units had been used for a set of tests, all units would have been required to have the same conductance on energisation. This is not impossible to achieve, but still difficult.

It should also be remembered that in practice, when one unit in a string of insulators flashes over, the complete string invariably flashes over, because critical unit stress is exceeded. This tends to indicate that one would be interested in single unit performance, although the behaviour of a number of units in series is not necessarily the same as a single unit.

Fig 15 shows the same curves when the measured conductance is adjusted by insulator form factor to give conductivity values. As expected, the form factor correction causes an appreciable change in the curve positions, but one curve still remains above the other. The form factor was calculated to be 0,738 for the Pilkington insulators, and 0,519 for the Bullers types. The integration was performed manually from the enlargements of diagrams of insulator cross-sections, by measuring the insulator diameter at equal increments of leakage distance. Some errors may have arisen in the method of obtaining the cross-section, and the graphical integration, but since the same methods were used for both insulator types, it is hoped that the same error resulted in both cases. Care must be taken in diameter accuracy close to the cap and pin, since the form factor is a function of the inverse of the diameter and serious errors could result. All possible care was taken, but the form factor figures quoted should only be taken as a guide, and it is preferable to obtain the cross-sections directly from the manufacturer, who may also be able to supply the form factor.

The error however, is estimated to be less than 5 %, and can be considered insignificant, especially since the curves are moved an equal amount if the error is the same for both insulators. Form factor for a particular insulator shape is given as before by :

$$F = \int_0^L \frac{ds}{\pi D(s)}$$

Where

s = leakage distance measured from one electrode

$D(s)$ = diameter at s

L = total leakage length

Conductivity = $F \times$ Conductance, thus true surface conductivity of the pollutant deposit is given by multiplying the measured conductance by the insulator form factor.

Therefore, by using different pollutant suspensions, various amounts of salt, and a variable amount of uniform wetting, separate pollution curves were obtained for the two different types of insulators tested.

The only criterion used to obtain these curves was the measured conductance, converted to conductivity by form factor.

The results re-inforce the conclusions drawn from the model insulator tests, namely, that provided pollutant layers are kept thin, and that moderate but uniform wetting is ensured, it does not matter what pollutant is used, and that pollution curves can be obtained by noting the insulator conductivity before energisation.

As it happens, the order of merit obtained in the laboratory is the same order of merit as that found in practice. The Pilkington type are found to work satisfactorily at first, but after appreciable

pollutant build-up, they are very trouble prone, whilst the Bullers flat disc type have been found to work satisfactorily throughout. The way in which the laboratory curves can be applied to tests conducted in the field will be discussed in the next chapter.

The relative increase in insulator performance under polluted conditions can now be analysed. The one thing that can be stated with certainty, is that in the laboratory tests with insulators having the same surface or specific conductivity, the Bullers flat disc type perform better than the Pilkington type. The increase in performance under laboratory conditions cannot be related to an absolute standard, or to the clean dry flashover value. For this reason, the lower curve in Figs 14 and 15 is used as the base curve, in a similar manner to model insulator tests previously. The voltage difference between the curves for equal conductance values can be expressed as a percentage of the voltage of the lower curve for the chosen conductance. If these percentages are taken at equal increments in conductance and averaged, an overall percentage increase in insulator performance can be quoted. The figure obtained is not necessarily significant, but it does give a figure to work with, especially when there are more than two insulator types to be compared.

Using this technique, the average increase in performance of the Bullers insulator when using conductance curves was found to be 12,5 % from Fig 14. When the conductance values were corrected by form factor to give the conductivity pollutant curve of Fig 15, the average increase was found to be only 8,2 %. This increase may seem low, but it must be remembered that the values are obtained for equal and uniform specific conductivities of pollutant for the two insulator types. The effect that the insulator shape had in determining

pollutant accumulation whilst in service has not been taken into account in the laboratory tests.

The next chapter deals with how the laboratory curves obtained with the method described above could be coupled with field results using similar insulators. In this way, an order of merit for insulators which includes site severity could be obtained, and used to decide which type of insulator is the most suitable for a particular site.

CHAPTER VII

APPLICATION OF TEST RESULTS

The effect of site severity on insulator performance cannot be ignored. The rate at which pollutant accumulates onto insulators, the amount accumulated, the rate at which it is removed, and the amount that is removed, all depend on several factors. These are, the type of pollutant at a particular site, the distance of the insulators from the pollution source, and the weather conditions at that site. The weather conditions include the rate, amount, and frequency of rainfall, the direction, speed and duration of wind, and the duration of high relative humidity values.

The primary effect of humidity is clear, since it makes the deposit conducting and causes arcing on the insulators, but the secondary effect is more subtle, since it causes leaching of soluble salts. From all the above, it is small wonder that the problem of insulator pollution has not been solved, especially when each factor is compounded with the effect of insulator shape.

It is therefore imperative that before an insulator type is chosen for a particular site, an evaluation be made of pollutant accumulation on insulators at that site. A number of methods have been proposed and are being used. Some strictly relate pollutant accumulation to weather conditions, while others use leakage current surge methods, by which the insulators' performance is judged under energised conditions.

A further simple method is proposed here, whereby information obtained in the field can be transcribed into laboratory

conditions. This is somewhat different to the method where the order of merit obtained in laboratory tests determines directly the insulator type selection for a particular site.

The proposed method is outlined below. Pollutant curves would first be obtained for a number of insulator types, in the laboratory, as was achieved in the previous chapter. The same types of insulators would be erected at a proposed site, either singly or in strings, and need not be energised. It is realised that pollutant accumulation under energised and unenergised conditions is different, especially regarding the accumulation of charged nuclei. However, all the insulator types under test at a given site would be unenergised, and the effect of electric stress would be absent on all types. Naturally, the collection of pollutant on some insulator types is affected more than others by electric stress, but only a relative, and not an absolute determination of pollutant accumulation would be required.

It has already been shown that insulator behaviour in the laboratory can be assessed by measuring the conductance or conductivity before testing, and conductance measurement application is proposed for field tests. Insulators at the test site would be lowered and sprayed with distilled water, and their conductance measured using a low voltage a.c. bridge method. This avoids dry band formation during measurement, and the effect of ionic polarisation is minimised. This can be done at any chosen interval and is an operation that is easily performed. The gaps between the electrodes and the insulating surface of the insulators would have to be filled with cement, or other suitable filler, as shown previously.

The values obtained from field measurements could now be marked on the curves obtained in the laboratory for the specific

insulator type in question. The position of these points would now determine the order of merit of insulators, so that a choice may be made for the particular site. Similar tests at intervals may give a different order of merit, or perhaps a seasonal order of merit, in which case a selection could possibly be made on a statistical basis.

A hypothetical example shows how the method could work. Assume that three different curves have been obtained for three different types of insulators shown in Fig 16. These curves will have been obtained in the laboratory using the predeposited, partially or fully saturated technique described previously. The curves give the order of merit for the insulators for a laboratory conductivity S of A, B, and C. This is because for the same conductivity S , insulator type A requires a higher voltage than type B, which in turn requires a higher voltage than type C for flashover to occur. Now assume that the conductivity measured in the field for insulator types A, B, and C is S_2 , S_1 and S_1 respectively. The order of merit for insulators at this time is then B, A, and C.

Thus although in the laboratory tests type A was the best insulator, when coupled with the field conditions, type B would be the most suitable. It is necessary to use conductivity and not conductance curves and values, since the measured conductance is affected by form factor to differing degrees for different insulator types, and an order of merit obtained using conductance values could easily be reversed when form factor is taken into account. This is especially significant if a large number of types are being tested and the insulator shapes differ markedly.

Lower conductivities would normally be recorded, in the short period usually available for a decision to be made on insulator

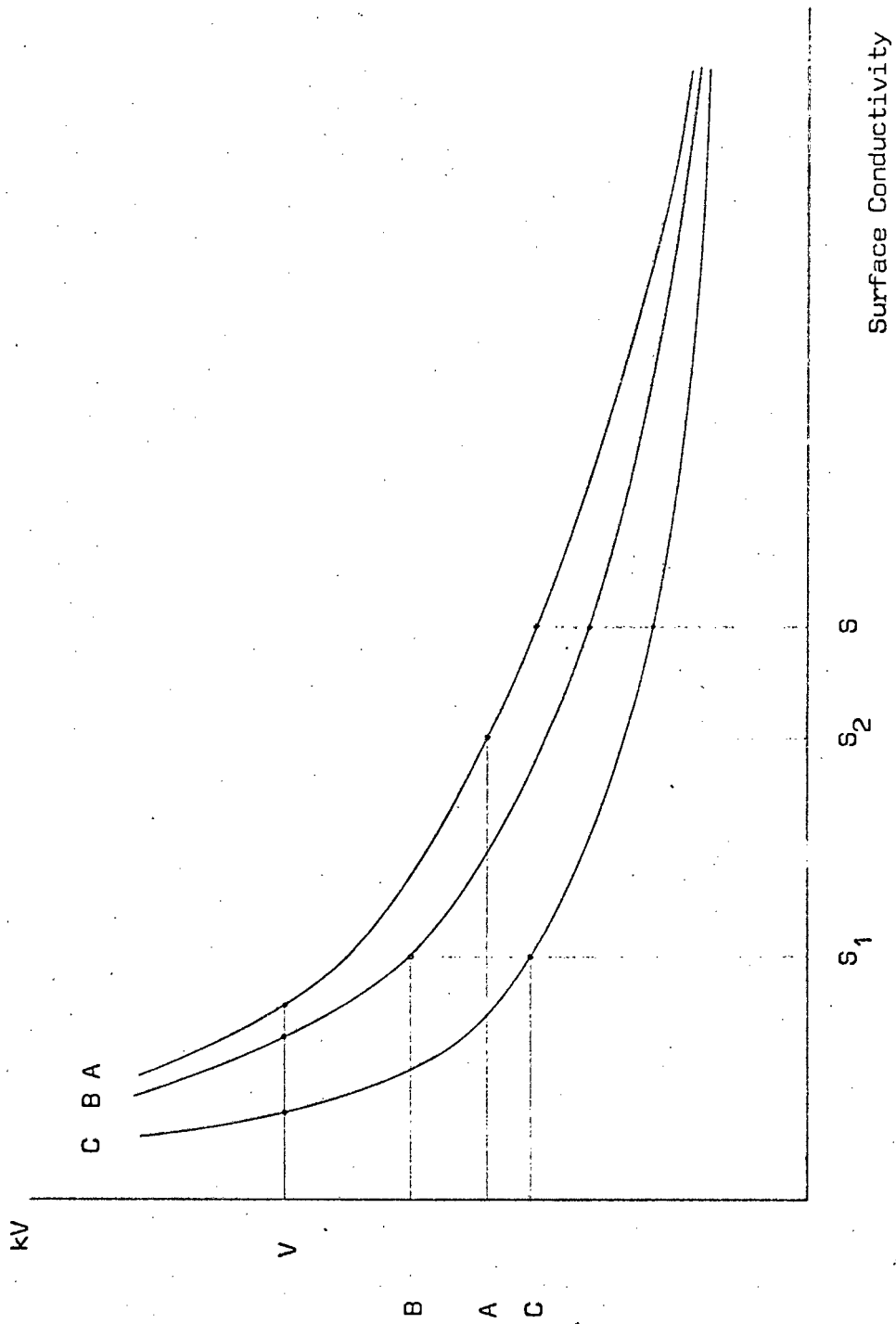


Fig 16 Hypothetical order of merit determination

selection for a particular transmission line or area, and the order of merit can easily be determined for these relatively lower values.

The curves tend to become asymptotic as higher conductivity values. If high conductivity measurements are encountered in the field, one of two criteria could be used for insulator selection. If the conductivities measured on all types is about the same, then the type that gave the highest curve (A) in the laboratory should probably be selected. If the conductivities measured are high but quite different, the type with the lower conductivity value should probably be selected. In the first case, a slightly higher withstand voltage is obtained, whilst in the second case, less pollutant has accumulated.

In addition, if previous orders of merit had been obtained, these should help in selection, since they will give an idea of the expected rate of pollutant accumulation.

Insulator selection using the method described is based on two factors. The effect of insulator shape and form factor for the same amount of pollutant, and equal conductivities, gave the pollution curve position in the laboratory. The effect of insulator shape and weather conditions on pollutant accumulation then gives the true order of merit for insulator types for use at a particular site.

The reasons why this method of insulator selection should work are as follows. In laboratory tests the pollutant is evenly distributed and evenly wet to give constant conductance per unit area of surface. The location of dry bands on energisation is therefore basically dependant on insulator shape, since this determines current density as a function of diameter or leakage length. Whether a unit flashes over or not is now governed mainly by the unit area conductance, or the amount of soluble salts present, which is in turn,

a function of the initial measured conductance. Thus for a uniform pollutant deposition and hence uniform specific conductance, the curve obtained in the laboratory, and therefore the probability of flashover, is determined by the insulator shape and the amount of soluble deposits. This effect is fixed or invariable for a particular insulator which is evenly polluted, and for an insulator in the field that becomes evenly polluted, the laboratory curve obtained determines its performance. However, insulators in the field are not evenly polluted, and that is why the laboratory curves have to be superimposed with field results to arrive at the final insulator performance.

Whether or not this method can be applied to coastal or salt pollution is debatable. The difficulty here is that for energised insulators, any salt nuclei adhering to the surface make the units conducting, and are easily dried onto the surface, resulting in a thicker deposit than on unenergised insulators.

It is not proposed that the method described above should replace any of the methods now being used. It should rather complement the other methods, since it is inexpensive, and easily used. It would not be necessary to use the a.c. bridge described earlier, since a low voltage oscillator bridge with any balance indicator would suffice.

If the method is validated, it would be possible to use it at many remote sites, where electric power is not available for tests under energised conditions.

One way in which the method could be validated, is to obtain an order of merit as described above, and compare it with the order of merit obtained by leakage currents for similar insulators, at the same site. It was therefore necessary to develop a leakage current measurement system to monitor insulator performance.

CHAPTER VIII

MONITORING LEAKAGE CURRENTS

THE MEASUREMENT PROBLEM

The analysis of leakage currents flowing over the surface of contaminated energised insulators is one way of determining the performance of such insulators in service. By noting the magnitudes and frequency of discharge currents, and comparing the figures obtained from different insulator types and suspension arrangements, two basic results can be obtained. The first is an order of merit for insulator types at a particular site by using magnitudes or frequency of discharges, or a combination of the two. The second is an idea of site severity if the same insulators are erected and tested at a different site.

Leakage current measurements in the laboratory on the other hand, can be divided into two major sections.

One is concerned with reproducing field conditions and results in the laboratory. In this way, leakage current analyses can be applied directly, or compared with leakage current results obtained from insulators at a test site.

The other is laboratory leakage current measurements, used solely to gain a better understanding of the flashover process. This was the line of investigation adopted.

A problem encountered in monitoring leakage currents is the large magnitude variation of these currents, making it desirable and often necessary to measure and record values ranging from a few milliamps to hundreds of milliamps. This requires a change of measurement scales or a number of recorders. Leakage currents often appear in bursts of high magnitudes, alternating with an almost constant,

low-magnitude current. Thus if a chart recorder is used, for example, and its range set for the higher magnitudes, the low values are often not discerned, or accurately measured on such a scale.

To overcome this problem, a logarithmic amplifier (log-amp) was used. The advantages and the disadvantages of using such a system are dealt with later.

It can of course be argued that one would not be interested in values of a few milliamps whilst surges of hundreds of milliamps are occurring. Unfortunately, after sixty years of problem solving in the field of contaminated insulation, it is not yet clear which are the important criteria, or what must be measured, especially regarding leakage currents.

It was not for the author either, to decide what was important at that stage, and thus cut out possibly useful information by a limited recording system. Irrelevant information can always be discarded at a later stage, but if it is not recorded in the first place, results obtained may give rise to misleading or unqualified conclusions being drawn. In effect, the system should be able to give all the information available from current discharges, irrespective of the recorder used to store such information. The limiting factor is then the recorder, and not the information capturing system.

It must also be remembered that the amount of information obtained from a particular recording system is governed by the effectiveness or resolution of such a system. It is also closely connected with cost, such as the sophistication of equipment, the amount of recording paper used, and the amount of time required for the analysis of results. An example is taken where possible results are obtained from a peak recording meter used in conjunction with an average recording meter. The latter is merely a peak recorder with a faster

time constant. Assume that in preselected timing interval the peak current recorded is 200 mA. The output recorded by the average meter, for equal average time-areas on the chart, could indicate a number of peaks close to or equal to 200 mA with a long, relatively inactive interval, or a large number of say 50 mA peaks, with only one of 200 mA, or any combination of current values. This clearly indicated the waste, and indeed the uselessness of such information, since few conclusions can be drawn from those results. The problem can be overcome by using a very fast time constant, which in the limit eliminates the peak recorder, but information is then gained at the cost of much more recording paper and analysis time.

Leakage currents flowing through energised polluted insulators can be measured directly, if the insulator string under test is isolated from earth by an extra stand-off insulator at the base of the string. This method, shown in Fig 17, requires a low impedance recorder so that the earth end of the string is kept earthy, and a sensitive protection system is needed in case of flashover. An alternative is to convert the leakage current to a voltage, using a known resistance at the stand-off insulator, and measuring this voltage, as shown in Fig 18.

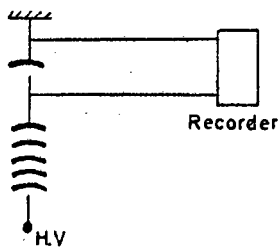


Fig 17 Low impedance current measurement

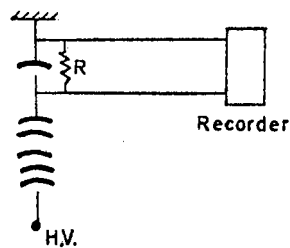


Fig 18 High impedance current measurement

A relatively large measurement voltage can be obtained in this way by using a high resistance value. It also overcomes diode volt-drop

if rectification of the voltage is used. Instrument protection is simplified but the high impedance circuit is more susceptible to interference.

To overcome the problem of interference, a low resistance was used at the stand-off insulator, whilst the low voltages produced were rectified by an operational amplifier (op-amp) rectifier circuit, eliminating the diode forward-voltage drop.

THE STAND-OFF INSULATOR

A stand-off insulator was designed and constructed which eliminated the measurement problem at the insulator end. Reference is made to Fig 19 and Photograph 10.

Two resistors (A) of about 400 ohms each were used in parallel to produce a low voltage from leakage currents. If 500 mA is used as the maximum measured current the system requires a protective voltage of about 100 V, and a Philips 4378 surge arrester (B) was connected across the resistors. This has a measured striking voltage of 115 V peak, and an energy discharge of 10 Watt-seconds and a 10 A current capability for three seconds. As further flashover protection, a small adjustable spark gap (C) is also used. The resistors, gas valve, and spark gap are enclosed in a 70 mm diameter tube (D), sealed with a cork gasket (E) and screw-on cap (F). This is to protect the spark gap from moisture, which would soon short out when the unit is used with fog or mist spray.

The unit should be able to withstand fair pressures caused by heating due to insolation, or cooling at nights, should it be used in the field.

A protected breather hole is considered unsatisfactory since condensation would take place inside the unit.



Photograph 10 The stand-off insulator

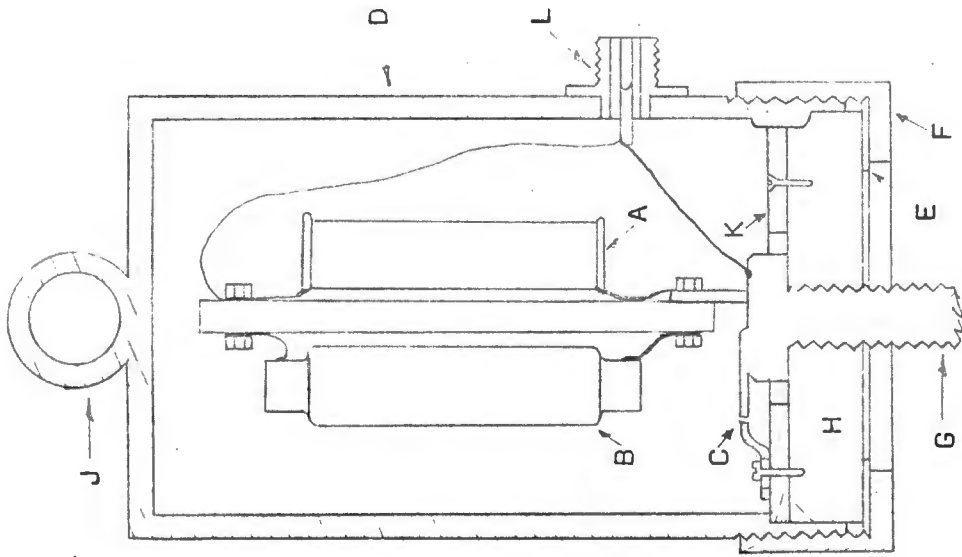


Fig 19 Stand-off insulator cross-section

The load that can be sustained by the unit is determined mainly by the tensile strength of the bolt connection (G) to the earthy end of the insulator, the shear stress of the insulating disc (H), and the eye hook (J) on top of the unit. Electrical connection between one end of the spark gap and the tube is by a brass ring (K) touching the tube when the unit is assembled. A U.H.F. connector (L) sealed onto the tube, provides electrical access between the resistors and an external screened lead. The distance between the cap and the connecting bolt need not be large since the potential difference between the two is normally lower than 100 V. A screened lead 10 m long was used between the stand-off insulator and the leakage current recorder, which was housed in the control area of the laboratory.

THE RECTIFIER

For model insulators or single discs to be tested in the laboratory, it was assumed that a leakage current of about 500 mA would constitute a flashover. This is an entirely arbitrary value and was chosen only for the system recording design. It does not mean that if a current 500 mA is reached a flashover ensues, but that the recorder will not monitor currents greater than that value. Thus the value is simply a recording protection limit, and flashover is monitored either visually, or with a fuse in the high voltage or low voltage supply circuits.

In the laboratory tests, a flashover was monitored visually, and a manually operated circuit breaker was used to disconnect the supply. A fuse-operated back-up was also used.

The problem of diode forward-voltage drop when using a low voltage source, which occurs with bridge rectifiers was overcome by

using an op-amp rectifier circuit, shown as part of Fig 20.

The recording end of the screened lead from the stand-off insulator is connected to a small 50 k Ω potential divider. This ensures a high impedance input, most of the generated current going to earth at the stand-off insulator. The low current flowing down the line also ensures a minimisation of interference pick-up. This divider was adjusted so that when 25 mA was flowing through the resistors at the stand-off insulator, an output of 500 mV was obtained. The calibration was performed using a digital voltmeter and an oscilloscope with the protection system at the stand-off insulator disconnected. The divider thus ensures that the input to the rectifier is only 10 V at flashover. The voltage is then fed to an op-amp rectifier. This has a diode D_1 in the feedback loop of the amplifier, the forward-voltage drop thus being divided by the open loop gain of the op-amp. In this way it was possible to faithfully rectify voltages of less than 2 mV peak, which is as sensitive as the oscilloscope will allow. The diode D_2 ensures that the op-amp does not saturate when the output swings to positive rail voltage as the negative half cycle input is encountered. The first amplifier is followed by a second op-amp which sums the half-wave rectified output from A_1 and the a.c. signal via R_3 and R_4 to give a full wave rectified output from A_2 . The value of R_3 was adjusted until both half waves were the same magnitude at the output of A_2 . R_8 and R_{12} are used to compensate for the op-amp offset currents.

The system rectifies faithfully up to 14 V peak, thus the maximum set by the stand-off insulator gas valve and potential divider is adequate. A fair number of flashovers occurred during the series of tests, the rectifier and stand-off insulators being totally unaffected by them.

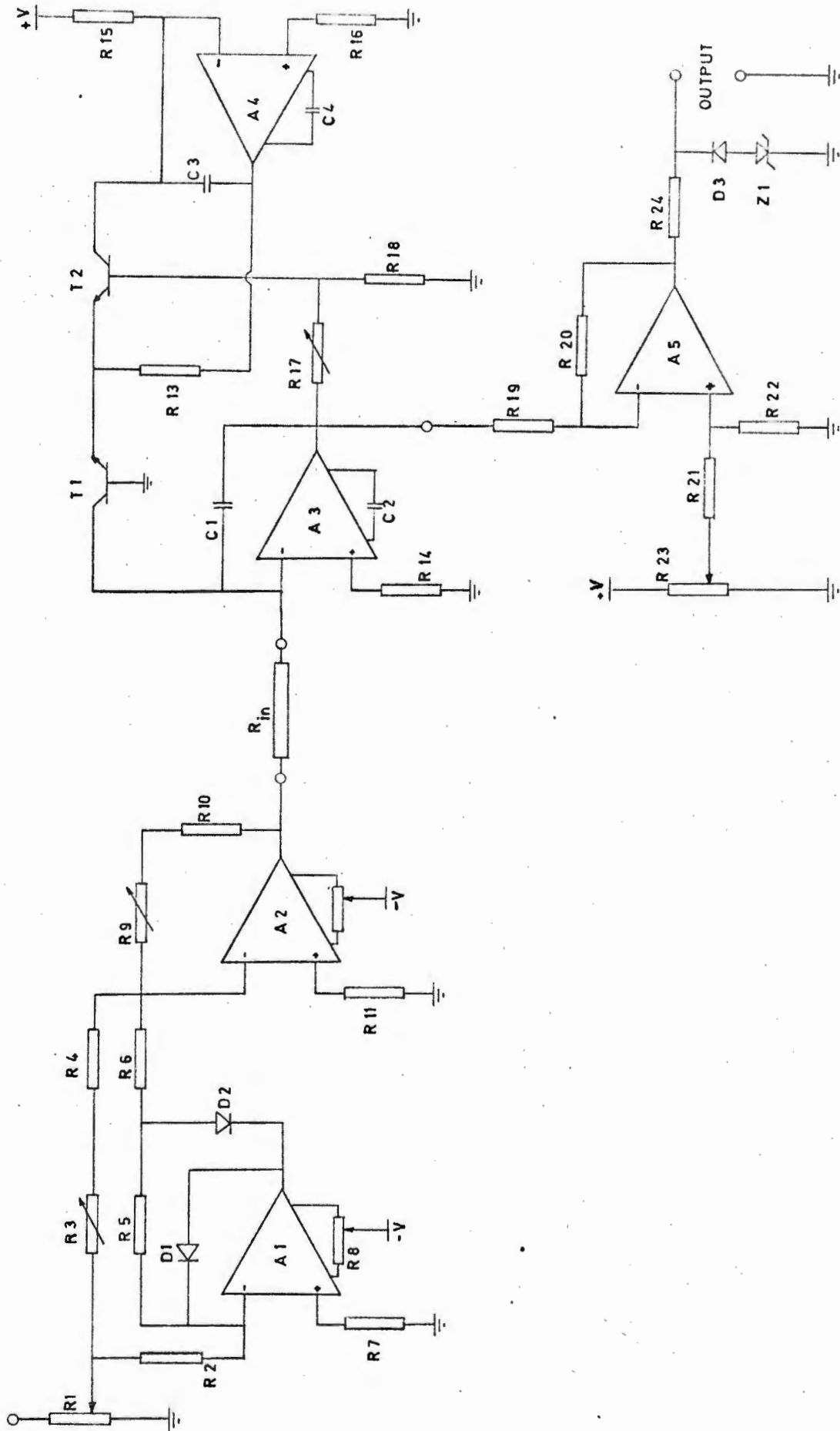


Fig 20 Rectifier, logarithmic amplifier, and comparator

A ₁	LM 741	R ₃	0 - 15 k	R ₁₄	1 k
A ₂	LM 741	R ₄	10 k	R ₁₅	1,5 M
A ₃	LM 741	R ₅	27 k	R ₁₆	1,5 M
A ₄	LM 741	R ₆	10 k	R ₁₇	0 - 22 k
A ₅	LM 741	R ₇	10 k	R ₁₈	1 k
D ₁	1N 4005	R ₈	100 k	R ₁₉	15 k
D ₁	1N 4005	R ₉	0 - 4,7 k	R ₂₀	15 k
D ₃	1N 914	R ₁₀	18 k	R ₂₁	15 k
Z ₁	3,3 V	R ₁₁	6,8 k	R ₂₂	15 k
T ₁ /T ₂	MD 8001	R _{in}	50 k	R ₂₃	1 M
R ₁	0 - 50 k	R ₁₂	100 k	R ₂₄	680
R ₂	27 k	R ₁₃	2 k	C ₁	330 pF
C ₂	330 pF	C ₃	150 pF	C ₄	330 pF

All resistances in ohms, 0,25 W.

Component values for Fig 20.

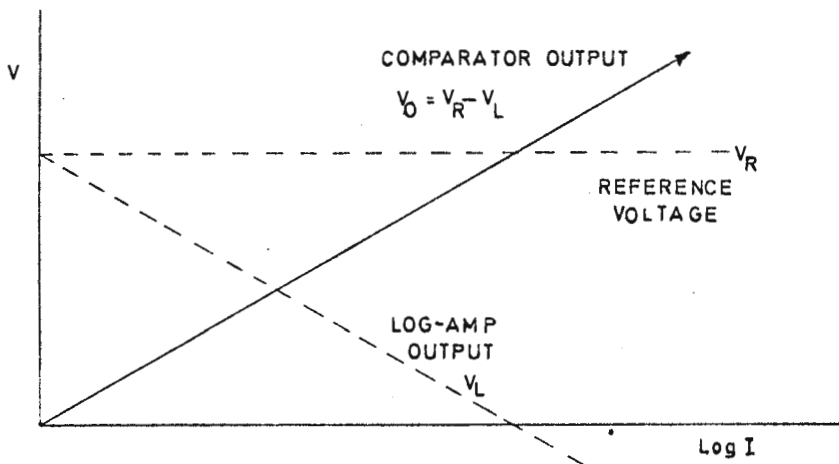


Fig 21 Comparator and log amp outputs

THE LOGARITHMIC AMPLIFIER

The circuit for the logarithmic amplifier is shown as part of Fig 20, and gives a logarithmic output voltage for a linear input current. The circuit relies on the logarithmic relationship between collector current and emitter-to-base voltage of a transistor, and uses a matched pair of transistors run in the grounded-base mode, in the feedback loop of an op-amp.

The current is created from the input voltage V_2 by the resistor R_{in} . Negative feedback forces the collector current of T_1 to be exactly equal to the input current. Negative feedback through A_4 also forces the collector current of T_2 to equal the current through R_{15} . Since the collector current of T_2 remains constant, the emitter-base voltage also remains constant. Therefore only the emitter-base voltage of T_1 varies with a change in input current, and hence the logarithmic relationship is established.

Accuracy for low input currents is determined by the error caused by the bias current of the first op-amp A_3 . At a higher input current in the order of 1 mA the transistors T_1 and T_2 limit accuracy. The log-amp output is 3 % accurate referred to the input for currents between 10 nA and 1 mA. At currents above 0,5 mA the transistors deviate from log characteristics due to emitter resistance, but for currents from 40 nA to 400 μ A the convertor is 1 % accurate referred to the input. If the upper ranges are often encountered, it is advisable to use larger transistors. In the prototype, the current into the log-amp generated by leakage currents at the stand-off insulator, was from 100 nA to 200 μ A, ensuring 1 % accuracy. The amplifier is affected by temperature, and R_{18} is a thermistor used to compensate for this. It must be noted that a 1°C temperature difference between the log

transistors , and the compensating resistor, results in a 0,3 % error, and the R_{18} should be placed thermally close to, or in contact with the dual transistor. Resistors R_{15} and R_{16} determine the current zero crossing on the output. For a rail voltage of 15V and 1,5 M resistors, zero crossing current is 10 μ A. Thus 10 nA at the input should produce 0 V at the output. In fact the output of the amplifier is positive decreasing linearly with the log of input current, and a subtracting op-amp was used at the output.

The gain of the amplifier can be set to give any rate of voltage change, per decade change in input current, by altering the value of R_{17} . On the prototype it was adjusted to give 1,0 V output per decade input. The range of gains available is from 0,2 to 3,0 V per decade.

The subtracting amplifier used at the output, ensures that for a chosen input current to be used at base value, the final output can be set to 0 V. The reference off-set voltage is set by a small potential divider R_{23} , one end of which is tied to the supply voltage, and the way in which the positive increasing output was obtained is shown in Fig 21.

For the case where there is no leakage current at the insulators and thus no output current to the log-amp, the amplifier output goes to positive rail (+15 V), and the final output goes to the negative rail minus the offset voltage from R_{23} . The amplifier output was later connected to a magnetic tape recorder, which has an input voltage of ± 5 V. A zener diode Z_1 was used to keep the output bound to - 4 V under this condition. The diode D_3 ensures that negative voltages create current flow through the zener, limiting the output to - 4 V, and that positive voltages are unaffected.

As before, in both the flashover condition, and the condition where no leakage current was flowing, the amplifiers were unaffected.

SYSTEM CALCULATION

The system is shown in block diagram form in Fig 22, and Table 1 gives the current and voltage values obtained at various points in the complete circuit, for conditions from no leakage current to flashover.

The actual value of the two resistors in parallel at the stand-off insulator was 216,85 ohms, and the measured gas valve inception voltage was 115 V peak. Thus for a leakage current I_1 flowing through the polluted insulator, the approximate current I_2 flowing down the line to the 50 k potential divider is :

$$I_2 = \frac{216}{50k} \cdot I_1 = 4,32 \times 10^{-3} I_1$$

Thus for $I_1 = 0,25$ mA, $I_2 = 1$ μ A, and for $I_1 = 250$ mA, $I_2 = 1$ mA.

Therefore the current flowing down the line to the rectifier is generally small, ensuring that any interference near the line causes minimum error. No problems were experienced throughout the tests, and the base level of the measurable current was thus chosen as 0,25 mA.

This value was again arbitrarily chosen, but leakage currents below 1 mA are not of real interest.

The 0,25 mA base level thus produced 5 mV at the input and output of the rectifier, and also made possible the use of 100 nA input current to the log-amp, instead of the 10 nA, further reducing possible error.

Therefore R_{in} for the log-amp was :

$$R_{in} = \frac{5 \times 10^{-3}}{100 \times 10^{-9}} = 50 \text{ k ohms.}$$

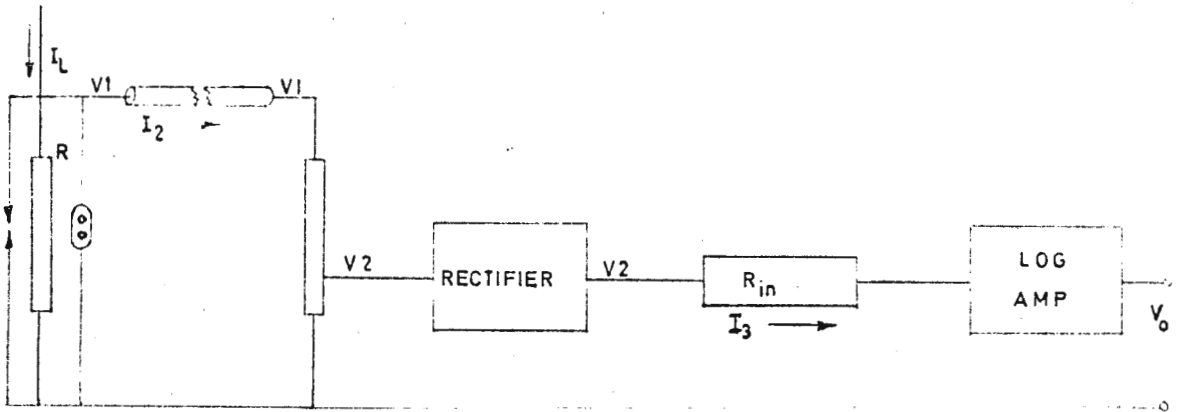


Fig 22 System block diagram

I_L	V_1	V_2	I_3	V_0	
0,00 mA	0,0 mV	0,0 mV	0,0 nA	-4,00	
0,25 mA	54,1 mV	5,0 mV	100 nA	0,00	
2,50 mA	541 mV	50 mV	1,0 μ A	1,00	
25,0 mA	5,41 V	500 mV	10 μ A	2,00	
250 mA	54,1 V	5,0 V	100 μ A	3,00	
500 mA	108 V	10,0 V	200 μ A	3,30	
F/O	530 mA	115 V	10,6 V	212 μ A	3,46

Table 1 System voltages and currents

At gas valve inception voltage, (flashover condition), only 10,6 V appear at the input and output of the rectifier, giving 220 μ A input to the log-amp, and hence 0,22 mA through the transistors. Therefore all values of voltage and current up to and including the flashover condition are well within the rectifier and log-amp limits. Four decades of in-put current is thus adequate, and the sensitivity of the log-amp was adjusted by R_{17} to give an output of 1,0 V per decade. The offset voltage at the subtracting amplifier was then set such that 0,25 mA flowing at the stand-off insulator gave 0 V at the output to the recording apparatus.

The output voltage V_o for leakage currents I_L in milliamps at the stand-off insulator, using 1,0 V per decade output is given by :

$$V_o = \text{Log}_{10} (4 I_L)$$

A small problem arises whether to use peak or R.M.S. values. Either can be used, but the problem must be looked at in conjunction with the proposed recording system. Because the output of the log-amp initially gives large variations for small changes in input current, an offset error arises if the amplifier is calibrated for peak values, and a meter-type recorder is used as instrumentation. However, the R.M.S. value of the logarithm of a sinusoidal function has no real meaning. All that can be used here is the average time-area under the output curve, giving some error. Alternatively, a meter with a long time-constant can be used, such that the indicated output tends to the peak of the half-waves. This tends to defeat the exercise of capturing a maximum amount of information, and more will be said about it in the next section.

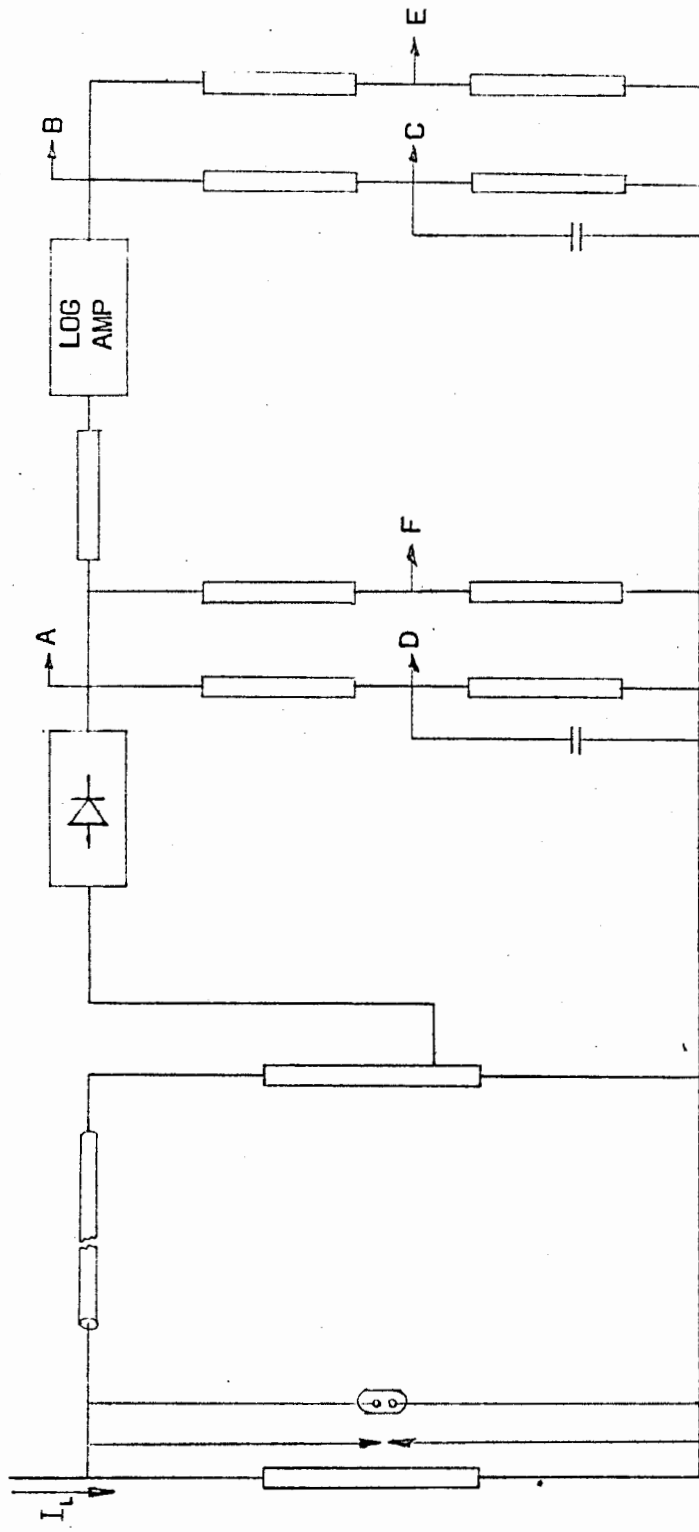
For the case where the output was recorded on magnetic tape, peak values of input currents and output voltages were used, calibration being adjusted accordingly.

RESULTS FROM LEAKAGE CURRENT MONITOR

In order to assess the aptness of different recorders in monitoring leakage currents, the output voltages at the rectifier and at the logarithmic amplifier were fed to two recorders.

The outputs were fed via suitable scaling, to two tracks of a Sefram pen recorder which has a frequency response of 20 Hz, and to four tracks of an S.E. 3006 ultraviolet galvanometric recorder with a 1000 Hz frequency response. Time constants for the various tracks were adjusted by means of capacitors to observe the effect of different recording systems. The points of measurement are shown in the block diagram of Fig 23. It can be seen from Fig 24 that some non-logarithmic records are off scale at times, and that although the pen recorder tries to follow the signal, due to its slow response time, it records a reduced trace without much detail. Using the logarithmic amplifier, all traces remain on scale, and the pen recorder gives a much improved trace compared to the one with plain rectification. This is due to the reduced amount of pen travel required for a large magnitude swing, thus decreasing effective instrument response time, and also giving a good representation of the galvanometric record.

Traces E and F have no time constant, while C and D have a time constant of about 0,025 seconds. These four records were obtained using the U.V. galvanometric recorder. Those of A and B have a time constant of 0,04 seconds, and come from the two tracks of the



C, D, E, F → Ultraviolet recorder
 A, B → Pen recorder

Fig 23 Output points for chart records

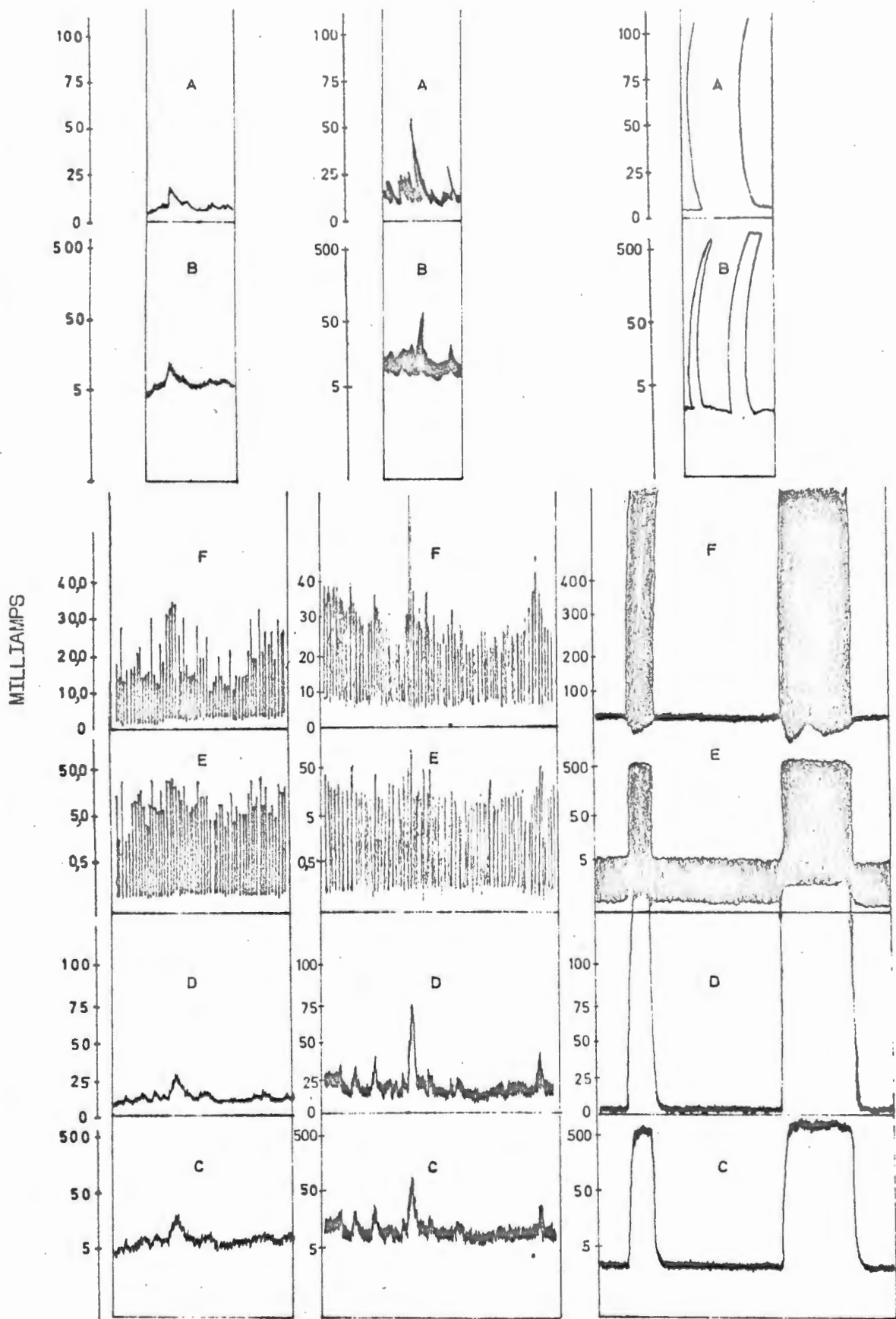


Fig 24 Typical leakage current records

Sefram pen recorder. It would thus seem that any time constant greater than about 0,05 seconds will only show average current, with a suppressed surge magnitude.

If accurate knowledge of current magnitude is required with only one recording system, small time constants are important. At the same time this also requires an increased chart speed, and therefore requires greater expenditure for long term application.

Although the logarithmic recorder overcomes the difficulty of scale changing, and improves the response time due to decreased pen travel, there is one main factor against it. The human eye is accustomed to interpreting linear changes in magnitude, and it requires considerable practice to interpret a logarithmic magnitude recording. In addition, most chart records are narrow, and a change of a millimetre or so, is difficult to discern. This small magnitude change may be a significant current change, perhaps of 100 mA, depending on the range chosen, and the position of the recording pen at the time.

These final problems can easily be overcome by using computer techniques, and the logarithmic system developed is ideally suited to these techniques.

The output from the logarithmic amplifier, now bound between ± 4 V, was recorded on a magnetic tape through one of the tracks of a Philips Analog 7 tape recorder. This tape recording was then analysed using the Electrical Engineering department's Varian 620 mini-computer.

A sample computer analysis, performed on results obtained from a polluted insulator test, is shown in Fig 25. Two sets of results are printed out for a number of half-cyclic peak value of currents between various limits. Two hundred consecutive half-wave peaks were analysed, or the equivalent of two seconds. As a further example,

NO. OF PEAKS GREATER THAN 50 MA. = 0
NO. OF PEAKS BETWEEN 30 MA. AND 50 MA. = 0
NO. OF PEAKS BETWEEN 25 MA. AND 30 MA. = 127
NO. OF PEAKS LESS THAN 25 MA. = 73
READY

NO. OF PEAKS GREATER THAN 40 MA. = 0
NO. OF PEAKS BETWEEN 25 MA. AND 40 MA. = 127
NO. OF PEAKS BETWEEN 20 MA. AND 25 MA. = 72
NO. OF PEAKS LESS THAN 20 MA. = 1
READY

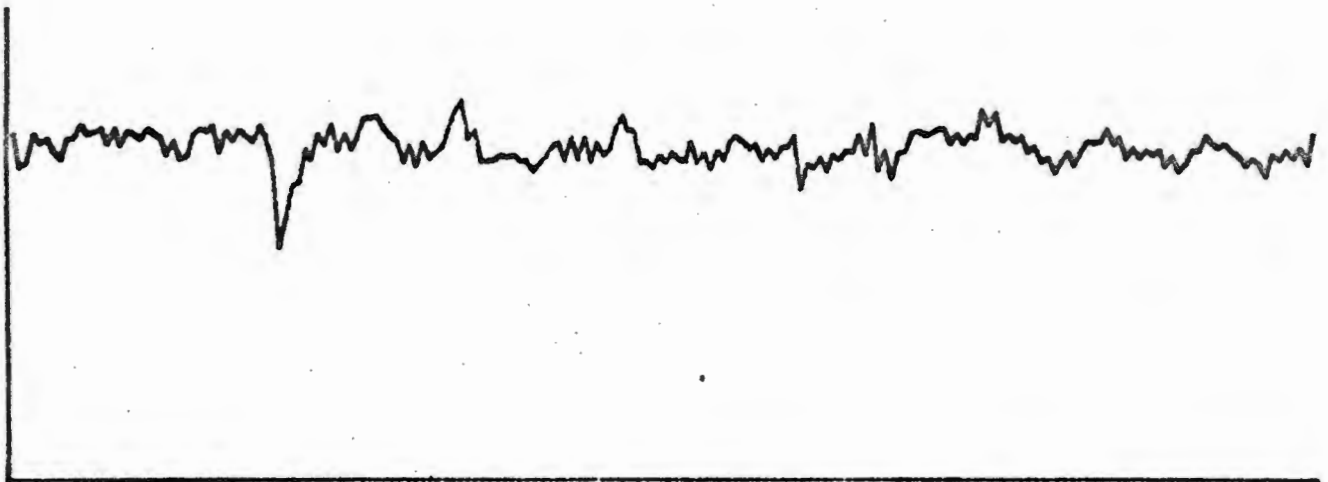
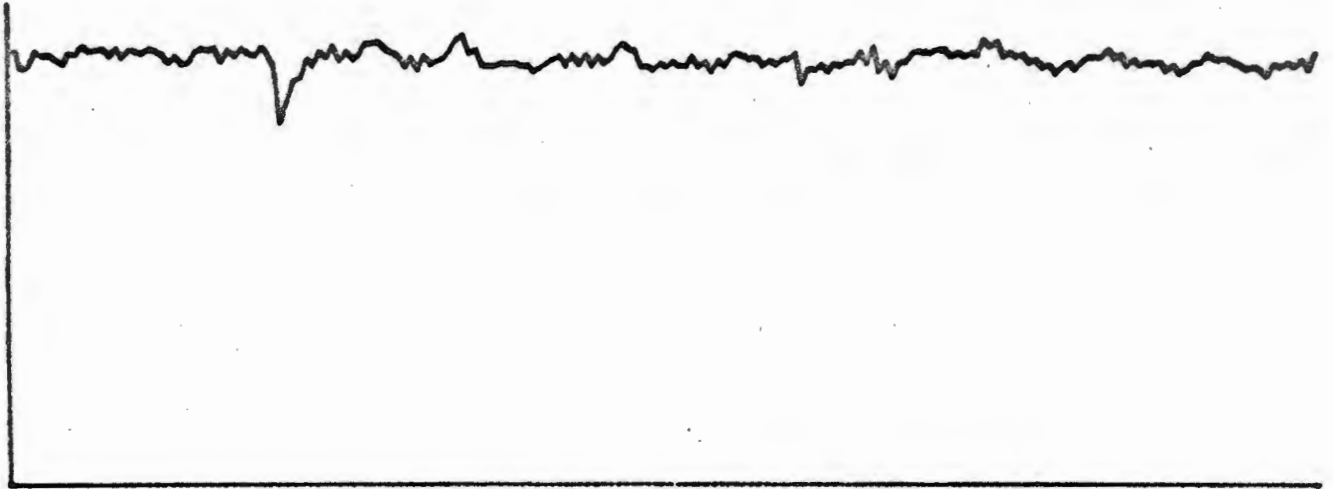


Fig 25 Computer analysis and display of a discharge

PEAK NO	VALUE		
1	2.44504	2	2.34489
3	2.3571	4	2.44504
5	2.41573	6	2.43038
7	2.39374	8	2.37176
9	2.43282	10	2.43038
11	2.46946	12	2.44504
13	2.45236	14	2.45969
15	2.41573	16	2.45969
17	2.41084	18	2.44992
19	2.44504	20	2.43282
21	2.45969	22	2.44259
23	2.43038	24	2.38397
25	2.42305	26	2.37176
27	2.38153	28	2.44504
29	2.45969	30	2.45236
31	2.46458	32	2.3913
33	2.44992	34	2.42305
35	2.45481	36	2.43527
37	2.42305	38	2.46458
39	2.43527	40	2.36199
41	2.04445	42	2.1617
43	2.28383	44	2.2936
45	2.40107	46	2.36637
47	2.44504	48	2.41084
49	2.46946	50	2.39619
51	2.44504	52	2.40107
53	2.43038	54	2.489
55	2.489	56	2.49389
57	2.45969	58	2.43527
59	2.42061	60	2.3571
61	2.41084	62	2.34489

Table 2 Measured output

Table 3 Corresponding Leakage Currents

RUN600			
1	26.5557	2	24.025
3	24.3203	4	26.5557
5	25.7886	6	26.1693
7	25.2279	8	24.6793
9	26.2333	10	26.1693
11	27.2123	12	26.5557
13	26.751	14	26.9477
15	25.7886	16	26.9477
17	25.6629	18	26.6857
19	26.5557	20	26.2333
21	26.9477	22	26.4909
23	26.1693	24	24.9826
25	25.9782	26	24.6793
27	24.9216	28	26.5557
29	26.9477	30	26.751
31	27.0797	32	25.1663
33	26.6857	34	25.9782
35	26.8164	36	26.2975
37	25.9782	38	27.0797
39	26.2975	40	24.4394
41	17.7904	42	20.0034
43	22.6018	44	22.8238
45	25.4134	46	24.5591
47	26.5557	48	25.6629
49	27.2123	50	25.2896
51	26.5557	52	25.4134
53	26.1693	54	27.7493
55	27.7493	56	27.8852
57	26.9477	58	26.2975
59	25.9149	60	24.3203
61	25.6629	62	24.025

READY

the 200 peaks are shown graphically, first as a logarithmic response, and the linearly. Table 2 gives the measured voltage as recorded on the tape, of the first 62 points from the start of the sampling, whilst Table 3 gives the corresponding leakage current values. The output is shown to six figures because that is the computer accuracy, but the results should only be read to two decimal places.

Table 2, Table 3, and Fig 25 are not meant to have a great significance in themselves, but are included as an example to show the power and versatility of this method and its application. The number of points that can be analysed is not limited to 200 or any other figure. It is also very easy either to store the calculated peaks onto computer tape, or re-run the magnetic tape with changed computer program parameters, to obtain results using different limits. In addition, if it is seen from a particular set of results that something of interest may have occurred, the relevant section can be easily accessed and displayed graphically.

Statistical analysis of results could also be used, merely requiring another computer program. Timing is simply achieved, since 100 peaks equal one second, assuming a 50 Hz supply frequency. The short and simple computer program used for the analysis is given in Appendix C for interest.

CONCLUSIONS

Tests started with contaminated cylindrical insulator models led to the predeposited prewet technique being applied to practical insulator shapes.

It was found that provided pollutant layers are kept thin, and excessive wetting is avoided, pollution curves for practical insulator shapes can be obtained by merely measuring the conductivity before energisation. Since surface conductivity can be used as the measurement criterion, it was also possible to use partial, but uniform wetting to achieve any desired conductivity for testing. This eliminates the problem of pollutant run-off, which occurs when insulators are wet to maximum conductivity. It was also found that any inert substance can be used as the pollutant, provided that conducting salts are present, and that measured conductivity before energisation is used to plot the pollution curve for the insulator type under test.

A method by which the curves obtained in the laboratory could be used to predict insulator performance in the field was evolved. This method superimposes the effects of insulator shape and site severity onto the laboratory curves, to give an order of merit for insulators under test at a given unenergised site.

A leakage current measurement and recording system was developed for laboratory and test site use. The system incorporates, a low impedance stand-off insulator to monitor currents, an op-amp rectifier to eliminate diode voltage drop, and a logarithmic amplifier to compress the range encountered when monitoring leakage

currents. It is particularly suited to computer analysis of results. The system can be used to gain a better understanding of the flashover process, and of the criteria governing flashover.

It must be stressed that the present power supply for tests in the High Voltage laboratory at the university is only adequate for single insulator units, and it would be desirable to replace the existing equipment with a better system, so that pollution tests can be conducted on insulator strings, or 'long-stab' type insulators.

Further investigation should be concentrated on two fields. The first is the analysis of leakage currents, both in the field, and in the laboratory. The second is the use of the proposed method of determining an order of merit for insulators. Insulators already erected at 'dead' sites by ESCOM, near Cape Town, could easily be used for field investigation, while similar insulator types to those in the field will be required for laboratory tests.

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APPENDIX A

CONDUCTIVITY BRIDGE

The full circuit of the split phase conductivity bridge is shown in Fig A1. The bridge arm containing the electrolyte cell consists of two sockets, SK1 and SK2, and the resistors selected by S1. The other bridge arm consists of R_3 and the bridge potentiometer VR1 in series with its range limiting resistor R_4 . These two bridge arms are fed in antiphase from the transformer.

The same antiphase voltages, in cross-over connection, drive the bases of two switch transistors T_1 and T_2 , connected to the centre points of the bridge arms. Each drive connection is via a diode, D_1 and D_3 . The arrangement is such that each transistor short-circuits the negative half-cycles of the bridge waveform it is sensing, as seen at the bottom end of R_{10} or R_{11} . These resistors are inserted to avoid short-circuiting of the bridge itself on negative half-cycles.

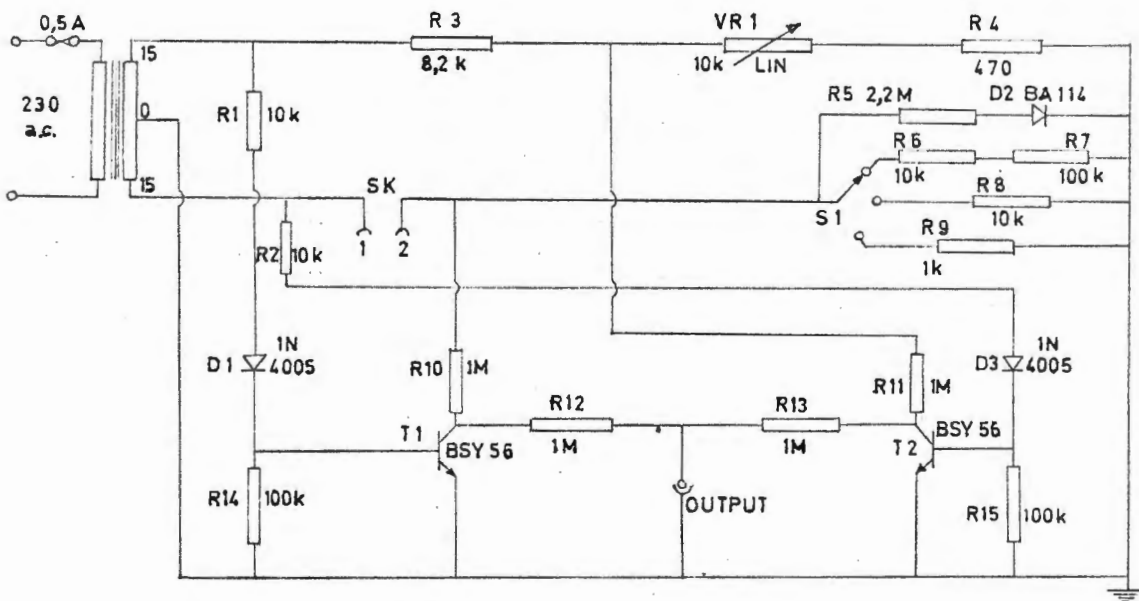


Fig A1 The conductivity bridge

However, the net impedance seen by the electrolyte cell bridge would be slightly lower on negative half-cycles, because R_{10} then shunts the resistors on S1 directly via T1, but only indirectly via the remainder of the switching resistor network R_{12} , R_{13} and T2 on the positive half-cycles when T1 is cut off. This amounts to slight partial rectification in this bridge arm, and R_5 and D_2 just cancel this by imposing the right amount of additional loading on the positive half-cycles.

This form of compensation is satisfactory only if the highest bridge arm impedance is at most 10 % of the electronic switch impedance. The latter is nominally 1 M Ω to match standard oscilloscopes, so that the highest bridge resistor value that can be used is 100 k Ω , corrected to 110 k Ω with R_6 to allow for the switch shunting effect.

The electronic switch operates entirely with a.c. voltages, requiring no separate rectified collector supply. Considering either transistor alone, when the bridge arm feeding its collector is describing a positive half-cycle, the transistor collector is receiving normal polarity, but the base is cut off because zero voltage is applied to it. The diode in series with the base drive holds off the actual negative voltage applied from the other bridge arm, which is just describing its negative half-cycle. Without the diode, reverse breakdown would occur between base and emitter of the transistor. The negative half-cycle in the bridge arm feeding the collector inverts the transistor, i.e. interchanges the roles of collector and emitter, a condition leading to particularly small residual switch voltages. At the same time the other bridge arm is now describing its positive half-cycle, so that the base diode conducts and turns the transistor hard on. The transistor thus behaves as a very efficient short-circuit to earth, especially as it is running inverted in this phase period. Only the signal from the other

bridge arm which is describing the positive half-cycle, can get through to the output terminal. Thus the composite signal at the output is a train of positive sine-wave half-cycles, with alternative ones belonging to the respective bridge arms

A P P E N D I X B

CLEAN MODEL FLASHOVER VOLTAGES

Model No.	Length cm	Diameter cm	Form Factor	Flashover Voltages															Corrected Mean kV	
				kV	kV	kV	kV	kV	kV	kV	kV	kV	kV	kV	kV	kV	kV	kV		kV
1	22,2	7,0	1,01	101,0	100,5	100,5	99,0	100,0	99,0	98,0	98,5	101,0	98,5	101,0	98,5	98,5	101,0	98,5	99,60	100,60
2	22,2	6,9	1,02	100,0	98,0	95,0	94,0	97,0	96,0	94,0	97,0	99,0	97,0	99,0	97,0	94,0	99,0	97,0	96,67	97,64
3	22,3	6,9	1,03	93,0	93,5	98,0	96,0	95,0	96,0	95,0	93,0	95,5	93,0	95,5	95,0	95,0	95,5	95,0	95,00	95,95
5	22,1	7,1	0,99	100,0	99,0	96,5	98,0	97,0	99,0	97,5	98,0	97,5	98,0	97,5	98,0	97,5	97,5	97,0	96,95	97,92
7	22,4	6,3	1,14	109,0	110,0	111,0	107,0	107,0	105,0	107,0	107,0	106,0	107,0	107,0	107,0	107,0	106,0	105,0	107,40	109,50
8	22,0	6,3	1,11	100,0	100,0	99,0	99,0	100,0	102,0	98,0	97,0	101,0	98,0	101,0	98,0	100,0	101,0	100,0	99,60	101,60
9	21,9	6,2	1,12	101,0	105,0	105,0	102,0	105,0	104,0	103,0	103,0	104,0	103,0	103,0	103,0	103,0	104,0	103,0	103,50	105,50
10	22,2	6,3	1,12	101,0	100,0	100,0	101,0	103,0	103,0	100,0	100,0	97,0	97,0	97,0	97,0	97,0	97,0	97,0	99,70	101,70
11	22,1	6,3	1,12	97,0	101,0	100,0	100,0	101,0	99,0	101,0	102,0	101,0	102,0	101,0	100,0	101,0	101,0	100,0	100,20	102,20
12	23,2	7,1	1,04	106,0	106,0	107,0	107,0	107,0	107,0	105,0	106,0	106,0	106,0	106,0	105,0	106,0	106,0	105,0	106,20	108,30
13	23,2	7,0	1,05	92,0	95,0	95,0	96,0	96,0	98,0	98,0	97,0	96,0	98,0	97,0	98,0	97,0	96,0	97,0	96,00	98,00
14	23,2	7,0	1,05	99,0	99,0	102,0	103,0	103,0	102,0	101,0	102,0	103,0	102,0	101,0	101,0	102,0	100,0	100,0	101,10	103,10
15	23,0	6,9	1,06	102,0	102,0	101,0	101,0	100,0	102,0	101,0	98,0	99,0	98,0	99,0	100,0	99,0	100,0	100,0	100,60	102,60
Total Mean																			101,90	

C	2,3	2,3	2,3	3,5	3,5	3,5	3,5	3,5	2,2	2,2
V	23,0	22,0	23,0	22,0	21,0	22,0	22,0	25,0	23,0	22,0
R	W	W	F	W	W	W	W	W	F	W
C	2,2	2,2	3,1	3,1	3,1	3,1	3,2	2,3	2,2	2,1
V	25,0	24,0	24,0	22,0	20,0	21,0	22,0	25,0	22,0	23,0
R	F	F	F	F	F	W	F	F	F	W

MODEL TESTS USING KAOLIN

C = Conductivity

V = Voltage

R = Result

F = Flashover

W = Withstand

C	0,8	1,0	1,8	2,0	1,8	1,9	2,0	3,0	2,0	2,1
V	29,3	29,3	27,0	26,5	26,0	24,0	24,0	24,0	24,0	24,5
R	W	W	F	F	F	W	W	W	W	W
C	3,2	3,6	2,8	6,5	5,4	6,0	4,6	4,8	3,5	3,6
V	23,5	22,0	22,0	20,0	20,4	20,0	20,4	20,0	21,0	20,5
R	F	W	W	F	F	W	F	W	F	W
C	2,5	2,2	3,0	1,5	2,0	2,0	1,6	1,3	1,1	1,6
V	23,0	24,0	22,0	24,0	23,0	24,0	26,0	30,0	30,0	26,0
R	F	F	F	W	W	W	W	F	W	W
C	2,4	5,2	1,6	1,4	3,6	2,0	2,3	4,1	6,9	3,1
V	23,0	20,5	27,0	27,0	21,0	22,0	22,0	20,0	20,0	24,0
R	F	F	F	W	F	W	W	W	W	F
C	2,2	4,2	1,8	3,3	4,3	4,0	5,2	2,1	2,4	3,6
V	24,5	20,0	26,0	23,0	20,0	22,0	21,5	21,5	21,5	21,0
R	F	W	F	F	W	F	F	W	W	F

BULLERS INSULATOR TESTS

C = Conductivity
 V = Voltage
 R = Result
 F = Flashover
 W = Withstand

C	2,2	5,6	5,8	7,1	5,8	7,2	8,6	5,6	10,3	5,3
V	23,0	23,0	25,0	23,0	23,0	22,0	21,0	22,5	20,5	25,0
R	W	W	F	F	F	F	W	W	F	F
C	6,1	6,4	7,2	8,2	6,5	15,9	19,0	16,0	1,7	3,9
V	22,5	21,5	21,0	20,0	21,5	19,5	19,0	19,0	29,6	26,0
R	F	F	W	W	F	F	F	F	F	F
C	3,3	9,5	7,8	10,5	5,3	5,7	8,3	14,0	16,0	13,8
V	25,0	20,0	21,0	19,5	24,0	22,5	20,5	18,5	18,0	19,0
R	F	F	F	F	F	F	F	F	F	F
C	3,8	2,5	3,5	3,8	5,1	4,0	2,0	4,8	8,5	11,2
V	25,0	26,0	24,0	24,0	21,0	22,5	26,5	23,0	19,5	19,0
R	W	W	F	F	W	W	W	F	W	W
C	16,7	14,8	12,4	2,7	4,6	18,6	16,7	5,5	13,1	9,0
V	17,5	18,5	19,0	26,0	22,5	18,0	18,0	22,0	18,5	20,5
R	W	W	W	F	W	W	W	F	W	W

PILKINGTON INSULATOR TESTS

C = Conductivity
 V = Voltage
 R = Result
 F = Flashover
 W = Withstand

C	4,4	8,4	17,0	14,0	17,0	14,0	4,8	7,2	6,0	0,2
V	16,0	14,0	16,5	18,0	15,0	15,0	19,0	19,0	20,0	22,0
R	W	F	F	F	W	W	W	W	W	F
C	5,0	4,4	3,1	9,7	7,4	4,6	3,2	5,0	4,4	3,0
V	21,0	20,0	22,0	18,5	18,5	22,0	25,0	20,0	19,5	22,0
R	F	W	W	F	W	F	F	F	F	F
C	2,6	1,4	6,2	0,4	4,8	2,5	2,7	5,2	4,0	7,6
V	21,0	24,0	19,5	28,0	19,0	23,0	24,0	19,5	20,5	18,0
R	W	W	W	W	W	W	F	F	W	W
C	19,0	10,6	14,0	9,7	1,2	6,5	8,6	11,6	6,7	10,3
V	17,0	17,0	17,5	17,5	30,0	18,5	18,0	17,0	19,0	17,0
R	F	W	F	F	F	W	F	W	F	W
C	12,0	4,4	7,0	4,5	6,0	5,8	5,7	6,8	3,5	3,1
V	18,0	20,0	21,0	20,5	20,0	21,0	19,5	18,5	23,0	22,5
R	F	W	F	F	W	F	W	W	F	F
C	3,1	4,5	7,0	2,4	3,6	1,0	4,0	5,2	8,0	5,6
V	23,5	19,5	18,0	23,0	21,0	29,0	21,0	19,5	18,5	19,0
R	F	W	W	W	W	F	W	W	F	F
C	7,2	4,2	14,0	19,0	7,1	8,5	5,6	11,7	4,6	5,4
V	18,5	20,0	17,0	16,5	18,5	16,0	18,0	16,0	17,0	19,0
R	F	W	W	F	F	W	F	W	W	F
C	12,0	6,0	7,0	8,0	5,5	6,6	7,7	12,0	9,0	20,0
V	17,0	17,5	17,0	17,5	17,5	19,5	22,0	20,5	20,0	17,0
R	F	W	W	W	W	W	F	F	F	W

APPENDIX C

Computer Program For Leakage Current Analysis

```

5  CALL MTAPEO
10 CALL REWIND
15 CALL   ADC, 1, 2, 6
20 CALL REWIND
80 LET L1= 1020
85 LET L2= 25
90 LET L3= 995      92 LET L4= 1000
95 LET F= 0
100 DIM A(200),P(200)
105 LET L= 200
110 LET K= 0
115 LET C1= 5/ 2047
120 LET C2= 3
125 LET C3= 200/ 1.9
127 LET C4= 40
130 LET C1= .1
135 LET C2=-.9
140 LET C3=-1
145 LET N1=N2=N3=N4= 0
150 LET V= 0
155 FOR I= 1 TO L
160 CALL   DMT,A(I)
165 IF A(I)> 2047 THEN 160
170 NEXT I
175 IF F= 1 THEN 230
180 LET M= 0
185 FOR I= 1 TO 15
190 IF A(I+V)< 0 THEN 220
195 IF A(I+V)<M THEN 205
200 LET M=A(I+V)
202 LET N=I
205 NEXT I
210 LET F= 1
212 LET V=N+V
215 GOTO 255
220 LET V=V+ 1
225 GOTO 185
230 FOR I= 1 TO 10
235 IF A(I+V)< 0 THEN 465
240 IF A(I+V)<M THEN 252
245 LET M=A(I+V)
250 NEXT I
252 LET V=I+V+ 7
255 LET K=K+ 1
260 LET P(K)=M*C1
265 LET M= 0
275 IF V>(L- 10) THEN 150
280 IF K< 200 THEN 230
285 PRINT "PEAK NO","VALUE"
290 FOR I= 1 TO 61 STEP 2
295 PRINT I,P(I),I+ 1,P(I+ 1)
300 NEXT I
302 WAIT 1000
304 CALL ERASE
305 GOSUB 475,C1

```

```

307 LET I= 1
310 CALL POINT,( 1/C3+02),(P(I)/C2+01)
315 FOR I= 1 TO 200
320 LET Y=P(I)/C2+01
325 LET X=I/C3+02
330 CALL LINE,X,Y
335 NEXT I
340 GOSUB 475,03
344 LET P1=EXP(P(I))* 2.30298
345 CALL POINT,( 1/C3+02),(P1/C4+03)
350 FOR I= 1 TO 200
355 LET P(I)=EXP(P(I))* 2.30298
360 LET Y=P(I)/C4+03
365 LET X=I/C3+02
370 CALL LINE,X,Y
375 NEXT I
376 WAIT 500
378 CALL ERASE
380 FOR I= 1 TO 200
385 IF P(I)>L1 THEN 410
390 IF P(I)>L2 THEN 420
395 IF P(I)>L3 THEN 430
400 LET N4=N4+ 1
405 GTO 435
410 LET N1=N1+ 1
415 GOTO 435
420 LET N2=N2+ 1
425 GOTO 435
430 LET N3=N3+ 1
435 NEXT I
440 PRINT "NO. OF 420 LET N2=N2+ 1
425 GOTO 435
430 LET N3=N3+ 1
435 NEXT I
440 PRINT "NO. OF PEAKS GREATER THAN";L1;"MA.=";N1
442 PRINT
445 PRINT "NO. OF PEAKS BETWEEN";L2;"MA. AND";L1;"MA.=";N2
447 PRINT
450 PRINT "NO. OF PEAKS BETWEEN";L3;"MA. AND";L2;"MA.=";N3
452 PRINT
455 PRINT "NO. OF PEAKS LESS THAN";L3;"MA.=";N4
457 GOTO 600
460 END
465 PRINT "END OF DATA"
470 END
475 SUP C
480 CALL POINT, 1,C
485 CALL LINE,-.9,C
490 CALL LINE,-.9,(.9+C)
495 RETURN
600 FOR I= 1 TO 61 STEP 2
605 PRINT I,P(I),I+ 1,P(I+ 1)
610 NEXT I
615 END
999 LET F= 100
1000 FOR I= 1 TO F
1010 PRINT P(I)
1020 NEXT I
1030 END
3442 LET I= 1

```