' K, tan δ ' OF ELECTRO-PORCELAIN DISCS UNDER HIGH VOLTAGE STRESSES

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ABSTRACT

Accurate measurements have been carried out of permittivity, tan δ, *versus* frequency, field strength and temperature on four types of porcelain. The temperature range was from room temperature to 90° C. The study of the effect of electrodes on K and tan δ on flat samples of porcelain discs, reported in an earlier paper, was extended to include higher voltage stresses in view of their importance in these measurements. Indigenous discs have been checked with regard to changes in body composition and firing temperatures against K and tan δ. The investigation brings out the possibility of adapting dielectric measurements for quality control on industrial applications.

INTRODUCTION

Porcelain is the most widely used dielectric in high voltage technology. There are ceramics like steatites, glass, frequentite, etc. These, however, for other reasons, are not so universally used for the manufacture of insulators and bushings.

Electro-porcelain or high tension porcelain, in general, is manufactured from the three principle raw materials, *viz.*, clay or kaolin, feldspar and quartz. Chemical constituents of these three raw materials contain Al_2O_3, SiO_2, Fe_2O_3, CaO, KNaO, MgO in different proportions with some impurities.

The firing temperature is usually 1300–1350° C. The final body of the electro-porcelain is non-porous and has a high dielectric strength in addition to other dielectric characteristics. The raw material compositions and manufacturing process, however, largely govern the dielectric characteristics of the finished product—the insulator.

It is important, in order to avoid frequent interruptions to service, that any porcelain that goes into the manufacture of high tension insulators for transmission lines should have good electrical and mechanical characteristics. There are several methods available to judge the characteristics of insulators. There are also tests prescribed by the several standard specifications laying down the requirements which have to be satisfied by the insulators. A non-destructive method of gauging the quality of the porcelain at an earlier stage in the manufacture on the disc samples would very much help in evaluating the performance of the electro-porcelain. It has been the object of this paper to assess the usefulness of the measurements of important dielectric characteristics, *viz.*, K and tan δ of porcelain discs or flat samples of porcelain in quality control.

Porosity is known to be an important factor in electro-porcelain and determines principally the dielectric strength and other dielectric characteristics of electro-porcelain. Non-porous porcelain discs have a high dielectric strength and comparative measurements of dielectric characteristics have been made on both porous and non-porous disc samples in order to assess the usefulness of this method.

(1) THEORETICAL CONSIDERATIONS

The dielectric loss in any insulation used for electrical purposes is given by

$$N_w = \text{EI} \cos \phi = E^2 w C \tan \delta \tag{1}$$

This dielectric loss dissipates itself as heat and volume dielectric loss could be expressed by

$$N_{w(\text{watts/cm.}^3)} = E^2 . 2\pi . f . \frac{C}{C_0} . \tan \delta$$

$$= \frac{\epsilon^2}{1 \cdot 8} . f . K . \tan \delta \tag{2}$$

(N_w is in watts and C is in Farads.
$\omega = 2\pi f$)

where ϵ = the field strength in volts/cm.

f = frequency of the applied voltage.

The variation of K. and tan δ, being the body characteristic of the insulation material, is a function of voltage stress, frequency and temperature, and is of great importance.

The dielectric constant 'K' and Power Factor, 'tan δ' of insulating material at power frequency high voltage stresses can be accurately determined by measurements on the high voltage Schering bridge. Fig. 1 gives the circuit diagram of the Schering bridge with the specimen inserted in guard-ring test condenser with suitable electrodes and a Standard Air Condenser for C and S respectively. The vector diagram for the series and parallel attangement of the loss component resistance to represent the imperfect condenser are given by Fig. 1 (*a*) and (*b*).

If C, be the capacity of the unknown guard ring test condenser

S, capacitance of the standard condenser

δ, the loss-angle

ϕ, the power factor angle

the

$$C = \frac{R_4}{R_3} S \tag{3}$$

and

$$\tan \delta = \omega C_4 R_4 = 0 \cdot 1\ C_4 \tag{4}$$

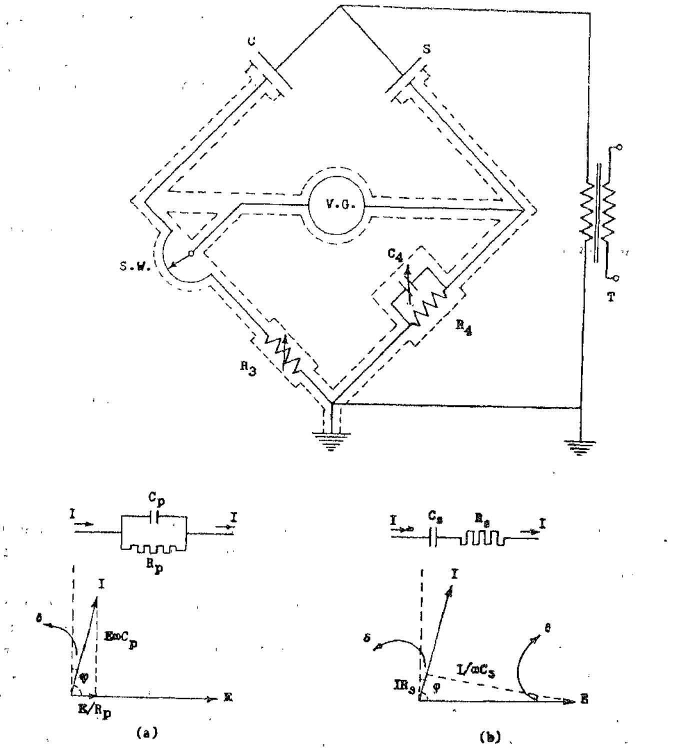
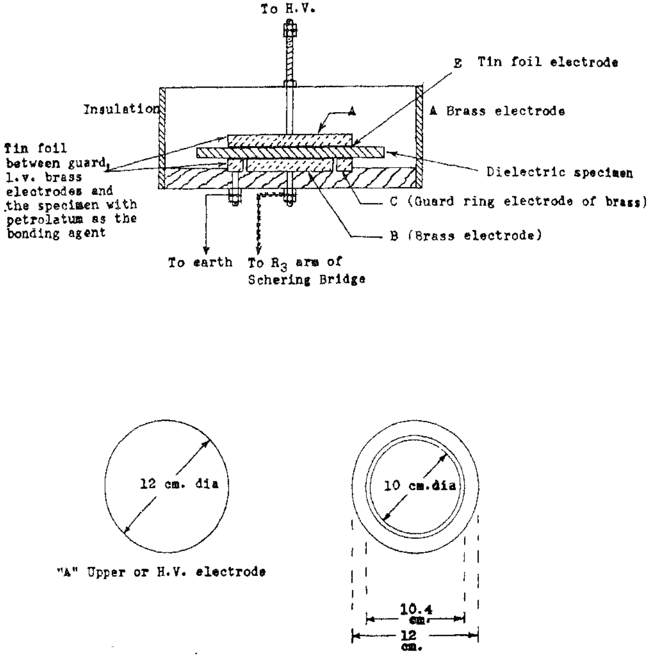


FIG. 1. Schering Bridge circuit: (*a*) Vector Diagram for the parallel arrangement of loss component resistance of the test capacitor; (*b*) Vector Diagram for the parallel arrangement of loss component resistance of the test capacitor for the series arrangement.

(2) EFFECT OF ELECTRODES IN THE MEASUREMENT OF K AND TAN δ ON PORCELAIN DISCS AT HIGH VOLTAGE STRESSES

The effect of applying various types of electrodes, *viz.*, brass with guard-ring, tinfoil, aquadag on porcelain discs of indigenous make at low voltage, has been the subject of a paper published earlier.[1] The ‘ electrode effects ’ study was further extended for high voltage stresses and dielectric measurements were carried out on imported and locally manufactured electro-porcelain discs. The most suitabl system of electrodes for measurements of K and tan δ is shown in Fig. 2. A and B are brass electrodes with C as guard-ring. E is tinfoil attached to the specimen dielectric with petrolatum.



"A" Upper or H.V. electrode

Guard and L.V. electrodes

FIG. 2. Details of electrode system for Dielectric Loss measurements on porcelain discs at power frequency high voltage stresses.

Bigger size electro-porcelain discs, necessary for measurement at high voltage stresses, were imported from well-known manufacturers of high tension porcelain insulators. These imported discs were also used for comparing the dielectric properties of indigenous electro-porcelain.

The imported discs classified as A, B and C had a diameter varying from 5″ to 7″, and thickness of about 250 mils with well-ground surfaces. They were guaranteed to have been prepared from the same body compositions used for making the high tension insulators. The indigenous sample D used had a diameter of 4·5″ and thickness of about ¼″.

The effect was studied under the following electrode arrangements:

(*a*) Plain brass with guard-ring,
(*b*) Controlled air-film of various thicknesses,
(*c*) Tinfoil-brass with and without adhesive,
(*d*) Aquadag with brass electrodes.

The effect of using only brass electrodes without tinfoil was investigated at increasing voltage stresses up to about 40 kV./cm. on the samples A and B. Similar experiment was conducted on the indigenous sample D up to about 14 kV./cm. It was not possible to extend the measurements to higher voltage stresses because of the smaller size of the locally manufactured disc. From the results of measurements on the Schering bridge, the K, tan δ/voltage characteristics are plotted in Figs. 3, 4 and 5, for the disc samples A, B and D respectively.

These experiments were conducted to study the effect of air-films of varying thicknesses in electrode arrangements at varying voltage stresses. Three different thicknesses, 5 mils, 7·5 mils and 10 mils of air-film, were introduced by using mica spacers between brass-plate electrode on the H.V. side and the porcelain disc. The K, tan δ/voltage characteristics are plotted in Figs. 3 and 4, for the samples A and B.

The electrodes of tinfoil were prepared to the correct sizes. They were inserted between the dielectric and the brass electrodes (1) without any adhesive, (2) with petrolatum as adhesive between the foil and the dielectric. From the results of the bridge measurements the K, tan δ/voltage characteristics are plotted in Figs. 3, 4 and 5, for samples A, B and D respectively.

The tinfoil electrodes were removed and aquadag conducting paint was applied with a fine brush. From results obtained for samples A and B, curves for the aquadag electrodes are plotted in Figs. 3, 4 and 5.

Referring to Figs. 3 and 4, the curves show the importance of avoiding the air-film between electrodes and dielectrics. The effect of air-film between the dielectric and electrodes is more pronounced at voltage stresses higher than 10–14 kV./cm. The apparent P.F. is fairly constant till the voltage stress corresponding to very nearly the critical corona point is reached. Thereafter, if the voltage stress is further increased, the P.F. is very high. It could also be seen from the curves, that with voltage stresses of 15–18 kV./cm., the apparent P.F. increases with the increase of thickness of air-film. This increase of measured P.F. may be attributed to the increased conductance of the air-film at the higher voltage stresses. The dielectric constant also shows a similar characteristic.

Tinfoil electrodes with bonding give results which show a steady characteristic for the P.F./voltage curve in Figs. 3, 4 and 5. The dielectric constant is higher than the values obtained with plain brass electrodes. The bridge balance was also easier with tinfoil-brass electrodes with adhesive even up to 50 kV./cm. and was free from fluctuations.

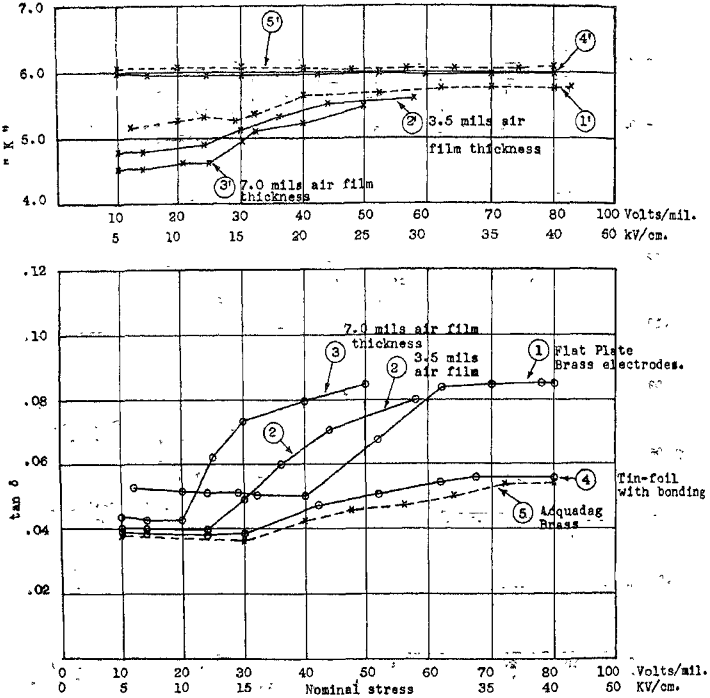


FIG. 3. K, tan δ/voltage stress characteristics with different electrodes on plain electro-porcelain disc sample "A".

Aquadag electrodes also give steady characteristic curves for K and tan δ at high voltage stresses. The values obtained with aquadag-brass electrodes are in agreement with those obtained by tinfoil-brass electrodes. Either of the electrode arrangements, therefore, could be used for measurements at higher voltage stresses up to 50 kV./cm.

Since application of aquadag electrodes involves some skill and takes a longer time to apply and remove, tinfoil-brass with petrolatum bonding may be used in practice without any serious error up to 50 kV./cm. at power frequency for routine type measurements.

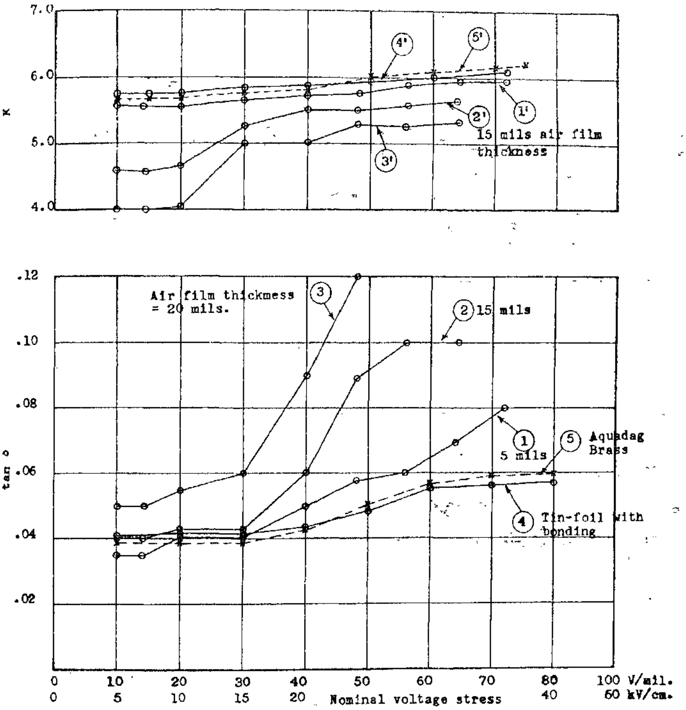


FIG. 4. Effect of different electrodes on K and tan δ for sample "B".

(3) VOLTAGE STRESS ON K AND TAN δ OF PORCELAIN

With imported samples, voltage stresses up to 40–50 kV./cm. could be applied because of the bigger size of the disc samples A, B and C. The system of guarding and shielding provided was found very helpful for accurate balancing of the bridge at higher voltage stresses. The results of the bridge measurements are plotted in Figs. 6, 7, 8 and 9, which show the K, tan δ/voltage characteristic for the imported samples, A, B, C as well as for indigenous non-porous sample D respectively. The voltage stress on disc D had to be limited to 10–15 kV./cm. on account of its smaller size.

(4) TEMPERATURE EFFECT ON K AND TAN δ OF PORCELAIN UNDER HIGH VOLTAGE STRESSES

The effect of temperature on the dielectric characteristics over the range was measured on both foreign and indigenous discs.

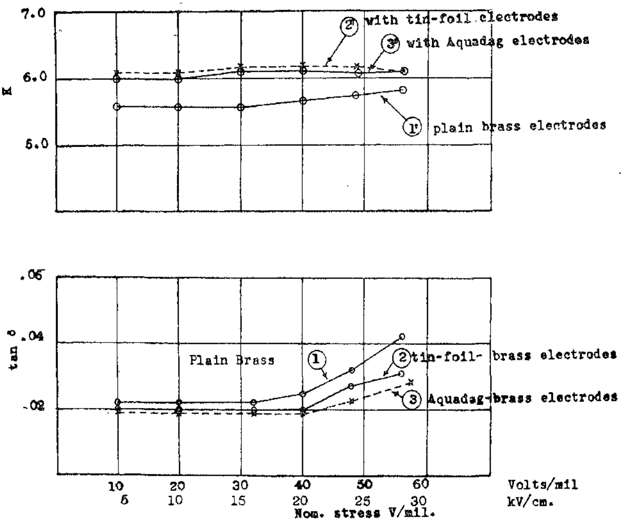


FIG. 5. Effect of different electrodes on K and tan δ of porcelain disc sample "D".

The specimen with the electrodes was kept in a conditioning oven Fig. 10 where temperature up to 110° C. could be controlled by means of an electronic relay.[2] A voltage up to 35 kV. could be applied to the samples through a bushing. The measurements were made on the Schering bridge after heating the specimen for 24 hours at each value of the temperature chosen.

The results of measurements on samples A and B of foreign make and sample D of indigenous are plotted in Figs. 11, 12 and 13 showing the effect of applied voltage stress at higher temperatures on K and tan δ of porcelain discs.

(5) EFFECT OF HIGHER FREQUENCIES ON K AND TAN δ

Since the same electro-porcelain body is also used in making insulators for telephone and telegraph purposes, measurements were made to determine the order of values for K and tan δ of discs at the order of frequencies in the range 1–50 Mc./s. on both indigenous and foreign discs.

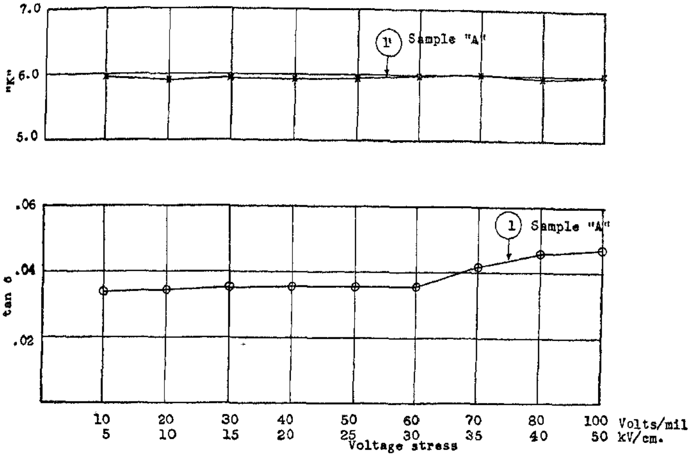


FIG. 6. K, tan δ/voltage stress characteristics on disc sample "A".

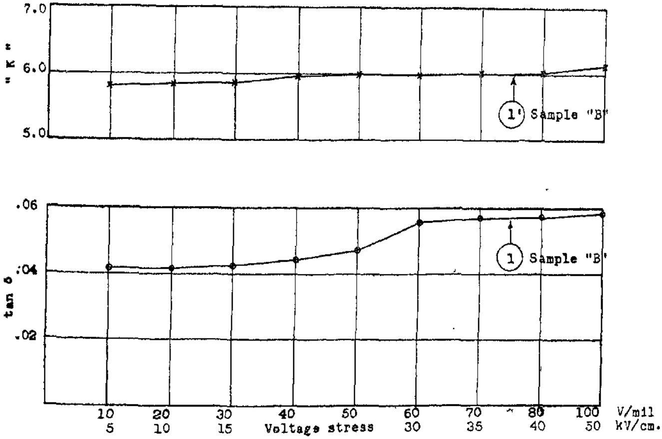


FIG. 7. K, tan δ/voltage stress on disc sample "B".

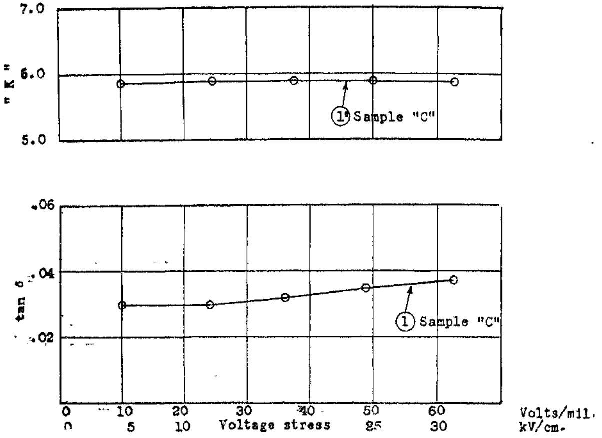


FIG. 8. K, tan δ/voltage stress on disc sample "C".

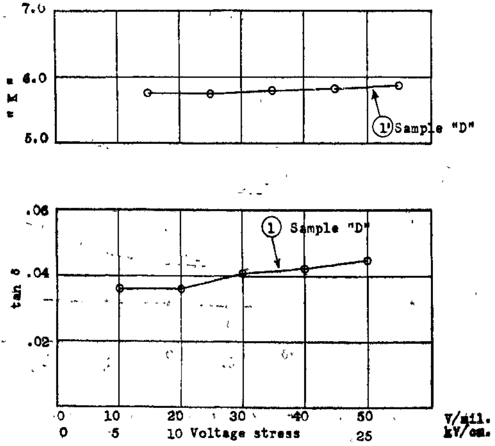


FIG. 9. K, tan δ/voltage stress on sample "D".

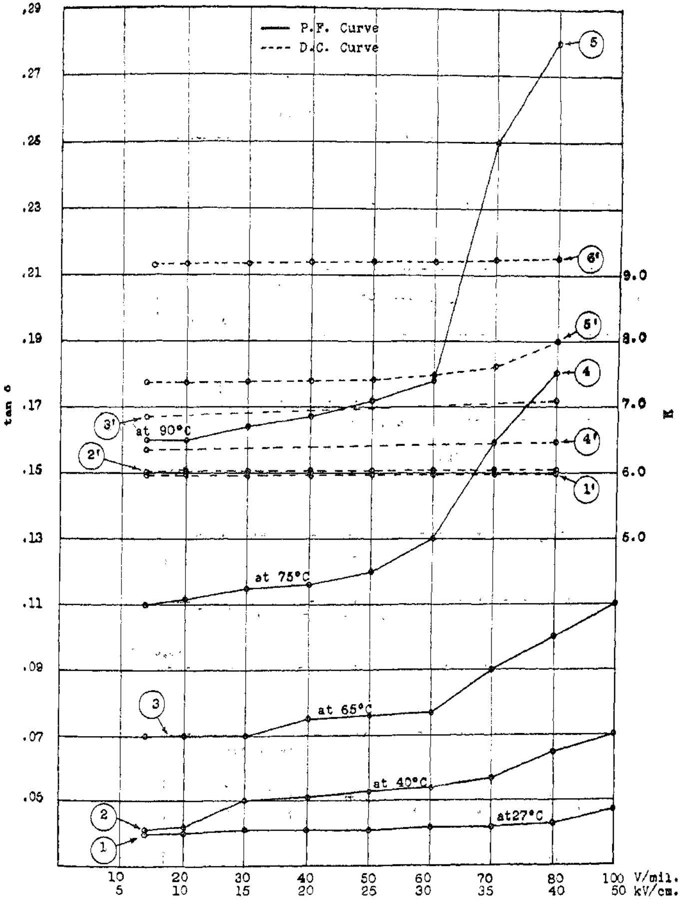


FIG. 11. Effect of temperature over the range 27° C. to 90° C. on K and tan δ of the electro-porcelain disc sample "A".

Measurements of dielectric constant and P.F. of insulating materials at frequencies above 1 Mc./s are done by the resonance circuit susceptance variation method. This method is well known and fully discussed by Hartshorn and Ward[8] and also described in the standard specification, A.S.T.M., 1946.

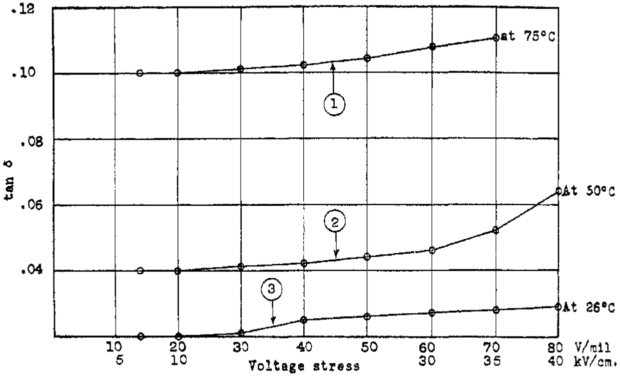


FIG. 12. tan δ/voltage stress at different temperatures on disc sample "B".

Figure 14 shows the 1–50 Mc./s., G.E. dielectric measuring equipment designed and built on the Hartshorn principle.

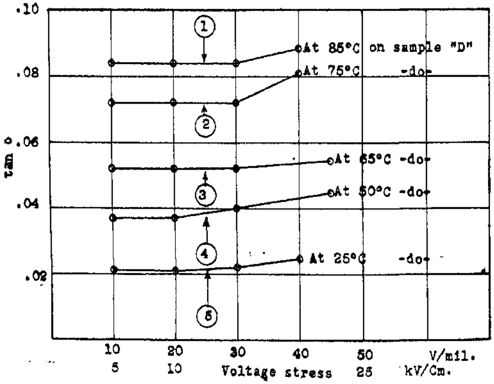


FIG. 13. tan δ *versus* voltage stress on sample "D" at different temperatures (K is fairly constant).

The equipment consists of the measuring head, oscillator, power supply and a micro-ammeter for resonance indication which are mounted within a metal cabinet.

The measuring circuit is given in Fig. 15 and measurements are made by detuning the resonant circuit containing the specimen under test so as to obtain half the voltage on either side of resonance. The resonance of the measuring head is indicated by a 0–20 micro-ammeter. The results of measurements on samples A, B and D are plotted in curves in Fig. 16.

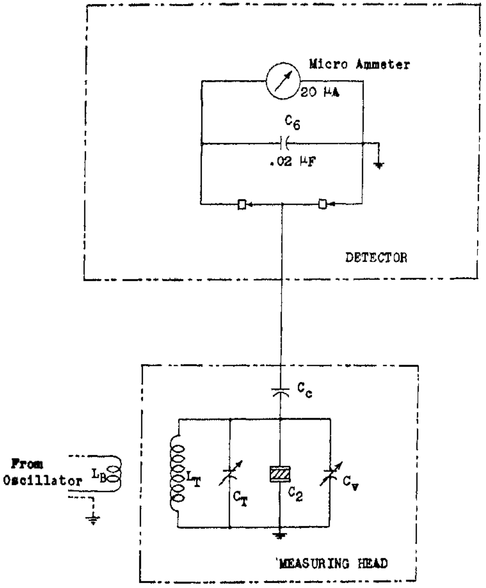


FIG. 15. Connection diagram for 1–50 Mc Dielectric Measuring Equipment.

(6) RESISTIVITY OF PORCELAIN DISCS

Volume resistivity of porcelain is very high and is characteristic of the body of the dielectric. Volume resistivities of the imported and indigenous porcelain discs were measured with a view to determine the quality of the porcelain.

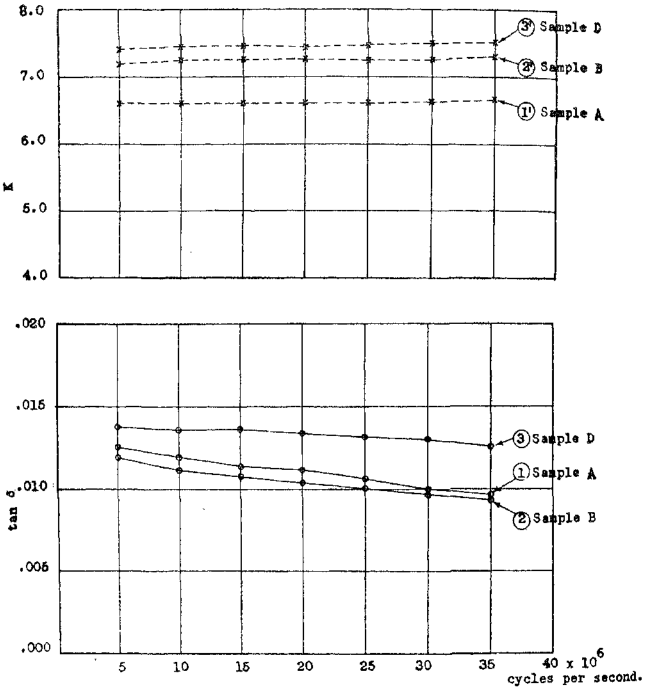


FIG 16. K, tan δ *versus* frequency on the samples of porcelain discs A, B and D.

The measurement of volume and insulation resistance was made in accordance with standard specification A.S.T.M. D. 257–46–13 (*a*) and (*b*), using a reflecting type galvanometer, universal shunt and 500 volts D.C. supply. Mercury, confined with rings, was used for the h.v., l.v. and guard electrodes. The low voltage electrode was formed by the mercury contained in the glass bowl.

The circuit diagram with the arrangement of electrodes for these measurements is given in Fig. 17, and the results in Table I.

(7) PORCELAIN DISCS WITH VARYING BODY CHARACTERISTICS

Preparation of experimental disc samples.—The chemical constituents of clay, feldspar and quartz used in the preparation of the working body of the electro-porcelain could be determined from a chemical analysis. The indigenous body of

TABLE I

Results of measurements of resistivity of electro-porcelain discs at R.T. with mercury electrodes on opposite sides of the ground samples at 500 Volts D.C. and D'Arsonval Galvanometer

Specimen identification No.	Vol. Resistance, R in Ohms	Vol. Resistivity Ω-cm.	Conductivity 'S' = 1/Ω mho-cm.$^{-1}$	Remarks
Disc A	42×10^{10}	13×10^{12}	$\cdot 077\times 10^{12}$	Ground discs A, B, C and D with dia. 5″ to 7″ and thickness about 6 mm. Calibration with standardi meg-ohm, $k = 50$ cm. at 1 metre scale distance. k is the calibration const.
Disc B	50×10^{10}	15×10^{12}	$\cdot 06\times 10^{12}$	
Disc C	71×10^{10}	23×10^{12}	$\cdot 043\times 10^{12}$	
Disc D	41×10^{10}	12×10^{12}	$\cdot 071\times 10^{12}$	
Smaller discs (3″×¼″)	R in ohms			
R.1	$1{\cdot}12\times 10^{10}$			Non-porous experimental discs
R.2	$1{\cdot}25\times 10^{10}$			
R.3	$1{\cdot}10\times 10^{11}$			
1.1.5	$1{\cdot}42\times 10^{10}$			
1.1.6	$3{\cdot}6\times 10^{10}$			
2.3.1	25×10^{10}			
2.3.3	23×10^{10}			
Smaller discs (3″×¼″)				
2.4.3	$1{\cdot}8\times 10^{9}$			Porous experimental discs
2.4.2	$1{\cdot}1\times 10^{9}$			
2.4.4	1×10^{9}			
2.4.6	$\cdot 8\times 10^{9}$			

the raw material used was analysed and the chemical composition in percentage of the Al_2O_3, SiO_2, etc., are shown in Table II for the experimental discs.

In order to study the dielectric characteristics of porcelain discs prepared from indigenous raw materials, samples of approximate size 3″ dia. and ¼″ thick were prepared in a local factory out of varying body compositions. They were fired in the same way as in the process of regular manufacture of insulators. Some porous discs were also made in the group for comparative measurements. The samples so prepared had rough surfaces and could not be used as such for dielectric measurements. All the discs were ground in a local factory in a special machine so that they had plain and parallel surfaces.

The smaller set of brass electrodes with guard-ring electrodes were used for the measurement of these smaller discs. Tinfoil was applied to the samples with petrolatum and measurements were made at power frequency voltage of 8 kV. on the high voltage Schering bridge.

Average values for the samples showing K, tan δ/body composition are plotted in Fig. 18, showing the range of variations for the discs.

(8) DISCUSSION OF EXPERIMENTAL RESULTS

The foregoing results give the comparative measurements of permittivity, tan δ and volume resistivity on the imported and indigenous electro-porcelain discs. For purpose of clarity, the results of the measurements are discussed under the following heads:

(1) Non-porous porcelain discs of both imported and indigenous quality.

(2) Experimental porcelain discs prepared from indigenous raw materials.

(1) *Non-porous Porcelain discs*

A comparative study of the dielectric characteristics of porcelain discs has been made. The dielectric properties could be considered under the following sub-heads:

(i) *Effect of voltage stress.*—Curves in Figs. 6, 7, 8 and 9 show the relationship between the permittivity, power factor and applied voltage stress at power frequency on the samples of the imported and indigenous porcelain discs.

The range of power factor variation is from 0·031 to 0·036 in the case of sample A, from 0·038 to 0·046 in sample B, from 0·029 to 0·032 in sample C and from 0·024 to 0·041 in the indigenous sample D over the range of applied voltage stress up to 30 kV./cm. The permittivity of the discs as a function of voltage stress vary between 5·9 to 6·1 in sample A, and 5·81 to 5·96 in sample B, from D. From these results it can be concluded that the K, tan δ/voltage characteristics of the indigenous disc compare favourably with similar characteristics of the imported discs and that it is possible to obtain from the indigenous raw materials, the quality of porcelain as the imported ones.

TABLE II

Body compositions of the experimental discs of porcelain size 3″×¼″ ground sample

Experimental discs identification No.	Raw material composition	% Chemical constituents	Firing conditions	Classification
1.1.2	Clay I 30%	Al_2O_3 22·95	Normal	Group I
1.1.3	Clay II 10%	SiO_2 65·33		
1.1.6	Feldspar 43%	Fe_2O_3 0·76		
1.1.1	Quartz 17%	KNaO 5·35		
1.2.4		CaO 0·31		
1.3.3		TiO_2 0·15		
1.3.4		L.O.I 5·07		
2.1.1				
2.1.3				
2.1.5				
2.2.1				
2.3.1	do.	do.	Under-fired	Group II (Porous discs)
2.3.2				
2.3.3				
2.4.2				
2.4.3				
2.4.4				
2.4.6				
1-A				
2-A				
3-A				
4-A				
3.1.2	do.	do.	Slightly over-fired	Group III
3.1.5				
3.1.6				
3.2.2				
3.2.3				
3.2.4				
3.2.5				
11–41				
11–42				
11–44				
R.1	Clay I 10	Al_2O_3 17·56	Normally fired	Group IV
R.2	Clay II 20	SiO_2 64·88		
R.3	Clay III 20	Fe_2O_3 0·77		
R.4	Feldspar 30	KNaO 4·23		
R.5	Quartz 20	CaO 0·48		
R.6		MgO 0·17		
R.7		TiO_2 0·31		
		L.O.I. 11·6		

The power factor increases gradually with increase of voltage stress whereas the permittivity does not show much variation with increase of voltage over the range covered in the measurements.

(ii) *Effect of temperature.*—The insulating properties of dielectrics usually deteriorate with increasing temperature. Figs. 11, 12 and 13 show a comparative study of the variation of K and tan δ with different voltage stresses at definite temperatures in the range between 25° C. and 110° C. From these curves it will be seen that at each temperature the power factor increases with increasing voltage stress. The dielectric constant, however, increases only slightly for the variation of voltage stress at that temperature. At higher temperatures the power factor and dielectric constant/voltage stress show considerable increase with the values of these quantities obtained at lower temperatures.

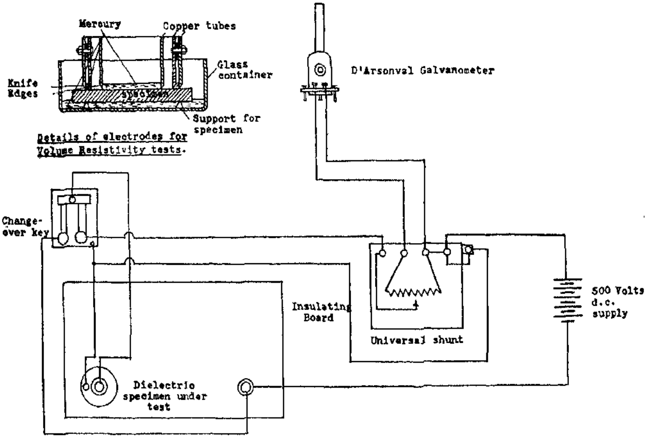


FIG. 17. Diagram of connections for Resistivity Measurements of Electro-Porcelain Discs.

The effect of higher frequencies in the range 1–50 Mc./s. on K and tan δ are plotted for the imported and indigenous samples in curves in Fig. 16. The power factor of porcelain is found to decrease whereas the dielectric constant is fairly steady with increasing applied frequency.

The resistivity of the samples are given in Table I. The volume resistivity of sample A is 13×10^{12} Ω-cm., sample B is $15 \cdot 6 \times 10^{12}$ Ω-cm., sample C is 23×10^{12} Ω-cm., and indigenous sample D is 13×10^{12} Ω-cm.

The above measurements show that the D.C. resistivity of all the non-porous discs are fairly high ranging from 13×10^{12} Ω-cm. to 23×10^{12} Ω-cm.

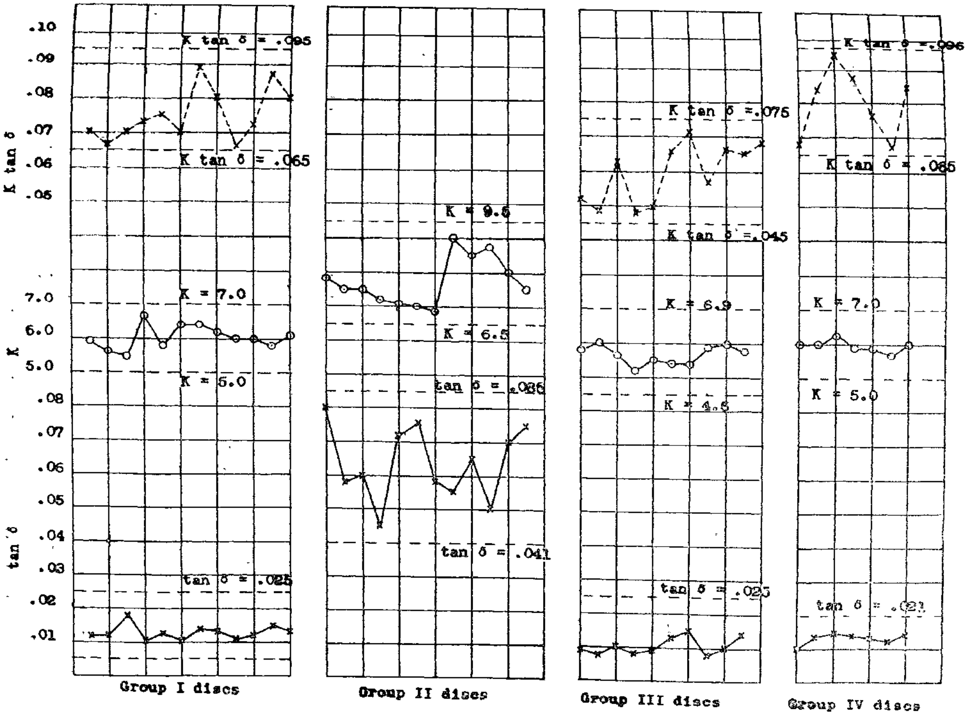


FIG. 18. Dielectric characteristics of experimental discs of porcelain, size $3 \times \frac{1}{4}''$.

(2) *Experimental discs*

The experimental discs are described in Table II with their identification numbers, percentage chemical compositions and firing conditions. These discs are classified under four groups and the results of the measurements of power factor and permittivity at a voltage stress of 14–15 kV./cm. and other dielectric characteristics are also given in the table.

The discs in group I had been fired in the normal way to a temperature of 1300–1350° C. Group II samples were prepared from the same body composition as in group I but under-fired at a temperature of 800° C. to 900° C. These discs were found to be porous in accordance with the porosity test of B.S.S. 137-1941. Group III discs were prepared from the same body composition as in group I but over-fired, the firing temperature being approximately 1380° C. Group IV discs were normally fired but with slightly varying body compositions in percentage of SiO_2 and Al_2O_3.

Graphs in Fig. 18 show the average values of the characteristics for the disc samples in the groups I to IV. Referring to Table II and Fig. 18 the results of dielectric measurements on the experimental discs prepared from indigenous raw materials show out some interesting characteristics. These could be considered under the following sub-heads:

(i) *Effect of porosity on K and tan δ.*—It could be seen that the average values of K, tan δ and loss factor (K, tan δ) for the porous discs in group II are much higher than the non-porous discs of groups I and III. The normally fired and over-fired samples show much lower values. The porosity of the discs is easily detected from the consideration of these results.

(ii) *Effect of body composition on K and tan δ.*—The discs in groups I and IV had been prepared with slight variation in percentage of Al_2O_3 and SiO_2 but fired in the normal way. The measured values of K and tan δ of group IV discs are found to be in agreement with the values obtained for group I discs. This seems to indicate that slight changes in the raw material compositions over the range used in the experiments, do not make much difference in the quality of the porcelain if the firing conditions are identical.

(iii) *Effect of over-firing on K and tan δ.*—The discs in group III contain the same body composition as in group I but were over-fired. The results of measurements show a lower value for the loss factor. These discs also exhibited some blisters and appear to have a lower mechanical strength.

(9) CONCLUSIONS

From the above measurements of K and tan δ on the porcelain disc samples, it may be possible to assess the quality of the porcelain at an earlier stage of manufacture of the finished product and thereby assist quality control with the measurements of K and tan δ on the discs. It would, however, be possible to find out the

FIG. 10

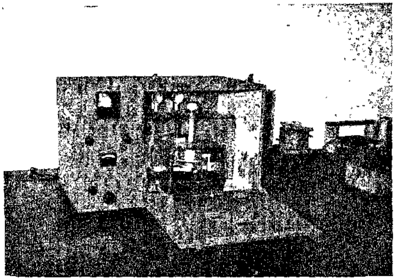


FIG. 14

porosity of the porcelain without actually conducting the porosity test as per B.S.S. 137–1941, Clause 18 and also gauge the quality of the finished product.

(10) ACKNOWLEDGEMENT

I should like to express my gratitude to Professor D. J. Badkas, for his kind help and encouragement.

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