# MEASUREMENT OF POWER FACTOR AND LOSS IN DIELECTRICS.

*By T. J. Mirchandani, G. Yoganandam, S. K. Roy and N. V. Narayanaswami.*

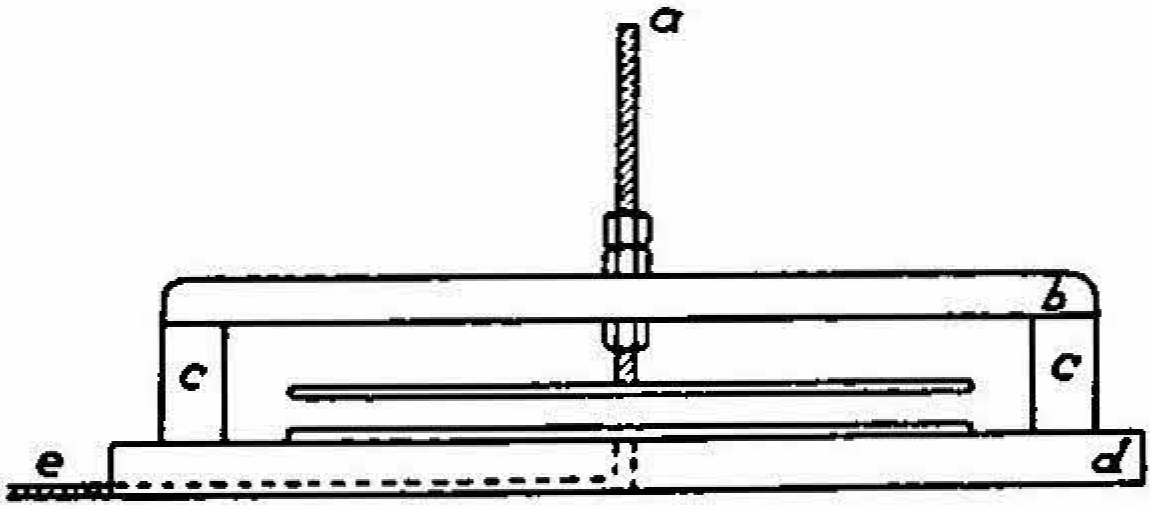
The behaviour of liquid and solid dielectrics under electric stress has formed the subject of experiment and analysis by numerous workers all over the world. For a long time physicists and chemists have investigated dielectric problems with special reference to their own branches and a vast amount of literature has thus accumulated on the subject; the absence of common ground however has led to a multiplicity of theories about the physical phenomenon, none of which can be said to have found universal acceptance.

To the electrical engineer, the dielectric problem first presented itself by the attenuation in telegraph and telephone cables. An intensive and careful study of absorption in dielectrics at telephone frequencies was undertaken by Fleming and others and resulted in a proper selection and control of the materials employed. The selection of gutta percha for submarine cable-insulation is an instance of the application of these researches.

In the field of heavy electrical engineering the increasing voltage of generation and transmission has brought into prominence the erratic performance of high voltage insulation in machines, apparatus, insulators, cables and condensers, and the problem has begun to be studied from the power engineer's point of view. Extensive work has been done by manufacturers of high voltage apparatus and cables, whose procedure has been to adopt certain materials and methods of construction which have proved satisfactory at lower voltages, and to study their suitability for the changed conditions of service. Breakdown voltages of dielectrics commonly used have been studied in great detail and various theories and hypotheses have been put forward to explain the observed phenomena. The fundamental problem is however not nearly solved, and ambiguity regarding the actual physical phenomenon of breakdown persists.

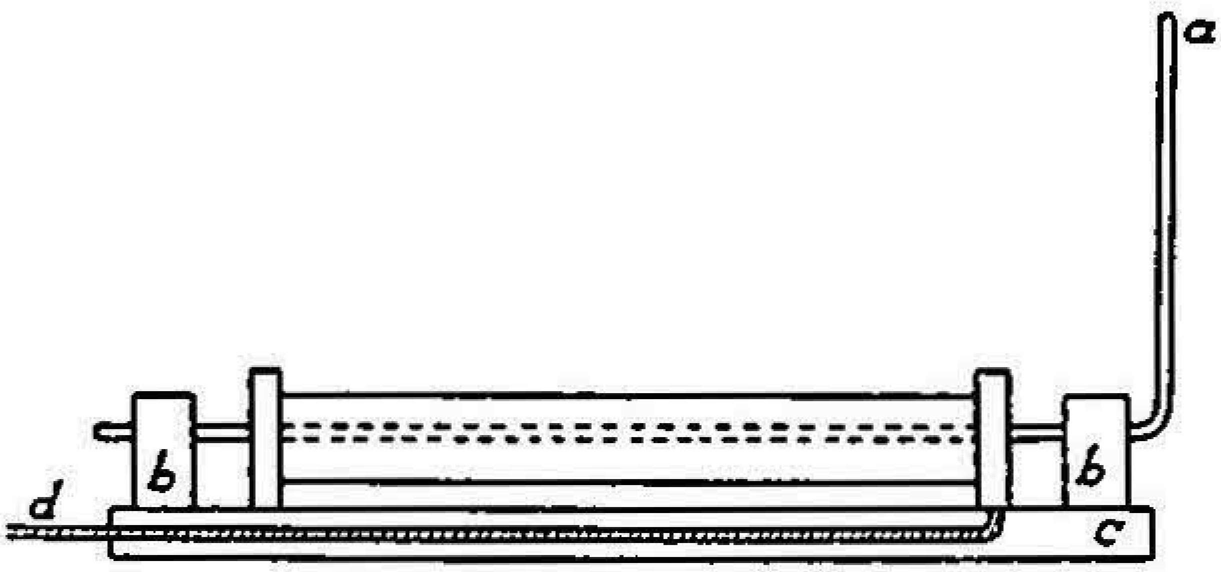
The line of attack originally proposed for this investigation differs in that an analytical study of the variation of power factor and loss was undertaken to ascertain whether there is any connection between these features and the process of breakdown under electric stress, in the hope that a reliable method of selecting materials for the different types of service may be evolved therefrom. The object was to ascertain quantitatively whether "the energy dissipation under constant A.C. voltage tending to increase itself owing to the rise of temperature" as observed by Fleming at high frequencies, and suggested by Whitehead as a cause of the anomalous behaviour of dielectrics, is really high enough at power frequencies to induce progressive deterioration of the insulating materials, and thus be the root cause of insulation breakdown. This line of research had unfortunately to be abandoned, because with the apparatus used, steady readings could not be obtained when the applied voltage exceeded a certain value, although this was much less than

Fig. 2 PARALLEL PLATE ELECTRODES




a - H.T. Lead
b - Brass rod of rectangular Section
c - Ebonite Supports
d - Wooden base
e - Sheathed Cable to Bridge from bottom electrode

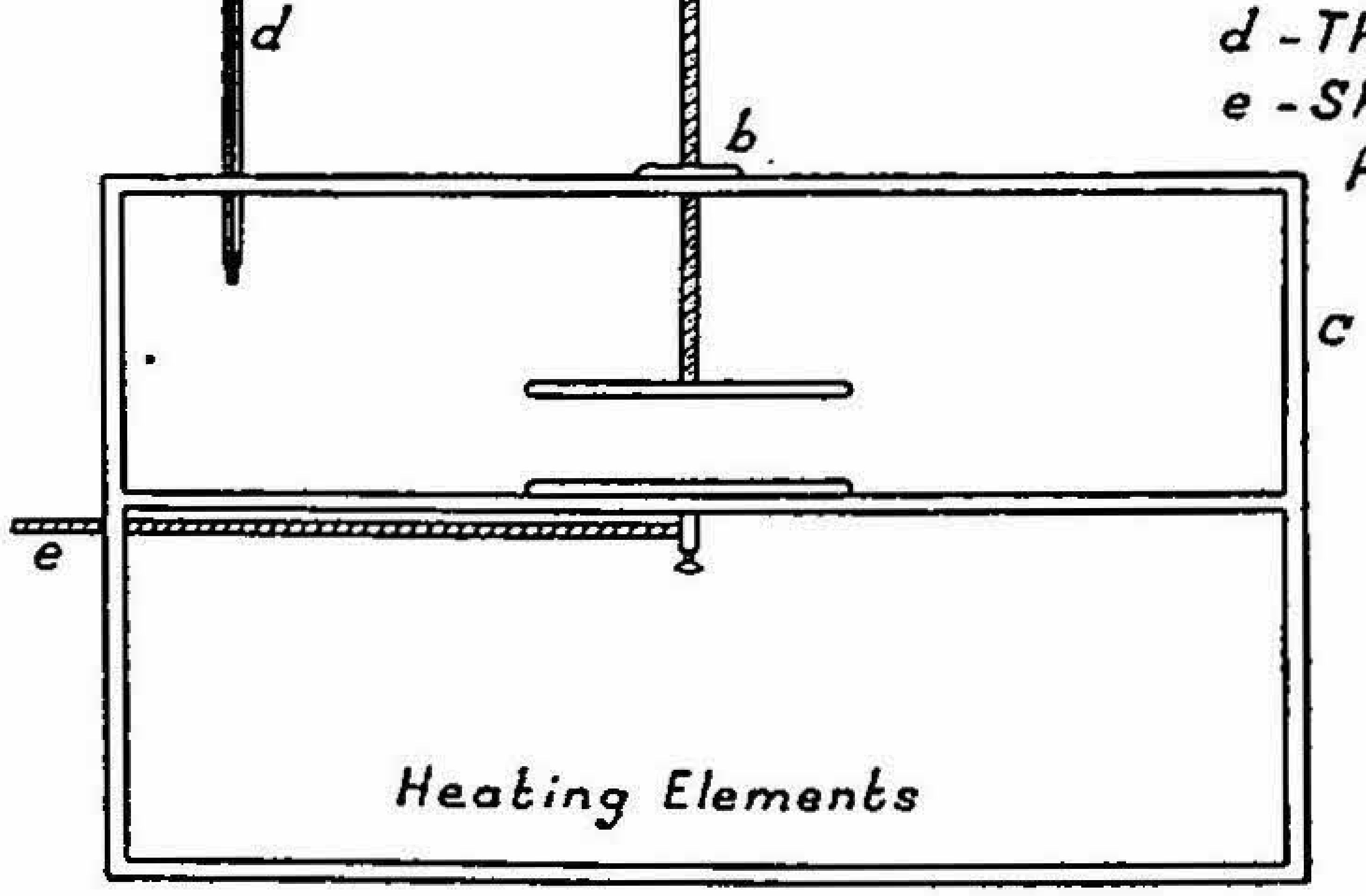
Fig. 3 CO-AXIAL CYLINDERS




a - H.T. Lead
b - Ebonite Supports
c - Wooden base
d - Sheathed Cable to Bridge from outer cylinder

Fig. 4 ELECTRODES FOR SOLID DIELECTRIC TESTING

(FRONT DOORS REMOVED)




a - H.T. Lead
b - Ebonite Bush to insulate the rod
c - Wooden enclosure with asbestos cement lining
d - Thermometer
e - Sheathed cable to bridge from bottom electrode

# Part I. Liquid Dielectrics.

*By T. J. Mirchandani, G. Yoganandam and S. K. Roy.*

The dielectrics tested were (*a*) transformer oil, (*b*) paraffin oil and (*c*) linseed oil.

The apparatus used is shown in Figs. 2 and 3. The liquid was contained in a glass trough with electrodes completely immersed. Both parallel-plate and concentric-cylinder electrodes were used to find out whether the different potential gradients in the two cases made any difference in the characteristics observed. Observations were also made with the plate electrodes 0.5 and 1 cm. apart respectively, in order to examine the effect of the surface and other stray losses, but no evidence of these was observed.

*Plate Electrodes* (Fig. 2).—These consisted of two circular plates of brass 20 cm. diameter and 3 mm. thick. The bottom electrode was mounted on a block of hard wood, which also carried two upright cylindrical supports made of ebonite. A cross-bar of brass with a threaded hole in the centre was fixed to the ebonite supports. The top electrode had a threaded brass rod soldered to it and the distance between the plates was thus adjustable. The capacity in air with 1 cm. separation was 30 micro-microfarads. The upper electrode was connected to the transformer and the lower to the bridge.

In the initial stage of the work, the upper electrode was also mounted on a block of hard wood and an earthed guard-ring surrounded the lower. The gap was then adjusted by altering the height of the ebonite uprights. The upper wood, however, warped badly at high temperatures and twisted the brass plate so that the distance between the electrodes did not remain uniform. In the final experiments therefore the upper electrode was arranged with the threaded rod as described ; and by using lock-nuts above and below the cross support, the gap was adjusted to the required value. The guard-ring was also abandoned because of the difficulty of avoiding sharp edges in construction. The results with and without the guard-ring showed no measurable difference.

*Cylindrical Electrodes* (Fig. 3).—The outer cylinder was of brass 3 mm. thick, 3.8 cm. inner diameter and 25.4 cm. long ; the inner one was a 6 mm. diameter copper rod bent at right angles as shown in the figure and connected to the high voltage terminal of the transformer.

(*a*) In the preliminary experiments, measurements of power factor and capacity were made with a comparatively impure sample of transformer oil filtered only once through a filter press. These measurements were made with the concentric cylinders and the parallel plates with gaps equal to 1 and 0.5 cm. respectively. The range of temperatures over which the readings were taken was 23° to 90°. Examination of these readings brought out certain features common to all three cases. They are—

(1) The power factor—stress curves are very nearly straight lines, the power factor increasing with stress.

(2) The power factor increases with temperature in this range.

(3) The slope of the power factor—stress curves increases with temperature to a small extent.

(4) The well-known minimum point on the loss—temperature curves does not appear within the region of 23–90°.

No definite theoretical conclusions could be drawn from these results except that a change in the physical properties of the oil with change of stress and temperature is indicated by the characteristics. Also, if reliance could be placed on Hochstadter's theory of the V curve of dielectric loss (*E.T.Z.*, 1922, **43**, 575, 612 and 641), namely, that the initial drop in the loss—temperature curves is due to dielectric hysteresis which has a negative temperature coefficient and the subsequent rise due to leakage resistance which has a positive temperature coefficient, then, obviously, the 23–90° range lies on the rising point of the V curve in which the effect of leakage resistance preponderates. If leakage resistance is taken to depend on the ionic condition of the oil (mobility of the ions), the increase of power factor, and therefore loss, with stress and temperature can be explained by assuming that both these quantities increase the mobility of the ions.

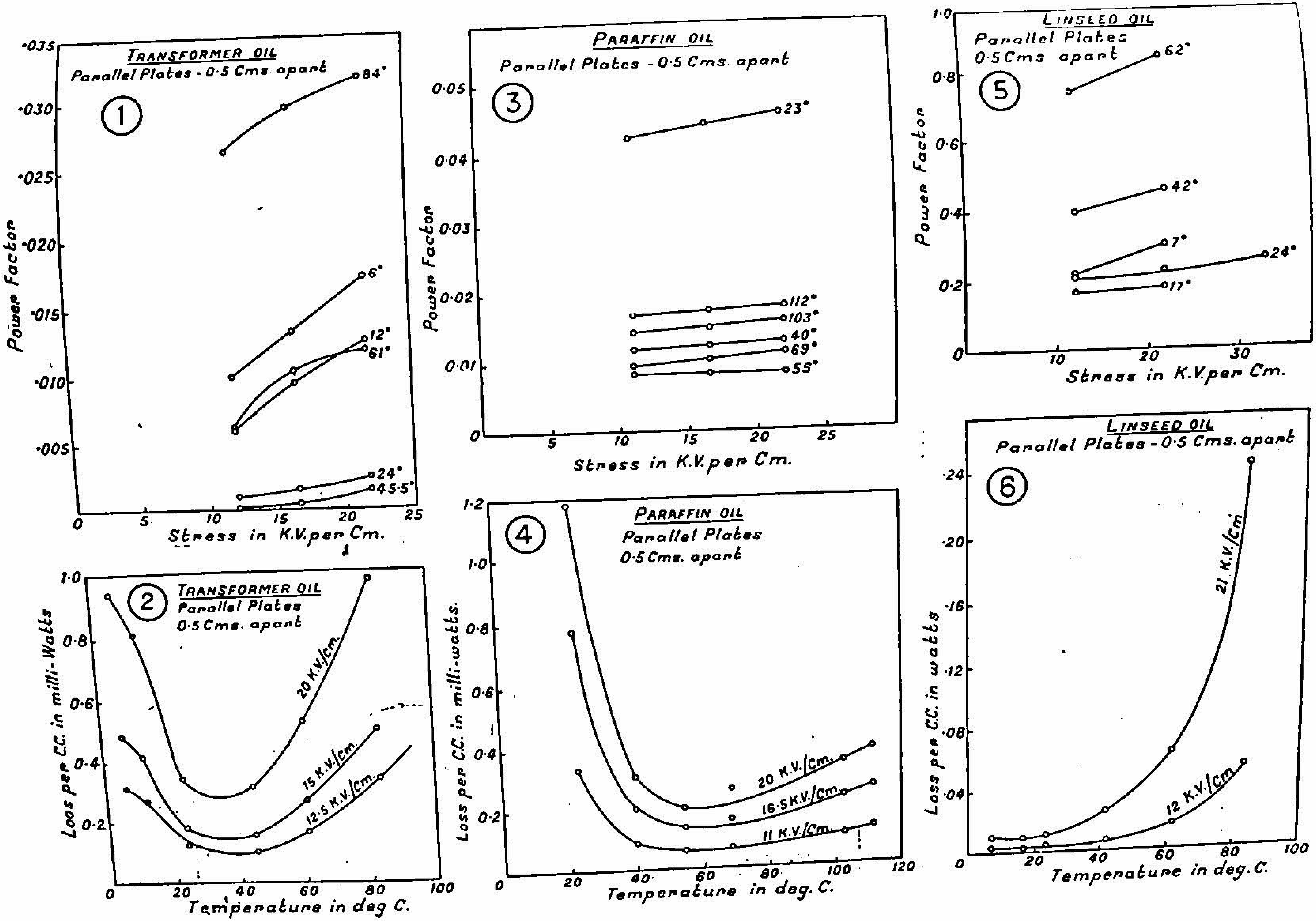
In the final measurements, the same sample of transformer oil was refiltered twice using specially dried filter papers in the filter press and tested for a wider range of temperature with a view to discovering effects not already observed. The parallel plate condenser with a gap of 0.5 cm. was used. The results are given in graphs 1 and 2, which show the power factor—stress and loss—temperature characteristics. The power factor—stress curves are nearly straight lines as before except the one for 61° which is slightly curved, probably due to experimental error.

Emmanueli, in the course of the discussion on Dunsheath's paper (*J.I.E.E.*, 1926, **64**, 97) observed that "mineral oils show a maximum in power factor which varies inversely with the temperature, *i.e.*, the higher the temperature, the lower the voltage at which this appears." No maximum has been observed in our experiments. The reason for this maximum point is not explained and is not obvious. The point of minimum loss is clearly shown in graph 2 and occurs at about 32° and this temperature appears to be constant for all stresses.

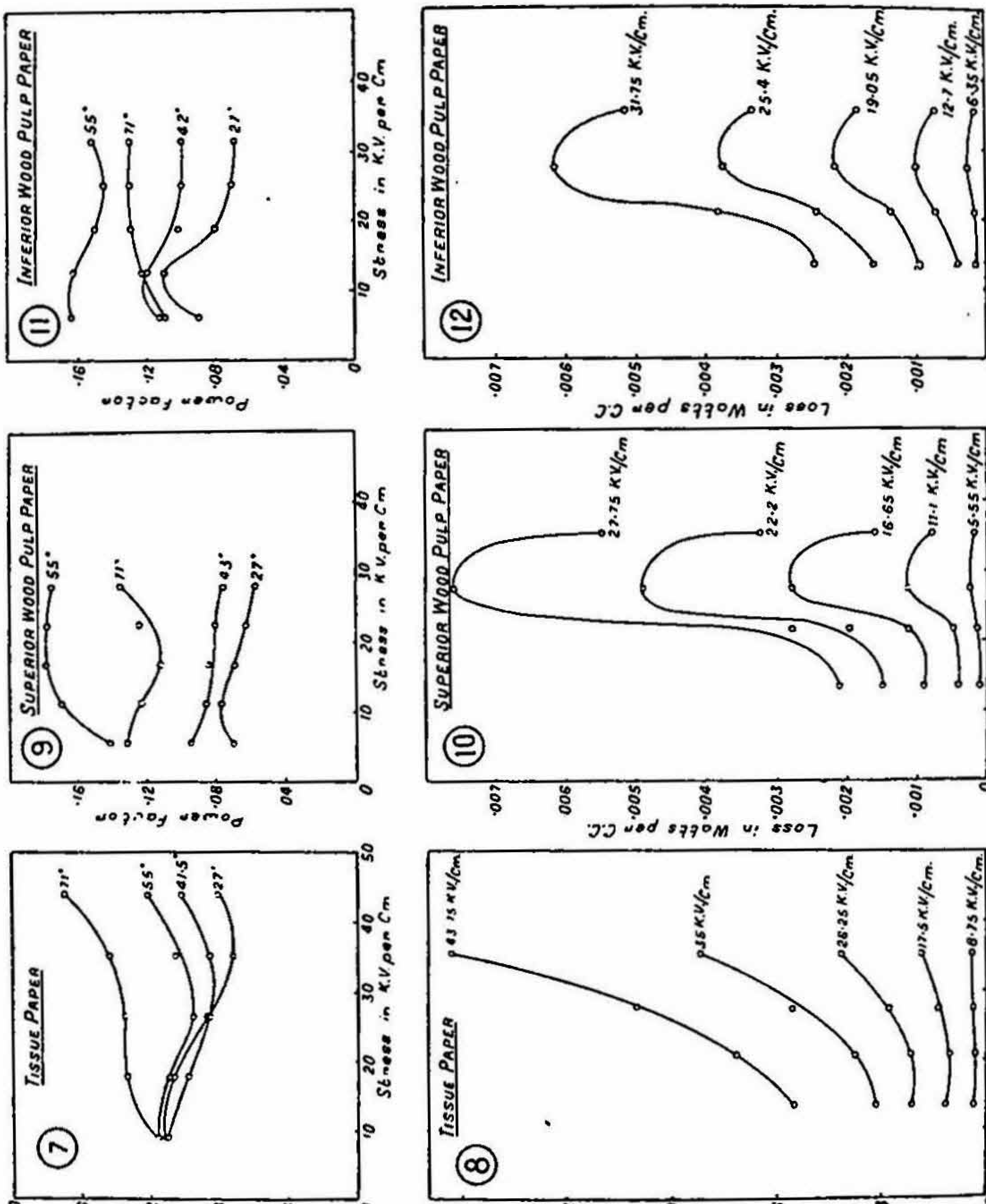
(*b*) Similar observations were made with paraffin oil using the parallel-plate condenser with a gap of 0.5 cm. It was considered needless to experiment with the concentric cylinder condenser, as it produced no new results in the case of transformer oil. The results are given in graphs 3 and 4.

As in transformer oil, the power factor—stress curves are straight lines, but show a lower rate of increase with stress. The point of minimum loss occurs at about 55° on the loss—temperature graph. The descending portion of the curve is very steep, thereby indicating that the component of dielectric loss which decreases with temperature does so at a very rapid rate in comparison with the other component which increases much less rapidly with temperature. In transformer oil, both these components appear to have approximately similar values, varying with temperature at nearly equal rates.

(*c*) Experiments with linseed oil were only partially successful as both the power factor and loss are abnormally high in spite of satisfactory dielectric strength. The power factor varies from 0.15 to 0.8. The readings obtained



1
TRANSFORMER OIL
Parallel Plates - 0·5 Cms. apart
Power Factor
Stress in K.V. per Cm.
84°
6°
12°
61°
24°
45·5°
3
PARAFFIN OIL
Parallel Plates - 0·5 Cms. apart
Power Factor
Stress in K.V. per Cm.
23°
112°
103°
40°
69°
55°
5
LINSEED OIL
Parallel Plates
0·5 Cms apart
Power Factor
Stress in K.V. per Cm.
62°
42°
7°
24°
17°
2
TRANSFORMER OIL
Parallel Plates
0·5 Cms. apart
Loss per CC. in milli-Watts
Temperature in deg C.
20 K.V./cm.
15 K.V./cm.
12·5 K.V./cm.
4
PARAFFIN OIL
Parallel Plates
0·5 Cms. apart
Loss per CC. in milli-watts.
Temperature in deg. C.
20 K.V./cm.
16·5 K.V./cm.
11 K.V./cm.
6
LINSEED OIL
Parallel Plates - 0·5 Cms. apart
Loss per CC. in watts
Temperature in deg. C.
21 K.V./cm.
12 K.V./cm.


7
TISSUE PAPER
Power Factor
Stress in K.V. per Cm
71°
55°
41.5°
27°
8
TISSUE PAPER
Loss in Watts per C.C.
Temperature in deg C
43.75 K.V./Cm
35 K.V./Cm
26.25 K.V./Cm
17.5 K.V./Cm.
8.75 K.V./Cm.
9
SUPERIOR WOOD PULP PAPER
Power Factor
Stress in K.V. per Cm
55°
71°
43°
27°
10
SUPERIOR WOOD PULP PAPER
Loss in Watts per C.C.
Temperature in deg. C.
27.75 K.V./Cm
22.2 K.V./Cm
16.65 K.V./Cm
11.1 K.V./Cm
5.55 K.V./Cm
11
INFERIOR WOOD PULP PAPER
Power Factor
Stress in K.V. per Cm
55°
71°
42°
27°
12
INFERIOR WOOD PULP PAPER
Loss in Watts per C.C
Temperature in deg. C.
31.75 K.V./Cm.
25.4 K.V./Cm.
19.05 K.V./Cm
12.7 K.V./Cm.
6.35 K.V./Cm.

indicate variations in power factor and loss similar to transformer and paraffin oils, and graph 6 shows that the loss is about ten times as great as in the other two oils.

Graph 31 shows the variation with temperature of the viscosities of the liquids tested.

## Part II. Solid Dielectrics.

*By T. J. Mirchandani and N. V. Narayanaswami.*

The solid dielectrics tested were : (*a*) tissue paper, (*b*) wood pulp paper (superior), (*c*) wood pulp paper (inferior) and (*d*) manilla paper.

The electrodes used in this experiment were circular brass plates 12.5 cm. diameter and 4.8 mm. thick and were enclosed in a wooden box (Fig. 4) lined with asbestos cement to prevent radiation. The temperature was controlled by two sets of heater coils, the current flowing through which was controlled by suitable resistances in the circuit to give different degrees of heating. In this apparatus it was not possible to go below laboratory temperature and therefore the full V curves of dielectric loss have not been obtained.

(*a*) Tissue paper was tightly held between the electrodes, the upper being connected to the transformer and the lower to the bridge. The number of layers tested in each case is given in the Appendix. Measurements of capacity and power factor were made, the loss calculated and the corresponding graphs 7 and 8 drawn. The general shape of the loss—temperature curve is the same as that for liquids, but the slope is steeper and the losses are higher. The power factor—stress curves differ radically from those for liquids. At all temperatures there is a fall followed by a rise, and the point where this rise begins is different for different temperatures ; but it is noticeable that for increasing temperatures, it is shifted to the side of smaller stress, *i.e.*, the rise begins at lower stresses for higher temperatures. It is also noticed that the initial fall in the power factor precedent to the rise tends to decrease with increasing temperature ; in graph 7 it has disappeared at 71°. This peculiar behaviour may be attributed to moisture in the air spaces of the paper, and the fall may be due to the moisture being gradually removed under the combined influence of stress and temperature. The subsequent rise in that case would correspond to the curve following its normal course.

(*b*) and (*c*) Graphs 9–12 refer to the two varieties of wood pulp paper tested. The power factor—stress curve 11 for inferior wood pulp paper resembles partially that for tissue paper but indicates rather erratic performance. The initial increase in power factor with stress seems inexplicable. There is no similarity between these curves and the corresponding curves for superior wood pulp paper except at one or two temperatures.

The loss—temperature curves exhibit a characteristic not hitherto observed, namely, a point of maximum loss at about 57°. Examination of the curve shows that the point of minimum loss lies perhaps near 30°. The sudden fall in loss after 55° must be due to a temporary change in the physical constitution or the chemical composition of the paper. That this change is temporary and peculiar to that particular temperature is shown by the fact that on cooling, the paper exhibited its normal characteristics and the same readings were obtained on reheating it. These points require investigation at greater length.

(*d*) Graphs 25 and 26 refer to manilla paper. The power factor—stress curve for higher temperatures bears a certain resemblance to those for liquids, though the actual value of the power factor is comparatively high. These curves do not show the erratic performance observed in the case of wood pulp paper. Manilla paper differs from tissue and wood pulp papers in that both the power factor—stress and loss—temperature curves have, at lower temperatures, a flat portion prior to a rise.

## Part III. Composite Dielectrics.

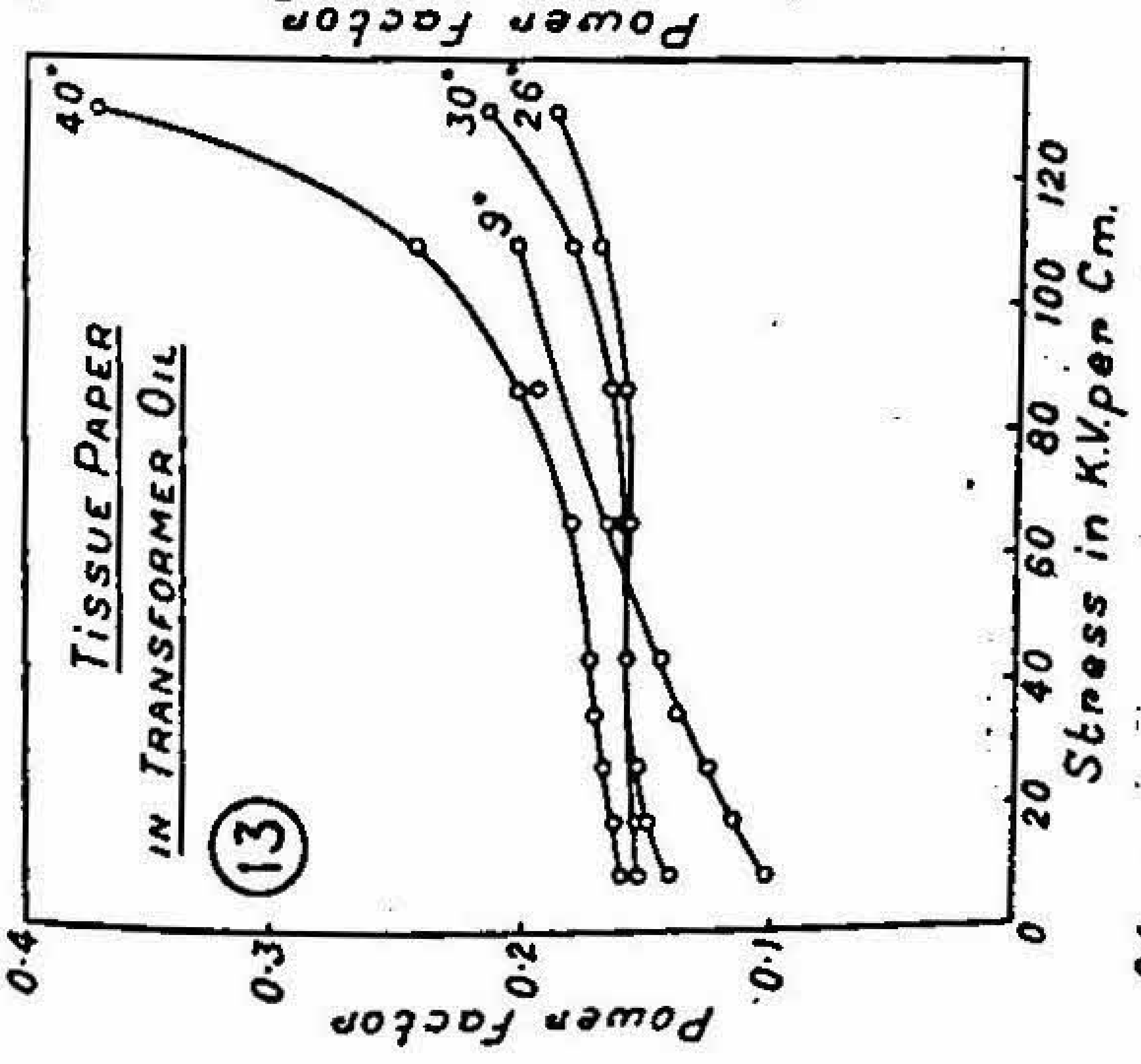
*By T. J. Mirchandani and N. V. Narayanaswami.*

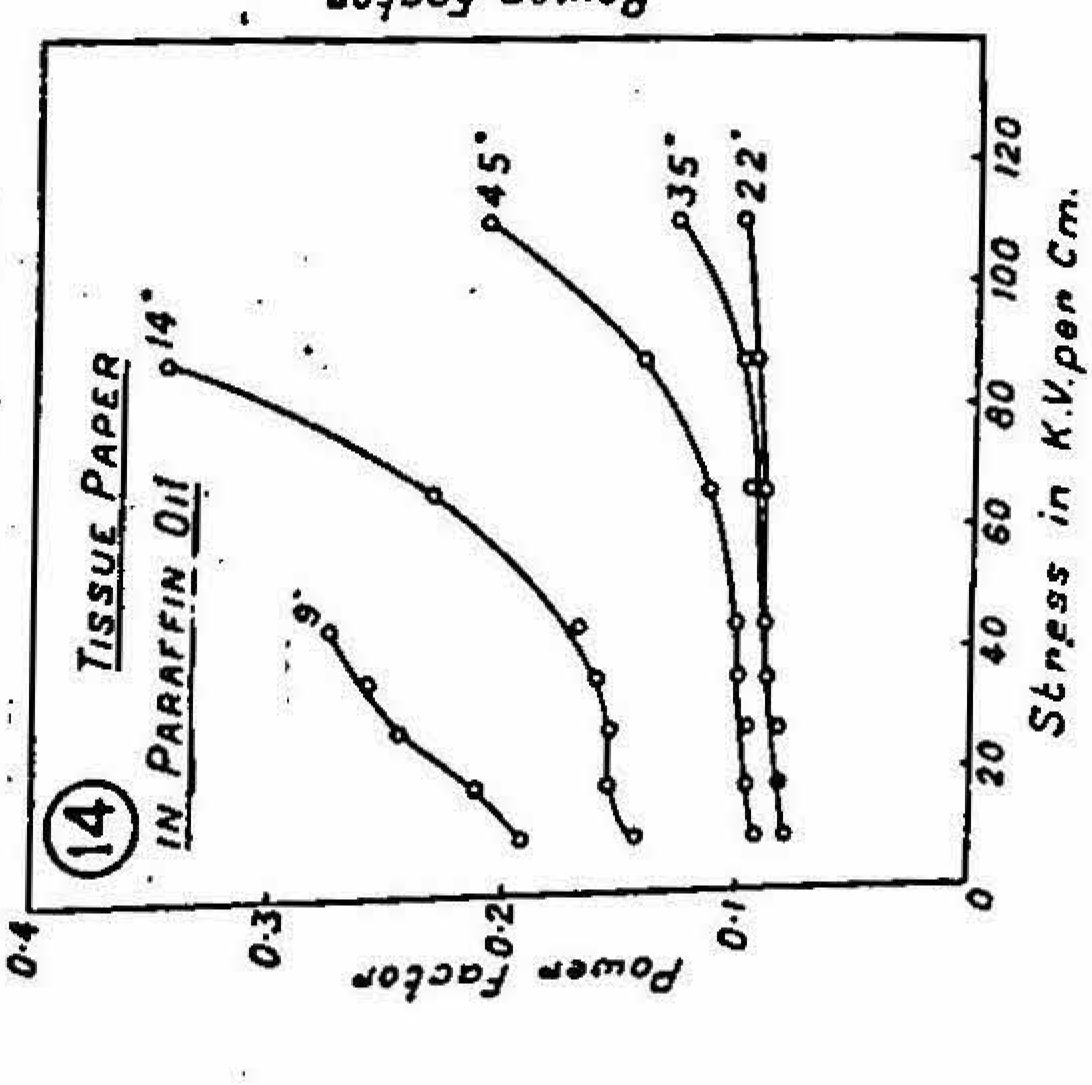
The apparatus used was the same as in Part I. Materials tested under Part II were introduced between the electrodes and kept immersed in a glass trough containing the liquid concerned. Sufficient time was allowed to elapse before testing to ensure that the papers were well soaked in the liquid. The number of layers in each case was the same as while testing the papers separately. The upper plate was screwed down to exclude any continuous film of oil between the layers. The composites with transformer and paraffin oils only were experimented upon. Graphs 13–24 and 27–30 incorporate the results obtained.

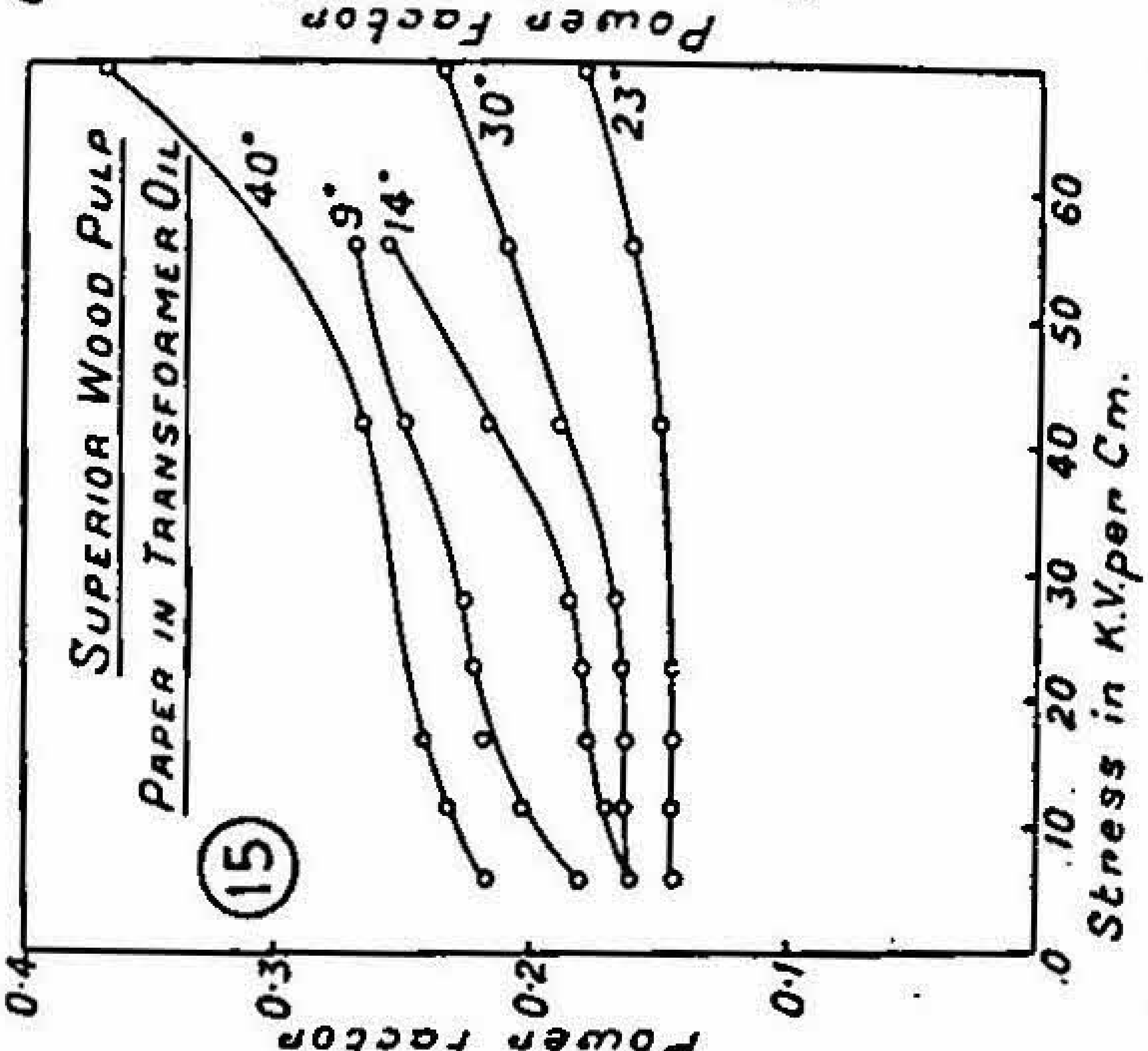
Examining the behaviour of the composite dielectrics, it is observed that they display some of the characteristics of ordinary built-up insulation. Their dielectric strength is greater than that of either of the component dielectrics, but this higher dielectric strength is accompanied by worse power factor and very much higher loss, which is several times that of the separate losses in the two dielectrics. This is perhaps due to the oil filling up the air spaces in the flexible dielectric.

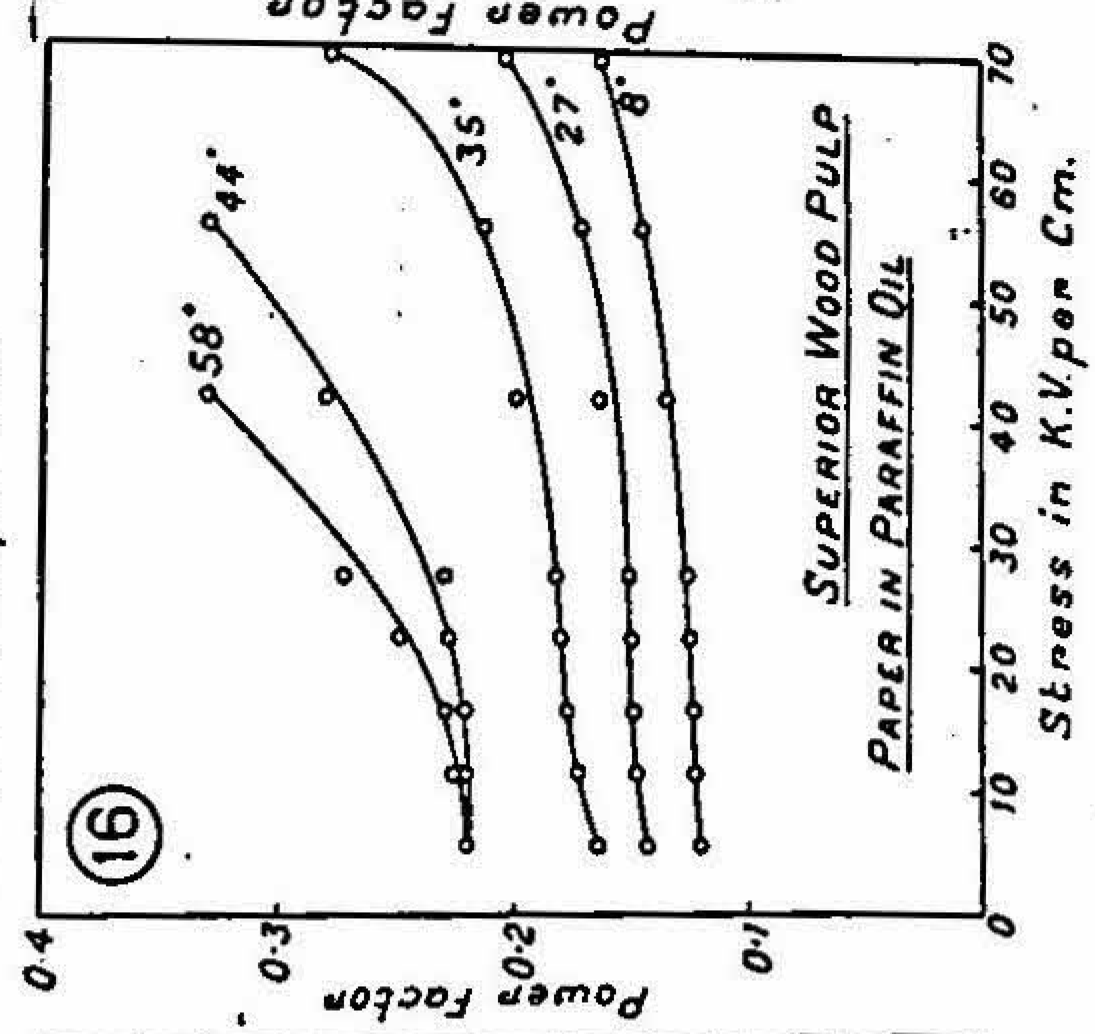
Graphs 13, 14, 19 and 20 represent the behaviour of tissue paper in combination with transformer and paraffin oils. The stress curves are of the same type as those for tissue paper alone, *i.e.*, most of them show points of inflection. This indicates that the properties of tissue paper are only slightly modified when in combination with these two oils. There is a point of minimum loss on the loss—temperature curve, but the V is not so pronounced as in the case of the oils.

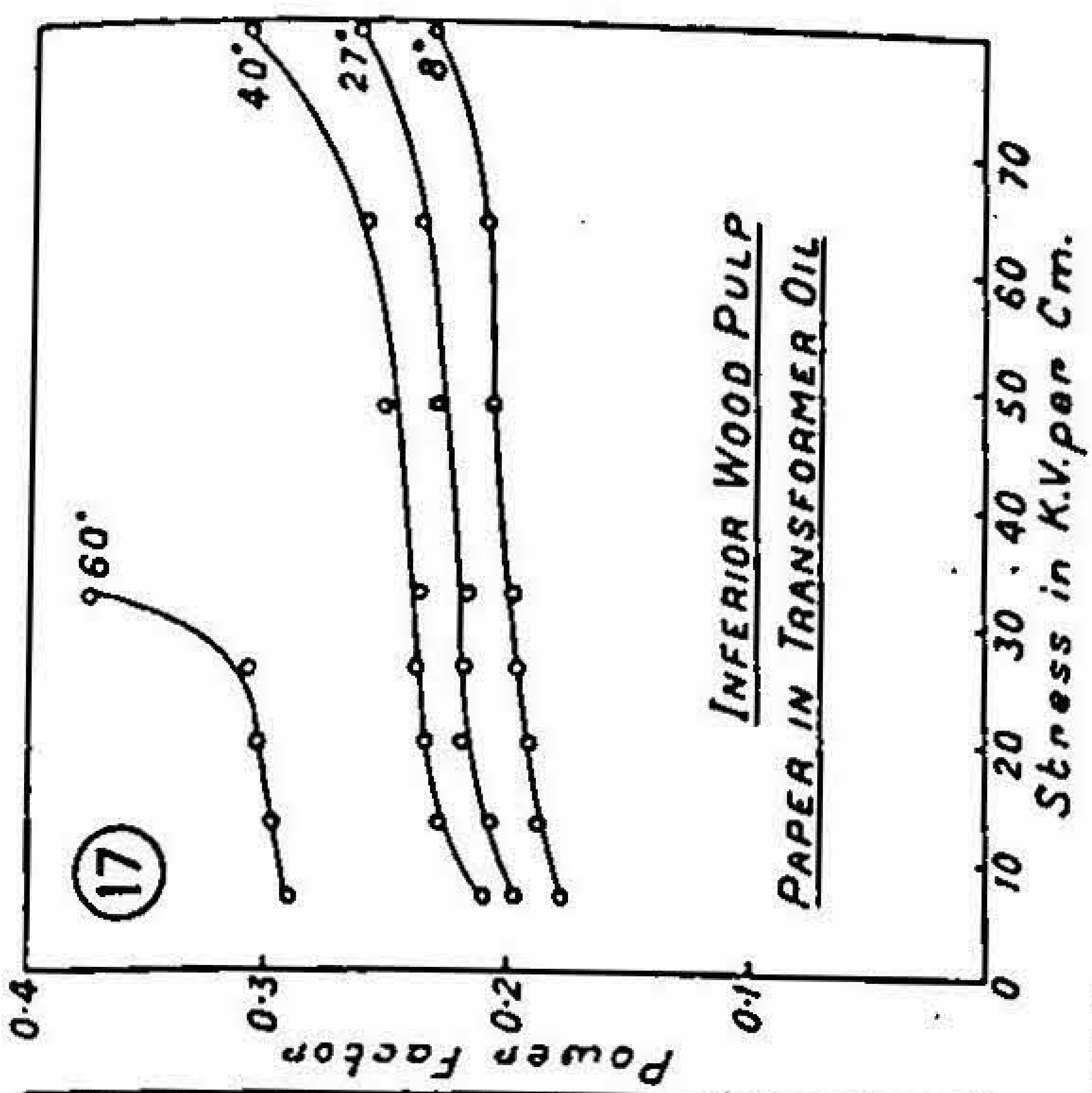
The point of minimum loss for tissue paper alone appears to be at about 30°, for transformer oil also at about 30°, and for paraffin oil at 55° but for both the composites it is at about 25°. An intensive study of the shift of this V-point due to the presence of two dielectrics may throw light on the relative values of the factors contributing to the loss in the materials. Of the two theories, namely, the one suggested by Hochstadter (*loc. cit.*) on the

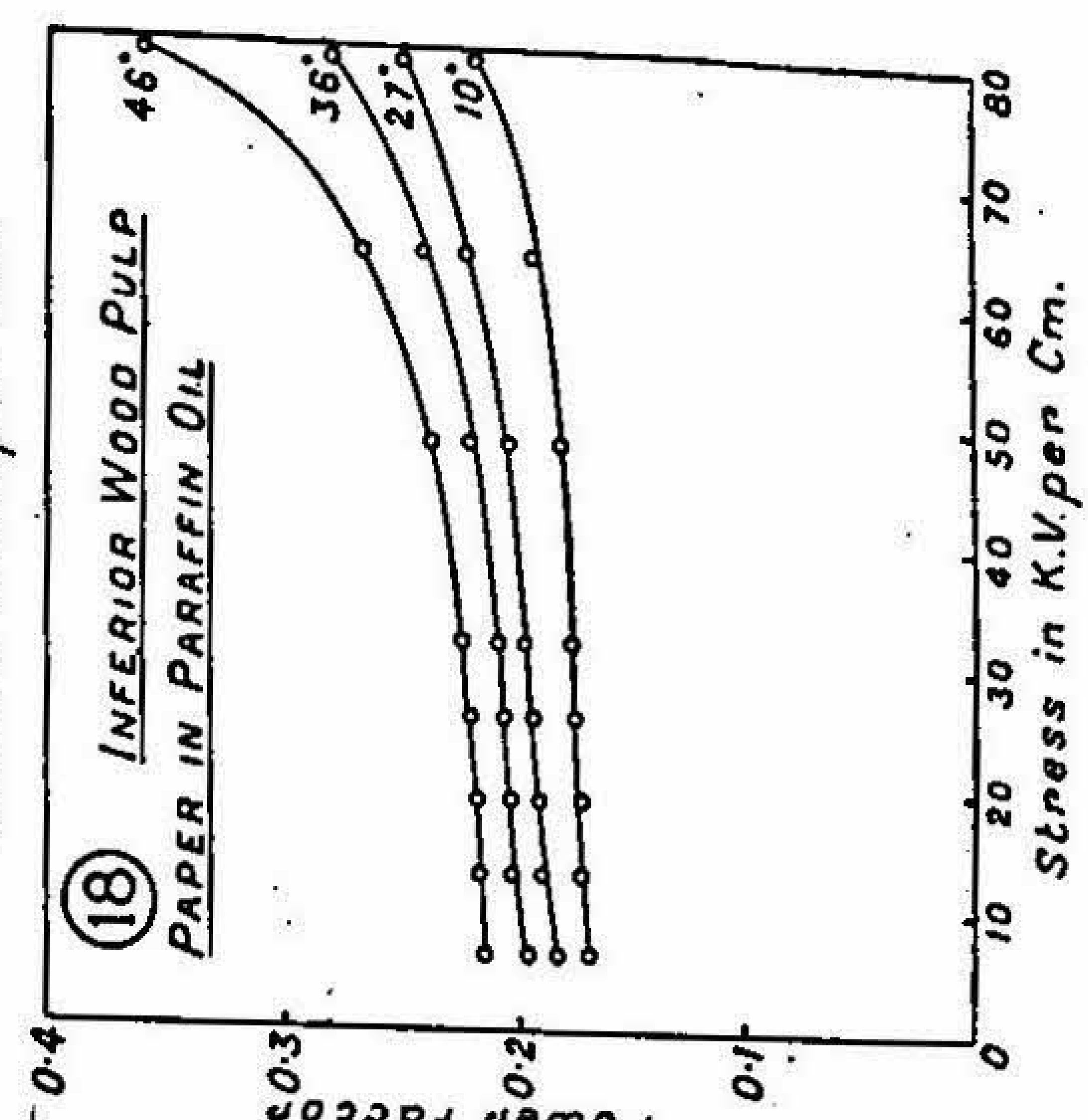

13
Tissue Paper in Transformer Oil
Power factor
Stress in K.V. per Cm.
40°
30°
26°
9°

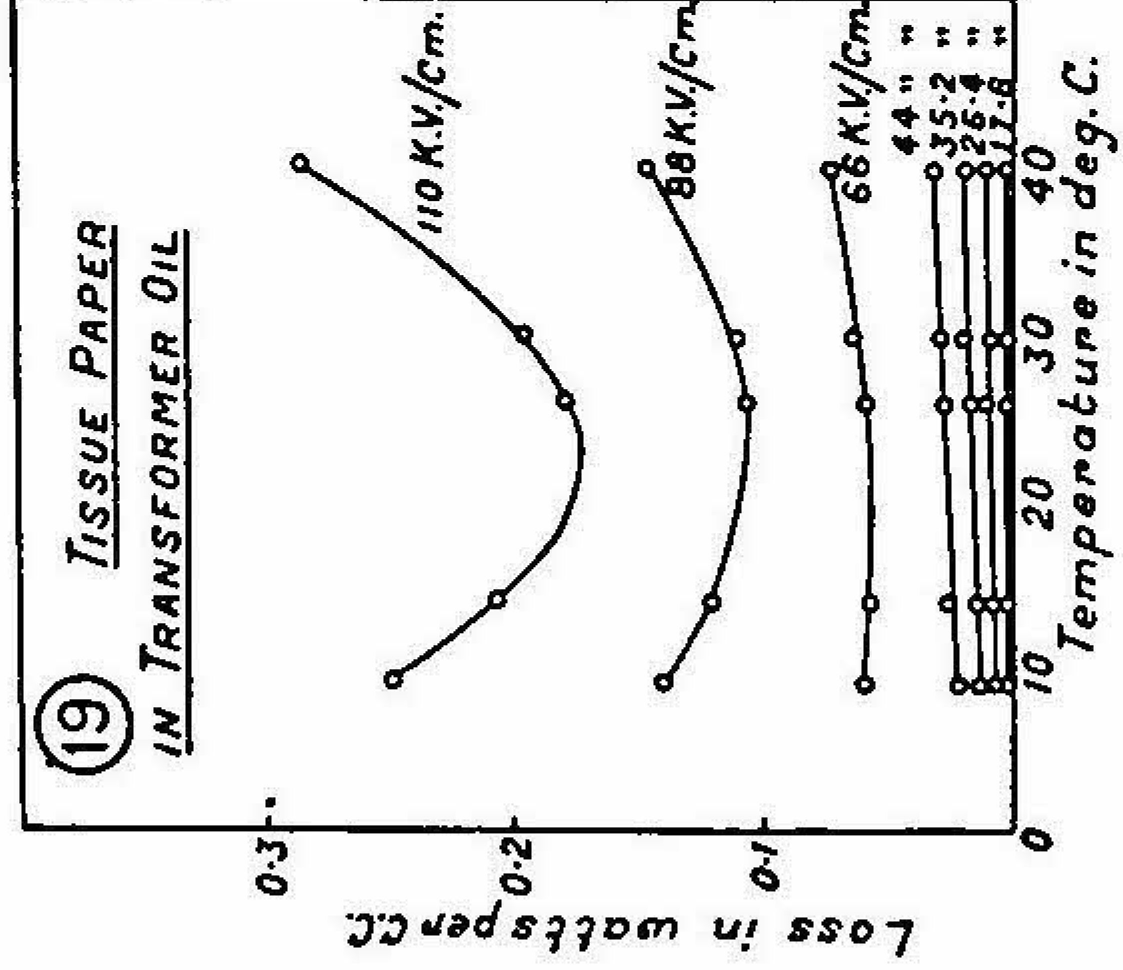

14
Tissue Paper in Paraffin Oil
Power factor
Stress in K.V. per Cm.
14°
9°
45°
35°
22°

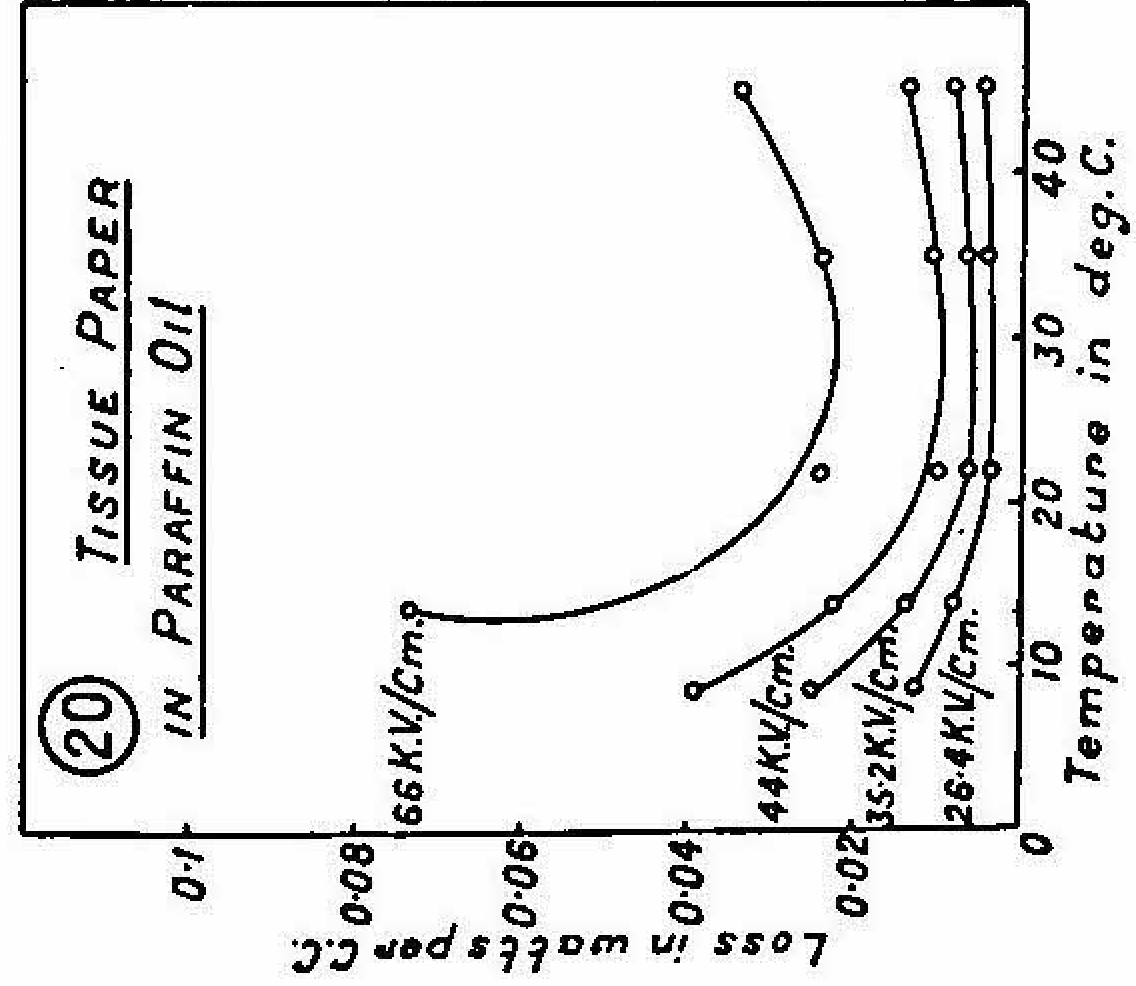

15
Superior Wood Pulp Paper in Transformer Oil
Power factor
Stress in K.V. per Cm.
40°
9°
14°
30°
23°

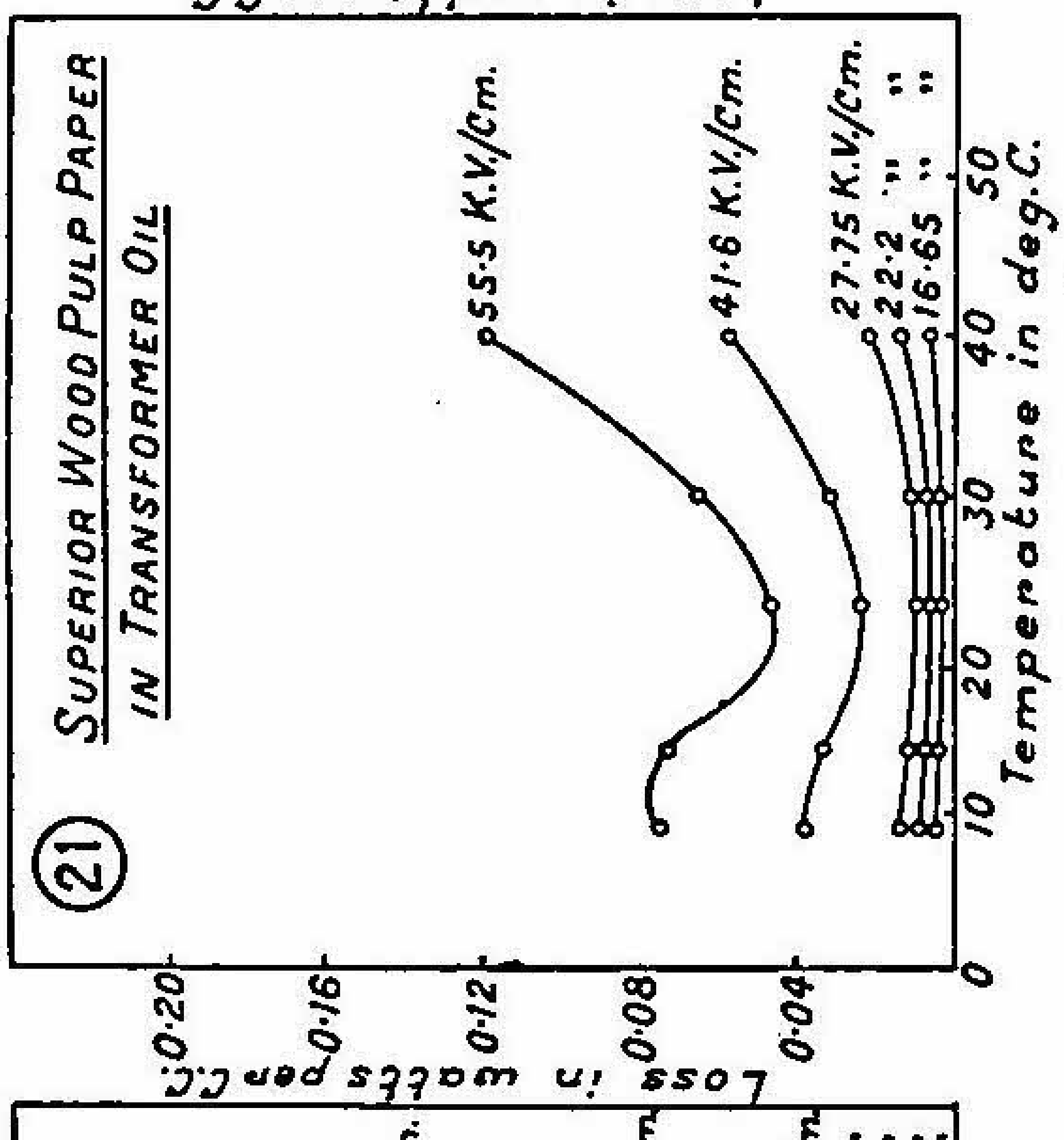

16
Superior Wood Pulp Paper in Paraffin Oil
Power factor
Stress in K.V. per Cm.
58°
44°
35°
27°
8°

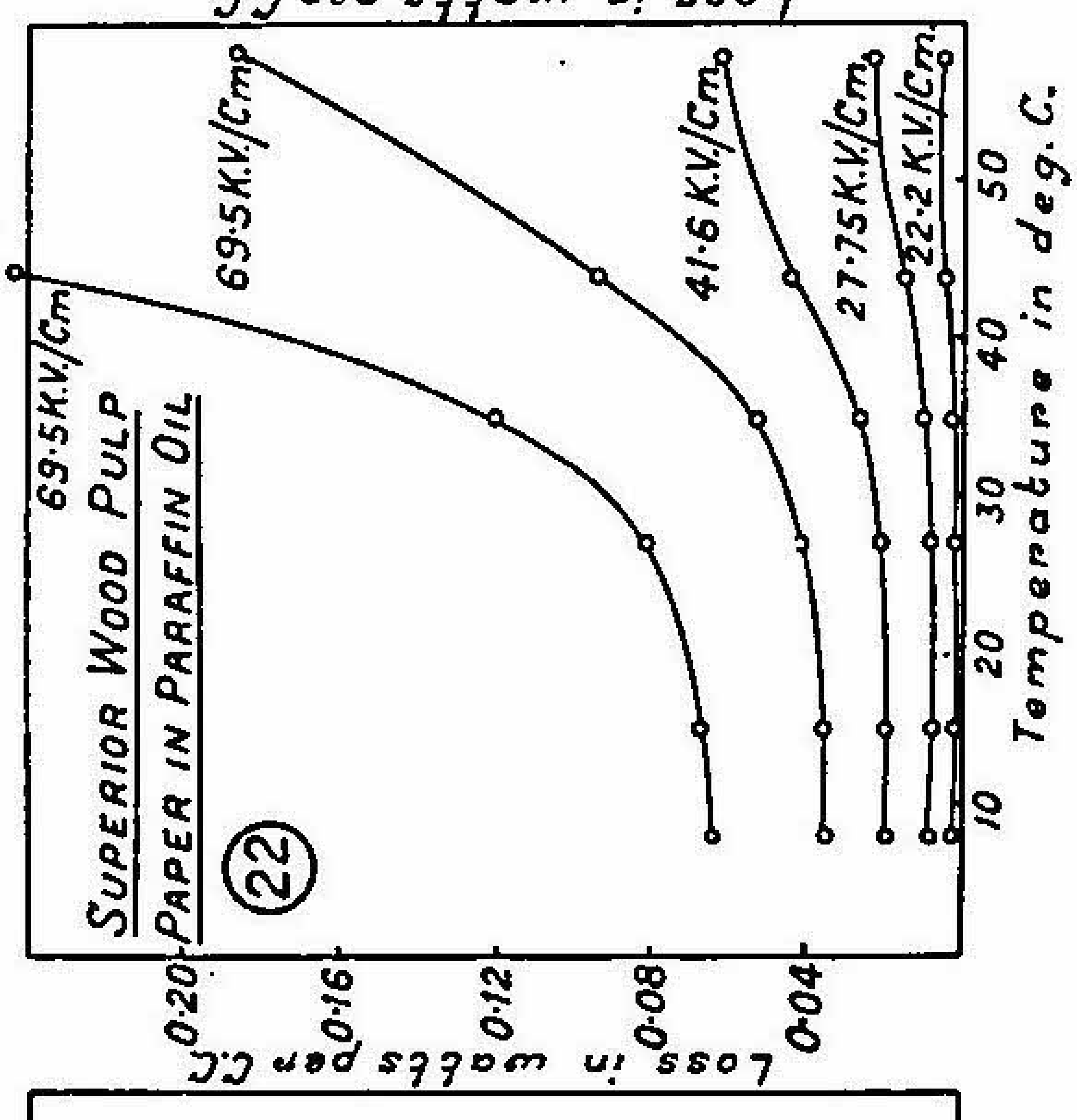

17
Inferior Wood Pulp Paper in Transformer Oil
Power factor
Stress in K.V. per Cm.
60°
40°
27°
8°

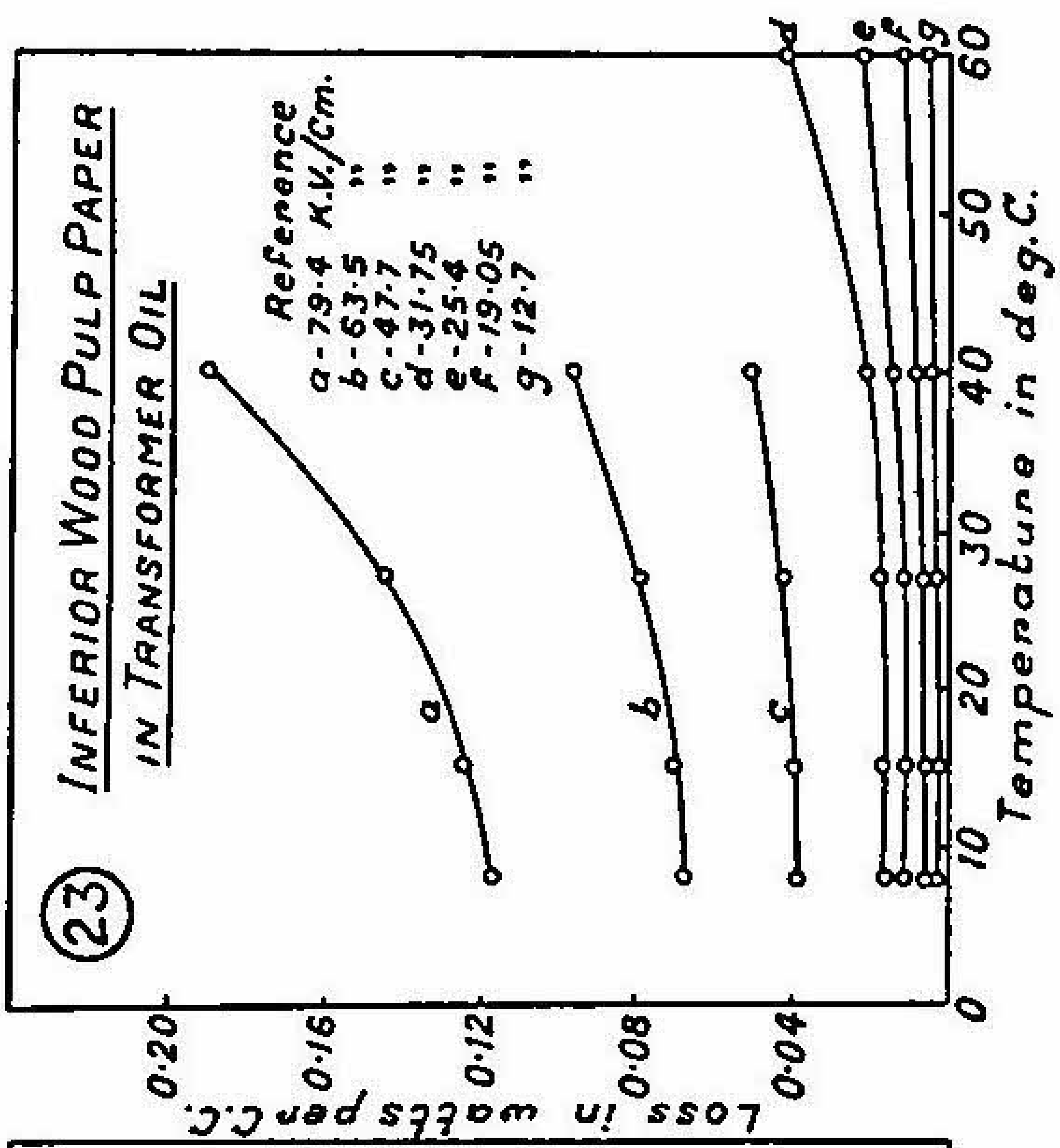

18
Inferior Wood Pulp Paper in Paraffin Oil
Power factor
Stress in K.V. per Cm.
46°
36°
27°
10°

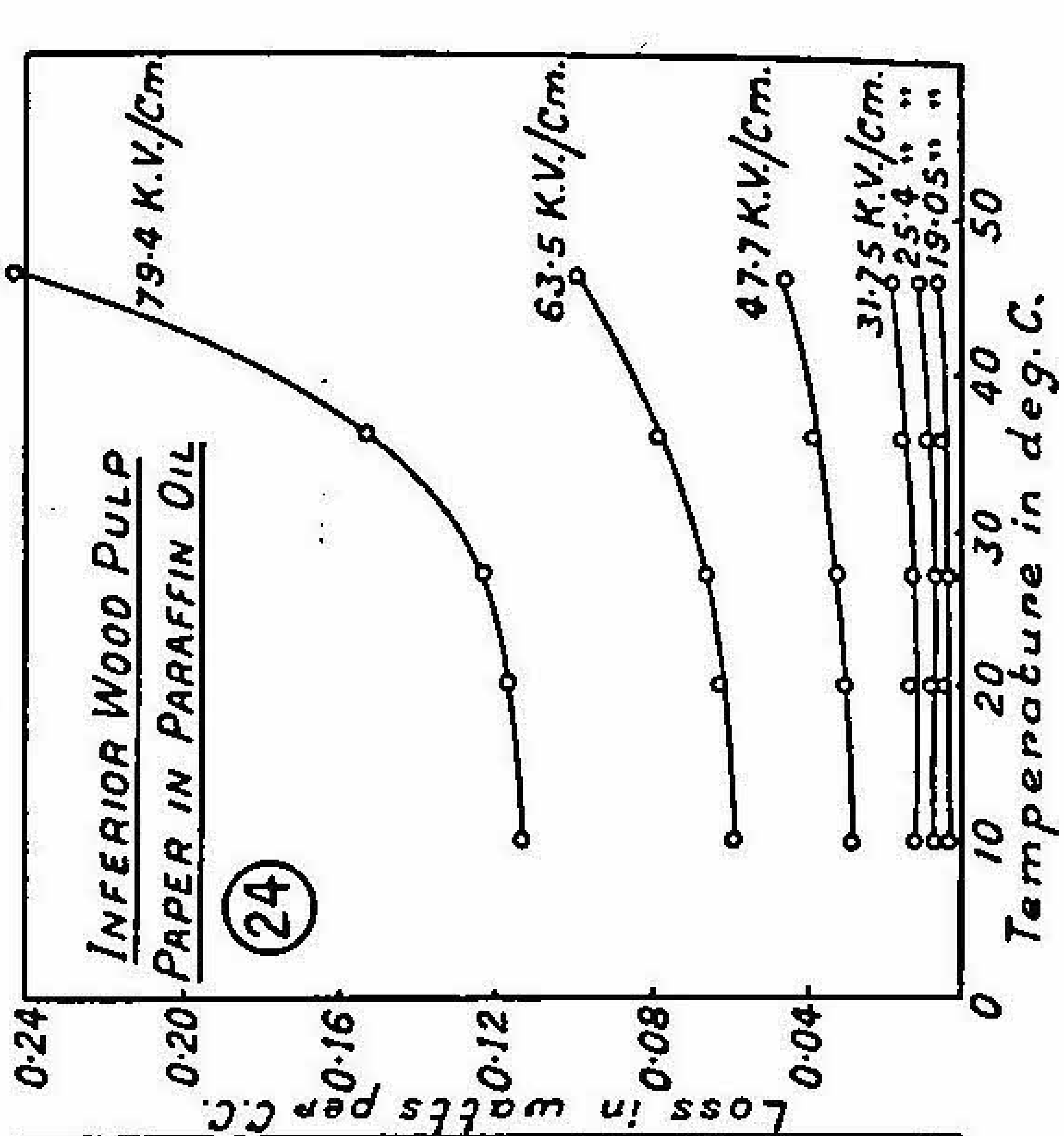

19
TISSUE PAPER
IN TRANSFORMER OIL
110 K.V./Cm.
88 K.V./Cm
66 K.V./Cm
44 " "
35·2 " "
26·4 " "
17·6 " "
Loss in watts per C.C.
0·1
0·2
0·3
Temperature in deg. C.
0
10
20
30
40


20
TISSUE PAPER
IN PARAFFIN OIL
66 K.V./Cm.
44 K.V./Cm.
35·2 K.V./Cm.
26·4 K.V./Cm.
Loss in watts per C.C.
0·02
0·04
0·06
0·08
0·1
Temperature in deg. C.
0
10
20
30
40


21
SUPERIOR WOOD PULP PAPER
IN TRANSFORMER OIL
55·5 K.V./Cm.
41·6 K.V./Cm.
27·75 K.V./Cm.
22·2 " "
16·65 " "
Loss in watts per C.C.
0·04
0·08
0·12
0·16
0·20
Temperature in deg. C.
0
10
20
30
40
50


22
SUPERIOR WOOD PULP
PAPER IN PARAFFIN OIL
69·5 K.V./Cm
69·5 K.V./Cm
41·6 K.V./Cm.
27·75 K.V./Cm.
22·2 K.V./Cm.
Loss in watts per C.C.
0·04
0·08
0·12
0·16
0·20
Temperature in deg. C.
10
20
30
40
50


23
INFERIOR WOOD PULP PAPER
IN TRANSFORMER OIL
Reference
a - 79·4 K.V./Cm.
b - 63·5 " "
c - 47·7 " "
d - 31·75 " "
e - 25·4 " "
f - 19·05 " "
g - 12·7 " "
a
b
c
d
e
f
g
Loss in watts per C.C.
0·04
0·08
0·12
0·16
0·20
Temperature in deg. C.
0
10
20
30
40
50
60


24
INFERIOR WOOD PULP
PAPER IN PARAFFIN OIL
79·4 K.V./Cm
63·5 K.V./Cm.
47·7 K.V./Cm.
31·75 K.V./Cm.
25·4 " "
19·05 " "
Loss in watts per C.C.
0·04
0·08
0·12
0·16
0·20
0·24
Temperature in deg. C.
0
10
20
30
40
50

basis of dielectric hysteresis and the other by Dunsheath (*loc. cit.*) on the basis of electrolytic conduction, it is impossible to say, with the available data, which accounts more satisfactorily for the shift in the minimum loss point above referred to.

Tests on the wood pulp papers with the two liquids (graphs 15–18 and 21–24) exhibit generally the same type of characteristics. The point of maximum loss observed in the wood pulp papers alone is not seen in any composites of the inferior variety; nor is it observed with the superior variety except in its combination with paraffin oil (graph 22). In this it is visible at about 57° at low stresses but at higher stresses it does not appear within the range of the graphs.

The inferior wood pulp paper composites do not show any point of minimum loss on the loss—temperature curves for the range 10–60°. On the other hand, the superior wood pulp paper-transformer oil composite shows a point of minimum loss at about 23°. The same paper in combination with paraffin oil does not show any minimum point in this temperature range. It would appear from this that in the case of oil-paper composites the individual electrical properties of these dielectrics are modified.

Results of tests on composites of manilla paper in transformer and paraffin oils are shown in graphs 27–30. These do not show any abnormal features except for point of inflection in the loss—temperature curve (graph 28). Points of minimum loss have not been reached.

*Conclusion.*

The following inferences can be drawn from the foregoing results:—

1. Increasing temperature and increasing stress do not produce the same quality of effect so far as losses are concerned.

2. Dielectric losses in insulating materials do not vary in strict proportionality with the square of the voltage as the dielectric constant and power factor vary with stress.

3. The power factor and losses of most of the composite dielectrics studied are worse than those of the individual components.

4. In composite dielectrics the properties of the composite are generally different from those of the components.

We wish to thank Professor J. K. Catterson-Smith for his encouragement during the progress of the work and Professor F. N. Mowdawalla for valuable suggestions in preparing the paper.

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[Accepted, 8-12-31.]

# APPENDIX.

## *Brief Specification of the Materials Tested.*

### Liquid Dielectrics.

| Dielectric | | Sp. gr. | B. D. V. at 22° C. Standard gap* | Viscosity |
|---|---|---|---|---|
| | | | k. v. | |
| Transformer oil | .. | 0.881 | 40.5 | Graph 31 |
| Paraffin oil | .. | 0.879 | 22.0 | ,, |
| Linseed oil | .. | 0.925 | 29.5 | ,, |

* The standard gap according to B. E. S. A. specification is 0.15 inch between 0.5 inch diameter spheres of steel or brass.

### Solid Dielectrics.

| Dielectric | Thickness per sheet in mils. | No. of sheets tested | Thickness of the test layer in mils. | B.D.V. of test layer between the plate electrodes | B.D.V. of composite in transformer oil | B.D.V. of composite in paraffin oil | Remarks |
|---|---|---|---|---|---|---|---|
| | | | | k.v. | k.v. | k.v. | |
| Tissue Paper | .. 1.12 | 40 | 45 | 7.40 | 41 | 36 | White, fairly porous. |
| Wood pulp paper (superior) | .. 2.96 | 24 | 71 | 13.75 | 25 | 35 | Dull white, smooth. |
| Wood pulp paper (inferior) | .. 2.59 | 24 | 62 | 6.90 | 34 | 38 | Greenish, coarse. |
| Manilla paper | .. 5.00 | 12 | 60 | 7.10 | 29 | 29 | Brownish, glazed on one side. |

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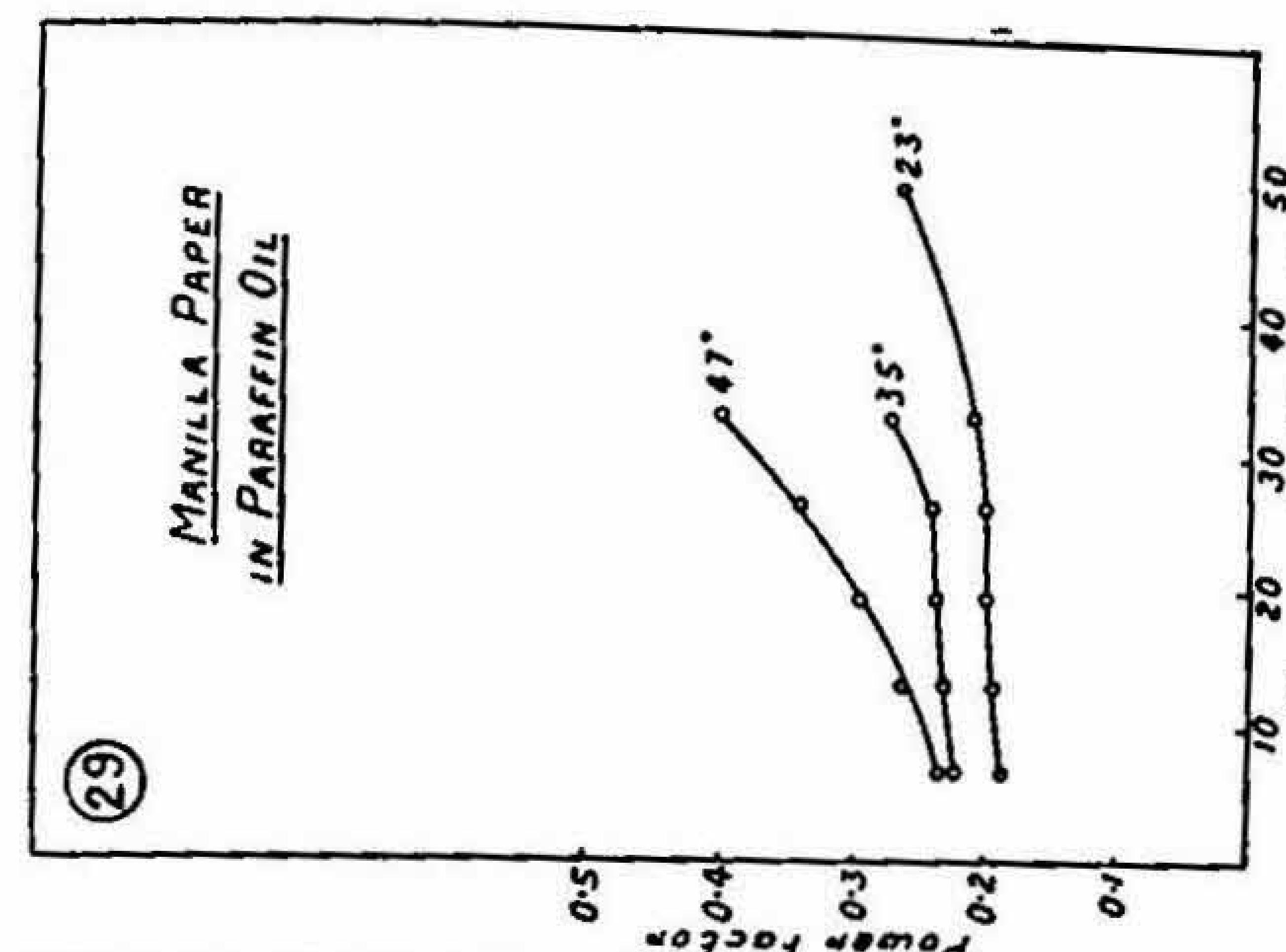
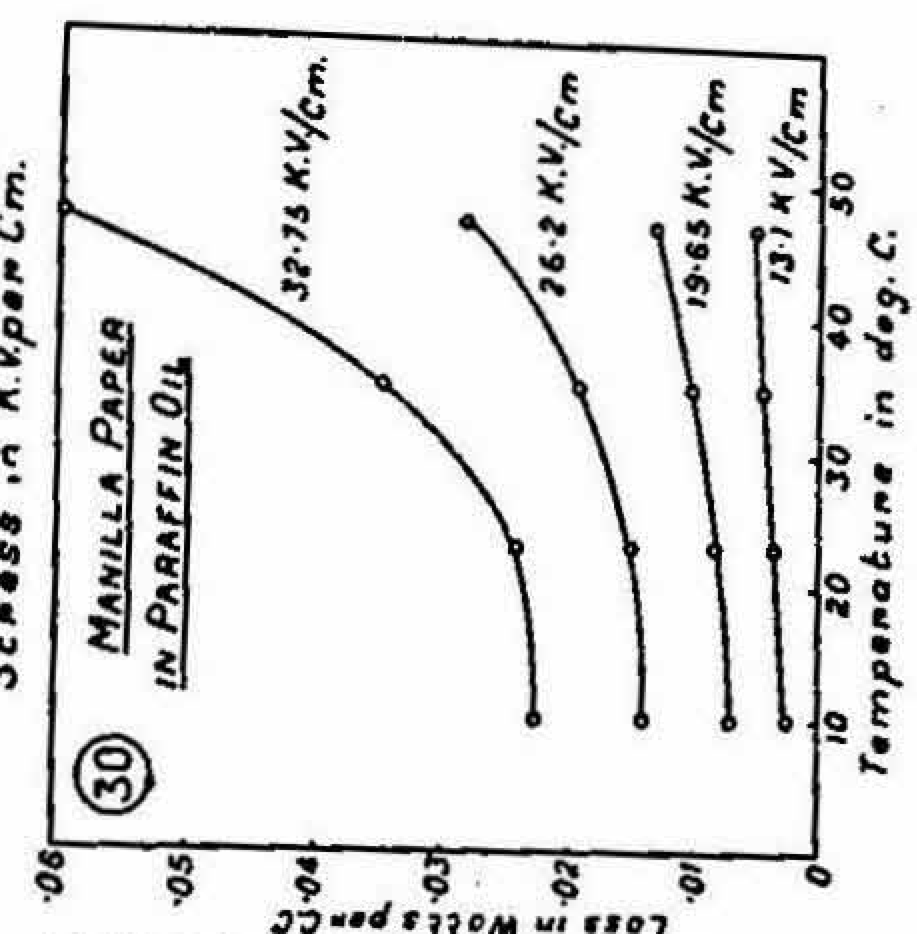
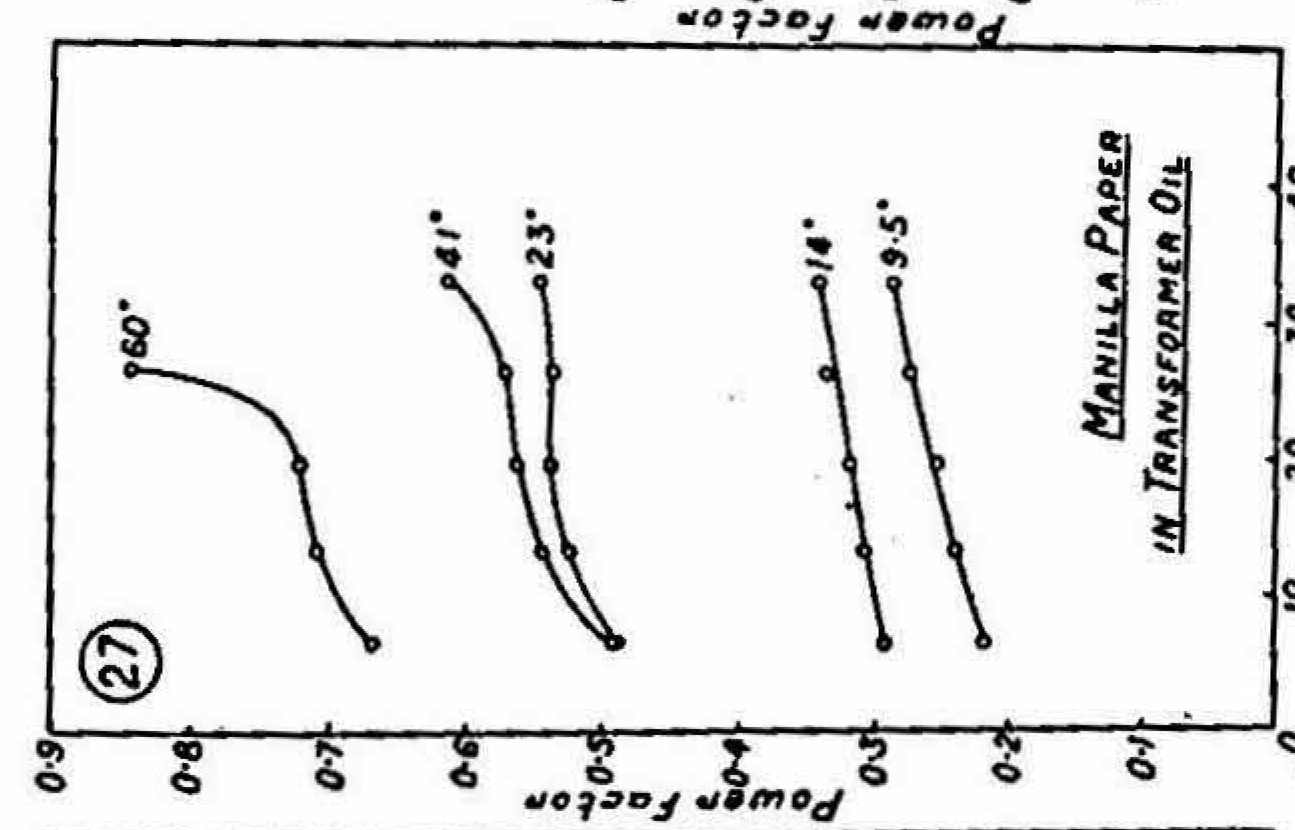
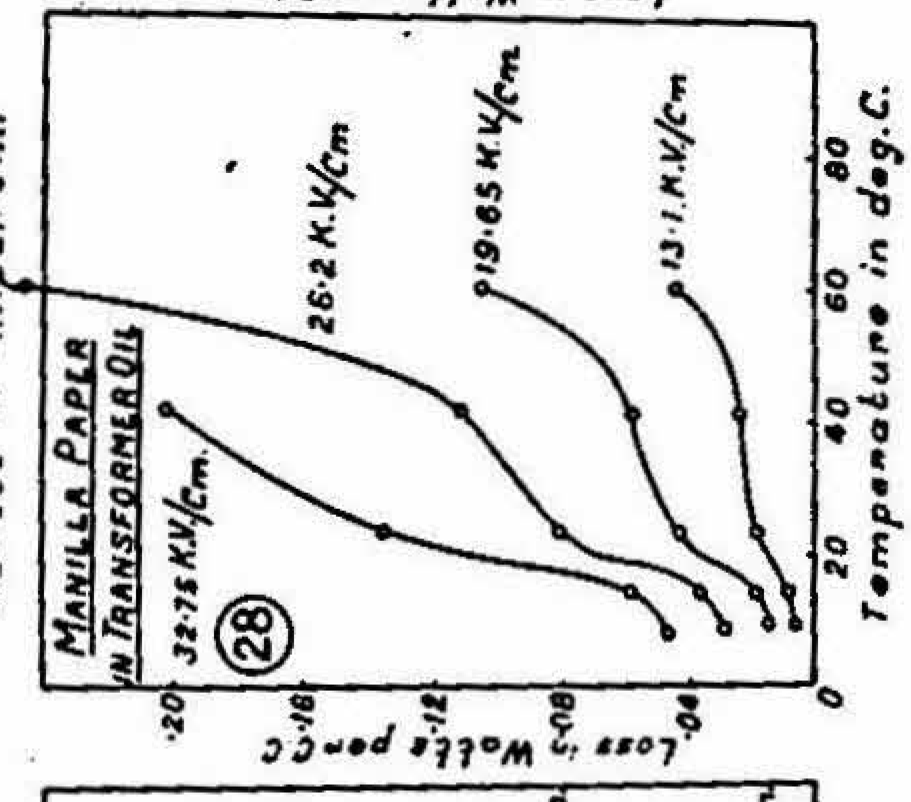
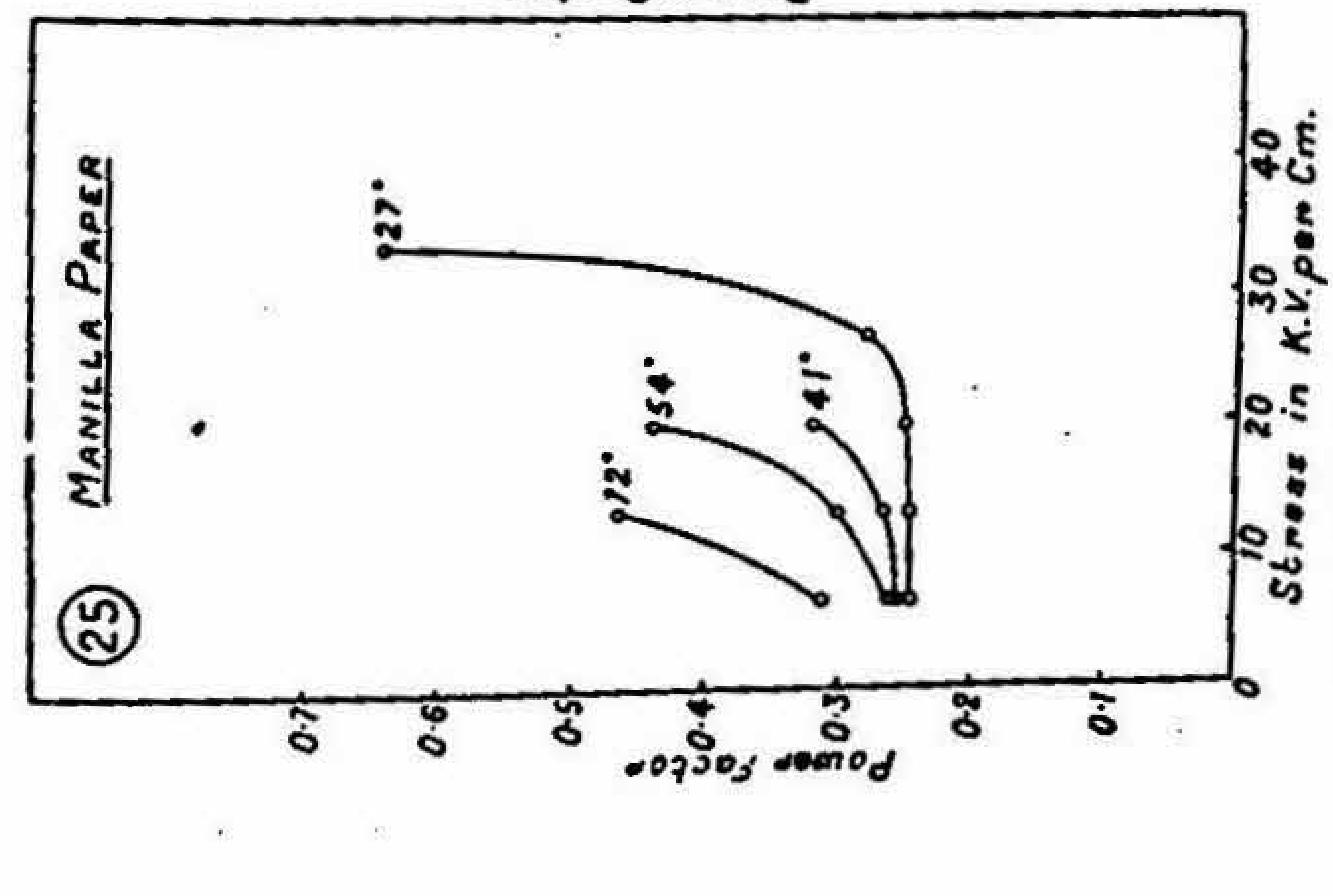
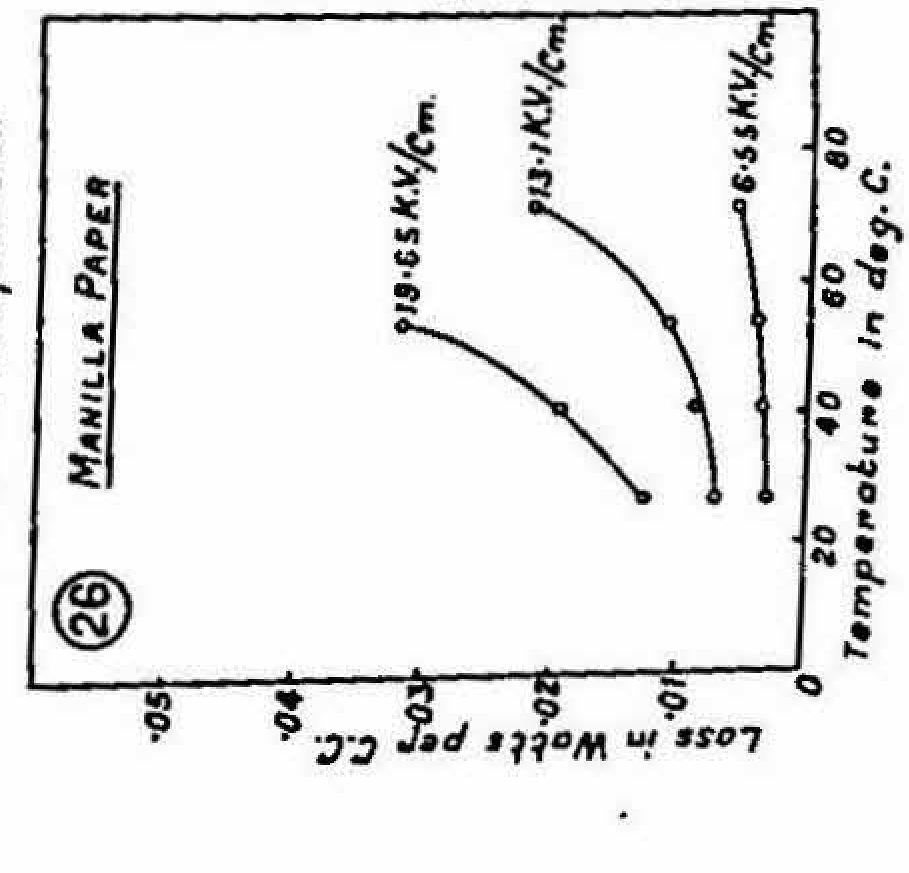

29
Manilla Paper
in Paraffin Oil
47°
35°
23°
Stress in K.V. per Cm.
Power Factor

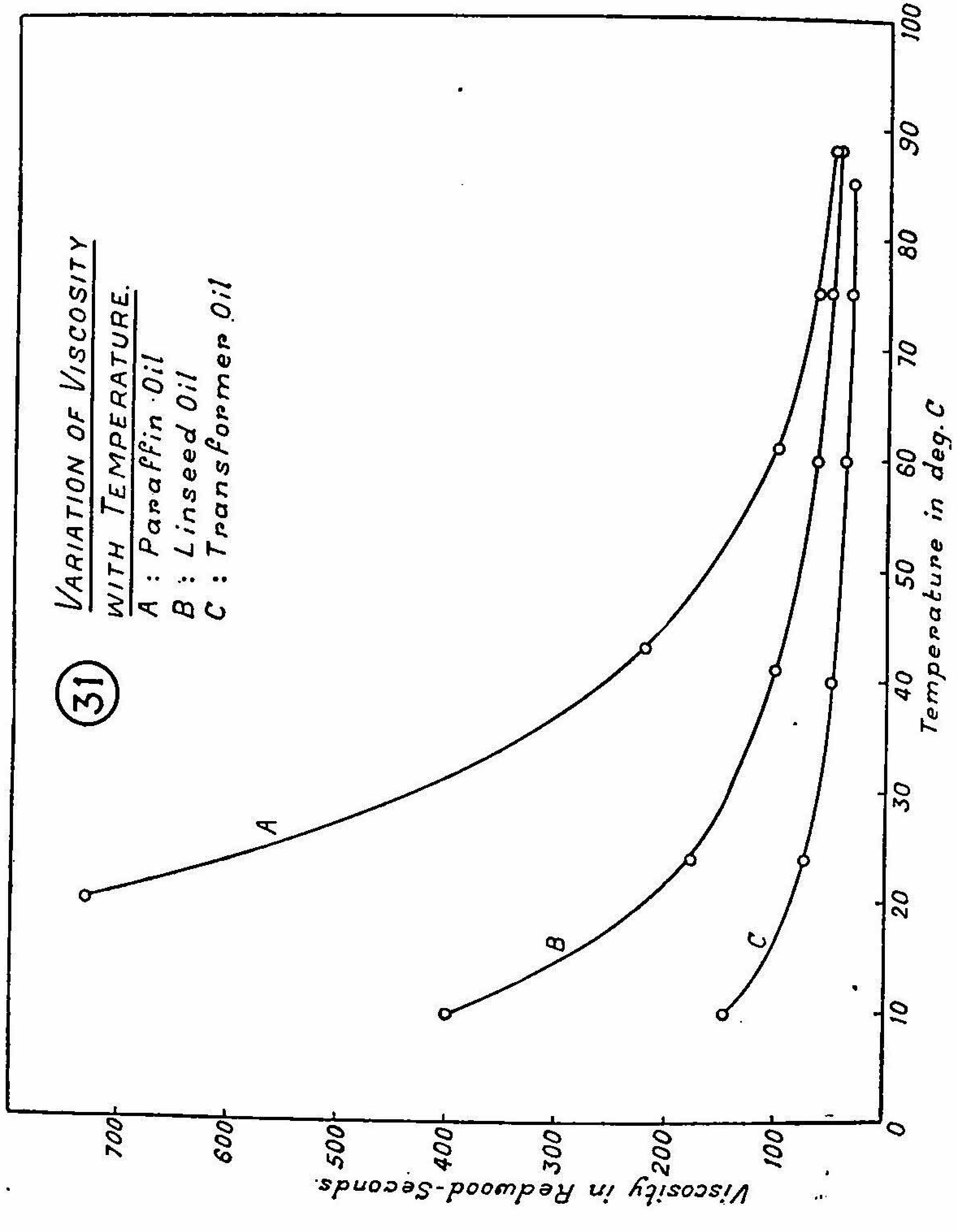

30
Manilla Paper
in Paraffin Oil
32·75 K.V./Cm.
26·2 K.V./Cm
19·65 K.V./Cm
13·1 K.V./Cm
Temperature in deg. C.
Loss in Watts per C.C


27
Manilla Paper
in Transformer Oil
60°
41°
23°
14°
9·5°
Stress in K.V. per Cm.
Power Factor


28
Manilla Paper
in Transformer Oil
32·75 K.V./Cm.
26·2 K.V./Cm
19·65 K.V./Cm
13·1 K.V./Cm
Temperature in deg. C.
Loss in Watts per C.C


25
Manilla Paper
72°
54°
41°
27°
Stress in K.V. per Cm.
Power Factor


26
Manilla Paper
19·65 K.V./Cm.
13·1 K.V./Cm
6·55 K.V./Cm
Temperature in deg. C.
Loss in Watts per C.C.


31
VARIATION OF VISCOSITY
WITH TEMPERATURE.
A : Paraffin Oil
B : Linseed Oil
C : Transformer Oil
A
B
C
Viscosity in Redwood-Seconds.
700
600
500
400
300
200
100
Temperature in deg. C
0
10
20
30
40
50
60
70
80
90
100