MEASUREMENTS OF THE DIELECTRIC

CONSTANT AND LOSS FACTOR OF WOOD SAMPLES

A THESIS

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by

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AND LOSS FACTOR OF WOOD SAMPLES

Approved:

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Date Approved by Chairman May 28, 1947

ACKNOWLEDGEMENT

In completing this work I wish to express my sincerest thanks to Professor M. A. Honnell, not only for suggesting the problem, but also for his valuable aid and guidance in its prosecution.

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DEFINITION OF SYMBOLS USED

a – Diameter in inches of inner conductor of co-axial test cell.

b – Diameter in inches of outer conductor of co-axial test cell.

C – Capacitance in farads.

C_A – Total equivalent air capacitance in micro-micro farads of the test cell.

C_c – Calculated air capacitance of the portion of the test cell enclosing the dielectric sample, 1.535 micro-micro farads.

C_o – Stray capacitance of the test cell in micro-micro farads.

C_W – Total equivalent capacitance of the test cell with wood as the dielectric.

C_1 – Reading of the tuning condenser dial with only the resonating coil in the circuit.

C_2 – Reading of the tuning condenser dial with the empty test cell in the circuit.

C_3 – Reading of the tuning condenser dial with the dielectric sample in the circuit.

e – Dielectric constant of sample.

e_w – Dielectric constant of Georgia pine.

e' – Loss factor of dielectric sample.

e'_w – Loss factor of Georgia pine.

e''_w – Corrected value of the loss factor of Georgia pine.

f – Frequency in cycles per second.

L – Inductance in henries.

ℓ – Length in inches of test cell.

Pf_A – Power factor of empty test cell.

Pf_w – Power factor of dielectric sample.

Pf'_w – Corrected power factor of dielectric sample.

DEFINITION OF SYMBOLS USED

Q - Ratio of the equivalent parallel resistance to the reactance of a coil or a condenser at resonance.

Q_1 - Reading of the Q-meter dial with only the coil in the circuit.

Q_2 - Reading of the Q-meter dial with the empty test cell in the circuit.

Q_3 - Reading of the Q-meter dial with the dielectric sample in the circuit.

Q_A - Equivalent Q of the empty test cell.

Q_w - Equivalent Q of the Georgia pine sample.

Q_w' - Corrected equivalent Q of the Georgia pine sample.

R - Equivalent parallel resistance of sample.

R_A - Equivalent parallel resistance of the empty test cell.

R_w - Equivalent parallel resistance of the Georgia pine sample.

R_w' - Corrected equivalent parallel resistance of the Georgia pine sample.

r_w - Volume resistivity in ohms-centimeters for Georgia pine.

r_w' - Corrected volume resistivity in ohms-centimeters for Georgia pine.

I. INTRODUCTION

The possibilities of utilizing dielectric heating in aviation, plastics, paper, textile, chemical, shoe, automotive, marine and process industries are the subject of much research in many of the large electrical manufacturing organizations at the present date[1]. With the increasing use of dielectric heating as a means of cooking, drying, dehydrating, sterilizing, curing, thawing and setting, the need for more information on the dielectric characteristics of many types of materials becomes apparent. Food, grain, tobacco, glue, rubber and lumber are some of the substances that fall into this category.

Considerable work has previously been done in the field of dielectric measurements. Sufficient information has been tabulated, in the handbooks and the literature, to indicate the characteristics of most of the general types of dielectrics. More detailed information is available for most of the materials that find practical use as insulation or dielectrics for condensers. However, for the great many dielectrics that find little use in the practical world, there is very little specific information. It was with this thought in mind that the work represented by this paper was performed.

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[1] Westinghouse Electric Corporation, Radio Frequency Heating Reference Book. p. 3.

The primary objective of the investigation was to present information on one of the materials in the higher frequency range, 30 to 200 megacycles. The secondary objective was to determine the factors involved in making measurements of this kind with the type 170-A Q-meter[2], and, from the investigation, to make recommendations for improving the technique of measurements and the design of the test cell.

The material used for the test sample was Georgia pine. This wood was chosen because it represents one of the predominant industrial woods of the state. Information on this material seemed desirable from the standpoint that dielectric heating might be employed in the future for drying the lumber.

Since the data obtained with the type of instrument used would assimilate some of the conditions incurred in the actual process of dielectric heating, the desirability of determining the absolute values of the quantities involved did not seem to warrant the added care and work. Therefore, the expected accuracy of the data, plus or minus 20 per cent, with the type 170-A Q-meter was decided to be sufficient to indicate the general trend of the properties of pine for the frequency range involved. When consideration is given to the fact that the dielectric properties will vary as a function of the moisture content, accuracies within these limits seem reasonable. Finally, if more accurate information was desired, the results of the investigation should enable suggestions and recommendations that would accomplish that.

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[2]Manufactured by the Boonton Radio Corporation, Boonton, N. J.

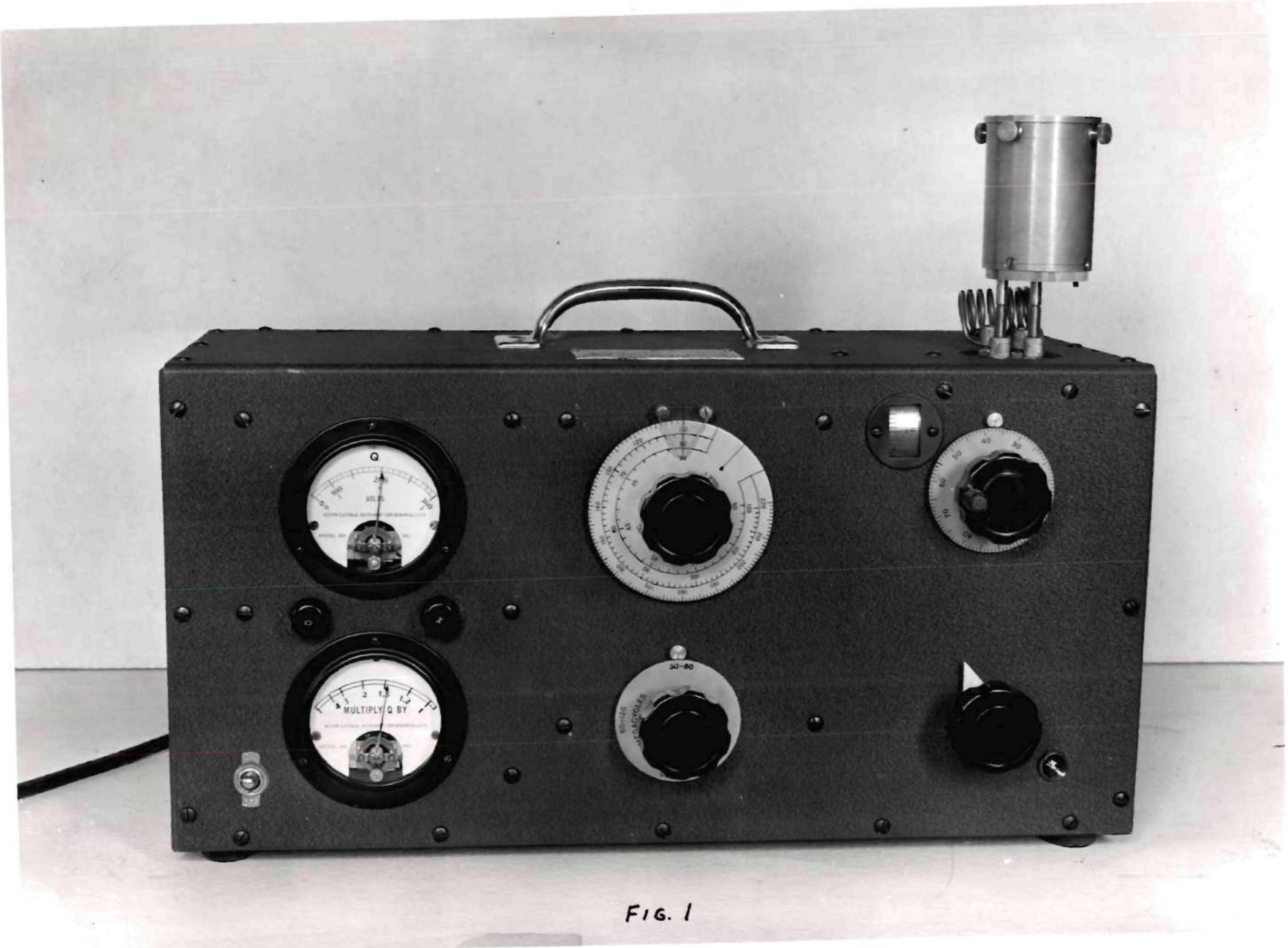

FIG. 1

II. DESCRIPTION OF APPARATUS USED

Previous work on soil samples by T. W. G. Richardson[3] lead to the use of a modified co-axial type test condenser similar to the one he used. An attempt was made to increase the total capacitance and at the same time to reduce the stray capacitance. This was accomplished by choosing a lower ratio of diameter of outer to inner conductor, and by removing all the polystyrene spacers from within the cell.

The resulting cell[4] consisted of a brass tube 2 11/16 inches long with a detachable lid. A bottom with a 1/2 inch hole for the exit of the inner conductor terminal was also made an integral part of this. The inner conductor, which was 1 3/4 inches in length, was rigidly mounted in place by means of a polystyrene disk held to the outside of the bottom piece by the terminal connections. Connection to the measuring instrument was made by banana plugs and receptacles.

The test sample was cut from dry Georgia pine to fit the co-axial cell with little tolerance. In appearance, the sample resembled a solid cylinder with a concentric hole down the center.

Four coils for the measuring instrument[5] were used to cover the frequency spectrum from 30 to 100 megacycles. These coils were wound of number 10 tinned copper wire. Coil forms were not retained because the wire was sufficiently stiff to hold its original shape.

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[3] Richardson, T.W.G., "A Determination of the Electrical Properties of Soil in the State of Georgia". Thesis. Georgia School of Technology, 1947.

[4] See Figure 3.

[5] Boonton Radio Corporation, Instructions and Manual of Radio Frequency Measurements for Q-Meters. pp. 4,8.

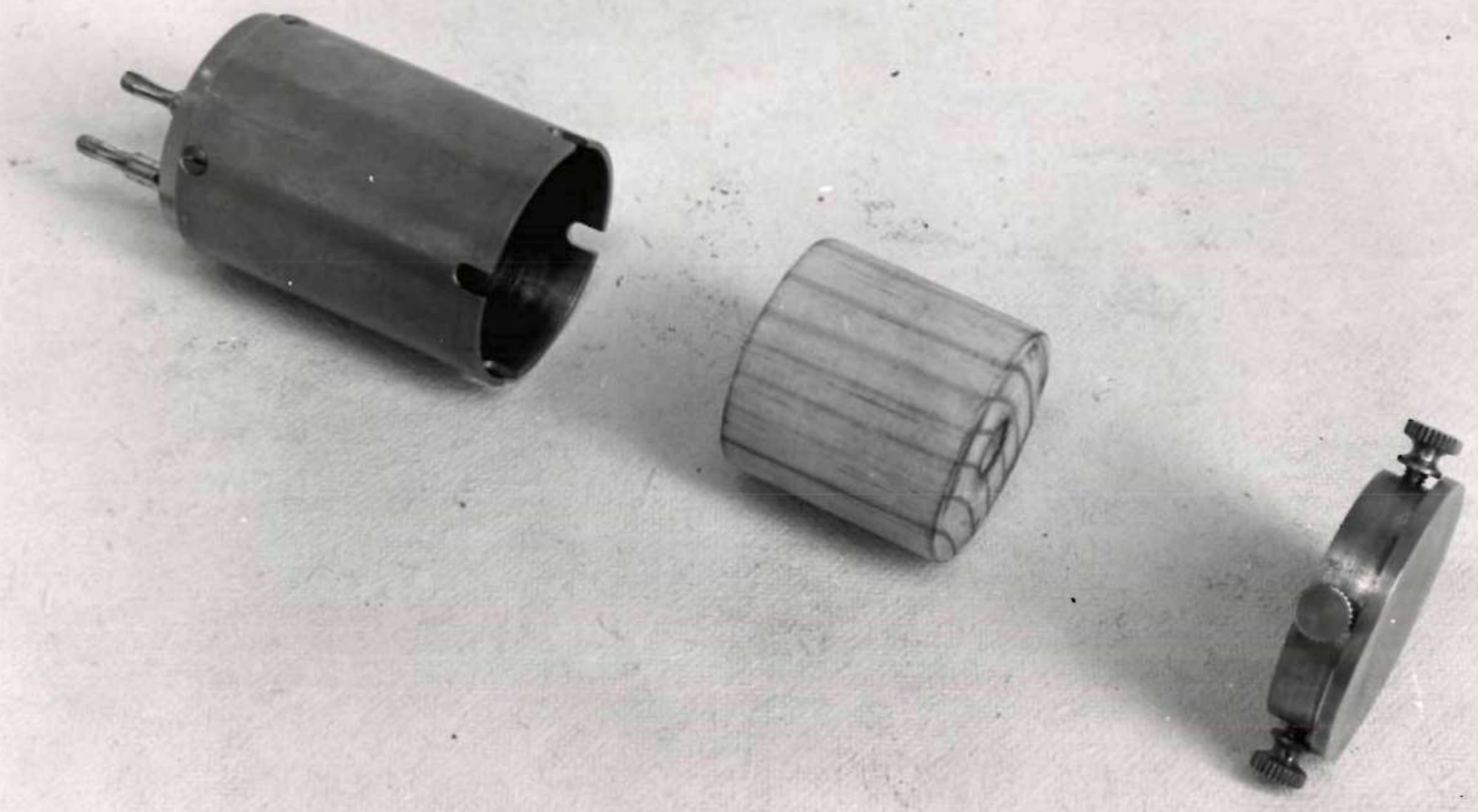


FIG. 2

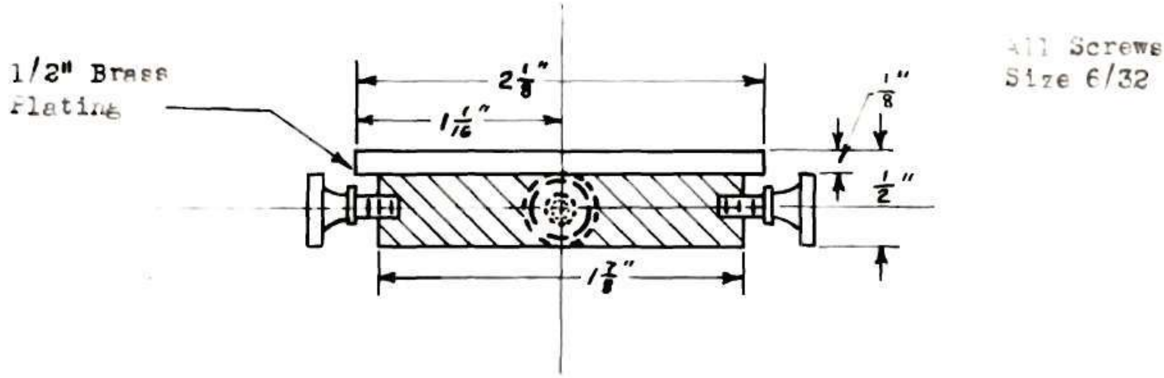
And due to the fact that any type of material placed in the field of the coil was found to lower the Q considerably, shielding was not employed. The Q of the coils were found to range from 375 to 260 at the lower end of the respective ranges. Attachment to the measuring circuit was made directly to the coil terminals.

The type 170-A Q-meter was the instrument used for making the measurements of the Q and the capacitance of the test cell and wood sample. Fundamentally, the principle of operation of the Q-meter involves inserting a known frequency and voltage in series with a coil and a condenser, tuning the circuit to resonance and measuring the Q across the condenser by means of a vacuum tube voltmeter calibrated directly in Q. The meter has a built-in oscillator variable in frequency from 30 to 200 megacycles. Four terminal binding posts are provided for the connection of an external coil and a condenser. A low-loss tuning condenser with a calibrated dial from 11 to 67 micro-micro farads is built in the meter and connected directly across the external condenser terminals. A calibrated frequency dial is provided for adjusting the oscillator.

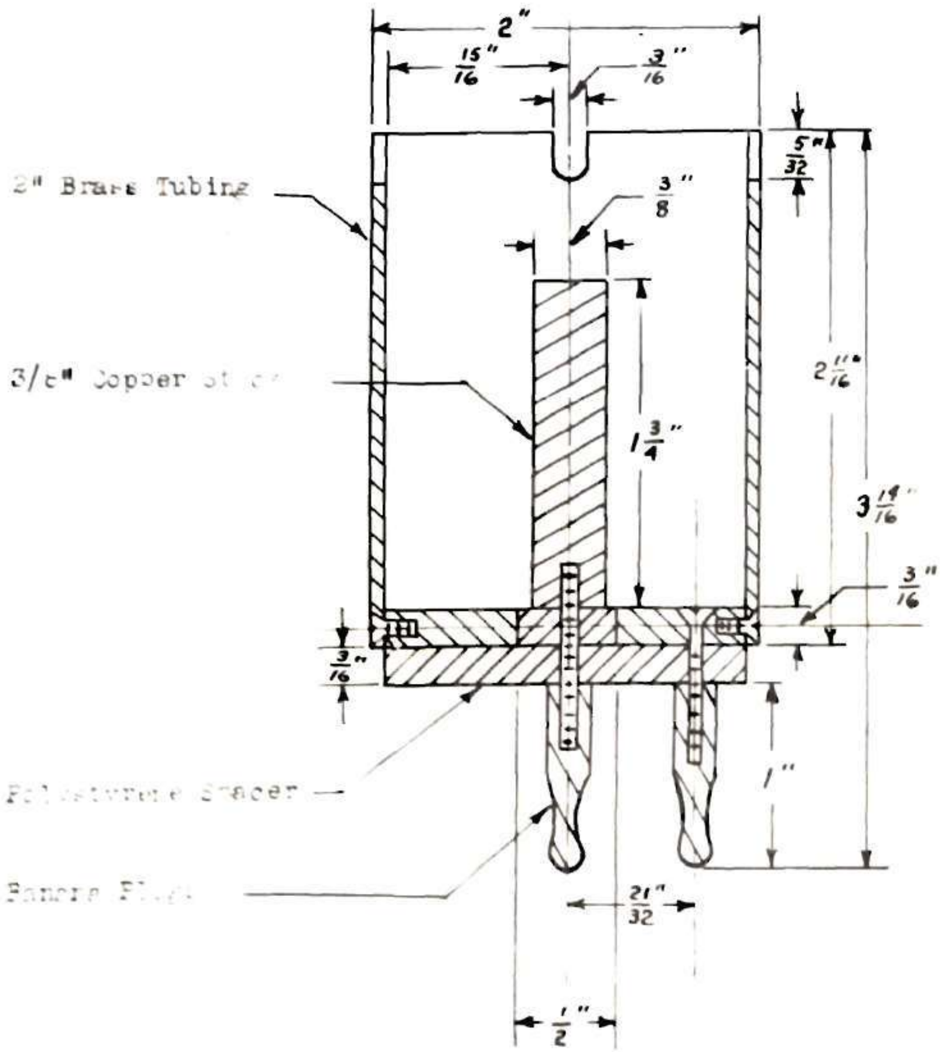
The frequency dial is calibrated within plus or minus 1 per cent accuracy, while the Q reading meter has a general accuracy of plus or minus 10 per cent. However, the latter is a function of full scale reading. Thus, for low Q readings the accuracy may be somewhat lowered. The tuning capacitance has an accuracy of approximately .5 micro-micro farad. Generally speaking, if sufficient care is taken the accuracy may be considerably improved from these values.

Figure No. 3

TEST CELL



Full Scale



III. METHOD OF MEASUREMENTS

In making the measurements, the coil covering the selected frequency was connected to the Q-meter, the oscillator adjusted to the desired frequency and the circuit tuned to resonance by the tuning capacitance. At resonance the Q and tuning capacitance readings were taken as Q_1 and C_1. The empty cell was then placed across the tuning condenser terminals and the circuit again tuned to resonance by the tuning condenser. The Q and the tuning capacitance readings, in this case, were called Q_2 and C_2. After removing the lid of the test cell and inserting the dielectric sample, the circuit was resonated for the third time by adjusting the tuning condenser. The readings obtained were designated Q_3 and C_3. From these three sets of readings all of the desired properties of the dielectric sample were calculated.[6]

The Q of the empty cell, Q_A, the Q of the test sample, Q_W, the equivalent parallel resistance of the empty cell, R_A, the equivalent parallel resistance of the test sample, R_W, the equivalent capacitance of the empty cell, C_A, and the equivalent capacitance of the test cell with the dielectric sample, C_W, were calculated from the following formulas:

$$Q_A = \frac{(C_1 - C_2)\ Q_1 Q_2}{C_1\ (Q_1 - Q_2)} \qquad (1)$$

$$Q_W = \frac{(C_1 - C_3)\ Q_1 Q_3}{C_1\ (Q_1 - Q_3)} \qquad (2)$$

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[6] Boonton Radio Corporation, Instructions and Manual of Radio Frequency Measurements for Q-Meters. pp. 6,7,13.

$$R_A = \frac{1.59 \; 10^5 \; Q_1 Q_2}{f \;\; C_1 \, (Q_1 - Q_2)} \qquad (3)$$

$$R_W = \frac{1.59 \; 10^5 \; Q_1 Q_3}{f \;\; C_1 \, (Q_1 - Q_3)} \qquad (4)$$

$$C_A = (C_1 - C_2) \qquad (5)$$

$$C_W = (C_1 - C_3) \qquad (6)$$

With the information from these calculations, it was then possible to find the power factor of the empty cell, Pf_A , the power factor of the test sample, Pf_W , and the resistivity of the test sample[7], r_W , from the additional formulas:

$$Pf_A = \frac{1}{Q_A} \qquad (7)$$

$$Pf_W = \frac{1}{Q_W} \qquad (8)$$

$$r_W = \frac{2\pi \ell \; R_W}{\ln b/a} \qquad (9)$$

where, ℓ is the length of the co-axial test sample and b/a is the ratio of outer to inner conductor in the test cell.

The test cell capacitance can be considered as being made up of two parts in parallel, C_c , and C_o .[8] C_o is the stray capacitance and C_c is the air capacitance of the portion of the test cell occupied by the dielectric sample. In the remaining portion of this paper the capacitance C_c will be called "the active capacitance".

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[7]Dawes, C. L., A Course in Electrical Engineering, Vol. I. p. 10.

[8]Feldman, C. B., "Optical Behavior of Ground for Short Radio Waves", Proc. I.R.E., Vol. 21, p. 765. 1933.

The active capacitance can be calculated directly from the general formula[9] for the capacitance of a co-axial condenser:

$$C_c = \frac{.612}{\log b/a} \quad \mu\mu f/in. \qquad (10)$$

where, b/a is the ratio of outer to inner conductor. The stray capacitance could then be calculated from:

$$C_o = (C_A - C_c) \qquad (11)$$

Finally, the dielectric constant, e_w, and the loss factor, e'_w, of the test sample were calculated:

$$e_w = \frac{C_w - C_o}{C_c} \qquad (12)$$

$$e'_w = (e_w)(Pf_w) \qquad (13)$$

These last two quantities completed the calculations. However, it was found in making the calculations for the equivalent parallel resistance of the test cell that the losses of the empty cell caused the calculated equivalent parallel resistance of the sample to be in error. It then became necessary to correct the values for R_w by taking into account the losses in the empty test cell. With a corrected R'_w, it also became necessary to correct Q_w, Pf_w and e'_w. In carrying out the correcting of R_w, it was assumed that the original calculated value for R_w was actually the equivalent resistance of the empty test cell and the sample in parallel.

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[9] Ware, L. A., and Reed, H. R., Communication Circuits, New York: John Wiley and Sons, Inc., 1944. p. 18.

The corrected value for the equivalent parallel resistance of the sample, R_w', was found by:

$$R_w' = \frac{R_w R_A}{(R_A - R_w)} \qquad (14)$$

Similarly, the corrected values for the Q_w, Pf_w and e_w' were obtained:

$$Q_w' = \frac{R_w' Q_w}{R_w} \qquad (15)$$

$$Pf_w' = \frac{1}{Q_w'} \qquad (16)$$

$$e_w'' = (e_w)(Pf_w') \qquad (17)$$

IV. DIFFICULTIES ENCOUNTERED

In general at frequencies above 10 megacycles, considerable attention must be given to many effects that are commonly neglected at the lower frequency ranges.[10] Stray coupling from nearby circuits, distributed and stray capacitance, contact resistance and skin effect all must be minimized. Portions of lighting and power circuits, coils and short circuited leads, power cords to equipment and many other objects may form resonant circuits which will affect the measuring circuit to a great extent.

In the substitution method, which was employed in this investigation, many of the sources of trouble cancel or do not enter into the calculations. This was true in the case of the coils used for the resonant circuit. The coils possessed the usual distributed capacitance, contact resistance and skin effect but due to the technique of measurements these factors contribute only indirectly to the accuracy. Since the coil Q was measured for each frequency, these factors did not enter into the calculations. However, with increase in contact resistance or skin effect, the Q of the coil dropped causing the Q reading with the dielectric sample in the circuit to be at the lower end of the scale. This had the effect of reducing the accuracy of that particular reading and the resulting calculations. Also, since the contact resistance was found to be a function of the pressure of contact with the binding posts, difficulty in making re-check measurements was present.

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[10] Hartshorn, L., Radio-Frequency Measurements by Bridge and Resonance Methods, New York: John Wiley and Sons, Inc., 1941. p. 192.

This could not be eliminated but could be overcome by replacing the coil in question and experimenting with the pressure of the contacts until the original Q reading was obtained.

The measurements were conducted within an enclosed screen-wire booth remote as possible from external fields. During the initial stages of the measurement process, however, difficulty was experienced in obtaining a reliable reading over a small band of frequencies. Apparently at this narrow band some external object in the booth was resonating and affecting the resonant Q of the measuring circuit. This, of course, resulted from not having the coil shielded. The trouble was removed by changing the position of the Q-meter. The physical realization of this difficulty came when it became impossible to adjust the circuit to resonance with out the Q indicator drifting around rapidly and erratically.

Another difficulty present was the inability to construct a coil from the wire used with sufficiently high Q to bring the Q readings well up on the scale when the dielectric sample was in the circuit. This also limited the upper range of frequency for the measurements. The coils wound for frequencies above 100 megacycles were found to have sufficiently low Q that readings could not be taken with the dielectric sample. In conjunction with this was the inability to secure a low enough ratio of diameters, inner to outer conductor, of the test cell to make the active capacitance over emphasize the stray. The trouble, in this case, resulted in not being able to read the Q. The ratio was therefore increased until the Q reading with the test sample appeared on scale.

V. SOURCES OF ERROR AND ACCURACY EXPECTED

The accuracy of the Q-meter calibration is approximately plus or minus 10 per cent up to 100 megacycles.[11] However, since the accuracy is a function of the full scale value, Q readings at the low end of the scale probably have an accuracy of 20 per cent. Low Q readings were characteristic of the wood sample throughout the measurements. Thus, it is believed that one of the major sources of error in the values for power factor and resistivity is due to the low Q readings. There is perhaps one compensating factor due to the fact that the change in Q, when the sample is inserted, appears in the formula for calculating the Q of the sample.[12] With larger changes in Q, this factor causes less deviation in the calculated value. Therefore, for low Q readings of the sample, the change in Q is large. This decreases the error so that it is quite possible that the overall accuracy might still approach 20 per cent.

Other factors related to the power factor and the resistivity are losses of the empty cell, surface resistance, air film between electrodes and sample, and losses in the electrodes.[13] The combined effects cause the accuracy of the power factor and the resistivity to be fairly low.

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[11] Boonton Radio Corporation, op. cit., p. 32.

[12] Ibid., p. 12.

[13] Hartshorn, L., Radio-Frequency Measurements by Bridge and Resonance Methods. New York: John Wiley and Sons, Inc., 1941. p. 193 ff.

Hartshorn, L., Ward, W. H., Sharpe, B. A., and O'Kane, B. J., "The Effects of Electrodes on Measurements of Permittivity and Power Factor", Journal of The Institution of Electrical Engineers. Vol. 75. 1934. p. 730.

The primary source of error in calculating the dielectric constant comes from the choice of the test cell capacitance. Since the approximate accuracy of the tuning condenser dial calibration is plus or minus .5 micro-micro farad, the accuracy of the values for the test cell capacitance could be expected to be 10 to 15 per cent.[14] If the test cell capacitance could be increased to approximately 20 micro-micro farads with the test sample inserted, the accuracy would be of the order of 2 to 3 per cent. However, as previously mentioned when the test cell capacitance was increased by decreasing the ratio of the outside diameter of the inner conductor to the inside diameter of the outer conductor, the Q reading with the sample was off scale.

Other factors involved in the accuracy of the dielectric constant would be the coupling between the coil and the test cell, the field distribution of the stray capacitance portion of the test cell, power line stability and body position during the measurements. These things are believed to be of minor importance compared to the source of error mentioned in the above paragraph.

The resulting overall accuracy of the values of the properties of Georgia pine is believed to be plus or minus 15 to 20 per cent.[15]

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[14] These figures are based upon the fact that the total air capacitance of the test cell was approximately 4 micro-micro farads.

[15] Check measurements with paraffin indicate the validity of these figures. See Chapter VI.

VI. RESULTS

The results of the investigation are illustrated graphically in Figures 4, 5, 6, 7, 8 and 9. Figures 4 and 5 show the characteristics of the Georgia pine sample. From these graphs, it can be seen that the dielectric constant experienced very little departure from the mean value, 2.36. The rise in the power factor and loss factor, in the range from 80 to 100 megacycles, is believed to result from the lower value of Q for the coil used in this range. This lower Q is associated with a smaller change in Q when the sample is in the circuit and a resulting greater error in the calculated value of Q for the sample. As has been previously discussed, the lower coil Q results in a lower Q reading with the sample in the circuit which further contributes to a reduction in the accuracy.

In conjunction with the measurements on pine, a sample of spruce and a sample of paraffin were investigated. While time did not permit measurements of these materials over the same range as pine, a portion of that range of frequencies was covered in both cases.

Measurements were conducted in the range of 30 to 40 megacycles for the spruce sample. Curves illustrating the results of this work are shown in Figure 6. Generally speaking, the conditions surrounding the measurements for pine applied also to spruce. The dielectric constant came out to be 2.26 compared to 2.36 for the pine.

Paraffin was used as a means of checking the results of the work on pine. Since paraffin is very stable and the value of the dielectric constant is known, it proved a valuable aid.

Measurements carried out from 30 to approximately 60 megacycles gave a mean value of 2.46 for the dielectric constant. This compares favorably with the values tabulated in the literature and in the handbooks,[16] most of which range from 2.1 to 2.5. If 2.1 is taken as the conservative value the results above would indicate an error of approximately 17 per cent. With a value of 2.2 as a base, the accuracy would be within 11 or 12 per cent. This would indicate that the results for pine would also fall within these limits. Validity of this statement is further enhanced by noting the comparable values of the tuning capacitance reading[17] for pine and paraffin. It is to be pointed out that, since the readings are approximately the same, the value of the dielectric constant should be nearly the same. The latter is apparent from the results, 2.36 compared to 2.46. If the dielectric constants are approximately the same, this means that any source of error due to field distribution would be essentially the same for paraffin as pine. Thus the results should contain comparable errors.

Due to the low-loss characteristics of paraffin, reliable data on the loss factor could not be taken. Calculated values for the conductivity resulting from the data taken are plotted to show this point in Figure 7. Reference to this figure shows that the conductivity is zero at three points and assumes random values at other points.

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[16]Attwood, S. S., Electric and Magnetic Fields. New York and London: John Wiley and Sons, Inc., 1941. p. 57.

Knowlton, A. E., Standard Handbook for Electrical Engineers. New York and London: McGraw-Hill Book Company, Inc., 1941. p. 356.

[17]See Figure 8.

The inability of measuring the loss characteristics evolves from the very small change in Q when the paraffin is inserted into the circuit as has previously been discussed.

The information illustrated in the curves for air, pine and paraffin in Figure 8 suggests a rapid method of getting an accurate indication of the dielectric constant of many materials. If a set of curves of tuning capacitance versus frequency for given dielectric constant values were plotted with a cell of fixed dimensions, very rapid checks of the dielectric constant of many materials would be possible. All that would be necessary would be to cut the samples to the given dimensions, take three or four readings of the tuning capacitance versus frequency and plot these values on the set of curves. If the curves were sufficiently close together, immediate indication of the value of the dielectric constant would be given. This would eliminate the tedious process of calculations.

The mean values of the results, believed to have an accuracy of within plus or minus 15 to 20 per cent, are given below:

	Pine	Spruce	Paraffin
e	2.36	2.26	2.46
e′	.115	.105	----

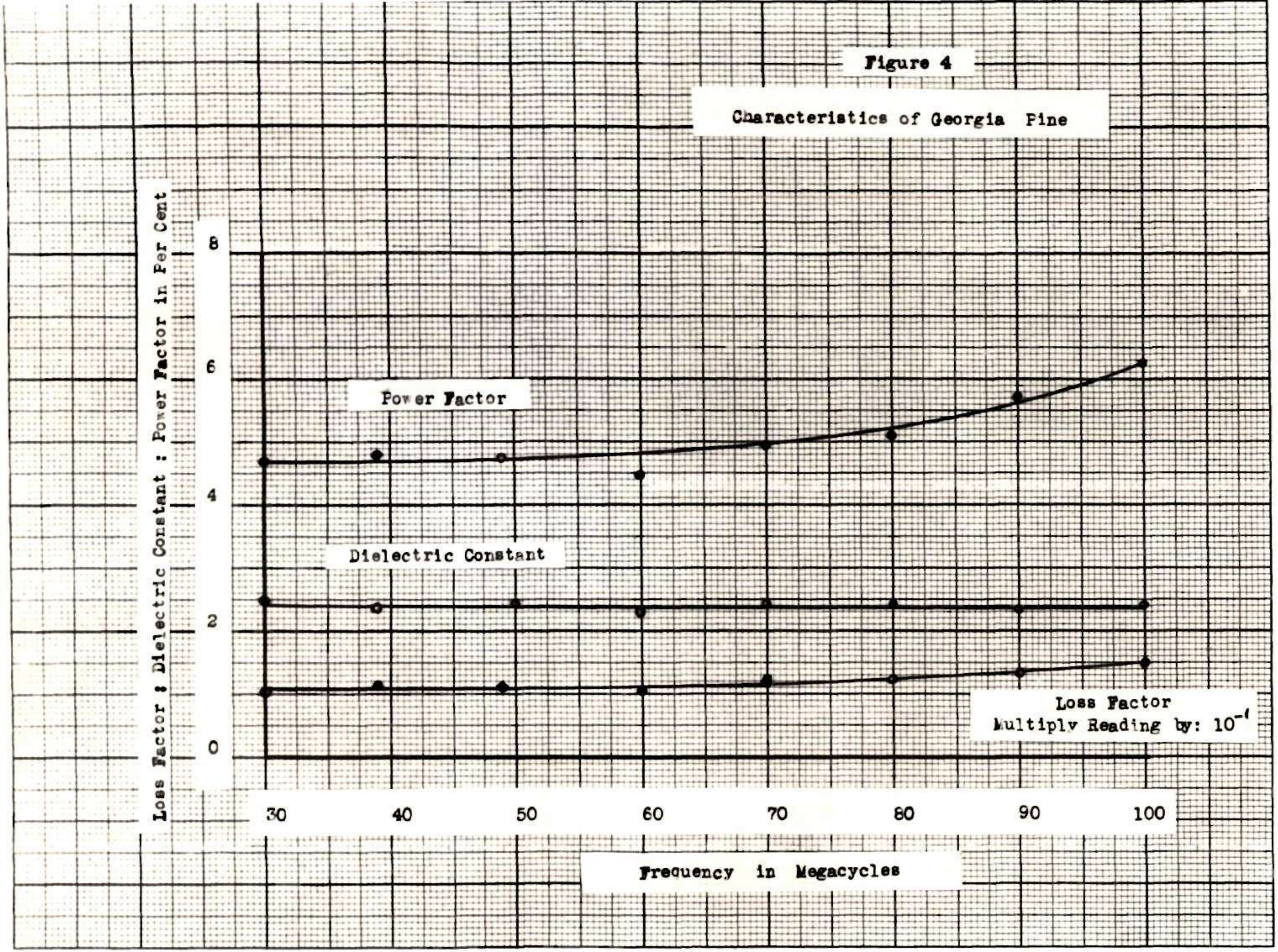

Figure 4

Characteristics of Georgia Pine

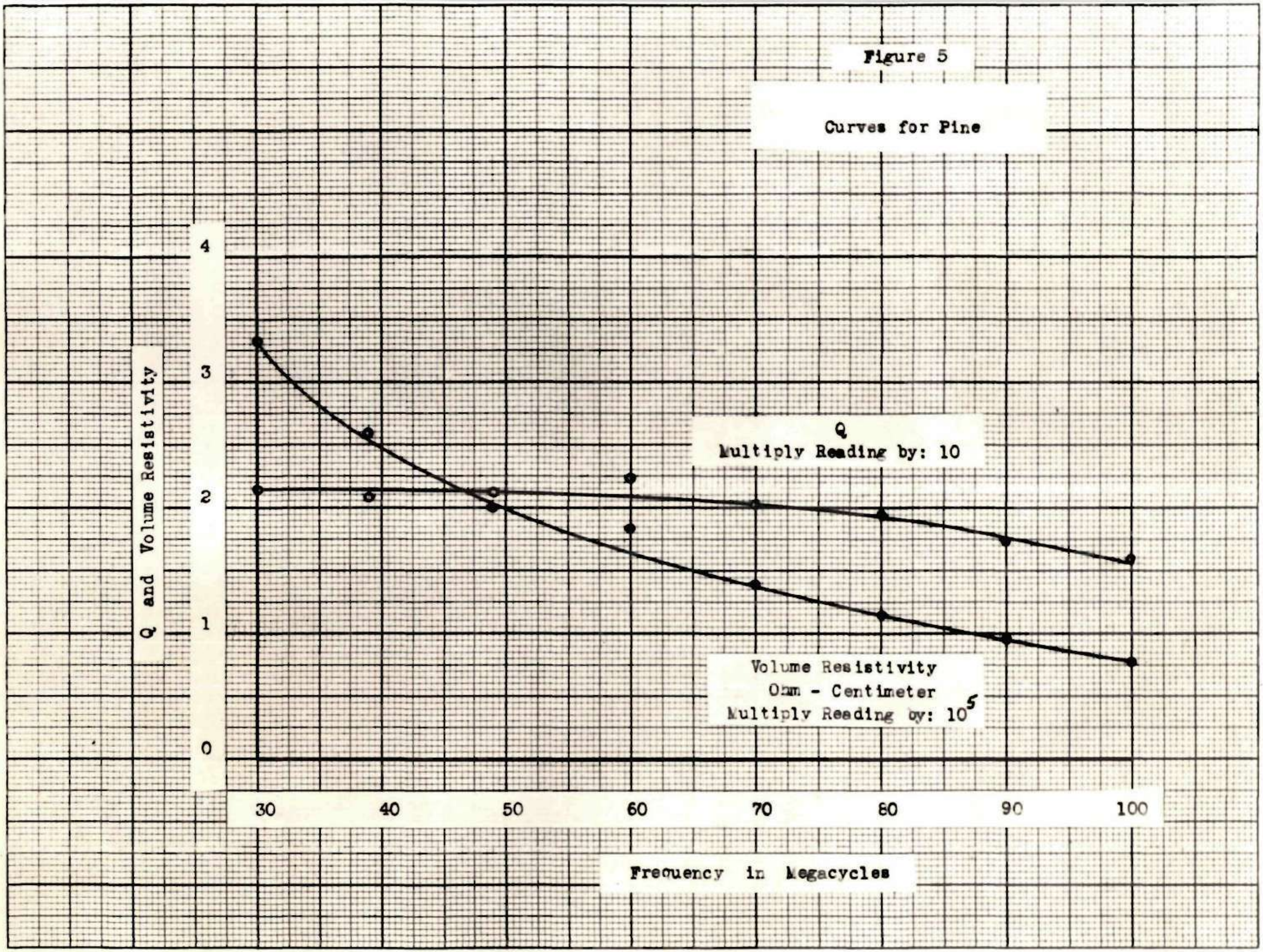
Figure 5
Curves for Pine
Q
Multiply Reading by: 10
Volume Resistivity
Ohm - Centimeter
Multiply Reading by: 10^5
Q and Volume Resistivity
0
1
2
3
4
30
40
50
60
70
80
90
100
Frequency in Megacycles

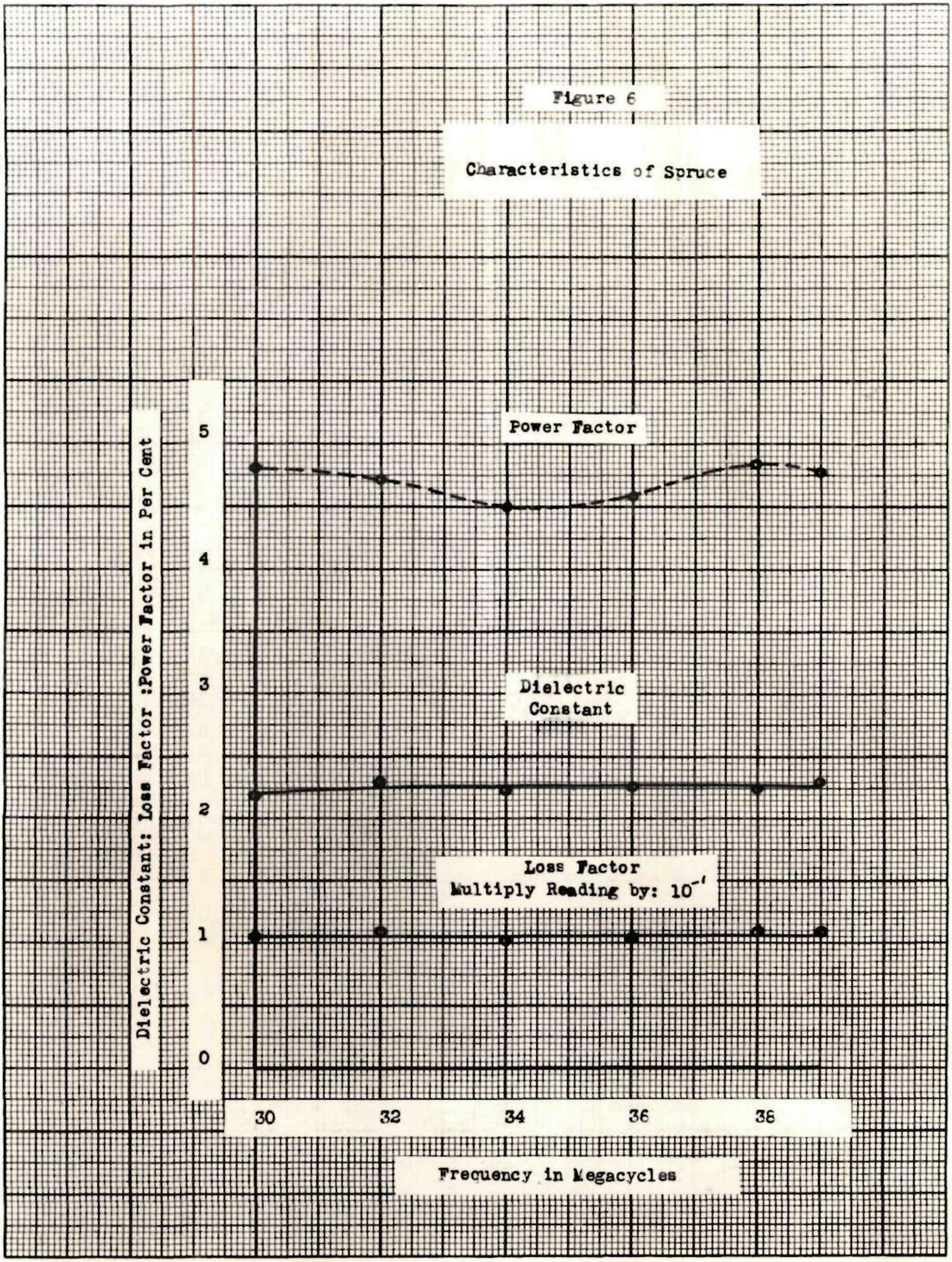
Figure 6
Characteristics of Spruce
Power Factor
Dielectric Constant
Loss Factor
Multiply Reading by: 10^{-1}
5
4
3
2
1
0
Dielectric Constant: Loss Factor :Power Factor in Per Cent
30
32
34
36
38
Frequency in Megacycles

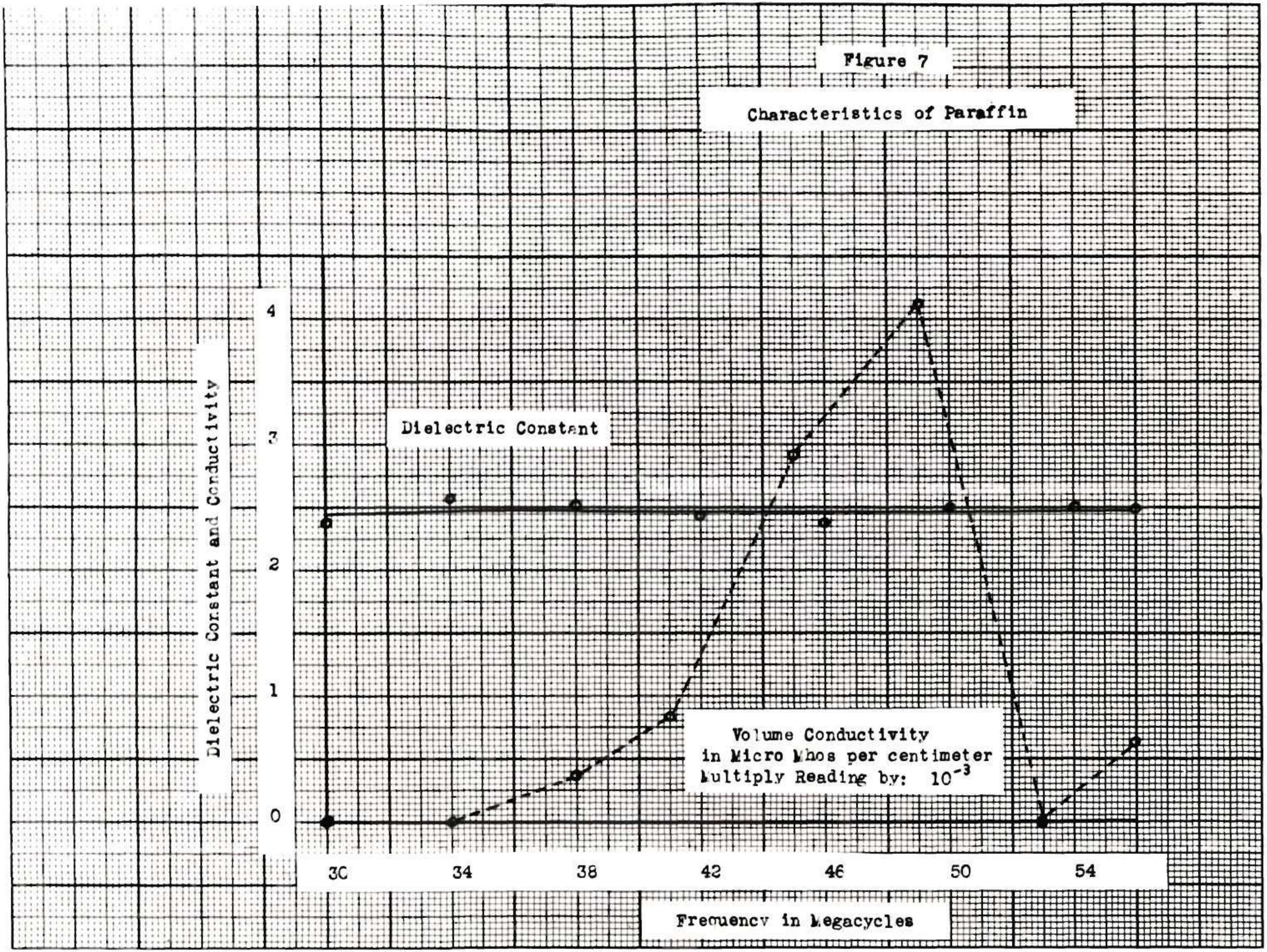

Figure 7

Characteristics of Paraffin

VII. CONCLUSIONS

From the results of the investigation, the technique and design could be improved to give expected accuracies in the range of 5 to 10 per cent.

The design of a new parallel plate test cell[18] with large area compared to the spacing would be the first step. Correct design of this condenser would involve minimum dielectric loss, lead inductance, electrode loss and contact resistance. This could be accomplished by using circular brass or copper plates, spaced by three cylindrical dielectric pieces of low-loss characteristics, with large flat strips of silver-plated copper for connection to the Q-meter. Air pockets at the surface of the dielectric could be excluded by polishing the parallel plates and coating the surface of the sample with a very thin coat of petroleum wax or other low-loss material. Experimentation with the size of the dielectric sample would be necessary to find the optimum area so the Q readings would appear on scale.

If the area of the sample was held considerably smaller than the parallel plates, the field distribution would be unchanged with insertion of the sample. This would mean that the stray capacitance would not change with dielectric material or frequency, and should remain essentially constant.

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[18] Hartshorn, op. cit. p. 183 ff.
Hartshorn, Ward, Sharpe and O'Kane, op. cit.
Boonton Radio Corporation, op. cit. p. 14

Under this condition greater accuracy could be expected for the dielectric constant. Making the capacitance of the test cell a large part of the total capacitance of the resonant circuit would bring the order of accuracy of the capacitance readings to 2 to 3 per cent. The portion of the capacitance occupied by the sample could be calculated directly from the general capacitance formula for a parallel plate condenser.

Improvement in design of the coils to be used with the resonant circuit could take place by using silver-plated copper tubing in the smaller sizes. The optimum shape for the highest Q would be a coil with a winding length approximately one third the diameter.[19] With coils having considerably higher Q than the ones used in the experiment, the accuracy of the calculated values of the Q of the sample should be considerably increased. This improvement would take place from the fact that the Q readings with the sample would be much higher on the scale and also because the change in Q would be larger. As a final step the connection of the coils to the Q-meter could be made in mercury cups. This could be accomplished by threading a small section of tubing so that it could fit directly onto the threads on the solid brass binding posts of the Q-meter. Suitable thumb screws could be attached to hold the coil rigid with its terminals down in the sections of tubing. These cups formed by the open top of the tube sections and the Q-meter terminals could then be filled with mercury to give intimate contact. With this arrangement the overall accuracy could quite easily be 5 to 10 per cent.

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[19]Hartshorn, op. cit. p. 151.

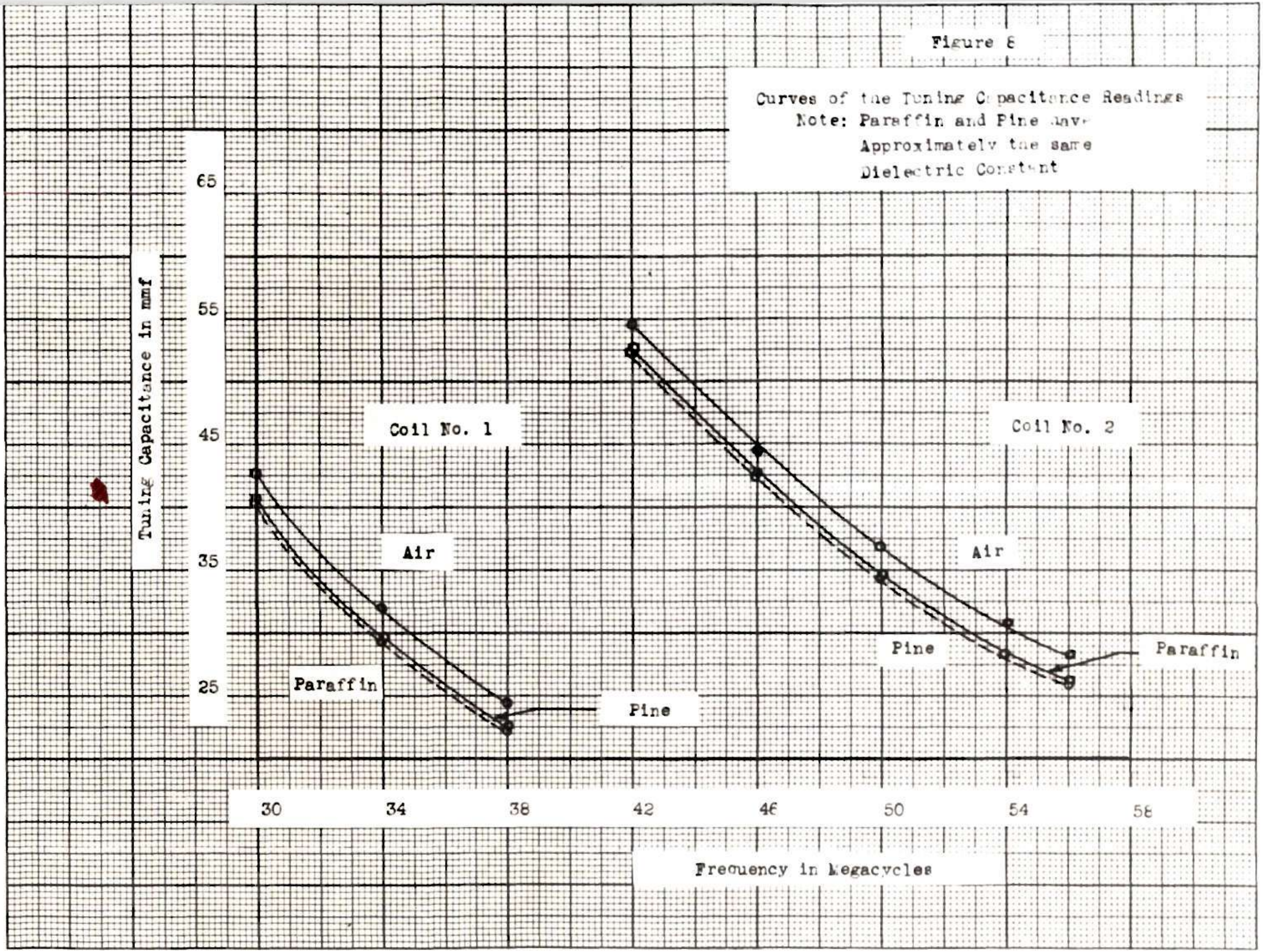


Figure 8
Curves of the Tuning Capacitance Readings
Note: Paraffin and Pine have
Approximately the same
Dielectric Constant
Tuning Capacitance in mmf
65
55
45
35
25
Coil No. 1
Air
Paraffin
Pine
Coil No. 2
Air
Pine
Paraffin
30
34
38
42
46
50
54
58
Frequency in Megacycles

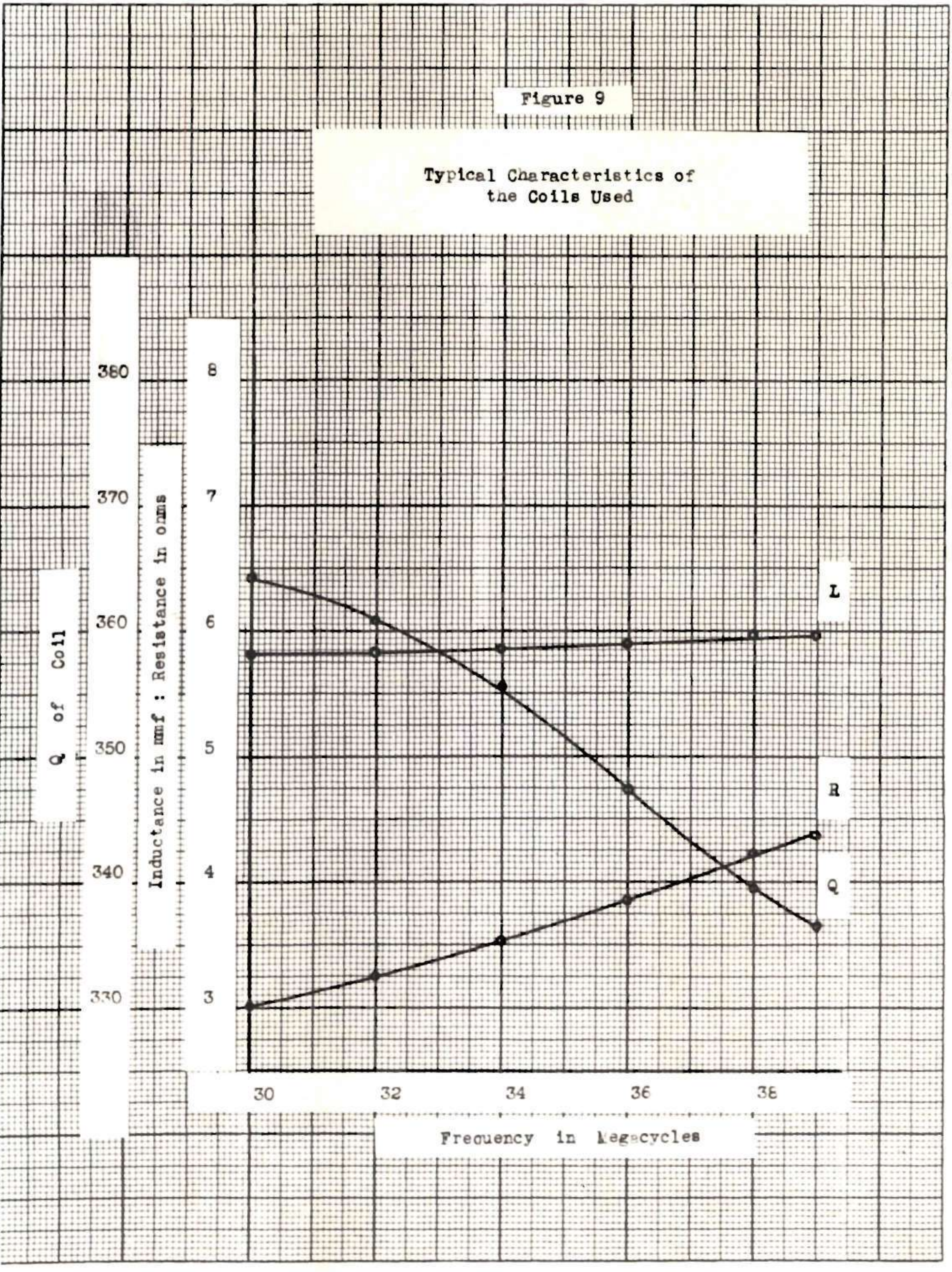
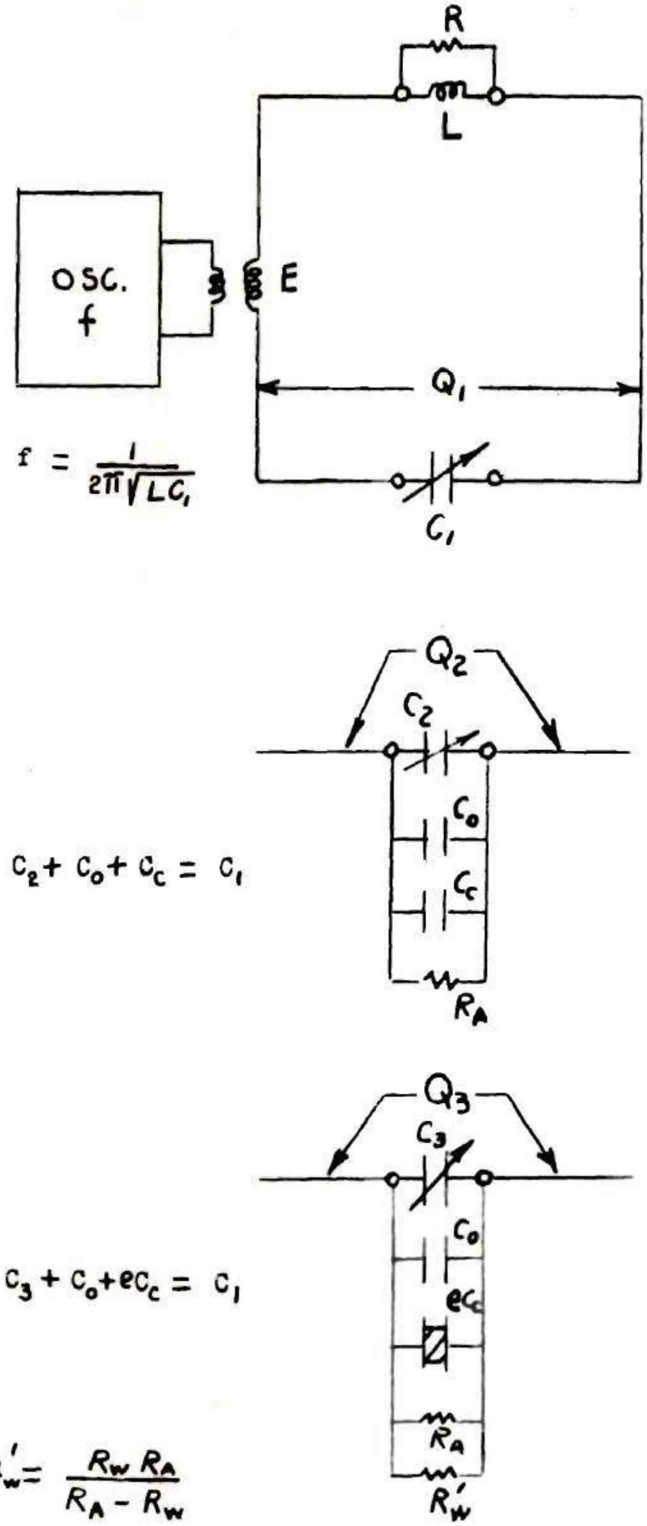


Figure 9
Typical Characteristics of the Coils Used
Q of Coil
Inductance in mmf : Resistance in ohms
380
370
360
350
340
330
8
7
6
5
4
3
L
R
Q
30
32
34
36
38
Frequency in Megacycles

Figure 10
Measuring Circuit Conditions



$f = \frac{1}{2\pi\sqrt{LC_1}}$

$C_2 + C_o + C_c = C_1$

$C_3 + C_o + eC_c = C_1$

$R_w' = \frac{R_w R_A}{R_A - R_w}$

TABLE I

TEST DATA FOR PINE

f	C_1	C_2	C_3	Q_1	Q_2	Q_3
30	46.3	42.7	40.4	375	327	111
31	43.4	39.7	37.4	375	324	105
32	40.7	36.8	34.6	375	321	100
33	38.3	34.1	32.0	372	316	96
34	35.7	32.0	29.5	367	314	92
35	33.6	29.8	27.5	363	310	89
36	31.6	27.8	25.6	359	304	83
37	29.8	26.0	23.7	356	299	81
38	28.3	24.4	22.2	354	293	78
39	67.5	63.9	61.8	363	336	142
40	64.1	60.6	58.6	363	337	138
41	61.0	57.5	55.3	365	336	133
42	58.1	54.5	52.4	367	334	129
43	55.5	51.8	49.7	369	333	125
44	52.9	49.3	47.1	369	332	121
45	50.5	46.8	44.6	366	330	118
46	48.2	44.3	42.4	366	327	112
47	46.2	42.5	40.3	365	325	110
48	44.3	40.5	38.6	362	323	106
49	42.4	38.7	36.4	360	320	102
50	40.6	36.8	34.6	357	315	99

TABLE I (Continued)

f	C_1	C_2	C_3	Q_1	Q_2	Q_3
51	39.0	35.1	33.0	355	312	96
52	37.4	33.6	31.4	352	309	92
53	35.7	32.1	29.8	350	300	90
54	34.5	30.7	28.4	345	298	88
55	33.3	294	27.3	343	292	85
56	32.2	28.3	26.2	340	289	82
57	30.9	27.1	25.0	337	282	80
58	29.8	26.0	----	334	279	----
59	28.8	25.0	----	331	301	----
60	64.3	60.8	58.8	327	300	132
61	62.3	58.7	56.8	327	299	130
62	60.3	56.8	54.7	327	299	127
63	58.3	55.0	52.7	327	298	124
64	56.7	53.1	51.0	331	298	122
65	55.0	51.4	49.2	331	297	119
66	53.3	49.7	47.6	332	297	117
67	51.7	48.1	46.0	331	296	113
68	50.2	46.4	44.5	330	293	112
69	48.8	45.2	43.0	328	291	109
70	47.3	43.8	41.6	326	289	106
71	46.0	42.2	40.2	326	288	102
72	44.6	41.0	39.0	325	288	101

TABLE I (Continued)

f	C_1	C_2	C_3	Q_1	Q_2	Q_3
73	43.4	39.8	37.4	325	287	99
74	42.2	38.7	36.3	325	285	97
75	41.2	37.5	35.2	324	283	93
76	40.1	36.3	34.2	323	281	92
77	39.0	35.3	33.1	322	278	90
78	38.1	34.3	32.1	318	275	88
79	37.0	33.2	31.0	314	270	85
80	36.0	32.3	30.1	312	268	83
81	35.1	31.3	29.2	312	266	81
82	34.2	30.4	28.3	313	266	80
83	59.5		54.1	264		105
84	58.1	54.6	52.6	267	253	103
85	56.8		51.2	269		102
86	55.4	52.0	49.9	270	254	101
87	54.1		48.3	272		99
88	52.8	49.3	47.2	273	256	98
90	51.7	47.0	46.0	276		98
91	49.4		44.9	277	260	97
92	48.3	44.7	43.7	278	257	95
93	47.2		42.6	276		92
94	46.2	42.7	41.6	275	252	91
95	45.3		40.6	272		88

TABLE I (Continued)

f	C_1	C_2	C_3	Q_1	Q_2	Q_3
96	44.3	40.7	38.7	270	248	84
97	43.4		37.6	268		82
98	42.5	38.9	36.7	267	246	80
99	41.7		35.8	266		79
100	40.8	37.2	35.0	265	242	77

TABLE II

CALCULATED DATA FOR PINE

f	e_w	e'_w	Pf_w	r_w	Q_w
30	2.50	.125	5.00	312	20.0
32	2.43	.121	5.00	288	20.0
34	2.63	.124	4.70	280	21.3
36	2.43	.119	4.88	262	20.5
38	2.43	.113	4.63	257	21.6
39	2.37	.120	5.07	245	19.7
41	2.43	.124	5.11	231	19.5
42	2.37	.122	5.12	219	19.5
44	2.43	.123	5.05	212	19.8
46	2.24	.117	5.2	200	19.2
48	2.24	.116	5.19	190	19.3
50	2.43	.120	4.93	182	20.3
52	2.43	.122	5.00	177	20.0
54	2.50	.120	4.80	170	20.9
56	2.37	.118	4.95	160	20.2
60	2.30	.111	4.85	172	20.6
62	2.36	.123	5.20	145	19.3
64	2.36	.121	5.15	147	19.4
66	2.36	.122	5.19	142	19.3
68	2.24	.116	5.20	137	19.3
70	2.43	.128	5.29	131	18.9

TABLE II (Continued)

f	e_w	e'_w	Pf_w	r_w	Q_w
72	2.36	.128	5.44	126	18.4
74	2.56	.133	5.18	122	19.3
76	2.36	.125	5.29	116	18.9
78	2.43	.127	5.22	113	19.2
80	2.43	.131	5.40	109	18.5
82	2.36	.127	5.40	106	18.5
84	2.30	.145	6.29	95	15.9
86	2.36	.147	6.21	94	16.1
88	2.36	.143	6.05	93	16.5
90	2.36	.140	5.95	92	16.8
92	2.36	.145	6.13	86	16.3
94	2.36	.149	6.33	83	15.8
96	2.30	.149	6.47	80	15.5
98	2.43	.157	6.45	76	15.5
100	2.43	.157	6.49	74	15.4

TABLE III

CORRECTED DATA FOR PINE

f	R_A	R'_w	e''_w	Pf'_w	r'_w
30	292	19.2	.101	4.7	333
39	270	14.9	.114	4.8	258
49	220	11.0	.110	4.7	200
60	156	10.6	.104	4.5	184
70	130	8.0	.120	4.9	139
80	105	6.6	.124	5.1	115
90	148	5.5	.134	5.7	96
100	109	4.4	.150	6.3	76

TABLE IV

TEST DATA FOR CELL

f	C_A	R_A
30	3.6	292
32	3.9	275
34	3.7	285
36	3.8	277
38	3.9	251
39	3.6	270
41	3.5	269
43	3.7	227
45	3.7	235
47	3.7	217
49	3.7	220
51	3.9	206
53	3.6	176
55	3.9	171
57	3.8	167
60	3.5	156
62	3.5	149
64	3.6	131
66	3.6	128
68	3.8	135
70	3.5	130

TABLE IV (Continued)

f	C_A	R_A
72	3.5	123
74	3.5	118
76	3.5	114
78	3.8	109
80	3.7	105
82	3.8	100
84	3.5	157
86	3.4	143
88	3.5	141
90	3.5	148
93	3.6	134
94	3.5	125
96	3.6	114
98	3.6	120
100	3.6	109

TABLE V

CALCULATED STRAY CAPACITANCE OF CELL

f	C_o
30	2.07
32	2.37
34	2.17
36	2.27
38	2.37
39	2.07
41	1.97
42	2.07
44	2.07
46	2.37
48	2.27
50	2.27
52	2.27
54	2.27
56	2.37
60	1.97
62	1.97
64	2.07
66	2.07
68	2.27
70	1.97

TABLE V (Continued)

f	C_o
72	1.97
74	1.97
76	2.27
78	2.27
80	2.17
82	2.27
84	1.97
86	1.87
88	1.97
90	1.97
92	2.07
94	1.97
96	2.07
98	2.07
100	2.07

BIBLIOGRAPHY

Attwood, S. S., Electric and Magnetic Fields, New York and London: John Wiley and Sons, Inc., 1941. p. 57.

Boonton Radio Corporation, Instructions and Manual of Radio Frequency Measurements for Q-Meters.

Brown, H. A., Radio-Frequency Electrical Measurements, New York and London: McGraw-Hill Book Company, Inc., 1938.

Chaffee, J. L., "Determination of Dielectric Properties", Proc. I.R.E., Vol. 21, October 1933. p. 1447

Feldman, C. B., "Optical Behaviour of Ground for Short Radio Waves", Proc. I.R.E., Vol. 21, June 1933. pp. 765, 792, 793.

Hartshorn, L., Radio-Frequency Measurements by Bridge and Resonance Methods, New York: John Wiley and Sons, Inc., 1941.

Hartshorn, L., Ward, W. H., Sharpe, B. A., and O'Kane, B. J., "The Effects of Electrodes on Measurements of Permittivity and Power Factor on Insulating Materials in Sheet Form", Journal of the Institution of Electrical Engineers, Vol. 75., 1934. p. 730 ff.

Hund, A., High Frequency Measurements, New York and London: McGraw-Hill Book Company, Inc., 1933.

Jeans, J. H., The Mathematical Theory of Electricity And Magnetism, Cambridge: University Press., 1941. p. 75.

Knowlton, A, E., Standard Handbook for Electrical Engineers, New York and London: McGraw-Hill Book Company, Inc., 1941. p. 356.

Rao, V. V. L., "The Q-meter and Its Theory", Proc. I.R.E., Vol. ~~23~~ 30, November 1942. p. 502 ff.

Schulz, E. H., and Anderson, L. T., Experiments in Electronics and Communication Engineering, New York and London: Harper and Brothers, 1943. p. 89 ff.

Smythe, W. R., Static and Dynamic Electricity, New York and London: McGraw-Hill Book Company, Inc., 1939. p. 560.