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Doctor's Dissertation

Electrical Resistance of Paper

by Archie John Deutschman, Jr.

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ELECTRICAL RESISTANCE OF PAPER

A thesis submitted by

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**in partial fulfillment of the requirements
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INTRODUCTION

Two basic electrical methods are now used for measuring or indicating the moisture content of paper on the machine. One method, which is based upon the measurement of the relative humidity of the air above the paper web, is employed to control the temperature of the drier sections. This control depends upon the relationship of the moisture in the paper to the relative humidity of the surrounding air. The second method (which is the one of interest in this study) depends upon the relationship between the moisture content and the electrical resistance of paper. This method is not generally used to control the drying process but is employed for recording the moisture content of paper.

It is desirable to maintain low moisture contents when paper is employed for electrical applications. To facilitate its use in this field, numerous studies have been carried out in the low moisture content range and theories have been set forth to explain the observed phenomena.

The resistance of paper at high moisture contents is important only on the paper machine. As a result, little work has been carried out in this range. Because of the lack of data regarding the mechanism and related phenomena in the high moisture range, this study was undertaken.

The paper web entering the drier section of the machine may contain up to 80 per cent water, and the resistance at this point would primarily be the resistance of the water in the sheet. As the paper web proceeds through the drier section, the resistance becomes more a property of the paper itself. Therefore, these investigations were carried out on specimens having a moisture content which might be expected at the dry end of the machine.

HISTORICAL REVIEW

A logical approach to a study of the electrical resistance, or conductance, of paper would involve a study of the phenomena with particular reference to cellulose. This resistance is a logarithmic function of the moisture content; however, it has been reported in the literature and it was found in this study that other variables common in the manufacture of paper affect the resistance offered by paper.

The exact mechanism of conduction in paper and cellulosic materials is not definitely known. Because of the very hygroscopic nature of cellulose, its moisture content is dependent upon the temperature and relative humidity of the surrounding atmosphere. In 1914, Evershed (1) made an extensive investigation of the effect of moisture on the resistance of a number of insulating materials, one of which was cotton. From his investigations he concluded that electrical leakage was almost entirely the result of moisture condensed on the external and internal surfaces. Kujirai and Akahari (2) determined quantitative relationships between insulation resistance and relative humidity for cotton, silk, and other fibrous insulating materials. Measurements of the conductance of individual cotton fibers as a function of relative humidity were made by Slater (3). His results indicated that, in the range of 40-80 per cent relative humidity, the logarithm of the conductance of the fibers is a linear function of the relative humidity. However, it was not shown in either case that the relationship between resistance and relative humidity was chiefly an attribute of the fibrous

structure, such as that of cellulose in the case of cotton.

Murphy and Walker (4) and Walker (5, 6) carried out considerable work with cotton fibers. They found that, if the logarithm of the moisture content (the atmosphere in which the samples were conditioned covered a range of 5 to 95 per cent) was plotted against the logarithm of the resistance, straight lines were obtained whose slopes were independent of the form of the sample and of the amount of impurities contained in the textile, but were characteristic of the kind of material tested. The fact that the position of these lines was dependent upon the amount of impurities indicated that the conduction may take place through water paths whose conductivity was dependent on the concentration of the electrolytes. If these water paths are pictured as forming a regular space-pattern, the elements of which change in dimension with the moisture content in a way characteristic of the textile, the observed relationship might readily be explained.

Murphy and Lowry (7) expanded the theory proposed by Murphy and Walker (4) to apply to dielectric loss and dielectric absorption in alternating current fields. They believed that the structure of a dielectric, free ions, adsorbed ions, and neutral molecules may each contribute to the loss and absorption and that the relative prominence of each of these components should depend upon the type of dielectric, the temperature, and other factors.

Seborg and Stamm (8) made measurements upon pulps which had been beaten. Their data showed that the resistance was independent of beating. These results would indicate that the so-called hydration of

papermaking pulp is not a true hydration but is probably a phenomenon of fiber-fiber bonding rather than fiber-water bonding. They also indicate that conductivity is associated with the submicro-structure of the fibers, which would not be appreciably altered by beating, rather than with their micro-structure.

Williams (9) suggested that, since conducting paths are present in cellulose, "sorbed" ions may conduct electricity. These "sorbed" ions may be more or less tightly combined with the cellulose and, as the voltage is increased, the conductivity is increased because of the desorption of more ions from the cellulose. Walker and Quell (10) found that acid washing of cotton increased the resistance up to 200-fold. Lamberts and Schulze (11) found that, by extracting condenser paper with water and making conductivity measurements upon the extract, an insight into the electrical behavior could be obtained. High contents of electrolytic materials were found in papers with poor dielectric properties.

These observations indicate that the concentration of electrolyte will have an important bearing upon the conductivity of the test specimen, and indicate agreement with the mechanism proposed by Murphy and Walker.

Whitehead (12) studied power factor, conductivity, dielectric constant, and dielectric loss as a function of paper density. He found that the observed increases were greater than could be accounted for by the increase in paper density alone. In his discussion, he suggested that the liberation into the insulating oil of ions absorbed on or contained in the fiber structure of the paper might account for the increased

loss and increased conductivity observed. Finch (13) pointed out that certain paper impurities caused reduction in insulating resistance and increased the corrosion of the copper wire. He found that chlorides, hydroxides, sulfates, and sulfides were the chief offenders. Because chlorides are particularly harmful, bleached pulps are avoided. Rosin-sized papers and papers made on machines with closed systems should not be used for electrical applications.

There are two discrepancies which are not entirely in agreement with the theory proposed by Murphy and Walker (4-6). Shorygin and Shorygin (14) discussed the observation that the electrical conductivity of air-dry paper was less than that of the water in it. The explanation offered is that not all pores filled with water reach from one electrode to the other, and that possibly part of the water is "bound." McLean and Kohman (15) found that, at low humidities where it is improbable that the absorbed water can be regarded as forming conducting liquid paths, the conductivity increases as the potential gradient and the temperature increase. The explanation was offered that ions which are strongly bound to the cellulose structure move against restraining forces when a potential is applied. It was observed that at low potential gradients the ions finally attained a condition of equilibrium, in which case the leakage current reached a constant low value and, when the potential was removed, a current flowed in the opposite direction. At high potential gradients the restraining forces may break down and some of the ions become free, thus causing an increase in current which is not reversible. Similar phenomena may be observed on a crystal surface containing adsorbed moisture. This behavior may be characteristic of surfaces containing adsorbed moisture or ions.

Gulver (16), in a report on the Brown Moist-O-Graph, stated that freshness, pH, speed, caliper, ambient humidity, and static would cause no effect upon the resistance of paper. He found that temperature, size, filler, stock, and dye did cause the resistance to vary and, in the actual use of the instrument, he reported that calibration was necessary for each type of paper and each machine run.

In view of these observations, it would be difficult to state definitely the exact nature of the mechanism of conduction of paper. In average papers, which normally are fairly high in ash content, the conductivity would probably be largely ionic, whereas in highly purified, dry papers the conductivity may be electronic. With this view in mind, a brief review of experimental procedures, methods of distinguishing between electronic and ionic conduction, and the theory of ionic conduction, are presented.

A survey of the field of dielectrics, without particular reference to cellulose, was made by Manning and Bell (17). The quotations in the following section are excerpts from this article.

"Substances are grouped roughly into metallic conductors, semiconductors, and insulators. At room temperature metallic conductors usually have a conductivity of $10^3 \text{ ohm}^{-1} \text{ cm.}^{-1}$ or greater. If the room-temperature conductivity of a substance is less than $10^{-10} \text{ ohm}^{-1} \text{ cm.}^{-1}$, it is classed as an insulator. The substances in the intermediate group are called semiconductors." In view of this definition of conductors, semiconductors, and insulators, ordinary paper would be classed as a semiconductor; however, specially purified papers (e.g., condenser papers)

would be classed as insulating papers.

*The mechanism of electrical conduction in solids may be either electronic or ionic, and various methods of distinguishing between the two types have been developed. In metals the conductivity is, of course, electronic, and may be, at room temperature, as high as $10^6 \text{ ohm}^{-1} \text{ cm.}^{-1}$. There are also insulators and semiconductors which owe their conductivity to electronic transfer. Because of their symmetrical structures, pure samples of diamond and sulphur must owe their feeble conductivity ($10^{-18} \text{ ohm}^{-1} \text{ cm.}^{-1}$, or less) to electrons. In heteropolar or ionic compounds there is the possibility of ionic transfer. At ordinary temperature the conductivity of rocksalt is about $10^{-16} \text{ ohm}^{-1} \text{ cm.}^{-1}$ and is due to ionic transfer. There are also semiconductors whose conductivity is ionic. The highest conductivity which has been observed is that of the high temperature form of AgI which has a conductivity of about $2 \text{ ohm}^{-1} \text{ cm.}^{-1}$.

EXPERIMENTAL METHODS

*Early investigations of the conductivity of insulators were made by Jacques and Pierre Curie (18) and published in 1888-1889. These thorough and capable workers established the basic method for conductivity measurements in which the sample, in the form of a plate or slab, is placed between two metal electrodes. One electrode, which should be provided with a guard ring to eliminate surface conduction effects, is connected through an arrangement of shunts and capacitances to ground. The current through the sample may be measured either by the drop across a standard resistance or by the time required to charge a condenser of known capacity to a given potential. The potential drop is usually

measured by an electrometer.

"The development of the high sensitivity D'Arsonval galvanometer provided a very direct means of measuring the conduction current in an insulator. The galvanometer, combined with an Ayrton shunt to provide proper damping and changes in sensitivity, is connected between the guarded electrode and ground. In this way currents as small as 10^{-10} ampere can be measured accurately, but the method has the disadvantages of limited sensitivity and inherently slow response.

"The quadrant electrometer as modified by K. T. and A. H. Compton (19) has a much higher sensitivity than the older form. Values of 5000 mm. per volt are not unusual."

The two disadvantages of using electrometers for making resistance measurements are the slow response of the electrometer and the manual effort required to apply the balancing e.m.f. to the resistor.

"In the past decade, two special electrometer tubes have been developed; the G. E. Type F. P. 54 (20-22), and the Western Electric Type D-96475 (23). In these the object is to reduce the grid current to the lowest possible value. The grid current in these tubes under normal operating conditions is less than 10^{-15} ampere, compared with about 10^{-10} in an ordinary radio tube. Since currents of the same order as the grid current can be measured, these special tubes extend the range of measurements by a factor of 10^5 beyond that of a high sensitivity galvanometer.

"In the simplest circuit for an electrometer tube, the change

in plate current is used to indicate a change in grid voltage. This arrangement suffers from instability, nonlinearity, and low amplification. The most prominent causes of instability are drift of filament and plate supply voltages and changes in tube characteristics with time.

"A more satisfactory arrangement is a balanced circuit employing only one tube and using a resistance network to compensate for changes in battery voltage and tube characteristics. A good comparative discussion of the various balanced circuits has been given by Penick (23). He shows stability characteristics for the Barth circuit, which is considered most generally useful of those he investigated. As battery voltage is varied, deflection of the galvanometer in the plate circuit decreases, and reaches a minimum at a particular battery voltage. When the circuit is operated in the neighborhood of this minimum, first-order effects of battery voltage fluctuations and changes in filament emission are eliminated. A very stable circuit results whose zero-point drift is negligible."

Tatel, Moncton, and Luhr (24) developed an electron amplifier using an ordinary tube. They used a pentagrid converter in which two of the grids were used as the plate. With their circuit the grid current was of the order of 10^{-10} ampere, thus making possible the measurements of currents of that magnitude. The amplifier, naturally, could not be used to measure currents of the same order as those measurable with the Western Electric or General Electric electron amplifiers; however, it would be quite satisfactory for measuring the resistance of most papers.

Instruments designed to measure the resistance of papers have

been reported and a few are in use for indicating the moisture content of paper. The Brown Moist-O-Graph (16) and the Barber-Colman (25) instrument may be used on the paper machine; the Hart moisture meter (26) and the Tag-Heppenstall moisture meter (27) have been suggested for laboratory testing.

METHODS OF DISTINGUISHING BETWEEN ELECTRONIC AND IONIC CONDUCTION

"One of the important questions to be settled before the phenomena of electrical conduction in solid salts can be understood is whether the conduction is due to the motion of electrons, positive ions, negative ions, or to two or more types simultaneously. Actually, it is probable that there will be some contribution from all three types, but for a given material at a particular temperature it is usually found that one type predominates.

"There are certain phenomena which usually accompany electrolytic conduction and which can usually be taken as evidence that a portion, at least, of the current is carried by ions. One of these phenomena is polarization. As was mentioned in the introduction, when a potential difference is applied to a substance like rocksalt, the current does not stay constant, but decreases with time. At ordinary temperatures, the change continues for minutes or even hours and the steady-state current may be less than 1/1000 of that which flowed when the potential difference was first applied. Another phenomenon which is sometimes difficult to investigate, but which is usually definite evidence for electrolytic conduction, is the actual appearance of material at an electrode.

"One of the best indicators that a portion of the conductivity is electronic is obtained from studies of the Hall effect. If a magnetic field is applied perpendicular to an electronic current, a potential difference appears perpendicular to the plane of the magnetic field and the current. Even for an electronic conductor the Hall effect sometimes vanishes in a certain temperature range, (28) but it is never found for a purely ionic conductor.

"However, the best method of determining what proportion of the total charge is transferred by each type of carrier is by studies of the applicability of Faraday's law of electrolysis, which should, of course, be valid for solid ionic conductors as well as for fused salts and water solutions. This method was developed by Tubandt (29) and has been applied by him and his associates to a large number of substances."

IONIC CONDUCTIVITY

"At temperatures near the melting point the conductivity of an ionic crystal is much less ambiguous than at lower temperatures. The conductivity may vary somewhat from one sample to another, but usually by much less than an order of magnitude. At these temperatures polarization phenomena are negligible.

"At lower temperatures the behavior is much more complicated than in the high temperature region. The effect of small amounts of impurities is much more marked and the conductivity depends upon the previous thermal history of the particular specimen.

"The variation of current in a dielectric with time was studied by Hopkinson (30, 31) and the Curies (18) more than fifty years ago. It was later studied by Tank (32) and Richardson, (33-35) and still later by Joffe (36, 37). Recently a number of Russian and German investigators have worked on the problem.

"The general phenomena are as follows: When a potential difference is applied to a dielectric the current changes with time. It has not been possible to determine the current at very small time intervals after application of voltage, but all results indicate that it rises very rapidly toward $t = 0$. At ordinary temperatures the steady-state value of the current may be reached only after several hours or even days and may be as low as 10^{-4} of that observed initially. If the specimen is short-circuited, it is found that a current, known as the discharging current, flows in the reverse direction. If the steady state has been reached before short-circuiting, the discharging current shows essentially the same variation with time as the charging current. At room temperature, for a poor conductor like rocksalt, the quantity of electricity which flows in the reverse direction is almost as large as that which flowed in the positive direction. If the steady state has not been reached, the quantity which flows during discharge is still approximately equal to the quantity which flowed during charge, but the initial current for discharge is equal to the difference of the initial and final currents during charge."

OBJECTIVES

The specific aim of this work was a study of the resistance of paper at high moisture contents. This involved the development or adaptation of equipment for measuring high alternating and direct current resistances. It was proposed to study the extent to which Ohm's law was obeyed and the influence of temperature, electrolyte content of the sheet, and chemical treatment of the pulp on the specific resistance of paper.

Further, correlation between certain chemical constituents and tests such as lignin, copper number, uronic acids, alpha-cellulose, and ash with resistance was to be attempted.

EXPERIMENTAL APPARATUS AND PROCEDURES

In brief outline, the resistance measurements were made on conditioned specimens which were placed between the test electrodes in a controlled relative humidity cabinet. The direct current resistances were obtained by applying a known voltage across the test specimen and a standard resistor and then indirectly measuring the current through the circuit by determining the voltage drop across the standard resistor with a vacuum-tube voltmeter. The alternating current resistances were measured by a Wheatstone bridge which employed a two-stage amplifier and cathode ray tube as a detector.

This section contains a detailed description of the apparatus and the experimental techniques.

THE CONTROLLED RELATIVE HUMIDITY CABINET

Two cabinets were constructed. One (the control cabinet) was used to condition the air which was circulated through the second cabinet (the testing cabinet), where the samples were conditioned and the resistance measurements made. The double-walled boxes were 3 feet wide, 3 feet high, and 2 feet deep. The 1.5-inch space between the 1/2-inch plywood walls was filled with redwood bark fiber to provide thermal insulation. The front of each cabinet was provided with a double window, 1 x 2 feet; the air space between the two pieces of plate glass furnished thermal insulation.

The back edge of each cabinet was hinged to the floor of the cabinet. The floor was fastened to the top of the laboratory desk so that the cabinet was opened by tilting it about the hinges. A strip of rubber tubing fastened to the bottom of the cabinet walls effected the seal against the floor; this seal was insured by drawing the cabinet tightly against the floor with stove bolts provided with wing nuts. All joints were caulked, and the inside of the cabinets was given two coats of moisture-resistant paint.

The testing cabinet was provided with two armholes (7 inches in diameter), which were fitted with sleeves and gloves so that the electrodes and specimens could be manipulated without opening the cabinet. When not in use, the armholes were covered with pieces of glass which were clamped against rubber-tubing gaskets cemented around the holes.

A bimetallic thermoregulator controlled the temperature in each cabinet. Throughout most of the work two 25-watt lamps in each cabinet provided the heat. At the higher temperatures it was necessary to use a 500-watt radiant heater; in this case, the thermoregulator operated a relay which controlled the heater.

Circulation of the air within each cabinet was effected by a 10-inch fan mounted on top of the cabinet. The motor was fastened above the cabinet and an extension shaft passed through the top to the fan blades. A short length of rubber tubing acted as a flexible coupling between the motor and fan shafts. Two brass plates screwed to the top of the cabinet, one inside and one outside, acted as bearings for the

extension shaft.

Two 1-inch pipes provided with couplings connected the two cabinets and carried the air from the control cabinet to the testing cabinet and back again. A hand vacuum cleaner produced this circulation of air between the cabinets. The vacuum cleaner motor was operated at reduced voltage, and the rate of air flow was further reduced by means of a $1/4$ -inch orifice in the inlet pipe to the testing cabinet. This provided an adequate flow of air and reduced the pressure differentials so that there was not an excessive leakage of air and moisture from the testing cabinet.

Trays of saturated salt solutions controlled the relative humidity of the air in the control cabinet during most of the work. At the higher temperatures the relative humidity was controlled by injecting steam into the conditioning cabinet. An electric hygrometer (38), in conjunction with an alternating current Wheatstone bridge type of recorder and controller, operated an electric janitor which opened and closed the lever-operated steam valve. The steam passed from the valve through a condensate trap to a T-tube, one leg of which was open to the room, and then into the conditioning cabinet.

A sketch of the testing cabinet is shown in Figure 1.

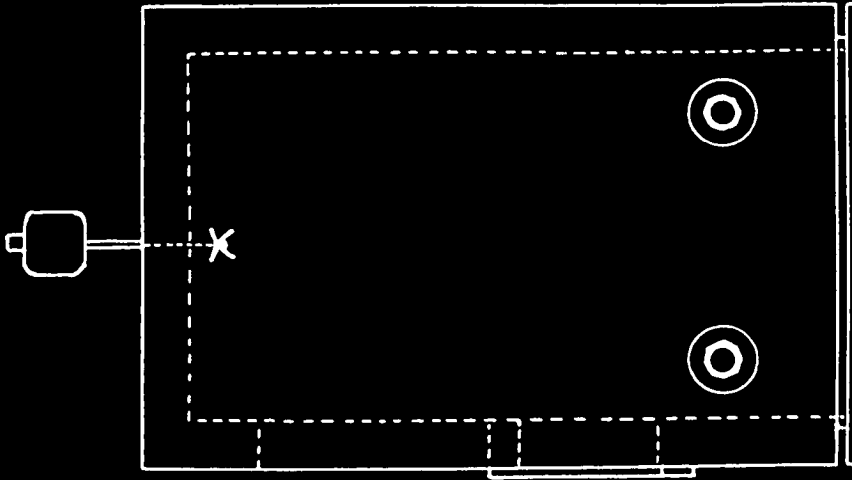
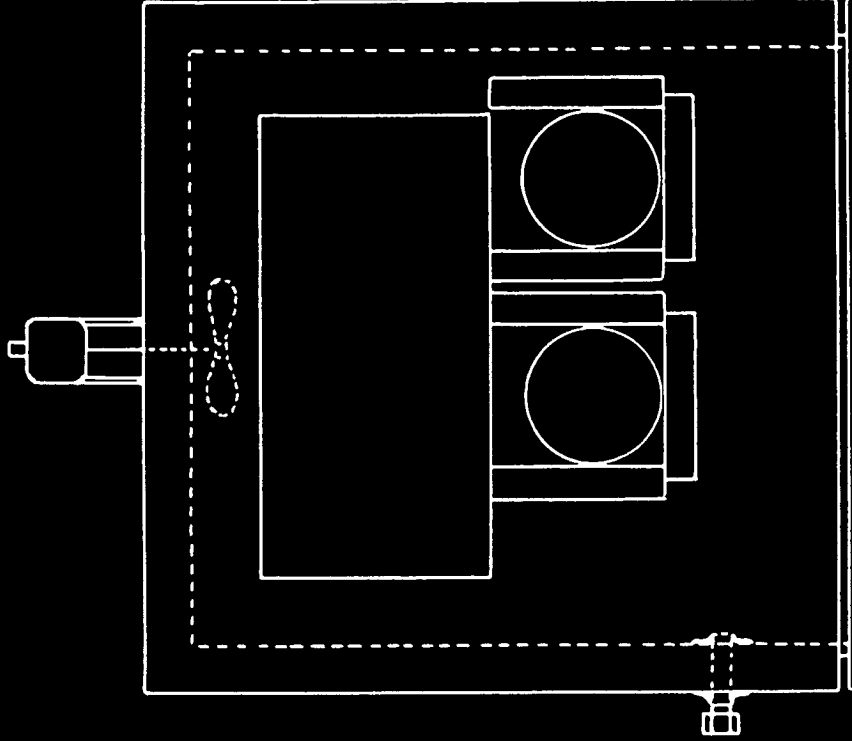
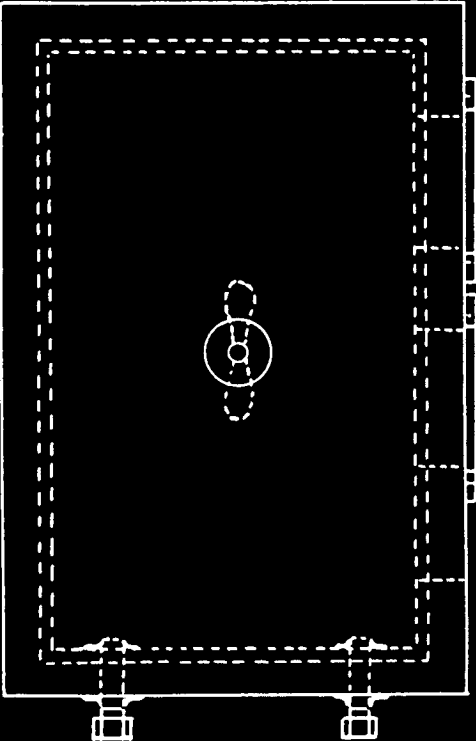
ELECTRODES

Two types of electrodes were used in the resistance measurements; one pair consisted of stainless steel and the other of mercury.

Figure 1

Cabinet Used For Testing Samples

Scale 1 inch = 10 inches



One of the stainless steel electrodes was a flat plate, which was used as the bottom electrode. The paper specimen was laid on this plate and the upper, disk-shaped electrode placed on it. The upper electrodes were made by soldering sheet stainless steel to the ends of iron rods of suitable diameter. These rods were then turned down to the desired final diameter, the stainless steel ends were faced off, and ground on plate glass with 600-mesh carborundum. Electrodes having diameters of 1.50, 2.54, and 3.08 cm. were prepared in this manner.

During the experiments in which the electrode pressure was varied, the weights of these electrodes were changed by placing additional weights on them.

For the work which required two mercury electrodes, the bottom electrode was a pool of mercury in a beaker. Two-centimeter lengths of glass tubing (having an internal diameter of 1.5 cm.) were cut, and one end of each tube was ground flat on plate glass using 200-mesh carborundum. The paper specimens were sealed to the ground ends of these tubes with a mixture of gum rosin and crude beeswax. The specimen-covered end of a tube was placed on the mercury in the beaker and 30 grams of mercury were poured into the tube; this mercury constituted the upper electrode.

D.C. RESISTANCE

A schematic diagram of the general arrangement for measuring the d.c. resistance of paper is shown in Figure 2. The resistance is measured indirectly by applying a known source of potential (V) across

the paper sample and a standard resistance and applying a counter e.m.f. between the standard resistor (R_s) and ground, until the point 3 between R_x (the resistance of the paper specimen) and the standard resistor (R_s) is at ground potential, as indicated by the voltmeter.

The counter potential (V_c) applied by the potentiometer to bring the point between the two resistances to ground potential, is equal to the voltage drop (V_s) across the standard resistor. Thus, the difference between V_c and V is equal to the voltage drop (V_x) across the unknown resistance. Using Ohm's law, the current (I) through the resistances is calculated as $I = V_s/R_s$. Knowing this current and the voltage drop across the paper sample, the resistance of the paper specimen is calculated as $R_x = V_x/I$.

D.C. VOLTMETER

Originally, a vacuum-tube voltmeter employing a 6F5 (as placed on the market by General Electric) was to be used for measurement of the d.c. resistance; however, failure of the tube and the impossibility of replacing the tube made conversion to another tube necessary. Tatel, Moncton, and Luhr (24) have described a voltmeter employing a pentagrid converter tube in a manner similar to that of the 6F5. This tube (1A6) was used in the modified circuit (Figure 3). The galvanometer was a Leeds and Northrup instrument (type R) having a current sensitivity of 10^{-10} ampere per mm.

PROCEDURE FOR MAKING D.C. RESISTANCE MEASUREMENTS

Before any measurements could be made, it was necessary to

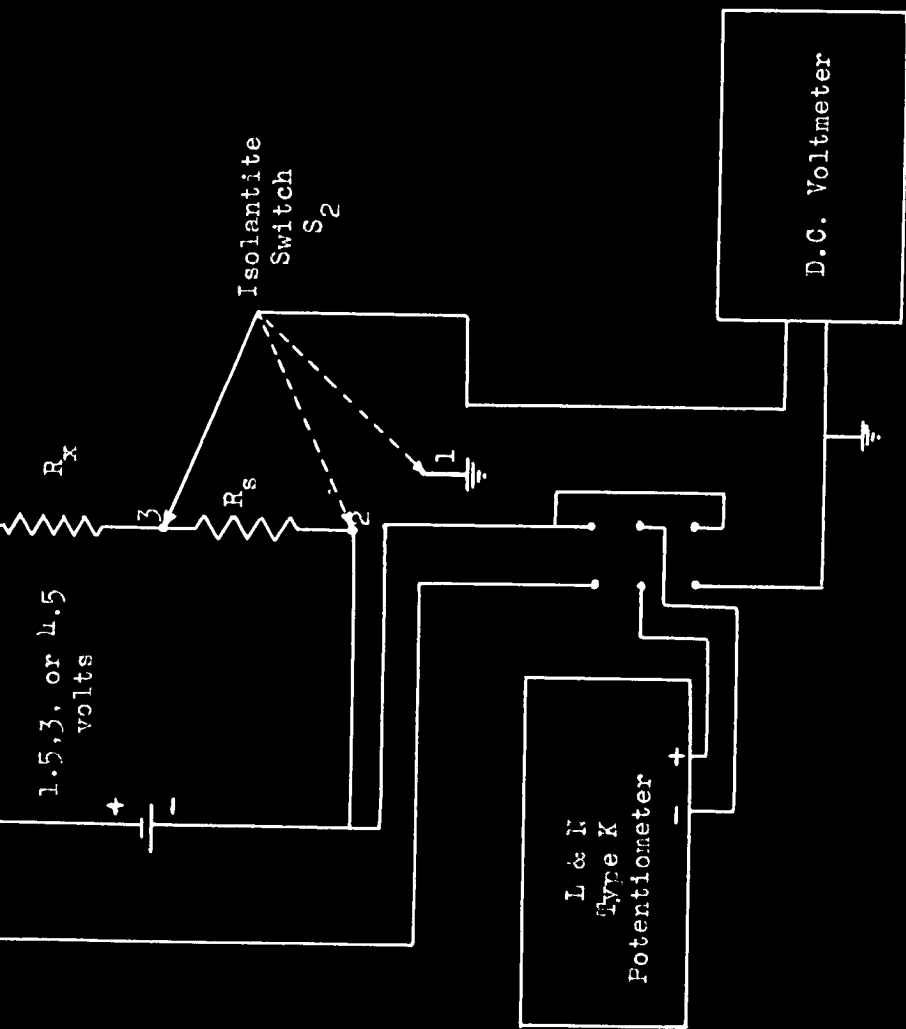
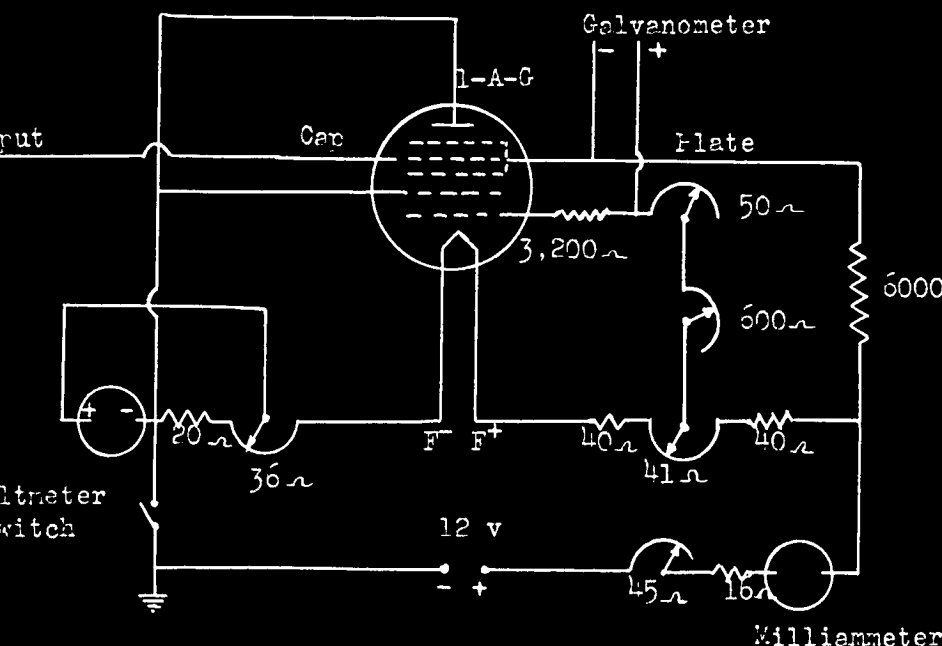


Figure 2

Schematic Representation of Setup
Used for Measuring D.C. Resistance

Figure 3

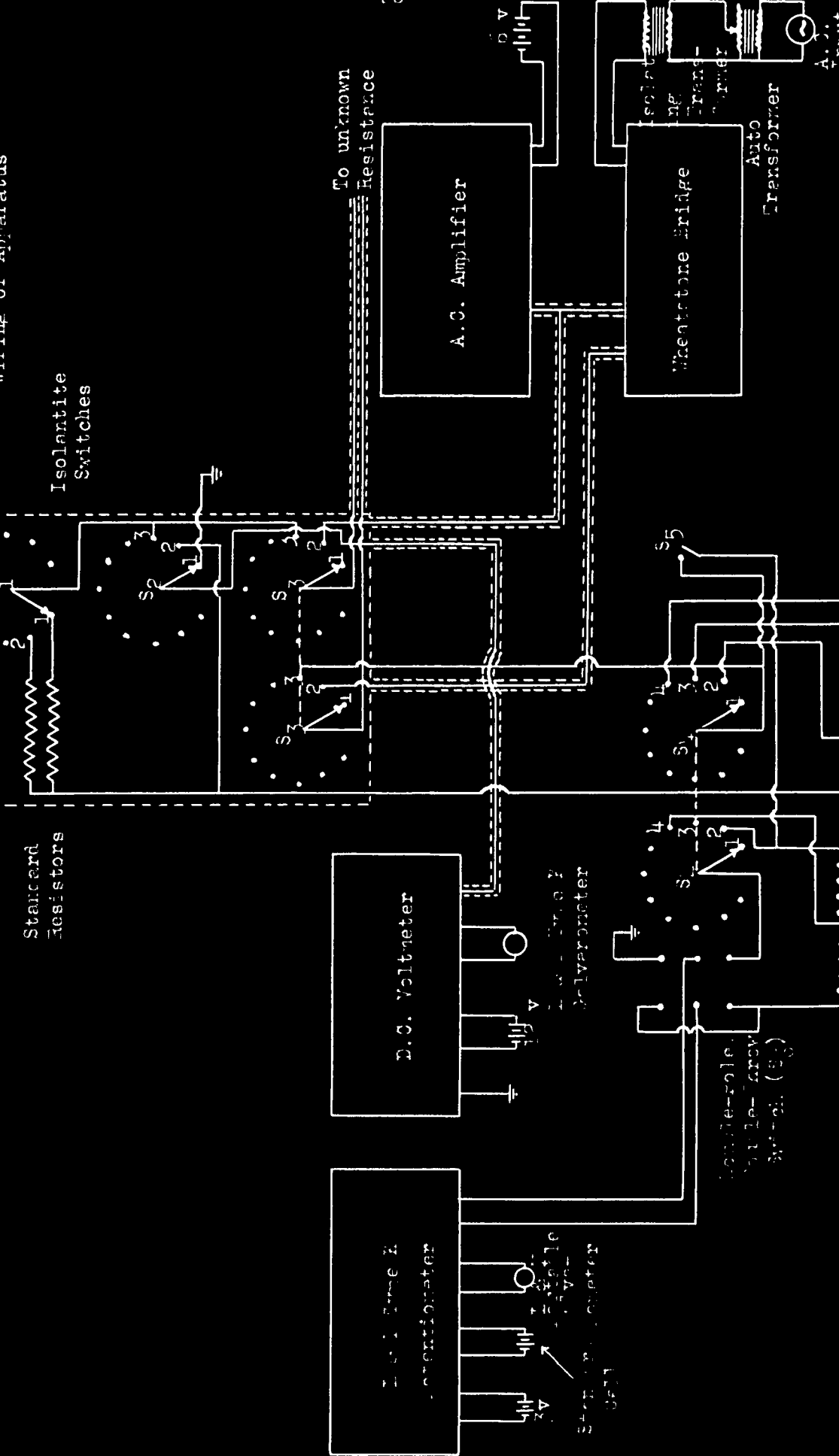
Wiring of D.C. Voltmeter



allow the voltmeter to warm up for a half an hour or more. In most cases the instrument was operated continuously, because little current was drawn from the storage batteries used for the filament supply.

The experimental procedure was the following, reference being made to Figure 4:

1. The desired voltage was applied across the sample and the standard resistor (Switch S_3 in position 3; S_4 in position 2, 3, or 4 depending upon the voltage desired).
2. The potentiometer was standardized against a standard cell.
3. With the control grid grounded (S_2 in position 1), the space grid potential was adjusted by changing the variable resistances in the space grid circuit to the value where variation of the effective supply voltage caused the galvanometer deflection to pass through a minimum. The plate supply voltage was then adjusted to the point just to one side of the minimum. The side of the minimum was chosen so that, when the instrument drifted, the drift was in the direction of the minimum.
4. With the control grid still grounded (S_2 in position 1), the potential of the space grid was adjusted with the variable low resistance in its circuit until the galvanometer showed no deflection.
5. The control grid was contacted at the point between the standard resistor and the unknown resistance (S_2 in position 3; S_6 was thrown up), and the counter e.m.f. supplied by the type K potentiometer was adjusted until the deflection of the galvanometer was again zero. The standard resistor used in the measurement was of the



same order of magnitude as the unknown resistance and was selected by the setting of \underline{S}_1 .

Because of the change in the resistance of the specimen with time, the value of the counter e.m.f. was taken exactly 5 minutes after the potential had been applied to the specimen.

6. Finally, the potential applied to the standard resistor and sample was measured by contacting the potentiometer across the battery, closing \underline{S}_5 , and balancing with the potentiometer.

CALIBRATION OF D.C. STANDARD RESISTORS

A precision 1-megohm resistor was placed in the position normally occupied by the unknown sample. The above-described procedure was followed, and the values of the two standard resistors used was calculated from the formula

$$\underline{R}_s = 10^6 \left(\frac{\underline{V}_s}{\underline{V} - \underline{V}_s} \right),$$

where \underline{R}_s equals the resistance of the standard resistor, \underline{V}_s equals the counter e.m.f., and \underline{V} equals the voltage applied across the standard resistor and the precision resistor. The values found for the two standard resistors were 1.06×10^6 and 0.228×10^9 ohms.

A.C. RESISTANCE

The Wheatstone bridge method of measuring ordinary resistances is one of the most common and convenient procedures used at present. A schematic sketch of such a bridge is shown in Figure 5.

WHEATSTONE BRIDGE

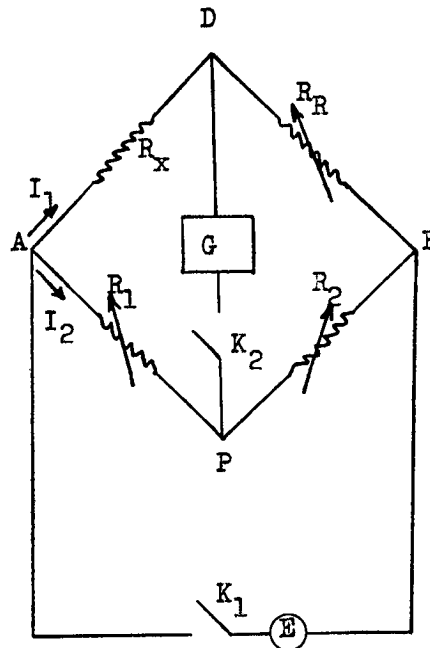


Figure 5

When the circuit is completed by closing the key K_1 , a current from a source of potential (E) divides at A ; part of it (I_1) flows through the circuit ADB and the other part (I_2) flows through APB . If R_X is the unknown resistance and the other three are known and adjustable, and are set so that no current flows through the galvanometer when the Key K_2 is closed, the points D and P are at the same potential. Under these conditions, the potential drop from A to D is equal to that from A to P , and that from D to B is equal to that from P to B . Therefore,

$$I_2 R_1 = I_1 R_X \text{ and}$$

$$I_2 R_2 = I_1 R_R$$

Dividing the first equation by the second,

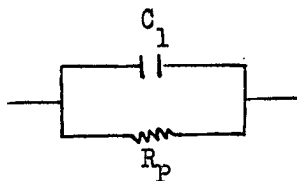
$$\underline{R_1}/\underline{R_2} = \underline{R_x}/\underline{R_R},$$

or

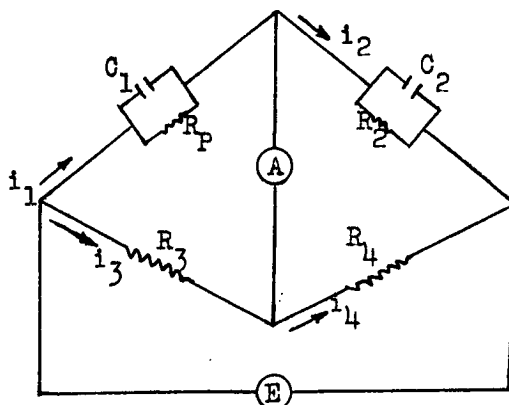
$$\underline{R_x} = \underline{R_1 R_R} / \underline{R_2}.$$

Many Wheatstone bridges, including the one used in this study, do not have three known variable resistances for measuring the unknown resistance. The bottom half of the bridge ($\underline{R_1}$ and $\underline{R_2}$) may consist of a uniform slide wire resistance and a sliding contact, which is connected to the detector. By changing the position of this contact, the ratio of $\underline{R_1}$ to $\underline{R_2}$ can be varied. The third resistance, however, must be known and, in cases where the range of resistances to be measured is large, a number of resistances of known values, depending upon the range through which the ratio of $\underline{R_1}$ to $\underline{R_2}$ can be varied, must be available.

The above discussion applies when d.c. voltages are used and does not represent a true picture of the actual circumstances involved in this work, i.e., a.c. operation. A more accurate picture may be obtained if the electrode-paper system is considered a "leaky" condenser. If the paper has an appreciable conductivity, such a condenser can be represented to a first approximation by a perfect condenser $\underline{C_1}$ and a parallel resistance $\underline{R_P}$.



A bridge capable of measuring the true resistance of the sample in the above system would be similar to the one used in this study, with one exception. Capacitances of the same order of magnitude as that of the paper-electrode system would have to be connected across the reference resistors. The balancing of this bridge would involve not only balancing the resistances but also an adjustment of the capacitance across the reference resistances to the point where the voltage and the current were in phase. This balance would be indicated by a minimum signal to the detector.



A.C. BRIDGE
Figure 6

At balance, it may be seen by application of Kirchhoff's laws that

$$Z_1 i_1 = Z_3 i_3$$

and

$$Z_2 i_2 = Z_4 i_4.$$

Because $i_1 = i_2$ and $i_3 = i_4$, $Z_1/Z_2 = Z_3/Z_4$ when the second equation above is divided into the first.

Actually, the impedances \underline{Z}_3 and \underline{Z}_4 are resistances and may be represented by \underline{R}_3 and \underline{R}_4 , respectively. The impedances \underline{Z}_1 and \underline{Z}_2 cannot be represented quite as simply. They are each made up of a capacitance and a resistance in parallel, and may be expressed by the complex equations for the admittances

$$\underline{Y}_1 = 1/\underline{Z}_1 = 1/\underline{R}_1 + j2\pi f \underline{C}_1 \quad (1)$$

and

$$\underline{Y}_2 = 1/\underline{Z}_2 = 1/\underline{R}_2 + j2\pi f \underline{C}_2, \quad (2)$$

where $1/\underline{R}$ is the conductance of the resistances and $2\pi f \underline{C}$ is the susceptance of the capacitances. Dividing Equation (2) by (1) gives

$$\underline{R}_2/\underline{R}_1 = \underline{C}_2/\underline{C}_1 = \underline{R}_3/\underline{R}_4,$$

because equality of complex quantities implies the equality of both real and imaginary parts.

If the balancing capacitance (Figure 6, \underline{C}_2) is omitted and the circuit shown in Figure 7 is used, the true resistance of the specimen is not measured. In such a case, the value measured is the impedance (see above paragraph)

$$\underline{Z}_1 = \underline{R}_p / [1 + (2\pi f \underline{C}_1 \underline{R}_p)^2] \quad (3)$$

This impedance will not differ materially from the resistance, \underline{R}_p , as long as \underline{R}_p is small compared with the reactance, $1/2\pi f \underline{C}_1$, of the capacitance of the electrodes.

In this study the balancing capacitance was omitted; thus, an error was introduced into all a.c. measurements. However, this error was negligible, according to the following calculation. Assume that it is permissible to make a 10 per cent error in measuring \underline{R}_p --i.e.,

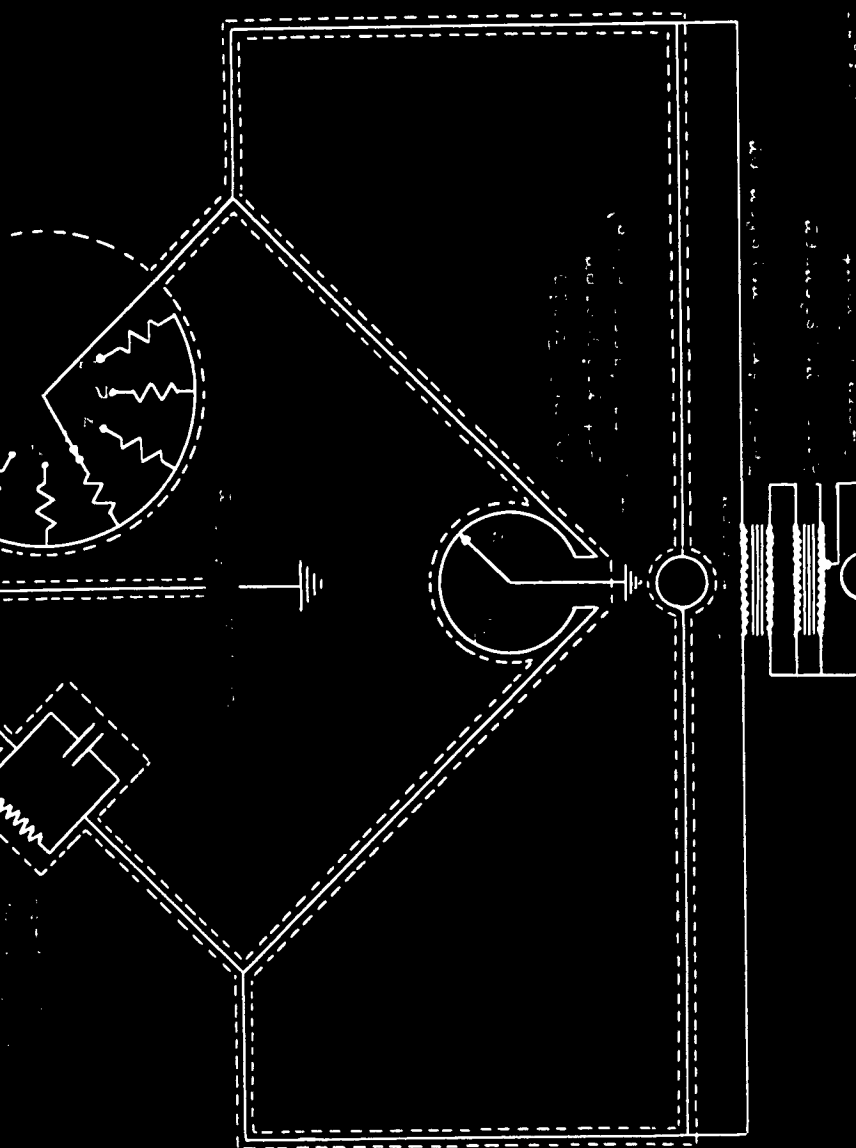
that the measured impedance may be only $0.9 R_p$. Using 1.50 cm. as the diameter of the condenser, assuming a dielectric constant of three for paper, and using the caliper of the thinnest sheet (0.0093 cm.) as the plate separation, the capacitance for 60-cycle current is

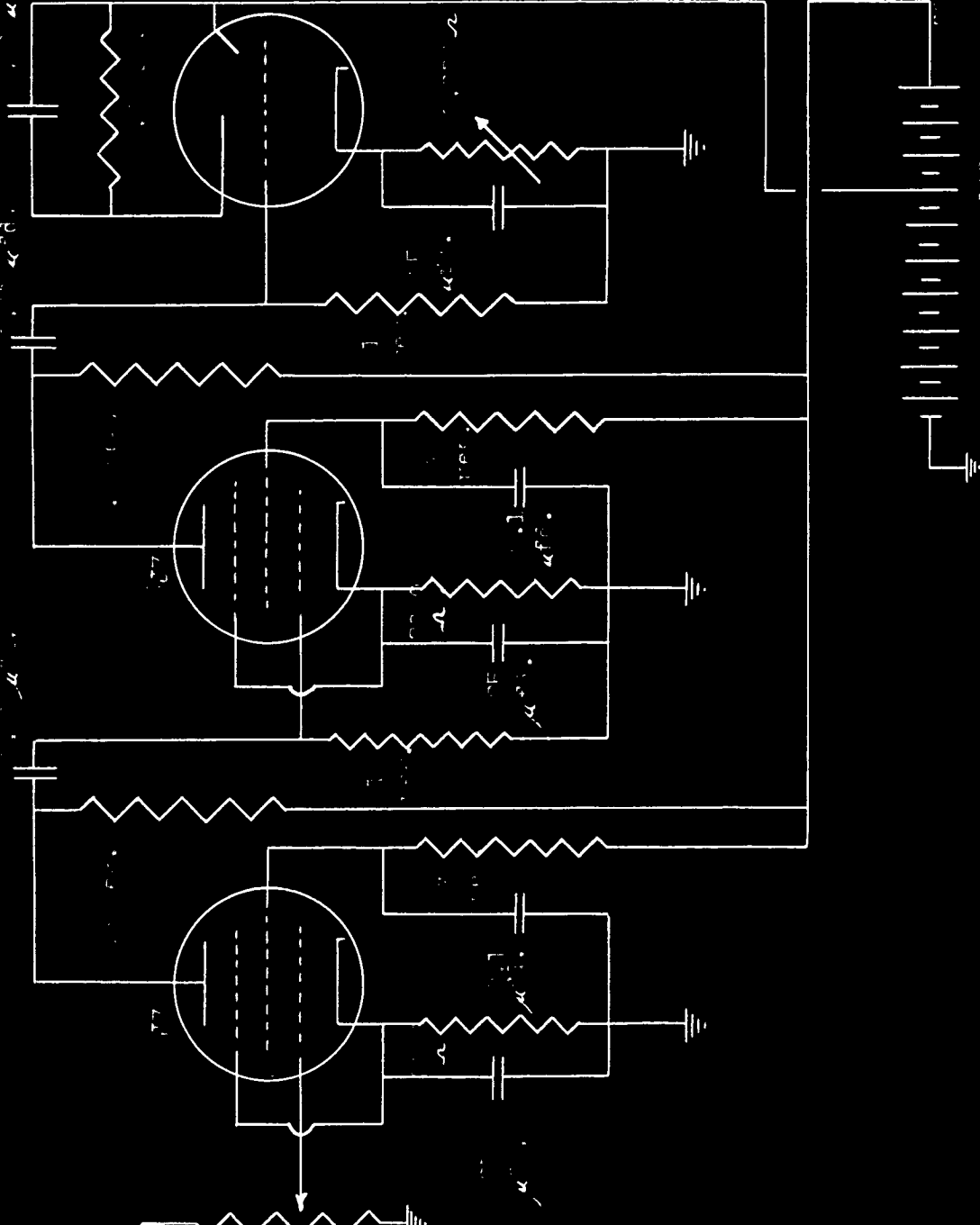
$$C = \frac{0.0885 \pi (0.75)^2 (3)}{0.0093} = 50.5 \mu\text{fd.}$$

Since the allowable error is 10 per cent, $0.9 R_p = Z_1$. Substituting in Equation (3) and solving, $R_p = 3.39 \times 10^7$ ohms and $Z_1 = 3.83 \times 10^7$ ohms. This calculation indicates that a capacitance correction was not necessary in this study, because all of the resistances measured were low in comparison with the calculated maximum measurable impedance, which would be within 10 per cent of the true resistance.

The bridge used in this study is schematically represented in Figure 7. A two-stage amplifier (Figure 8) was used to detect the balance of the bridge. The output of the second stage of the amplifier operated an electron eye tube, which remained closed when there was no signal to the input of the amplifier. Later the signal from the second stage was carried to an oscilloscope, which indicated the balance by a minimum amplitude in the wave form.

Because high resistances were to be measured by the bridge, extreme insulation precautions had to be undertaken. In order that the measurement of the resistances might be successfully carried out, all leads on the upper half of the bridge were of the bus bar type shielded by grounded copper pipe. The occasional supports necessary to prevent shorting of the wire and pipe were polystyrene disks. The leads on the lower half of the bridge were made with highly insulated, shielded,





microphone cable in which the shield was grounded. Further precautions against pickup from stray electrical fields were taken by covering all reference resistors, power supply leads, and the General Radio potentiometer rheostat with grounded metal shields. Because danger of leakage resistances had to be eliminated, the switch used in the instrument for the reference resistances was of the single-gang, multiple-pole, Isolantite type.

The unknown resistance was roughly balanced, in the upper part of the bridge, by selecting a reference resistance of the same order of magnitude. These reference resistors covered a range from 10^4 to 10^9 ohms. The lower part of the bridge consisted of a General Radio potentiometer rheostat (type 471). This potentiometer had a dial equipped with a vernier and, by reference to the calibration curve of the potentiometer or slide wire, the ratio of R_1 to R_2 for any dial reading could be obtained.

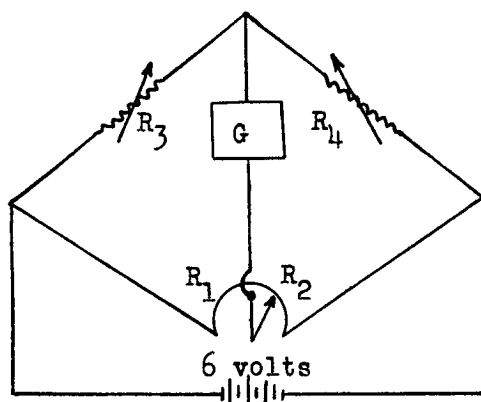
For most measurements, voltage was applied to the bridge through an isolating transformer. This transformer, in turn, was supplied by an autotransformer (Variac) operated from the 110-volt supply. When frequency studies were made, the voltage from the variable frequency motor-generator was supplied to the bridge through a voltage divider.

The detector used with the bridge was a two-stage amplifier employing 6J7 tubes. Each stage was shielded from the other, and the filament current was supplied by a 6-volt storage battery to eliminate the possibility of 60-cycle pickup. The amplifier operated a 6E5

electron-ray tube or an oscilloscope. The entire amplifier, as well as the plate supply batteries, was mounted in a metal chassis.

CALIBRATION OF A.C. BRIDGE SLIDEWIRE

In order to calibrate the General Radio type 471 potentiometer rheostat used as the slide wire in the a.c. bridge, another Wheatstone bridge was set up employing two Leeds and Northrup (0-999 ohms) standard resistance boxes in the upper arms of the bridge and the potentiometer as the lower arm of the bridge. A Leeds and Northrup portable galvanometer was used for detecting the balance point, and 6 volts were employed for the power supply. By variation of the two standard resistance boxes, it was possible to obtain the ratio of the resistance of one side of the potentiometer to the other at various settings of the dial. Figure 9 shows the calibration curve for the slide wire, and Table I presents the data.



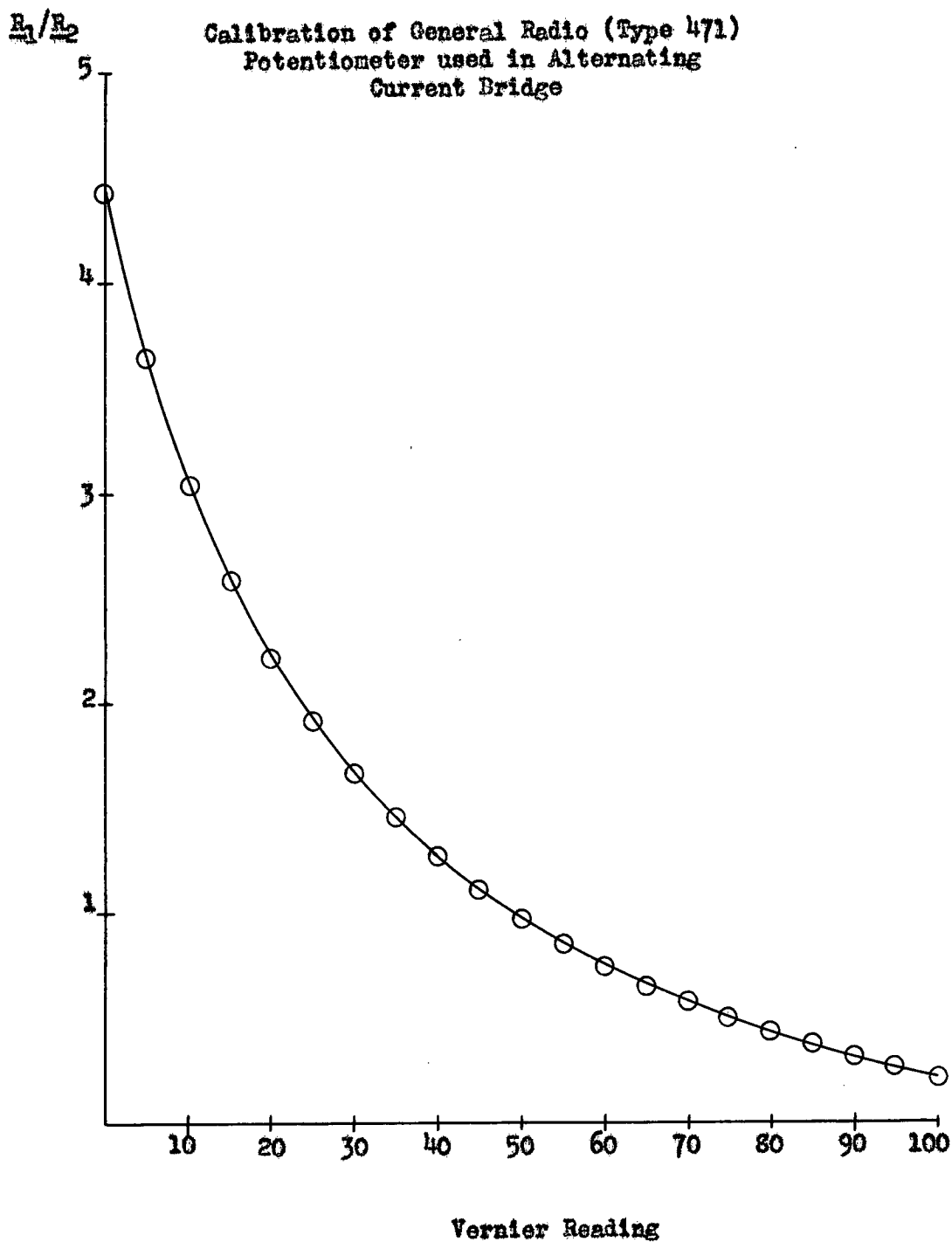
R_3 and R_4 Leeds and Northrup (0-999 ohms) standard resistance boxes
 G Leeds and Northrup portable Galvanometer
 R_1 and R_2 1000-ohm, type 471 General Radio potentiometer rheostat

TABLE I

CALIBRATION OF GENERAL RADIO (TYPE 471) POTENTIOMETER USED IN
ALTERNATING CURRENT BRIDGE

Vernier Reading	R_3 ohms	R_4 ohms	R_1/R_2
100	200	880.2	0.2272
95	200	733.9	0.2725
90	200	609.5	0.3283
85	300	781.1	0.3841
80	300	675.65	0.4440
75	400	779.2	0.5133
70	400	683.5	0.5852
65	400	593.57	0.6739
60	400	521.0	0.7678
55	500	572.8	0.8729
50	500	502.6	0.9948
45	500	442.4	1.1302
40	500	389.2	1.2847
35	500	340.6	1.4680
30	700	418.3	1.6734
25	700	367.25	1.9061
20	700	317.95	2.2016
15	700	273.05	2.5636
10	800	266.3	3.0041
5	800	318.7	3.6580
0	800	180.2	4.4395

Figure 9



CALIBRATION OF A.C. REFERENCE RESISTANCES OF BRIDGE

A known resistance of suitable value was placed in the position normally occupied by the unknown resistance (Figure 4 or 5). One of the reference resistances was connected, and the bridge was balanced by adjustment of the slide wire. The slide wire ratio determined from previous calibration of the slide wire was divided into the value of the known resistance to obtain the value of the reference resistance. In cases of high values of the reference resistances, it was necessary to place a correspondingly high resistance in the position of the unknown resistance and calibrate this resistance against one of the lower reference resistances. Then, the next higher reference resistance was calibrated against the resistance in the unknown position. Table II presents these calibration data.

PROCEDURE FOR MAKING A.C. MEASUREMENTS

This measurement was quite simple. Reference is again made to Figure 4. After the electrodes were placed in position, switch S_3 was placed in position 2, the slide wire was set in the middle of the scale, and the supply voltage was adjusted. The reference resistance which gave the minimum signal to the eye tube or the oscilloscope was selected, and the final adjustment to a minimum signal was made with the slide wire.

The resistance of the sample was then calculated by noting the slide wire ratio corresponding to the vernier reading and multiplying this value by the value of the reference resistance. The

TABLE II

CALIBRATION OF REFERENCE RESISTANCES IN ALTERNATING CURRENT BRIDGE

Switch Position	Calibrating Resistance ohms	Vernier Reading	R_1/R_2	Reference Resistance ohms
1	9.220×10^3	51.6	0.953	9.680×10^3
2	1.500×10^5	35.0	1.470	1.020×10^5
3	1.000×10^6	54.6	0.885	1.130×10^6
4	1.500×10^7	37.0	1.400	1.070×10^7
5	1.500×10^7	90.8	0.320	4.690×10^7
6	1.263×10^8	55.0	0.873	1.445×10^8
7	1.263×10^8	96.0	0.264	4.780×10^8
8	1.350×10^9	37.3	1.390	0.972×10^9
9	1.350×10^9	42.0	1.223	1.102×10^9

voltage supply to the bridge was controlled by the Variac. In cases where the frequency was varied, the voltage was controlled by a voltage divider and the frequency controlled by the speed of the motor driving the variable frequency generator. The speed of this motor was measured with a Strobotac and was controlled by variation of the position of the brushes on the commutator of the motor.

WIRING OF APPARATUS

The actual wiring of the complete apparatus for d.c. and a.c. measurements is shown in Figure 4, and only the more important points will be discussed in this section. The leads to both electrodes were introduced through the floor of the testing cabinet. The lead from the electrode to the standard resistances in the case of the d.c. measurements and to the reference resistances in the case of the a.c. measurements was carried in a grounded copper pipe. The supports necessary to prevent shorting of the wire inside the pipe were polystyrene disks. The lead from S_2 to the grid of the d.c. voltmeter was the only other lead shielded in this manner. The other shielded leads used in the apparatus were highly insulated, shielded, microphone cable. For further protection against leakage, switches S_1 , S_2 , and S_3 were insulated with Isolantite.

By use of a double-pole, double-throw knife switch (S_6), the type K potentiometer could be used to supply the counter e.m.f. and also to measure the applied voltage in the d.c. circuit. This potentiometer could not be used to measure voltages greater than 1.6 volts.

unless a greater supply voltage was supplied to it. To avoid this inconvenience, the voltage divider arrangement shown in Figure 4 was employed. At voltages greater than 1.6 volts, only a known fraction (0.231) of the actual voltage was measured.

PREPARATION OF STOCK

During the preliminary investigations and the consideration of variables which might influence the resistance of paper, certain precautions in making measurements became necessary. Because the phenomenon of conduction may be electronic, ionic, or both, the presence of electrolytes in the test specimens must be eliminated or the test specimens should be prepared in such a manner that the electrolyte content is uniform and constant; otherwise, the effects of variable electrolyte content might mask the effects of changes in the other variables under study. Initially, efforts were made to eliminate the electrolytes from the pulp before the preparation of test samples, by the use of acid extraction, by dialysis, and finally by means of electrodialysis, but they met with little success. On the basis of the experimental work and reports in the literature (39, 40), it was concluded that it would be difficult to eliminate electrolytes completely and, hence, it was decided to use test specimens which had a uniform and controlled ash content. To achieve this aim, all pulp was subjected to a prolonged extraction with a definite volume and concentration of calcium chloride solution, and the test sheets were prepared under identical conditions each time.

All samples were stirred continuously for 24 hours with 100

times their weight of 0.5-molar calcium chloride. This suspension of pulp in 0.5-molar calcium chloride constituted the stock used in sheet-making.

In one series of experiments the starting pulp (unbleached western hemlock sulfite) was chlorinated, bleached, and treated with caustic to prepare an alpha pulp. Samples were withheld at each stage and converted into test specimens to determine the effect of chemical treatment upon the resistance of paper.

The procedures used in the chemical treatment of the pulp were as follows. Eight hundred grams of unbleached sulfite (permanganate number of 11) at 3.5 per cent final consistency and 80° F. were treated with 22 grams of chlorine (dissolved in water) to practical exhaustion of the chlorine. The stock was then washed with cold water, pressed, broken up, and stored.

Five hundred grams of this chlorinated stock at 5 per cent consistency and 100° F. were treated with 1.5 per cent chlorine in the form of bleach liquor to practical exhaustion of the chlorine. The resulting stock was thoroughly washed with water, pressed, broken up, and stored.

The final chemical treatment consisted in the preparation of an alpha-cellulose from a portion of the above bleached pulp. Institute method 421 (41) was used for the preparation of the pulp.

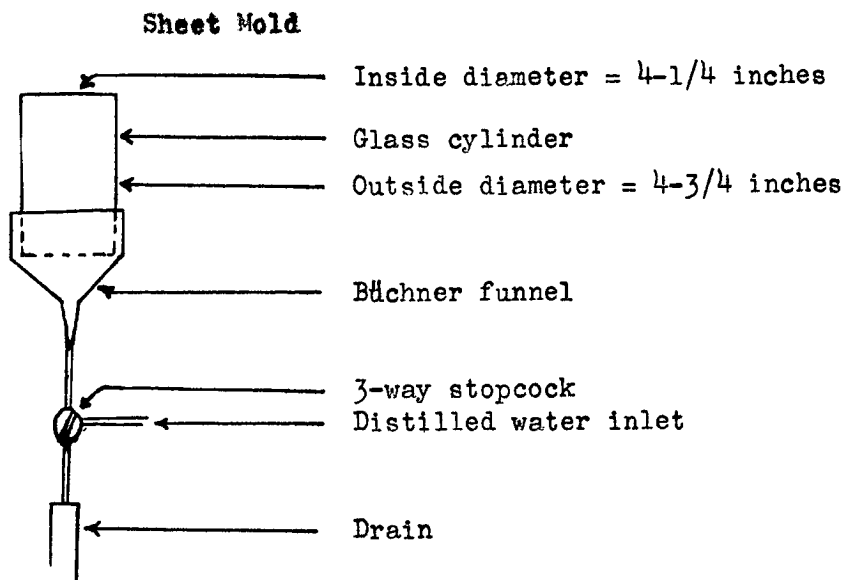
SHEET MOLD USED FOR THE PREPARATION OF TEST SPECIMENS

The procedure for the preparation of sheets was basically the same as that specified in TAPPI Standard T 205 m-40 (42). However, since the dimensions and construction of the sheet mold used were different from those of the British mold, certain deviations from the accepted procedure were necessary.

The sheet mold consisted of a glass cylinder $4\frac{3}{4}$ inches in diameter prepared by cutting both ends off a reagent bottle, a Büchner funnel into which the cylinder fitted, some rubber tubing, a 3-way stopcock, and a wooden box which supported the entire setup. The area of the sheet was 14.2 square inches, and a 0.56-gram sheet corresponded to the standard 1.2-gram sheet of the TAPPI Standard. The glass cylinder was ground flat on one end and was held against a rubber gasket (made of light rubber tubing which was cemented to the Büchner funnel) by heavy rubber bands, thus securing a watertight seal.

The required amount of stock was poured into the cylinder, and distilled water was introduced through the stopcock to fill the cylinder to within $1/2$ inch of the top. During the study of the dependence of resistance upon caliper, 0.5-molar calcium chloride rather than distilled water was used to fill the cylinder. The stock was stirred in the manner specified, and the water or calcium chloride solution was drained off. The sheet was formed on a 150-mesh wire, which was held flat by spot soldering at its periphery to a heavier backing wire.

After the sheet was formed, the cylinder was removed and the wire, which rested inside the rubber gasket, was taken out and placed on a blotter. Two more blotters were placed on the sheet, which was couched from the wire in the manner specified by the TAPPI Standard. The pressing of the sheets was carried out in the usual manner.



Upon completion of the pressing, the paper sample remained fixed to the chromium disk; however, because the sheet was of a smaller diameter than the disk it could not be dried in the usual manner. To accomplish this, the disk and sample were placed on a board and a metal ring having an inside diameter of 3-1/4 inches was placed on the paper. The metal ring was held firmly against the sample and disk by a thin strip of wood which, in turn, was held to the board with carriage bolts and wing nuts. All samples were air dried and then conditioned in the testing cabinet for at least 24 hours before testing.

EXPERIMENTAL WORK

The first step in making resistance measurements of a heterogeneous material (such as paper) is the construction of an electrode system which will furnish results reproducibly and accurately. It was decided that it would be desirable, first, to investigate the dependence of the resistance upon the area of the electrodes in contact with the test specimen; second, to make a study of the pressure of the electrode; and, finally, to study different types of electrodes. Upon the basis of the above studies, the electrode system used for subsequent measurements would be selected.

In all tests using a stainless steel electrode system, the bottom electrode was a sheet of stainless steel insulated from the grounded shield by a flat piece of polystyrene, and the top electrode was a disk of the metal of the desired diameter. The electrode area was varied in three steps by successively using upper electrodes of three different areas. In the actual measurements, it was necessary to make certain that the pressure of the various electrodes was known and controlled; otherwise, the results could not be compared.

Irregularities in the caliper of the test specimen might cause variations in the results obtained. The following steps were taken to eliminate this factor when measurements were made with electrodes of different areas. The specimens were first calipered, and an area of each specimen having constant thickness was marked. During

the resistance measurements, care was taken to place the electrodes within the designated area. Table III shows the results of the resistance measurements on handsheets of unbleached sulfite pulp. In further tests (Tables IV and V), a machine-made rag drawing paper of uniform caliper was used. A third series of tests was carried out with an analytical grade of filter paper. This paper was not only uniform in caliper but also had a very low ash content, which would tend to minimize variations that might be caused by changes in ash content over the surface of the sheet. These results (Table V) show the least dependence of the specific resistance upon the electrode area.

A further variable which had to be considered, not only in the above but in all measurements, was that resulting from the mechanical operation of placing the load upon the various electrodes. It was found, during preliminary tests, that variations in the measured resistance resulted if the load was not placed on the electrode in such a manner that the center of gravity of the added weights was over the center of the electrode. Thereafter, care was taken to load the electrodes symmetrically.

To study the effect of electrode pressure, different loads were placed on the top electrode so as to vary the pressure from 0.1 to 0.7 kg./sq. cm. Tables III and V present results for three different electrode areas. The data in Tables IV and VI are for an electrode with a diameter of 1.5 cm. The samples were unbleached sulfite, 100 per cent rag drawing paper, and Genuine Whatman filter paper No. 42. The most uniform results were found with the rag drawing paper

TABLE III

VARIATION OF RESISTANCE WITH ELECTRODES OF DIFFERENT AREAS AND
DIFFERENT LOADS PER UNIT AREA

Sample, 100% unbleached sulfite
Humidity at which samples were conditioned, 85%
Caliper of test samples, 0.0042 inch
Voltage applied across a.c. bridge, 110 volts
Temperature at which test was carried out, 30° C.

Direct Current Resistance

Weight g.	Wt./Unit Area kg./cm. ²	Voltage Applied volts	V_s volts	R_s ohms	R_x ohms	Specific Resistance ohms-cm.
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Electrode specifications:

Diameter, 1.5 cm.

Area, 1.765 sq. cm.

176	0.1	1.593	0.138	1.059×10^6	11.16×10^6	18.48×10^8
352	0.2	1.594	0.109	1.059	14.49	23.80
458	0.3	1.593	0.107	1.059	15.40	25.50
705	0.4	1.592	0.218	1.059	6.66	10.85
882	0.5	1.594	0.183	1.059	8.17	13.50
1058	0.6	1.594	0.300	1.059	4.59	7.60
1235	0.7	1.594	0.260	1.059	5.97	9.88

Electrode specifications:

Diameter, 2.54 cm.

Area, 5.07 sq. cm.

507	0.1	1.594	0.426	1.059×10^6	2.97×10^6	14.10×10^8
1014	0.2	1.594	0.612	1.059	1.70	8.07
1521	0.3	1.594	0.604	1.059	1.73	8.24
2028	0.4	1.595	0.553	1.059	1.99	8.54
2535	0.5	1.594	0.627	1.059	1.63	7.74
3042	0.6	1.594	0.601	1.059	1.75	8.31
3549	0.7	1.595	0.610	1.059	1.70	8.07

Electrode specifications:

Diameter, 3.076 cm.

Area, 7.44 sq. cm.

744	0.1	1.593	0.330	1.059×10^6	4.05×10^6	28.20×10^8
1488	0.2	1.594	0.245	1.059	5.82	40.50
2232	0.3	1.594	0.462	1.059	2.59	18.00
2976	0.4	1.594	0.185	1.059	6.34	44.20
3720	0.5	1.594	0.700	1.059	1.35	9.42
4464	0.6	1.594	0.683	1.059	1.41	9.82
5208	0.7	1.594	0.652	1.059	1.52	10.60

TABLE III (Cont.)

Alternating Current Resistance

Weight g.	Wt./Unit Area kg./cm. ²	Reference Resistance ohms	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
Electrode specifications: Diameter, 1.5 cm. Area, 1.765 sq. cm.						
176	0.1	1.13x10 ⁵	63.5	0.70	0.791x10 ⁶	13.08x10 ⁷
352	0.2	1.13	64.0	0.69	0.780	12.88
458	0.3	1.13	60.0	0.77	0.870	14.37
705	0.4	1.13	82.5	0.41	0.463	7.66
882	0.5	1.13	85.0	0.38	0.429	7.10
1058	0.6	1.02x10 ⁵	12.0	2.82	0.288	4.77
1235	0.7	1.02	19.5	2.24	0.199	3.29

Electrode specifications: Diameter, 2.54 cm. Area, 5.07 sq. cm.						
507	0.1	1.02x10 ⁵	32	1.59	1.62x10 ⁵	7.70x10 ⁷
1014	0.2	1.02	51	0.97	0.990	4.70
1521	0.3	1.02	63	0.71	0.725	3.44
2028	0.4	1.02	60	0.77	0.785	3.72
2535	0.5	1.02	73	0.54	0.551	2.64
3042	0.6	1.02	65	0.67	0.683	3.24
3549	0.7	1.02	70	0.58	0.591	2.81

Electrode specifications: Diameter, 3.076 cm. Area, 7.44 sq. cm.						
744	0.1	1.02x10 ⁵	23	2.02	2.06x10 ⁵	14.32x10 ⁷
1488	0.2	1.02	30	1.67	1.704	11.87
2232	0.3	1.02	50	1.00	1.020	7.12
2976	0.4	1.02	28	1.77	1.805	12.56
3720	0.5	1.02	53	0.72	0.735	5.11
4464	0.6	1.02	69	0.60	0.612	4.26
5208	0.7	1.02	68	0.62	0.633	4.41

TABLE IV

RESISTANCE AS A FUNCTION OF CHANGING WEIGHT OF ELECTRODE
PER UNIT AREA

Sample, 100% rag drawing paper
Humidity at which samples were conditioned, 85%
Caliper of test samples, 0.0047 inch
Voltage applied across a.c. bridge, 110 volts
Temperature at which test was carried out, 30° C.
Electrode specifications:
Diameter, 1.5 cm.
Area, 1.765 sq. cm.

Direct Current Resistance

Weight g.	Wt./Unit Area kg./cm. ²	Voltage Applied volts	V_x volts	$\frac{R_x}{R_0}$ ohms	$\frac{R_x}{R_0}$ ohms	Specific Resistance ohms-cm.
176	0.1	1.593	0.092	1.059×10^6	1.771×10^7	2.62×10^8
352	0.2	1.593	0.101	1.059	1.573	2.33
458	0.3	1.550	0.081	1.059	1.916	2.84
705	0.4	1.550	0.113	1.059	1.340	1.984
882	0.5	1.550	0.129	1.059	1.180	1.748
1058	0.6	1.550	0.144	1.059	1.158	1.715
1235	0.7	1.550	0.165	1.059	0.888	1.312

Alternating Current Resistance

Weight g.	Wt./Unit Area kg./cm. ²	Reference Resistance ohms	Vernier Reading	$\frac{R_1}{R_2}$	$\frac{R_x}{R_0}$ ohms	Specific Resistance ohms-cm.
176	0.1	1.13×10^6	54.0	0.90	1.018×10^6	15.08×10^7
352	0.2	1.13	59.5	0.78	0.781	11.55
458	0.3	1.13	66.0	0.65	0.735	10.87
705	0.4	1.13	91.0	0.32	0.362	5.36
882	0.5	1.02×10^5	7.0	3.40	0.347	5.14
1058	0.6	1.02	12.5	2.28	0.284	4.21
1235	0.7	1.02	18.5	2.31	0.236	3.50

TABLE V

VARIATION OF RESISTANCE WITH ELECTRODES OF DIFFERENT AREAS

Sample, 100% rag drawing paper
 Humidity at which samples were conditioned, 77%
 Caliper of test samples, 0.463 inch
 Voltage applied across a.c. bridge, 110 volts
 Weight of electrode per unit area, 0.6 kg./sq. cm.
 Temperature at which tests were carried out, 30° C.

Electrode	1	2	3
Electrode diameter, cm.	1.5	2.54	3.076
Electrode area, sq. cm.	1.765	5.07	7.04
Direct current resistance			
V , volts	1.593	1.593	1.594
V_s , volts	0.054	0.114	0.100
R_s , ohms	1.059×10^6	1.059×10^6	1.059×10^6
R_x , ohms	3.04×10^7	1.39×10^7	1.58×10^7
Specific resistance, ohms-cm.	4.57×10^9	6.00×10^9	10.0×10^9
Alternating current resistance			
Reference resistance, ohms	1.02×10^7	1.13×10^6	1.13×10^6
Vernier reading	92.0	71.2	72.4
R_1/R_2	0.31	0.57	0.55
R_x , ohms	0.316×10^7	0.644×10^6	0.622×10^6
Specific resistance, ohms-cm.	4.75×10^8	2.78×10^8	3.90×10^8

TABLE V (Cont.)

Sample, Genuine Whatman Filter paper No. 42
 Humidity at which samples were conditioned, 52%
 Caliper of test samples, 0.0046 inch
 Voltage applied across a.c. bridge, 110 volts
 Weight of electrode per unit area, 0.0158 kg./sq. cm.
 Temperature at which tests were carried out, 30° C.

Electrode	2	3
Electrode diameter, cm.	2.54	3.076
Electrode area, sq. cm.	5.07	7.44
Direct current resistance		
V, volts	4.79	4.80
V _s , volts	0.414	0.646
R _s , ohms	0.228x10 ⁹	0.228x10 ⁹
R _x , ohms	2.236x10 ⁹	1.468x10 ⁹
Specific resistance, ohms-cm.	9.64x10 ¹¹	9.28x10 ¹¹
Alternating current resistance		
Reference resistance, ohms	4.69x10 ⁷	4.69x10 ⁷
Vernier reading	44.0	58.0
R ₁ /R ₂	1.165	0.81
R _x , ohms	5.47x10 ⁷	3.80x10 ⁷
Specific resistance, ohms-cm.	2.35x10 ⁹	2.40x10 ⁹

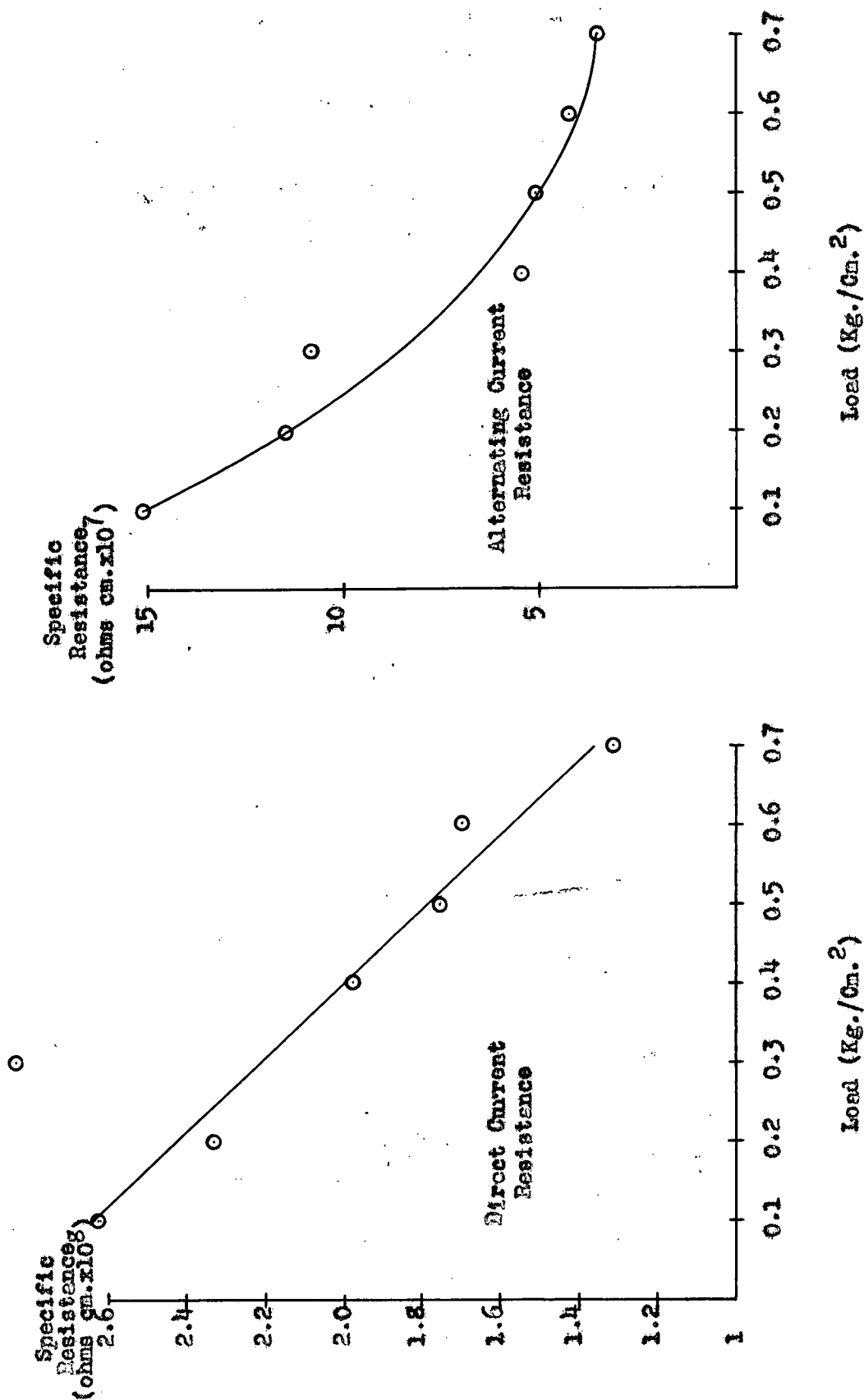
(Table IV); these are plotted in Figure 10.

From the data of Tables III, IV, and V, it is apparent that the resistance decreases with increasing load. This suggested that the contact resistance between the paper specimen and the electrodes was an important factor in the resistance measurements and also that the surface character of the specimen and the type of electrode would have an influence upon resistance. To study these effects and also to achieve the third aim stated in the first paragraph of this section, the mercury electrodes previously described were used for making resistance measurements. It was thought that such electrodes would form a more intimate contact with the surface of the test specimen and that the results obtained would be more independent of the surface character of the sheet. Resistance measurements were made on the same specimens with stainless steel electrodes of the same diameter and pressure, as well as with greater pressures. The results of these tests are given in Table VI.

While making measurements with the mercury electrodes, an unexpected difficulty arose which was not encountered when the stainless steel electrodes were used. It was found that a potential difference existed between the electrodes after the applied a.c.f. had been removed. In normal operation, the upper electrode was positive with respect to the lower. This residual potential difference had the same polarity. Such a potential difference could possibly have been formed when the copper leads were introduced into the mercury pools. However, when the leads were reversed, the potential was not

Figure 10

Specific Resistance As A Function Of Electrode Pressure



of the same magnitude but was in the same direction. It also varied from specimen to specimen. If this potential difference were due to the leads, the residual e.m.f. would be of opposite polarity and of the same magnitude when the leads were reversed and would be constant from specimen to specimen. Thus, the leads were not the source of the residual e.m.f. Another possible source of this potential difference could have been the mercury-paper-mercury system. Some type of reaction may have taken place between the mercury and the constituents of the paper. It was unlikely that the effect was due to polarization phenomena, for two reasons. In all measurements, the voltage across the specimen was less than 1.5 volts. It is not very probable that such a small voltage could cause the effect observed. Also, this small potential difference remained constant after the applied voltage had been removed, which would not be characteristic of a polarization potential. In the light of these observations, it appears as though the potential were due to some reaction between the mercury and paper.

Upon completion of the above work, the selection of an electrode system for subsequent measurements was in order. From the point of view of selecting an electrode which would furnish a more intimate contact with the paper and reduce the contact resistance the mercury electrodes would be most desirable. However, primarily because of the erratic residual e.m.f. and, secondarily, because of the difficulty of keeping the electrode in a perpendicular position on account of the buoyant effect of the mercury on the glass cylinder supporting the test specimen, the mercury system was not used.

A stainless steel electrode system was employed for several reasons. Since the electrodes were to be exposed to atmospheres of high relative humidities, it was necessary to use some material which would be resistant to corrosion. Further, the metal could be readily machined and polished. The diameter selected for the electrode was 1.5 cm., because the anvils of the instruments used for calipering paper have that diameter and such a diameter would cover enough of the area of the test specimen to give a fair approximation of the caliper of the sample and yet not cover enough of the area to include many of the irregularities in the sheet.

It can be seen in Tables III, IV, and VI that the most consistent and reproducible results were found when the load on the electrode per unit area was high. In Tables III and IV, the greatest changes in resistance with pressure occurred at the lowest loads per unit area, whereas at the higher loads the resistance tended to approach a lower limiting value. On the basis of this observation and the fact that the load per unit area on the anvil of caliper testers was in the range of the higher loads, it was decided to use a load of 0.6 kg./sq. cm. for the following tests.

While making the electrode area and load studies, the samples selected for testing were very uniform in caliper. It was considered desirable, upon completion of the above studies, to carry out an investigation of the effect of caliper upon the resistance of the paper sample. If the results showed that the specific resistance was independent of the caliper, they would indicate that paper behaved like a

homogeneous dielectric.

To carry out these tests, samples of varying caliper were prepared from 100 per cent unbleached sulfite. In making up the test samples, it was found necessary to use an aqueous solution of the same calcium chloride molarity as that employed for extraction of the pulp, because each sheet of a different caliper required a different volume of the stock suspension; consequently, if distilled water were used for filling the cylinder of the sheet mold, as was the usual case, the dilution would be changed for each sheet and a varying ash content would result. By employing an aqueous solution of the same molarity as that used for extraction there could be no dilution in the cylinder; thus, the sheets would have a uniform electrolyte content. The data are shown in Table VI.

The resistance of conductors increases with increasing temperature whereas the resistance of insulators ordinarily decreases with an increase in temperature. In order to check the validity of this statement with regard to paper, a 100 per cent rag paper and a 100 per cent unbleached sulfite paper were studied. However, another complicating factor was introduced when paper was tested. As the temperature was increased, in spite of the fact that the relative humidity of the conditioning atmosphere was maintained constant, the moisture content of the paper (as shown in Table VII) decreased with increasing temperature and, consequently, obscured the effect of temperature upon the resistance of the test specimen. Thus, in interpreting the results obtained, the effect of moisture content must be considered.

TABLE VI

VARIATION OF RESISTANCE WITH CALIPER OR SHEET
AND TYPE OF ELECTRODE

Humidity at which samples were tested, 85%
Temperature at which tests were carried out, 30° C.
Voltage applied across bridge, 110 volts
Sample, 100% unbleached sulfite
Electrode specifications:
Diameter, 1.5 cm.
Area, 1.765 sq. cm.

Direct Current Resistance

Caliper inch	Voltage Applied volts	$\frac{L}{A}$ volts	$\frac{R}{A}$ ohms	$\frac{R}{L}$ ohms	Specific Resistance ohms-cm.
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Mercury Electrodes

Electrode weight, 30 g.
Pressure of electrode per unit area, 0.017 kg./sq. cm.

Series 1					
0.0132	0.9751	0.8830	1.059×10^6	1.102×10^5	0.580×10^7
0.0118	1.1718	0.7063	1.059	6.97	4.09
0.0082	1.0148	0.6714	1.059	5.41	4.59
0.0076	1.0376	0.7142	1.059	4.79	4.38
0.0048	0.9790	0.8081	1.059	2.23	3.23
0.0043	0.9760	0.7896	1.059	2.50	4.05

Series 2					
0.0130	0.9323	0.9146	1.059×10^6	2.04×10^4	1.09×10^6
0.0105	0.8963	0.7374	1.059	8.70	5.75
0.0081	0.9318	0.8852	1.059	5.57	4.78
0.0076	0.8685	0.8054	1.059	5.66	5.17
0.0054	0.8967	0.8730	1.059	2.87	3.73
0.0044	0.8691	0.8460	1.059	3.01	4.77

Stainless Steel Electrodes

Electrode weight, 30 g.
Pressure of electrode per unit area, 0.017 kg./sq. cm.

Series 1					
0.0142	1.5583	1.0344	1.059×10^6	5.35×10^5	2.62×10^7
0.0118	1.5728	1.0287	1.059	5.59	3.29
0.0109	1.5540	0.9997	1.059	5.86	3.73
0.0080	1.5297	0.8350	1.059	8.81	7.57
0.0056	1.5350	0.9376	1.059	6.75	8.37
0.0041	1.5530	1.1139	1.059	4.17	7.06

TABLE VI (Cont.)

Caliper inch	Voltage Applied volts	V_m volts	R_m ohms	R_x ohms	Specific Resistance ohms-cm.
Series 2					
0.0123	1.5806	0.7323	1.059×10^6	10.66×10^5	6.02×10^7
0.0110	1.5738	1.0616	1.059	5.11	3.22
0.0095	1.5544	0.9001	1.059	7.70	5.64
0.0069	1.5622	1.0957	1.059	4.50	4.54
0.0055	1.5002	0.9740	1.059	5.71	7.23
0.0044	1.5458	1.0340	1.059	5.24	8.29

Stainless Steel Electrodes

Electrode weight, 1059 g.

Pressure of electrode per unit area, 0.6 kg./sq. cm.

Series 1					
0.0142	1.5549	1.3589	1.059×10^6	1.528×10^5	0.748×10^7
0.0118	1.5462	1.3545	1.059	1.429	0.842
0.0109	1.5816	1.3886	1.059	1.471	0.936
0.0080	1.6037	1.4281	1.059	1.302	1.120
0.0056	1.5534	1.4048	1.059	1.119	1.478
0.0041	1.5683	1.4284	1.059	1.039	1.761
Series 2					
0.0123	1.5342	1.3943	1.059×10^6	1.062×10^5	0.601×10^7
0.0110	1.5340	1.2856	1.059	2.02	1.274
0.0095	1.5345	1.3886	1.059	1.12	0.821
0.0069	1.5943	1.4480	1.059	1.07	1.080
0.0055	1.5344	1.3744	1.059	1.232	1.56
0.0044	1.5566	1.3714	1.059	1.43	2.26

Alternating Current Resistance

Caliper inch	Reference Resistance ohms	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
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Mercury Electrodes

Electrode weight, 30 g.

Pressure of electrode per unit area, 0.017 kg./sq. cm.

Series 1					
0.0132	9680	98	0.25	2420	1.271×10^5
0.0118	9680	100	0.23	2230	1.311
0.0082	9680	102	0.22	2160	1.851
0.0076	9680	102	0.22	2160	1.977
0.0048	9680	107	0.18	1740	2.52
0.0043	9680	111	0.15	1450	2.35

TABLE VI (Cont.)

Caliper inch	Reference Resistance ohms	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
Series 2					
0.0130	9680	102	0.22	2160	1.155×10^5
0.0105	9680	103	0.21	2060	1.366
0.0081	9680	105	0.20	1940	1.667
0.0076	9680	113	0.13	1260	1.152
0.0054	9680	120	0.10	960	1.245
0.0044	9680	125	0.08	757	1.223

Stainless Steel Electrodes

Electrode weight, 30 g.

Pressure of electrode per unit area, 0.017 kg./sq. cm.

Series 1					
0.0142	9680	11.5	2.84	2.75×10^4	1.343×10^6
0.0118	9680	10.5	2.94	2.85	1.657
0.0109	9680	3.0	3.98	3.85	2.45
0.0080	9680	8.0	3.28	3.17	2.72
0.0056	9680	8.5	3.20	3.10	3.85
0.0041	9680	25.0	1.90	1.84	3.12

Series 2					
0.0123	9680	86.5	0.37	0.357×10^5	2.02×10^6
0.0110	9680	50.0	1.00	0.968	6.11
0.0095	9680	37.0	1.39	1.345	9.87
0.0069	9680	43.5	1.18	1.140	11.11
0.0055	9680	43.0	1.20	1.161	14.70
0.0044	9680	27.0	1.81	1.750	27.60

Stainless Steel Electrodes

Electrode weight, 1059 g.

Pressure of electrode per unit area, 0.6 kg./sq. cm.

Series 1					
0.0142	9680	93	0.29	2810	1.373×10^5
0.0118	9680	101.5	0.22	2060	1.211
0.0109	9680	105.5	0.30	1940	1.228
0.0080	9680	114.0	0.13	1260	1.082
0.0056	9680	118.0	0.11	1060	1.316
0.0041	9680	120.0	0.08	775	1.312

Series 2					
0.0123	9680	120	0.10	968	0.547×10^5
0.0110	9680	117	0.11	1065	0.673
0.0095	9680	117	0.11	1065	0.782
0.0069	9680	116	0.12	1160	1.170
0.0055	9680	120	0.10	968	1.223
0.0044	9680	118	0.11	1065	1.683

TABLE VII

EFFECT OF TEMPERATURE UPON THE RESISTANCE OF PAPER

Humidity at which samples were tested, 67%
 Voltage applied across bridge, 110 volts
 Pressure of electrode per unit area, 0.6 kg./sq. cm.
 Electrode specifications
 Diameter, 1.5 cm.
 Area, 1.765 sq. cm.

<u>Direct Current Resistance</u>					
Temperature	Voltage Applied	V_s	R_s	$\frac{R}{L}$	Specific Resistance
° C.	volts	volts	ohms	ohms	ohms-cm.
Sample, 100% rag drawing paper					
Caliper of samples, 0.00473 inch					
30	1.551	0.8967	0.2279×10^9	1.660×10^8	2.75×10^{10}
40	1.549	1.1846	0.2279	0.703	1.162
50	1.557	1.0155	0.2279	1.203	1.91
60	1.554	0.8959	0.2279	1.673	2.77
Sample, 100% unbleached sulfite					
Caliper of samples, 0.0042 inch					
30	1.551	1.1613	0.2279×10^9	7.64×10^8	1.263×10^{10}
40	1.557	1.2827	0.2279	4.87	0.805
50	1.557	1.1954	0.2279	6.91	1.142
60	1.554	1.4097	0.2279	2.33	0.386
Sample, 100% unbleached sulfite					
Caliper of samples, 0.0042 inch					
30	1.551	1.3227	0.2279×10^9	3.93×10^8	0.650×10^{10}
40	1.559	1.3493	0.2279	3.53	0.584
50	1.556	1.1310	0.2279	8.55	1.413
60	1.554	1.4065	0.2279	2.39	0.395

TABLE VII (Cont.)

<u>Alternating Current Resistance</u>					
Temperature ° C.	Reference Resistance ohms	Vernier Reading	$\frac{R_1}{R_2}$	$\frac{R_x}{R_2}$ ohms	Specific Resistance ohms-cm.
Sample, 100% rag drawing paper Caliper of samples, 0.00473 inch					
30	1.07×10^7	32.0	1.59	1.70×10^7	2.81×10^9
40	1.07	45.0	1.13	1.21	2.00
50	1.07	59.5	0.78	0.835	1.38
60	1.07	64.0	0.69	0.738	1.22
Sample, 100% unbleached sulfite Caliper of samples, 0.0042 inch					
30	1.07×10^7	48.5	1.04	1.112×10^7	1.84×10^9
40	1.07	67.0	0.64	0.685	1.133
50	1.07	63.0	0.71	0.760	1.258
60	1.13×10^6	19.0	2.28	0.258	0.427
Sample, 100% unbleached sulfite Caliper of samples, 0.0042 inch					
30	1.07×10^7	58.0	0.81	0.866×10^7	1.432×10^9
40	1.07	76.0	0.50	0.535	0.885
50	1.07	70.0	0.58	0.621	1.028
60	1.07	85.5	0.38	0.407	0.674
Moisture content of samples					
Temperature ° C.		Moisture %			
30		10.85			
40		10.98			
50		8.10			
60		8.93			

If paper follows Ohm's law, variations in the applied voltage in alternating current resistance measurements should have no effect upon the measured resistance of the test specimen. An autotransformer, operated from the 60-cycle line voltage, furnished the desired voltage to the bridge. The voltage studies were carried out by adjusting the voltage to different values and then measuring the resistance of the sample. The results for two specimens are given in Table VIII and are plotted in Figure 11. It was found that paper does not follow Ohm's law and that the resistance decreases with increasing voltages.

The study of the effect of alternating current frequency upon the measured resistance was carried out using a slightly different voltage supply to the bridge. A variable speed motor was connected to a variable frequency generator; thus, by varying the speed of the motor, the frequency of the current generated could be controlled. The frequency of the current produced was calculated by using the formula

$$f = S/30.$$

where f equals the frequency of the current and S equals the speed of the motor in revolutions per minute. The lowest frequency at which the generator could be operated and still maintain a constant 10-volt output was 15 cycles per second. The terminals of the generator were shunted by a voltage divider which maintained a 10-volt supply to the bridge at the various frequencies. The data obtained are given in Table IX and are plotted in Figure 12.

Electrolytes are always present in paper and may or may not have a profound effect upon the resistance of the test specimen. To

TABLE VIII

EFFECT OF VARIABLE 60-CYCLE VOLTAGE
UPON THE RESISTANCE OF PAPER

Humidity at which samples were tested, 77%
 Temperature at which samples were tested, 30° C.
 Sample, 100% unbleached sulfite
 Pressure of electrode per unit area, 0.6 kg./sq. cm.
 Electrode specifications
 Diameter, 1.5 cm.
 Area, 1.765 sq. cm.
 Caliper of sheet, 0.00494 inch
 Reference Resistance, 1.13×10^6 ohms

Sample I

Voltage Applied volts	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
10	20.5	2.18	2.46×10^6	3.46×10^8
20	20.5	2.18	2.46	3.46
30	21.5	2.12	2.40	3.37
40	22.0	2.08	2.35	3.30
50	22.5	2.06	2.33	3.28
60	22.5	2.06	2.33	3.28
70	22.5	2.06	2.33	3.28
80	23.5	2.00	2.26	3.18
90	23.5	2.00	2.26	3.18
100	23.5	2.00	2.26	3.18
110	24.5	1.94	2.19	3.09
120	24.0	1.97	2.22	3.12
130	24.2	1.96	2.21	3.11

Direct Current Resistance of Sample

Voltage Applied Volts	V_s volts	R_x ohms	R_x ohms	Specific Resistance ohms-cm.
1.593	0.129	1.059×10^6	1.20×10^7	17.05×10^8

TABLE VIII (Cont.)

<u>Sample II</u>				
Voltage Applied volts	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
10	25.4	1.85	2.12×10^6	3.01×10^8
20	27.1	1.81	2.05	2.91
30	27.5	1.79	2.02	2.87
40	28.7	1.76	1.99	2.83
50	28.3	1.73	1.96	2.78
60	29.9	1.68	1.90	2.70
70	30.0	1.67	1.89	2.69
80	31.0	1.63	1.84	2.62
90	31.7	1.60	1.81	2.55
100	31.8	1.59	1.80	2.56
110	31.7	1.60	1.81	2.57
120	32.2	1.58	1.79	2.54
130	32.5	1.57	1.78	2.53

Direct Current Resistance of Sample

Voltage Applied volts	V_s volts	R_s ohms	R_x ohms	Specific Resistance ohms-cm.
1.595	0.116	1.059×10^6	1.35×10^7	19.20×10^8

Figure 12

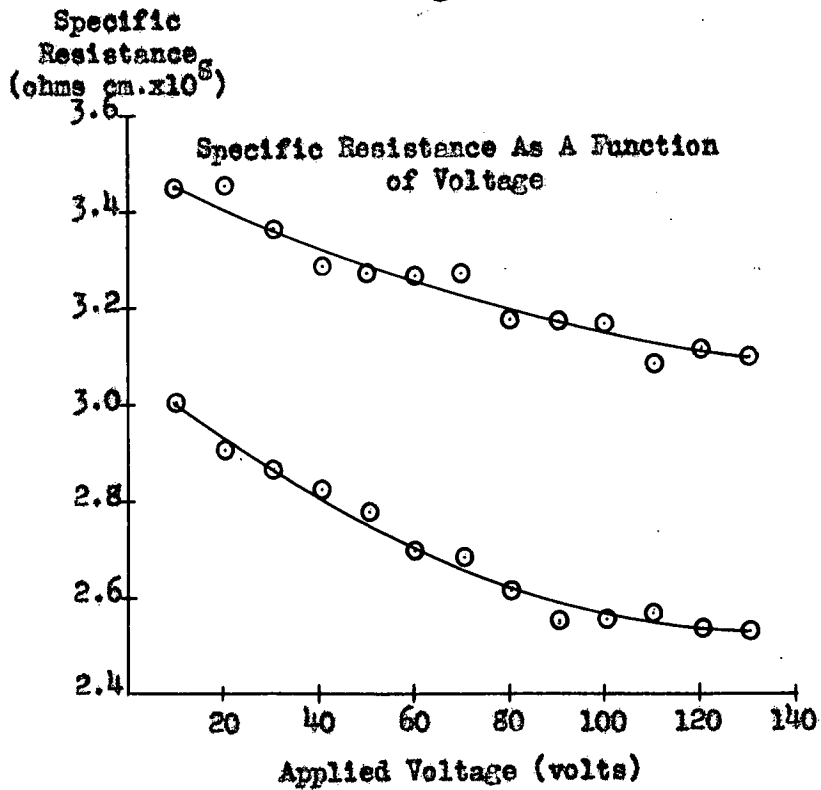


Figure 11

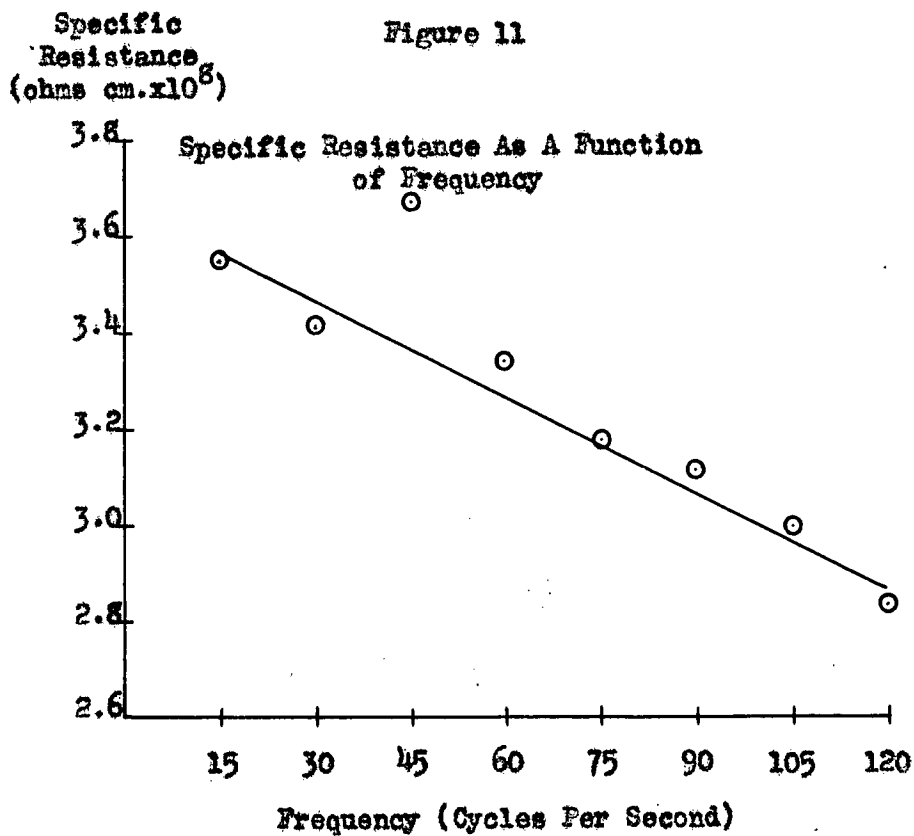


TABLE IX

EFFECT OF VARIABLE FREQUENCIES UPON THE RESISTANCE OF PAPER

Humidity at which samples were tested, 77%
 Temperature at which samples were tested, 30° C.
 Sample, 100% unbleached sulfite
 Pressure of electrode per unit area, 0.6 kg./sq. cm.
 Electrode specifications
 Diameter, 1.5 cm.
 Area, 1.765 sq. cm.
 Caliper of sheet, 0.0049 inch
 Voltage applied to bridge, 10 volts

Frequency cycles/sec.	Reference Resistance ohms	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
15	1.13×10^6	20.0	2.20	2.49×10^6	3.54×10^8
30	1.13	21.5	2.12	2.40	3.41
45	1.13	19.0	2.28	2.58	3.67
60	1.13	22.0	2.08	2.35	3.34
75	1.13	24.0	1.97	2.23	3.17
90	1.13	24.4	1.94	2.19	3.11
105	1.13	26.4	1.86	2.10	2.99
120	1.13	28.2	1.76	1.99	2.83

Direct Current Resistance of Sample.

Voltage Applied volts	V_x volts	R_x ohms	R_x ohms	Specific Resistance ohms-cm.
1.595	0.116	1.059×10^6	1.35×10^7	19.20×10^8

study this important variable, sheets of different ash contents were prepared from unbleached sulfite. The stock was subjected to the usual extraction with 0.5-molar calcium chloride, filtered, washed with two portions (100 times the weight of the dry stock) of distilled water, and treated for 24 hours without stirring in calcium chloride solutions of varying molarities (1.0, 0.1, 0.05, 0.01, 0.005, and 0.001). The object of the first extraction was to remove ions other than calcium. The second treatment controlled the final ash content of the sheet. After the second treatment of the pulp, the test specimens were prepared, dried, conditioned, and tested in the usual manner. The data presented in Table X and plotted in Figure 13 indicate that the ash content has a very marked effect upon the resistance of the sample. There is a certain electrolyte content above which further increases cause a lower rate of decrease in the resistance. Below this critical region, the resistance increases very markedly.

It seemed desirable to ascertain whether pulps of different degrees of purity -- e.g., unbleached, chlorinated, bleached, and alpha pulps -- would show the same resistance when the ash content and moisture content were held constant. Such a study was carried out by starting with an unbleached sulfite pulp and preparing samples typical of the various stages of purification. Test sheets were made and the resistances measured. The data in Table XI indicate that resistance is roughly independent of the degree of purity of the pulp.

TABLE X

EFFECT OF SALT CONCENTRATION UPON THE RESISTANCE OF PAPER

Humidity at which samples were tested, 85%
 Temperature at which samples were tested, 30° C.
 Sample, 100% unbleached sulfite
 Pressure of electrode per unit area, 0.6 kg./sq. cm.
 Electrode specifications
 Diameter, 1.5 cm.
 Area, 1.765 sq. cm.
 Caliper of samples, 0.0035 inch
 Voltage applied to bridge, 110 volts

Direct Current Resistance

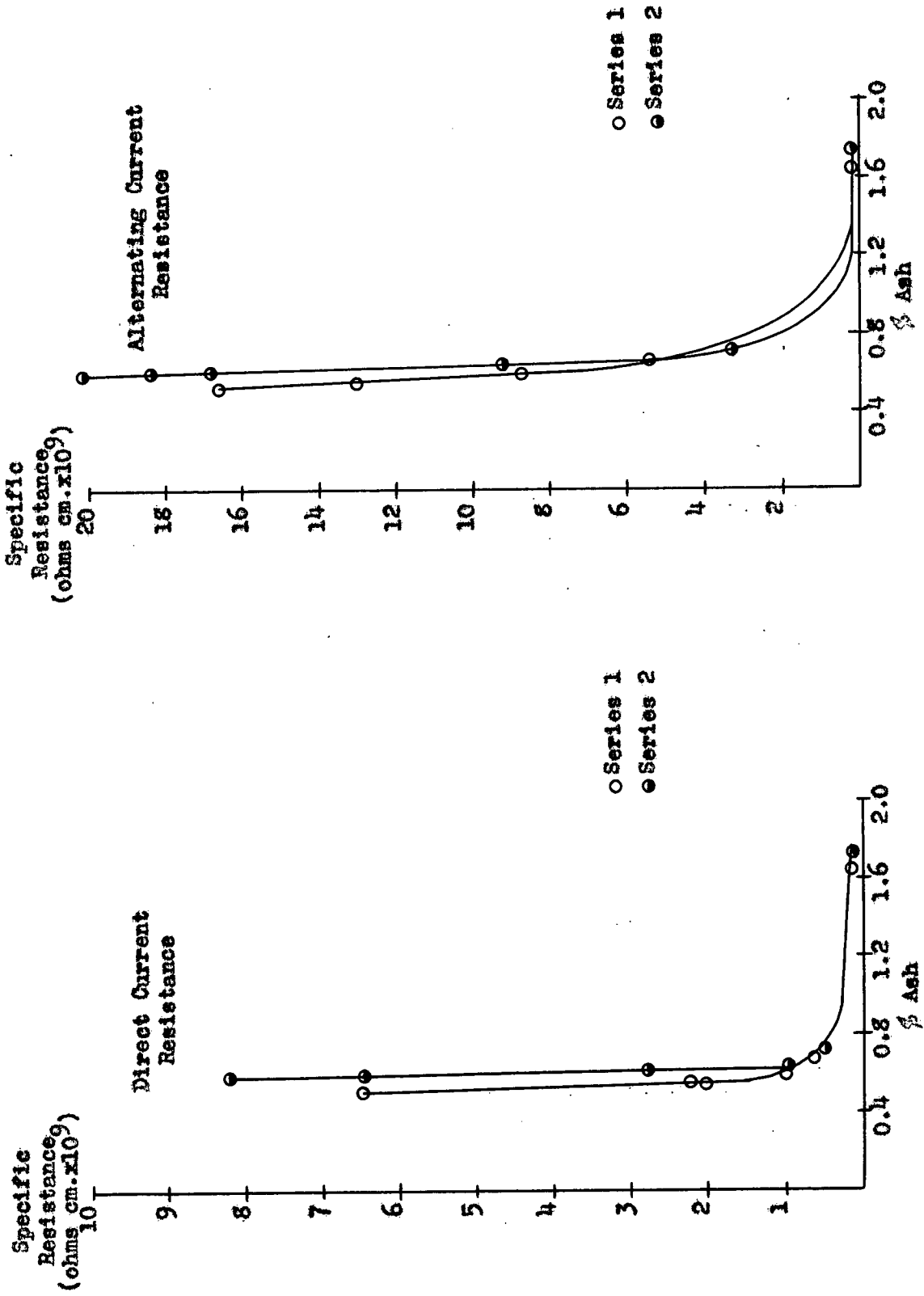
Ash Content %	Moisture Content %	Voltage Applied volts	V_x volts	R_x ohms	R_x ohms	Specific Resistance ohms-cm.
Series 1						
1.636	16.25	1.5561	0.9595	1.059×10^6	0.658×10^6	0.1308×10^9
0.674	16.45	1.5556	0.4093	1.059	2.98	0.592
0.608	14.80	1.5585	0.2693	1.059	5.07	1.008
0.554	15.70	1.5593	0.1477	1.059	10.13	2.015
0.558	15.18	1.5563	0.1348	1.059	11.18	2.22
0.519	15.08	1.5638	1.3813	0.228×10^9	32.50	6.46
Series 2						
1.745	17.78	1.5721	0.9517	1.059×10^6	0.69×10^6	0.1374×10^9
0.717	16.86	1.5539	0.5049	1.059	2.19	0.435
0.639	13.74	1.5543	0.2821	1.059	4.78	0.950
0.601	14.13	1.5466	0.1098	1.059	13.88	2.76
0.589	15.32	1.5570	1.3638	0.228×10^9	32.30	6.42
0.577	15.42	1.5611	1.3212	0.228	41.40	8.23

TABLE X (Cont.)

<u>Alternating Current Resistance</u>						
Ash Content %	Moisture Content %	Reference Resistance ohms	Vernier Reading	R_1/R_2	R_x ohms	Specific Resistance ohms-cm.
Series 1						
1.636	16.25	9680	77.0	0.48	0.0464×10^5	0.0922×10^7
0.674	15.45	1.13×10^6	99.0	0.24	2.71	5.39
0.608	14.80	1.13	88.0	0.35	3.96	7.86
0.554	15.70	1.13	70.0	0.58	6.56	13.01
0.558	15.18	1.13	70.0	0.58	6.56	13.01
0.519	15.08	1.13	61.5	0.74	8.36	16.61
Series 2						
1.745	17.78	9680	59.0	0.79	0.0765×10^5	0.152×10^7
0.717	16.86	1.02×10^5	31.5	1.61	1.64	3.26
0.639	13.74	1.13×10^6	82.0	0.41	4.63	9.20
0.601	15.13	1.13	57.5	0.82	9.27	18.41
0.589	15.32	1.13	61.0	0.75	8.48	16.86
0.577	15.42	1.13	54.0	0.90	10.17	20.20

Figure 13

Relationship Between Specific Resistance And Percentage Ash



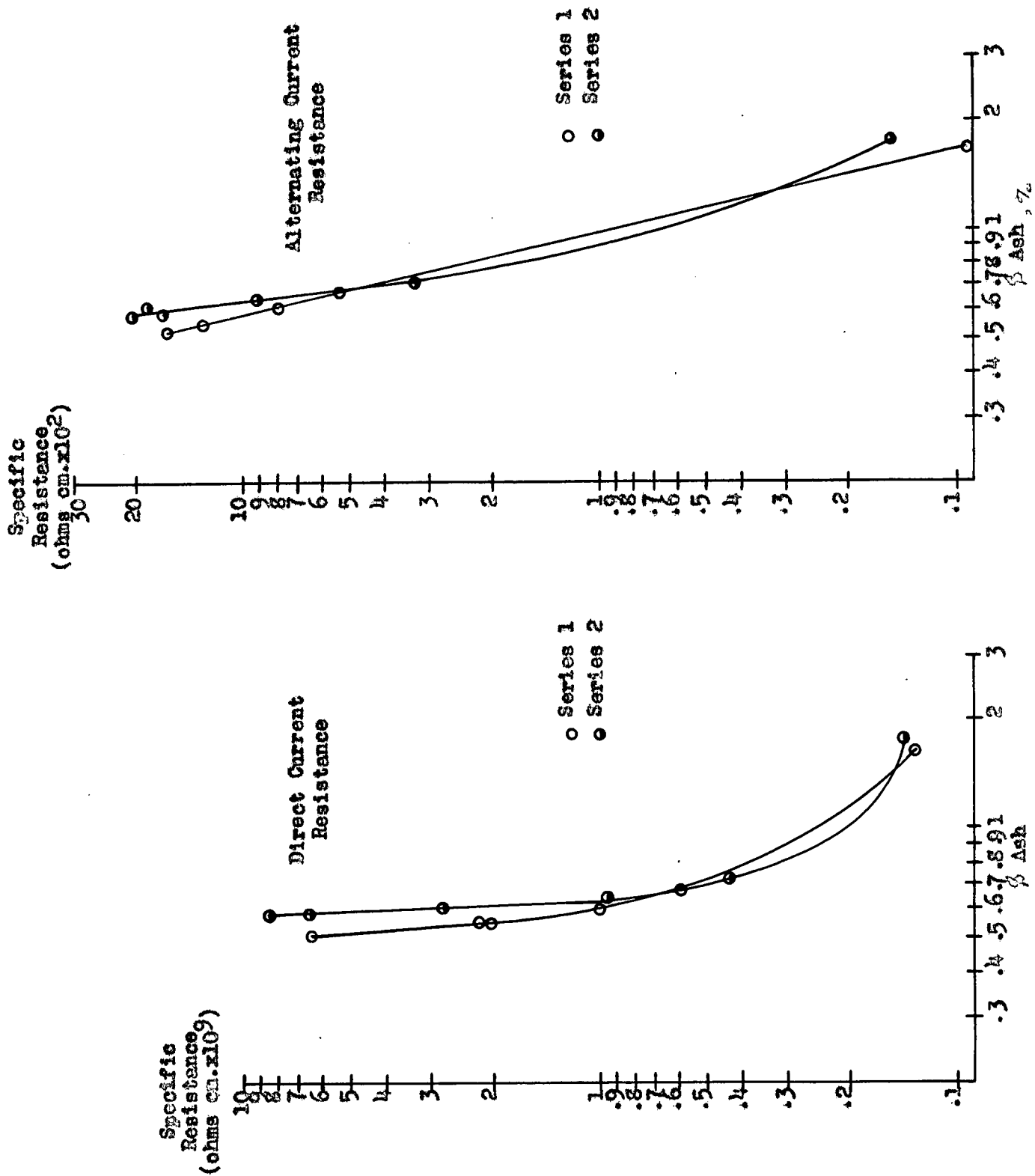


Figure 13 (Cont.)

TABLE XI

ELECTRICAL RESISTANCE AS A FUNCTION OF DEGREE OF PURITY

Humidity at which samples were tested, 85%
 Temperature at which samples were tested, 30° C.
 Pressure of electrode per unit area, 0.6 kg./sq. cm.
 Electrode specifications
 Diameter, 1.5 cm.
 Area, 1.765 sq. cm.
 Voltage applied to bridge, 110 volts

Direct Current Resistance

Type of Pulp	Caliper inch	Voltage Applied volts	$\frac{V}{L}$ volts	$\frac{R}{L}$ ohms	$\frac{R}{x}$ ohms	Specific Resistance ohms-cm.
Unbl.	0.0042	1.5457	0.8243	1.059×10^6	0.927×10^6	1.53×10^8
Chlor.	0.0042	1.5683	0.8144	1.059	0.980	1.64
B1.	0.0042	1.5265	0.6862	1.059	1.297	2.15
Alpha	0.0084	1.5522	0.5514	1.059	1.920	1.590

Alternating Current Resistance

Type of Pulp	Caliper inch	Reference Resistance ohms	Vernier Reading	$\frac{R_1}{R_2}$	$\frac{R}{x}$ ohms	Specific Resistance ohms-cm.
Unbl.	0.0042	1.02×10^5	37.5	1.37	1.398×10^5	2.32×10^7
Chlor.	0.0042	1.02	41.0	1.25	1.275	2.11
B1.	0.0042	1.02	41.0	1.25	1.275	2.11
Alpha	0.0084	1.02	43.0	1.19	1.210	1.003

DISCUSSION OF RESULTS

This study was intended to improve our knowledge of the effect of some variables upon the electrical resistance of paper. In particular, it was hoped to gain a better insight into the mechanism of conduction at high moisture contents.

The order of the following discussion will be that used in the section entitled "Experimental Work," because in each series of experiments one variable was studied while the other variables were held constant.

Selection of an electrode system was necessary to facilitate this study. Its selection depended not only upon the most suitable material available but also upon its physical construction, such as area of contact with specimen and pressure of the electrode per unit area of contact. To accomplish this aim, resistance as a function of the area, the weight per unit area, and the type of electrode were investigated.

Data presented in Tables III and V were obtained by using flat stainless steel electrodes of three areas. Those presented in Table III describe the effect of different pressures as well as different areas; thus, in reading this table comparison of results for one electrode with those for another should be made only at identical pressures.

The results in these two tables are erratic, because of the paper variables which are difficult to control. Such paper variables as surface character, ash content, and caliper are particularly difficult to maintain identical from specimen to specimen when handsheets are tested. Also, the symmetry of loading of the electrodes has an appreciable effect upon the measured resistance. To eliminate these difficulties as far as possible, a machine-made paper and a filter paper (Table V) were also tested.

By consideration of these data in their entirety, it is observed that the specific resistance is dependent upon the electrode area, except in the case of very uniform papers. In Table III, it is apparent that the results for the electrode of 2.54-cm. diameter are lower than those for the other electrodes. This may be a result of differences in the samples tested, because different handsheets were used with the various electrodes. It may also be noted that the results are less erratic at the higher loads per unit area and the values for the different electrodes approach each other more closely at the higher pressures. This latter effect is obviously a result of more intimate contact of the electrode with the entire surface of the test specimen, eliminating surface variations to a greater extent. At the lower loads, irregularities in the sheet surface would cause poor contact resulting in higher resistances. At the higher loads, many such protrusions are reduced and a more intimate contact is obtained. This condition would be conducive to results more characteristic of the paper specimen.

The data presented in Table V were obtained by measuring the resistances of two commercial papers. It was hoped that such papers, because of their uniformity, would eliminate the variations resulting from irregularities in properties across the specimens. The results for the rag drawing paper were not consistent, probably because this paper was hard sized and there was a slight cockle in the sheet; thus, irregularities in the surface would not be as readily reduced by heavy loads upon the electrode. Such factors could cause the erratic results observed. In the case of the filter paper, the caliper was constant, the sheet was soft, and there was no cockle. Tests carried out with electrodes of different diameters on filter paper showed the specific resistance to be independent of the electrode area in spite of the fact that the load per unit area was comparatively small.

Data on resistance as a function of electrode pressure are presented in Tables III, IV, and V. Because of the unsteady nature of the results for handsheets (Table III), measurements were also carried out on a 100 per cent rag drawing paper (Table IV). The machine-made paper would be expected to yield more consistent results for two reasons. It would be more uniform in caliper and ash, and the electrode was not moved during the study.

Observation of the data in these tables shows that the measured resistance decreases with increasing load. The data given in Table IV and plotted in Figure 10 indicates that the alternating-current resistance tends to approach a lower limiting value. This same trend is borne out in Table III with the three different electrodes for both

alternating and direct current resistance measurements.

Such results may be due to a compression of the test specimen, a decrease of the contact resistance because of a more intimate contact with the surface of the test specimen at the higher loads, or a combination of the two factors.

The caliper of the sample under the range of pressures used for these studies was measured with a Federal caliper tester. This measurement revealed that the compression was very slight and, consequently, could not explain the observed decrease in resistance.

TABLE XII

COMPRESSION OF SHEET WITH INCREASING PRESSURE
ON ANVIL OF CALIPER TESTER

Caliper inch	Pressure kg./sq. cm.
0.00453	0.1
0.00453	0.2
0.00453	0.3
0.00452	0.4
0.00452	0.5
0.00452	0.6
0.00450	0.7

The remaining possibility is a reduction of the contact resistance. This possibility is quite reasonable when the nature of paper is considered. Fibers or groups of fibers protruding from the surface of the test specimen could readily support the electrode at the lower pressures. At higher pressures, the fibers and fiber groups would be forced back toward the surface of the specimen, permitting more of the sample to come into contact with the electrode, and would

be reflected in the measurements by a decrease in resistance.

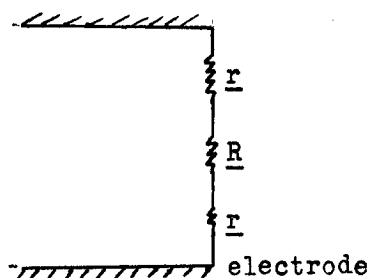
To facilitate further the study of contact resistance, as well as the effect of a different type of electrode upon the resistance, mercury electrodes were used for a series of samples of different calipers. The data may be found in Table VI. As previously pointed out, an electrochemical potential existed when the direct current resistance was measured, which made the data of questionable value. This potential was apparently a result of some type of reaction between the mercury and the electrolyte constituents of the paper. However, comparison of the alternating current resistances obtained with the mercury electrodes and those obtained with the flat plate electrodes of identical pressure and area readily show that the resistance measured with mercury electrodes is more than ten times lower than the corresponding values obtained with the plate electrodes. This observation further indicates the importance of contact resistance when measuring the resistance of paper. This result was not unexpected. It was originally hoped that, by use of mercury electrodes, the variations arising from irregularities in the surface of the samples would be eliminated; however, the electrochemical potential made the use of these electrodes impractical.

Mercury, because it is a liquid, would fill the larger voids in the surface of the sheet; however, because the surface tension of paper-air is less than that of both mercury-paper interfacial tension and mercury-air surface tension, the mercury does not wet the paper and will not fill the small voids. It is seen that the alternating current resistances measured by mercury electrodes at a pressure of

0.017 kg./sq. cm. are of the same magnitude as those measured with plate electrodes at a pressure of 0.6 kg./sq. cm. This substantiates the fact that the mercury does not entirely fill the surface interstices. The resistances measured with the mercury electrodes would be lower than those obtained with the stainless steel system at higher pressures, if the mercury entirely filled the surface voids, because the stainless steel cannot make complete contact.

If paper were homogeneous and contact resistances were negligibly small compared with the resistance of the paper, the specific resistance would be independent of the caliper of the specimen. Observation of the data in Tables III, IV, and VI show the contact resistance to be an important factor in the measured resistance, particularly when low pressures are applied to the electrodes. These results indicate that the specific resistance cannot be independent of the caliper of the test specimens.

If the resistance of the paper is considered to be made up of equal contact resistances (\underline{r}) on either side of the sample and the resistance of the paper itself (\underline{R}), the specific resistance as measured (ρ') may be expressed as



$$\rho' = A(2\underline{r} + \underline{R})/\underline{t}, \quad (b)$$

where \underline{A} is the area of the electrode and \underline{t} is the caliper of the specimen. Solving Equation (4) for \underline{r} .

in which $\frac{RA}{\ell}$ would be the true specific resistance (ρ) of the paper and would remain constant if paper behaved like a homogeneous dielectric. If this is an accurate picture, it can be seen that the measured specific resistance is not independent of the caliper.

All of the specimens tested were prepared under identical conditions, varying only the caliper; thus, it would be reasonable to assume that the contact resistance from sample to sample would be constant. Then, for two samples, adding appropriate subscripts,

$$R = (\ell_1/2A)(\rho_1^i - R_1A/\ell_1) = (\ell_2/2A)(\rho_2^i - R_2A/\ell_2) \quad (7)$$

or

$$R = (\ell_1/2A)(\rho_1^i - \rho) = (\ell_2/2A)(\rho_2^i - \rho). \quad (8)$$

Solving for ρ ,

$$\rho = (\ell_1\rho_1^i - \ell_2\rho_2^i)/(\ell_1 - \ell_2). \quad (9)$$

Substituting values obtained from Table IV (Series 1, direct current resistance, 0.6 kg./sq. cm. pressure on electrodes) in Equation (9) and solving for the true specific resistance (ρ), the following results are obtained:

ℓ_1 inch	ℓ_2 inch	ρ_1^i ohms-cm.	ρ_2^i ohms-cm.	$\frac{A}{\ell}$ sq. cm.	ρ ohms-cm.
0.0142	0.0118	0.748×10^7	0.842×10^7	1.765	2.83×10^6
0.0109	0.0080	0.936	1.120	1.765	4.28
0.0056	0.0041	1.478	1.761	1.765	6.69

These sample calculations and similar calculations on the remainder of the data show that either the assumption that the contact resistance remains constant from one measurement to the next is not

valid or that the true specific resistance does not remain constant for papers of different caliper but identical in other respects.

If the contact resistance remains constant, the increase in specific resistance observed with decreasing caliper would be due to an increase in the true specific resistance of the paper. Such an increase in the true specific resistance might be the result of a greater discontinuity in the conducting paths through the sheet as the thickness (or caliper) decreases.

It may be shown that the contact resistance forms part of the measured resistance even when the pressure on the electrodes is high or when mercury electrodes are employed. Using the above data taken from Table IV and substituting in Equation (8), it is found that the contact resistance is approximately one-fifth of the actual measured resistance.

$$\text{Contact resistance } (2r) = 3.74 \times 10^4 \text{ ohms}$$

$$\text{Measured resistance } (R_x) = 1.528 \times 10^5 \text{ ohms}$$

Because temperature variations are always present on a paper machine, its effect upon the resistance was studied. It is a well-known fact that the resistance of conductors increases with increasing temperature, whereas that of insulating materials decreases under the same conditions.

When the temperature of the conditioning atmosphere is changed, the moisture content of the test samples also changes in spite of the

fact that the relative humidity is maintained constant. The interpretation of the data presented in Table VII can be carried out only if the results are interpolated to the same moisture content and then compared.

According to Murphy and Walker (4), if the logarithm of the resistance is plotted against the logarithm of the percentage moisture content of the specimen, a straight line will be obtained whose slope is independent of the impurities and is dependent only upon the material in question. Their work dealt primarily with cotton and other textiles; however, since cotton and paper are both cellulosic in nature, it may be expected that the slope of the line would be the same for paper. For this reason a temperature study might yield a family of parallel lines at different positions relative to the ordinates for the various temperatures.

Using the same slope given by Murphy and Walker (4) and plotting the data in Table VII for temperature studies, the curves in Figure 14 are obtained for the alternating current resistance of an unbleached sulfite sample. Interpolating all resistances to a 10 per cent moisture content, it is apparent that that resistance decreases with increasing temperatures. The interpolated data from Figure 14 are given in Table XIII.

It is found that, over a restricted temperature range (43-46), conductivity can be expressed by a formula of the van't Hoff (47) form for dielectrics:

Figure 14

Logarithm Of Specific Resistance As A Function Of Logarithm Of Moisture Content
For Different Temperatures

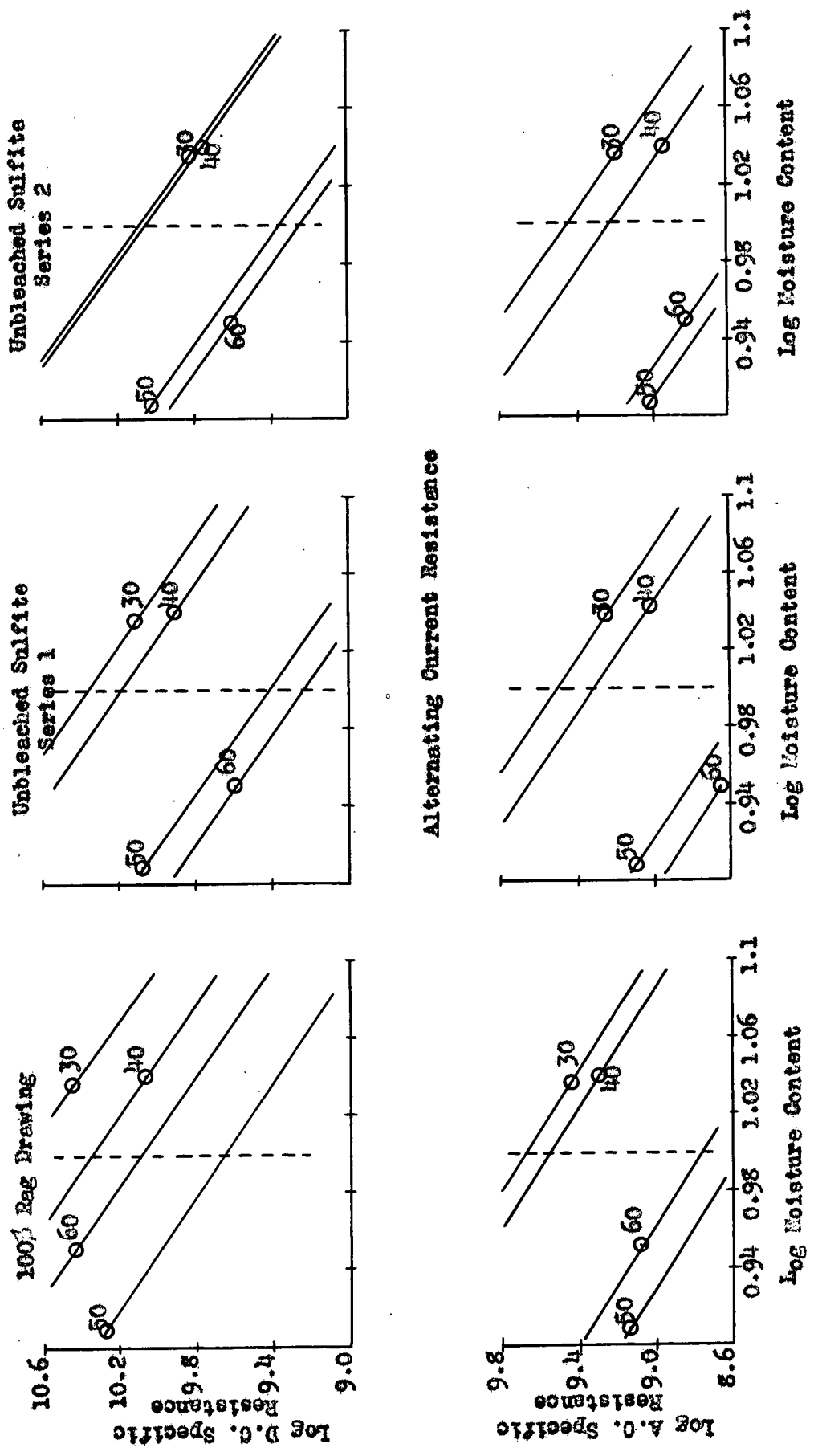


TABLE XIII

SPECIFIC RESISTANCE EXTRAPOLATED TO 10 PER CENT
MOISTURE CONTENT FOR TEMPERATURE STUDIES

Direct Current Resistance

Temperature ° C.	Specific Resistance, ohms-cm.		
	100% Rag Drawing	100% Unbleached Sulfite Series 1	Series 2
30	5.01×10^{10}	2.29×10^{10}	1.20×10^{10}
40	1.27	1.51	1.10
50	0.45	0.26	0.22
60	1.20	0.17	0.17

Alternating Current Resistance

30	4.90×10^9	3.16×10^9	2.69×10^9
40	3.55	2.09	1.66
50	0.36	0.30	0.28
60	0.58	0.20	0.22

$$\rho = \underline{A} \exp (-\underline{B}/\underline{T}),$$

where ρ is the conductivity, \underline{T} is absolute temperature, and \underline{A} and \underline{B} are constants. \underline{B} is usually the same for different specimens of the same material, but \underline{A} may vary from sample to sample. This formula predicts a very rapid variation with temperature at low temperatures. Such a trend was observed to follow when paper was tested. The measured resistance was highest at the lowest temperatures.

It would not be surprising to find that paper fails to follow Ohm's law in an alternating current field, because such deviations have been observed (48, 49) with many dielectrics. The expression for Ohm's law is

$$\underline{E} = \underline{I}\underline{Z}.$$

where \underline{E} is the voltage applied, \underline{I} is the current through the specimen, and \underline{Z} is the impedance. It has already been pointed out that the bridge used measures the impedance of the sample. If the idealized circuit (a resistor and capacitor in parallel) is considered, the impedance, as previously indicated, is

$$\underline{Z} = \underline{R}_p / \sqrt{1 + (2 \underline{fCR}_p)^2},$$

where \underline{R}_p is the true resistance of the sample, \underline{f} is the frequency of the applied voltage, and \underline{C} is the capacitance of the electrode system. It can be seen that the applied voltage does not enter into the equation for impedance; however, the data presented in Table VIII show definitely that the impedance, or resistance, of the sample decreases with increasing voltage. If Ohm's law were followed, the impedance would remain constant when the voltage is the only variable changed.

Since this is not the case, Ohm's law is not obeyed.

McLean and Kohman (15) observed this same effect. They offered the explanation that ions which are strongly bound to the cellulose structure move against restraining forces when a potential is applied. At low potential gradients, ions finally attain an equilibrium position; in this case, the leakage current reaches a constant low value and, when the potential is removed, a current flows in the opposite direction. At high potential gradients, the restraining forces may break down and some of the ions become free, thus causing an increase in current which is not reversible.

Data for frequency studies are presented in Table IX and plotted in Figure 12. From these data, it can be observed that the resistance decreases with increasing frequencies; however, since the impedance and not the true resistance is measured, the observed effect may be due to the susceptance of the electrodes. R_p for the idealized circuit is

$$R_p = Z / \sqrt{1 - (2\pi f C Z)^2}.$$

The capacitance (C) of the electrode system is

$$C = 0.0885 \pi r^2 k / t,$$

where r is the radius of the electrode, k is the dielectric constant of paper (assumed to be 3), and t is the caliper of the sample or plate separation of the electrodes. The susceptance of the electrode system would be greatest at the highest frequencies used. Thus, when the values found in Table IX for the frequency of 120 c.p.s. are substituted in the above equation, the following values are obtained:

$$\underline{C} = 37.7 \mu\text{fd.}$$

and

$$\underline{R_p} = 2.00 \times 10^6 \text{ ohms,}$$

whereas

$$\underline{Z} = 1.99 \times 10^6 \text{ ohms,}$$

which is not significantly different from the impedance measured. The susceptance of the electrodes at the lower frequencies would be less, and the measured impedance would still more closely approximate the true resistance of the sample. Hence, the measured impedances are essentially equal to the true resistances. It may be concluded that the resistance of paper increases, in the range studied, with decreasing frequencies of the applied voltage.

Murphy and Lowry (7) suggested that, upon expansion of the theory proposed by Murphy and Walker (4) to include alternating currents, the structure of a dielectric, free ions, adsorbed ions, and neutral molecules may each contribute to the total dielectric adsorption and dielectric loss. The relative prominence of each of these components should depend on the type of dielectric, the temperature, and other factors.

It is suggested in present theories of electrolytes in solution that each ion is surrounded by an ionic atmosphere of central symmetry resulting from the combined effect of Coulomb forces between the charged ions and the thermal agitation. When an external potential is applied, the electrical force overcomes the ordinary frictional resistance to the motion of the ions and they move toward the electrode

of opposite charge. When the ions move from the center of their fields, a force (known as the relaxation force) resists the movement. If the frequency of the impressed a.m.f. is increased to a point where the period of oscillation of the ion becomes comparable with the time of relaxation, the dissymmetry in the ionic atmosphere will decrease, the effect of the electrical force of relaxation will diminish, and the equivalent conductance will increase. At the moisture contents existing when the papers were tested, this phenomenon and the forces binding the ions to the cellulose may apply.

If such is the case, the relaxation forces will be greater at frequencies below the critical period of oscillation. As the frequencies decrease, the relaxation forces would increase and the resistance would increase. This phenomenon may explain the observed increase in resistance with decreasing frequency.

Studies carried out upon the resistance as a function of the ash, or electrolyte, content in paper yielded information regarding possible mechanisms for electrical conduction. The data are presented in Table X and are plotted in Figure 13. This figure indicates that resistance decreases at a lower rate when the ash content is above a critical region. As the ash content decreases below this critical region, the resistance increases very rapidly.

A mechanism which might be used to explain the observed results may be based upon the existence of two types of conduction. In ranges of high electrolyte content, the conduction might be almost entirely due to ions; however, as the electrolyte content approaches

lower values, there may be insufficient ions to conduct the current and a transition to ionic conduction by the water adsorbed may take place. Cellulose is very hygroscopic, and the water adsorbed is tenaciously held. This water could only enter into conduction with difficulty. Thus, the transition from electrolytic conduction to the ionic conduction of water would be indicated by the break in the curves shown in Figure 13.

Another explanation can be offered for this range of ash contents if the conduction is again considered a result of two factors. At high ash contents, the conductivity is limited by the conduction of the pure ash; at low ash contents, the conducting paths are no longer continuous paths through electrolyte, but broken paths through electrolyte interrupted by strongly adsorbed water. As the ash content is decreased from high values, a critical value is reached; this is indicated by a sharp change in the curve, where the conducting paths are no longer continuous and further decreases in the ash content result in a sharp increase in the resistance.

The equation for the curves shown in Figure 13 has the approximate form $(\rho' - \underline{a})(\underline{C} - \underline{b}) = \underline{c}$, where ρ' is the specific resistance, \underline{C} is the concentration of the electrolyte, and \underline{a} , \underline{b} , and \underline{c} are constants. The constants in the equation can be evaluated in terms of the latter explanation: \underline{a} would be the resistance of the pure electrolyte at the moisture content it has in the sheet, \underline{b} would be the ash content below which the resistance would theoretically go to infinity, and \underline{c} would be a proportionality constant. It is obvious,

however, that even at zero ash content the resistance has a finite value, obviating the above interpretation of the data unless, at the higher resistances, the phenomenon of ionic conductivity of the water plays a more important role. If such were the case, there would be a gradual shift of the curve toward zero ash content with a rapid increase in the resistance at the same time.

In view of these observations, a possible mechanism of conduction at high moisture contents may be postulated. At very low ash contents, the conduction may be due largely to the ionic conduction of the water. In the intermediate range of ash contents, the conducting electrolyte paths are broken by the higher resistant adsorbed water, whereas, at higher ash contents, the conductivity may be due largely to the ionic conductivity of electrolytes in the paper and is finally limited, as the ash content increases, by the conductivity of the ash itself.

Murphy and Walker (11) pointed out that the logarithm of the resistance is a linear function of the logarithm of the moisture content. The slope of this line is dependent only upon the type of material in question, and its relative position to the ordinates is governed by the ash impurities present in the material. This latter observation appeared to follow when unbleached, chlorinated, bleached, and alpha pulps prepared from the same original stock were tested. It was found that all of these specimens had approximately the same resistance, indicating that organic impurities present in paper had little influence. Since the organic materials in paper are noncon-

ductors, the trend observed is understandable.

CONCLUSIONS

Investigation of the resistance of paper as a function of electrode area revealed that the specific resistance was not independent of the electrode area except in the case of a very uniform paper. Variations in caliper, surface character, and ash content, within the test specimens, caused the observed results.

In the light of studies carried out with different electrode pressures upon samples of different calipers, it was observed that the contact resistance formed an appreciable part of the measured resistance, particularly when the pressure of the electrodes was low. At higher pressures, the resistance of the samples decreased and approached lower limiting values. This was probably due to a corresponding decrease in contact resistance. The compression of the sheet was very small and could not explain the decrease observed.

Because the contact resistance (ρ_c) makes up a portion of the measured resistance, the specific resistance (ρ') calculated is not the true specific resistance of the sample but is

$$\rho' = \frac{A(2r + R)}{t}$$

where A is the area of the electrodes, R is the true resistance of the paper, and t is the caliper of the paper. Application of a modified form of this equation to the studies carried out on papers of different calipers showed that the specific resistance increased with decreasing caliper. A greater discontinuity in the conducting paths at

the lower calipers could cause the results observed.

A series of tests using a mercury electrode system further indicated that contact resistances did form an appreciable part of the resistance of paper. Although the mercury made a more complete contact with the sample than the flat plate electrode at equal pressures, by applying a comparatively high pressure to the flat plate electrodes, results of the same magnitude as those for mercury were obtained.

If higher pressures were used with flat plate electrodes, the protrusions in the specimens would be reduced, resulting in a compression in the area of such protrusions. This, in turn, may be responsible for the lower resistances observed because of increased conduction in the compressed area. However, it may be pointed out that work by Seborr and Stamm (8) showed that beating pulp did not alter the resistance. Such beaten pulps would have a higher density, and the above explanation may not be valid.

It is also possible, when the flat plate electrodes were used with higher pressures, that the contact resistance was reduced. If this were the case, the mercury electrodes could not have made complete contact with the specimen. Also, this would indicate that, if sufficient pressure were applied, the flat plate electrode would have the advantages of the mercury electrode and not its disadvantages.

A series of experiments carried out on samples at different temperatures but at the same relative humidity showed that temperature variations had a marked influence upon the resistance of the samples.

The resistance decreased 15 times as the temperature was increased through a range of 30° C.

It was found that paper failed to obey Ohm's law. Increases in the alternating current voltage across the sample resulted in a decrease of the impedance of the sample. It was suggested by McLean and Kohman (15) that, as voltage is increased, more ions which are bound to the cellulose were displaced, resulting in a lower resistance.

It was found that the resistance increased with decreasing frequencies. Because, at lower frequencies, the relaxation forces counter to the movement of ions may be greater, this increase would result from a greater resistance to the movement of conducting ions.

When samples of high electrolyte contents, but identical in other respects, were tested, it was observed that the resistance appeared to be less dependent upon the ash content than at lower ash contents. As the electrolyte concentration decreased, a critical region was reached below which the resistance rose markedly. It is suggested that at very low ash contents the conduction may be caused largely by the ionic conductivity of electrolytes and water, whereas at high ash contents the conduction may be produced largely by ions.

Tests on unbleached, chlorinated, bleached, and alpha pulp prepared from unbleached sulfite were undertaken. It was observed that resistances of the samples were not appreciably different. This is in line with the theory of conduction advanced by Murphy and Walker (4). The differences in the pulps are due primarily to organic materials

which are nonconductors and would not influence the resistance of the paper.

SUMMARY

Instruments were constructed for measuring both the alternating and the direct current resistance of paper. Precautions were taken to avoid leakage currents and pickup from stray electric fields.

Techniques were developed, in the preparation of the test specimens, to control the individual variables independently of each other.

All specimens were conditioned for 24 hours before testing in specially constructed cabinets of controlled humidity and temperature.

The samples included handsheets, one commercial paper, and an analytical grade of filter paper.

A stainless steel electrode system was finally adopted for testing, after it was found that a mercury system proved impractical.

The data obtained indicate that the specific resistance is dependent upon the area of the electrode, except in cases where the paper is very uniform.

The resistance was observed to decrease with increase in electrode pressure, approaching a limiting value at higher loads.

Studies upon papers of different calipers showed that the contact resistance formed a portion of the measured resistance, and also indicated that the true specific resistance of the specimen did

not remain constant but increased with decreasing caliper.

Temperature studies showed that the resistance decreased with increasing temperatures.

Failure of paper to follow Ohm's law was observed when the applied alternating current voltage was varied. Resistance of paper decreases with increasing applied voltage.

Variation in frequency showed that the resistance of paper increased with decreasing frequencies.

Studies of the resistance of paper at various ash contents indicated that the conduction at low ash contents is due primarily to water. In the intermediate range, the conduction is due to both water and electrolyte. The resistance at high electrolyte content is finally limited by the conductivity of the electrolyte-fiber system.

Organic impurities commonly present in paper do not appreciably alter the measured resistance.

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