

# The Institute of Paper Chemistry

Appleton, Wisconsin

Doctor's Dissertation

**A Study of Certain Factors Influencing  
the Dielectric Strength of Paper**

by Daniel O. Adams

May, 1943

**LOAN COPY**  
To be returned to  
**EDITORIAL DEPARTMENT**

**A STUDY OF CERTAIN FACTORS INFLUENCING**

**THE DIELECTRIC STRENGTH OF PAPER**

A thesis submitted by

Daniel O. Adams

A.B. 1939, Oberlin College

M.S. 1941, Lawrence College

in partial fulfillment of the requirements  
of The Institute of Paper Chemistry for  
the degree of Doctor of Philosophy from  
Lawrence College, Appleton, Wisconsin

May, 1943

**EDITORIAL OFFICE**

## TABLE OF CONTENTS

	Page
INTRODUCTION	1
HISTORICAL SURVEY	4
APPARATUS	16
PREPARATION OF PAPER SAMPLES AND TEST PROCEDURES	28
Preparation of Pulp	28
Preparation of Paper Sheets for Testing	28
Desiccation of Samples	31
Testing of Samples for Dielectric Strength	33
EXPERIMENTAL	37
DISCUSSION OF RESULTS	51
CONCLUSIONS	75
SUMMARY	80
LITERATURE CITED	83

## INTRODUCTION

Paper is desirable as a dielectric or electrical insulator because it has high electrical resistance, high specific inductive capacity (dielectric constant), and low <sup>power</sup> paper factor (dielectric loss). In addition to its electrical properties, paper is relatively cheap and readily obtainable and is supplied in sheet form having high flexibility and sufficient tensile strength to withstand stresses occurring during the fabrication of electrical equipment. For these reasons, the use of paper in the electrical industry is widespread.

Paper holds a practical monopoly in the field of insulation of high-voltage transmission lines where it is applied in several layers as a continuous spiral wrapping. It is widely used as the dielectric medium in condensers. In this case, two or more very thin sheets of paper are laminated with metal foil electrodes and the whole rolled up on itself. In this manner condensers of large area (hence, high capacity) can be made in a compact form. Paper and paperboard are also used as insulation and spacers in electrical equipment such as transformers.

Unfortunately, paper is very hygroscopic and, with absorption of moisture, its high resistance decreases and its dielectric loss rapidly increases. Both these properties are markedly affected by even slight traces of moisture; therefore, precautions must be taken to dry all paper insulation prior to fabrication and to maintain it in a dry state. Commercially, this is accomplished by placing the paper in an evacuated chamber at an elevated temperature until dry and then im-

## LIST OF ILLUSTRATIONS

Figure		Page
1	Test Chamber	19
2	Electrode System	22
3	Schematic Diagram - Vacuum and Gas Pressure Systems	25
4	The Effect of Relative Humidity on the Gas Pressure-Breakdown Gradient Relation	40
5	The Effect of Temperature on the Breakdown Gradient of Paper at 100 lb./sq.in.	42
6	The Effect of Temperature on the Gas Pressure-Breakdown Gradient Relation	44
7	The Effect of Density on the Breakdown Gradient at Various Pressures at 60° C.	46
8	The Effect of Sheet Density on the Gas Pressure-Breakdown Gradient Relation	47
9	The Effect of Sheet Thickness on the Breakdown Gradient at Various Pressures at 60° C.	49
10	The Effect of Sheet Thickness on the Gas Pressure-Breakdown Gradient Relation	50
11	A Comparison of the Observed Breakdown Gradient of Paper with the Calculated Dielectric Strength of Nitrogen	53
12	The Observed Breakdown Gradient of Paper and the Calculated Breakdown Gradient of Gas in the Intensified Field	58
13	The Effect of Relative Humidity on the Observed Breakdown Gradient, the Calculated Values for Gas, and the Barrier Action at 20° C.	66
14	The Effect of Temperature on the Observed breakdown Gradient, the Calculated Values for Gas, and the Barrier Action	69
15	The Effect of Sheet Density on the Observed Breakdown Gradient, the Calculated Values for Gas, and the Barrier Action at 60° C.	70
16	The Effect of Sheet Thickness on the Observed Breakdown Gradient, the Calculated Values for Gas, and the Barrier Action at 60° C.	73

pregnating the paper with some water-repellent compound, usually an oil, resin, or wax. The dry impregnated paper is then fabricated into a condenser or cable wrapping, and enclosed in a moisture-vaporproof sheath.

In the use of a dielectric or insulator, that property known as its dielectric strength is of utmost importance. It imposes an upper limit to the voltage stresses to which the dielectric may be subjected with safety. Dielectric strength is that faculty of a dielectric which enables it to offer an extremely high resistance to the flow of electric current, despite the voltage stress. If, however, the voltage stress exceeds the dielectric strength of the material, phenomena known as breakdown or failure occur and the dielectric becomes conducting. The exact nature of breakdown and the mechanisms by which it occurs are unknown. With solid dielectrics, the damage occurring at breakdown is irreparable and subsequent applications of voltage give breakdown at lower voltages than originally.

The dielectric strength of a material is determined in practice by placing a sample between electrodes and subjecting it to a voltage stress until breakdown occurs. Generally, the magnitude of the voltage stress is increased in accordance with some arbitrary time schedule. The dielectric strength of the material is then expressed in terms of the voltage stress at the instant of breakdown--i.e., the total voltage at breakdown divided by the thickness of the sample. The values for the dielectric strength thus obtained depend upon the previous history of the dielectric, the conditions of the test, the time-voltage schedule, and the geometry of the test equipment.

The dielectric strength testing of paper has been carried out largely on impregnated paper samples, frequently in the form of fabricated condensers or cables. In this way the paper can be tested directly under conditions simulating those of use. At the same time, changes in moisture content during the period of test are minimized and corona, with its damaging effects, is practically eliminated. However, the dielectric properties of the impregnant are superimposed on those of the paper in a complex fashion. This, together with the effects of the several variables associated with the impregnation process, such as completeness of impregnation, creates uncertainties in the interpretation of the results.

Control tests of dielectric strengths of paper for electrical uses are frequently carried out in room air without impregnation. In this case, the presence of corona and moisture content variations probably distort the results and make interpretation uncertain, if not impossible.

The object of the present study was to investigate the dielectric strength of paper and certain of the variables effecting it. As a result of this investigation, it was hoped that information may be obtained concerning the mechanism by which breakdown occurs. The samples of paper were not oil-impregnated, but were tested in an atmosphere of compressed nitrogen. By varying the pressure, the dielectric strength of the impregnating gas can be made to vary continuously without appreciably affecting the other electrical characteristics of the fiber-gas combination.

## HISTORICAL SURVEY

Most of the research work on the dielectric strength of paper has been carried out by the manufacturers of electrical equipment involving paper as a dielectric. A large portion of the results obtained in this work is retained by these manufacturers as an industrial secret. As a result, the information appearing in the literature on this subject is very fragmentary, and many of the gaps must be filled by analogy with the behavior of other dielectric materials.

The paper manufacturers who supply the electrical industry with its paper have published practically nothing concerning the dielectric strength of paper. This may indicate either a lack of research or a desire to keep the results of such research confidential.

Because of the fact that most of the information on paper dielectrics comes from the electrical industry, it is only natural that the great mass of it concerns the use requirements of the paper. Most of the tests are run on impregnated papers, often on completely fabricated condensers and cables. The interpretation of these results in terms of the unimpregnated papers is uncertain, if not impossible.

A good review of the literature up to 1932 on the dielectric strength of dielectrics in general is found in the book of S. Whitehead (1). This publication contains a good discussion of the phenomenology and a review of the theories of dielectric breakdown set forth at that time. Briefer reviews of the general subject are given in the books of Peek (2) and Finer (3). J. B. Whitehead devotes a chapter of his

monograph on impregnated papers (4) to the dielectric strength of impregnated paper.

The materials used as test electrodes and the configuration of these electrodes have been the subject of much study. Although this work has been carried out, for the most part, on dielectrics other than paper, the results are probably applicable to all dielectrics. The consensus of the results on the effect of various electrode materials is given by Miner (3). He states that, provided the electrode material does not hamper the dissipation of thermal energy from the sample, it will have no effect on its dielectric strength. This statement is confirmed by the work of Clark and Montsinger (5), who observed a change in the dielectric strength of paper when they changed from metal electrodes to wooden electrodes faced with tin foil. Various metallic electrodes gave essentially identical results.

The standard procedures for testing the dielectric strength of insulating materials (6) prescribe test electrodes having the edge rounded to a given radius of curvature. The necessity of this step has been the subject of some controversy. Clark and Montsinger (5) reported a difference of less than 1 per cent between the dielectric strengths of paper tested with electrodes having square edges and those having rounded edges. This was the average result of 92 trials with each electrode. Miner (3) stated that the agreement of the dielectric strengths as tested by the square- and the rounded-edged electrodes occurs only for thin samples. Data obtained on materials other than paper confirm this (1, 7). It is possible that the difference is the

result of discharge occurring in the surrounding medium at the higher voltages required for thick samples. This discharge would be more likely to occur in the case of the electrodes with square edges.

Apparently the area of the test electrodes has an effect on the measured dielectric strength. In general, the dielectric strength decreases as the area of the electrodes increases. This is especially true with thin samples of a heterogeneous material such as paper (7-9). S. Whitehead (1), Peek (2), and Milnor (10) stated that this drop can be accounted for statistically. The greater the electrode area, the greater the probability of inclusion of a weak spot within that area and, hence, the lower the observed dielectric strength. S. Whitehead (1) and Milnor (10) derived equations describing this effect which show good agreement with experimental results. Kennelly and Wiseman (11) studied this effect using varying numbers of small electrodes in parallel. In this way the effect of a large area could be obtained by using an increased number of small electrodes. They found that the area tested had no effect upon the dielectric strength. They attributed the decrease observed by other investigators to the poorer degree of contact between the test sample and the electrodes as the area increases. Hill (12) checked the work of Kennelly and Wiseman and obtained essentially the same result.

No doubt the most important variable in dielectric strength measurement is the duration of the voltage stress. Voltages below the value causing instantaneous breakdown may result in eventual breakdown if applied for sufficiently long periods of time. Probably the best

known equation describing this phenomenon is that of Peek (2), which is sometimes referred to as "Peek's law." It is

$$V = V_0 \left[ 1 + \frac{a}{\sqrt[4]{t}} \right],$$

where

$V$  = applied voltage,

$V_0$  = voltage causing breakdown in an infinite time,

$t$  = time required for breakdown to occur at voltage  $V$ , and

$a$  = a constant.

This is an empirical equation first derived to fit experimental data on the dielectric strength of paper. In this instance, the times were varied from a fraction of a second to 60 seconds. In discussing this equation, S. Whitehead (1) stated that it adequately describes the experimental result of time voltage studies on all dielectrics where any definite order exists. He further stated that it has been shown to be in error for tests lasting more than a day. J. B. Whitehead (4) reported that most engineers in the field prefer to use relations in which the voltage varies as the reciprocal of some root of the time. Values from the square root to the seventeenth root have been employed. A number of other formulas have been suggested on the basis of several of the theories of dielectric breakdown but, for the most part, these are difficult to use and rarely describe the situation as well as the simpler formulas of Peek and others.

Clark (13) carried out interesting experiments on paper dielectrics in which he repeatedly subjected a sample to a voltage stress for short intervals of time until breakdown occurred. He found that the total time to breakdown was the same regardless of the number of

intervals, provided each interval was in excess of 40 per cent of the total time. Apparently, the effects of repeated voltage stresses are cumulative.

The effects of voltage wave-form on the dielectric strength of solids are not clear. Miner (3) stated that commercial variations from the sine wave have no effect on the test results but that more drastic distortions might. It is reported (14) that the dielectric strength of paper depends upon the peak voltage. S. Whitehead (1) concluded that dielectric strength depends on both peak and root-mean-square values of the voltage and is measurable by neither of these quantities alone.

According to Harvey (15), the dielectric strength decreases with frequency increase and the value at radio frequencies may be only 10 to 20 per cent of the value at commercial frequencies. The values for frequencies up to 100 cycles per second are more or less constant. The effect of frequency on the dielectric strength of most organic materials is adequately described by the equation of Vogel (16),

$$\underline{V} = \underline{V}_0 / \underline{f}^n,$$

where

$\underline{V}$  = the breakdown voltage,

$\underline{V}_0$  = a reference voltage,

$\underline{f}$  = the frequency in cycles per second, and

$\underline{n}$  = a constant between 0.0 and 0.5.

Miner (3) stated that the effect of frequency is slight in materials having low resistivity, such as moist paper.

Miner (3), in discussing the effects of temperature on dielectric strength, wrote: "If moisture is present, speculation on the effect of temperature is useless. Data can be found to prove almost any relation." Moisture-absorbing dielectrics generally improve in dielectric strength upon heating in air. Most theories of dielectric breakdown, especially the so-called thermal theories, demand that temperature increase have an unfavorable effect on the dielectric strength. This effect is pronounced if the dielectric loss of the material is high. S. Whitehead and Nethercot (17) found that, in long-time tests, the dielectric strength of greaseproof and condenser tissues remained constant with temperature variations. On short-time tests, breakdown voltage was reached within a few seconds and dielectric strengths decreased with temperature increase. This difference in results may be caused by a drying of the paper during the long-time tests.

Gaseous ionization or corona has deleterious effects on fibrous insulation (18). This may be the result of the formation of ozone and oxides of nitrogen.

The effects of electrolyte content on the electrical properties of paper have been reported by Finch (19, 20) and Kohman (21). Finch stated that concentrations of chloride ion as low as 0.03 per cent are objectionable. The effect of chloride involves its reaction with the electrode materials, forming products which catalyze the degradation of the oil impregnant. Kohman (21) stated that ash contents below a certain upper limit have no observable effect on the dielectric strength of paper.

Kohman (21), referring to the work of Riley and Scott, stated

that a paper sheet containing a pinhole had a lower dielectric strength than gas alone at the same electrode spacing. Gyemant (22) found that paper containing holes up to 0.2 mm. in diameter had a dielectric strength 20 to 30 per cent higher than air at the same spacing. These statements appear to be contradictory.

In general, the dielectric strength of cellulose decreases with increased moisture content. Kohman (21) stated that moisture contents below 0.1 per cent have no effect on the properties of the insulation.

Kohman (21) reported that thermal degradation of paper appears to have no effect on the dielectric strength of paper. Samples which were aged in an oven for 20 hours at 150° C. were tested and, although the paper was discolored and brittle, the dielectric strength remained the same or had improved slightly.

The density of a sheet of paper has an effect on the dielectric strength. J. B. Whitehead (23-25) found that the dielectric strength of impregnated paper insulation decreased as the density increased. The effect was observed with two different oils as impregnants. He explained this as the result of the increased dielectric constant of the denser sheets. With increase in the dielectric constant of the sheet, the field within the oil channels between the layers of paper would increase and, hence, breakdown at a lower over-all voltage would occur. Later, he included a factor which depended upon the ions absorbed from the paper into the oil, thus increasing the conductivity of the oil. Because the higher density sheets contained a higher ratio of fiber to oil, the

number of ions thus absorbed would increase with sheet density. Under the applied voltage, these ions migrated to the edges of the oil channels where, according to Whitehead, they acted as space charges and increased the stress in the oil-paper interface. By this mechanism, the dielectric strength of the denser sheet was smaller than that of the less dense sheet.

The dielectric strength of paper has been observed to decrease with increasing thickness of the paper sheet. This effect was studied by Clerk and Montsinger (5). They found that the thickness-dielectric strength relation could be expressed by the following equation:

$$\underline{V} = \underline{A} \underline{d}^{\underline{n}},$$

where

$\underline{V}$  = the breakdown voltage,

$\underline{d}$  = the sample thickness, and

$\underline{A}$  and  $\underline{n}$  = the constants.

$$0.5 < \underline{n} < 1$$

The constants  $\underline{A}$  and  $\underline{n}$  were found to vary with a number of the variables which affect the dielectric strength of paper. Recently J. B. Whitehead (24, 25) found that the dielectric strength of impregnated paper decreased with increasing thickness. He explained this by the same mechanism used to explain the effect of density--namely, the thicker sheet involved a greater ratio of fiber to oil and, hence, a greater concentration of ions which could form space charges within the oil channels.

The porosity of a sheet of paper is thought by some to have a

marked effect upon its dielectric strength. Mannelli (26) stated that the greater the "impermeability" of a sheet of paper, the greater the dielectric strength.

There are nearly as many theories on the cause and mechanism of dielectric breakdown as there are workers in the field. Most of these theories fall into either of two classes: electrical theories or thermal theories. Proponents of the electrical theories feel that breakdown depends upon the motion of electrically charged particles (ions, or electrons) within the dielectric. Breakdown is supposed to occur when the field within the dielectric is sufficient to accelerate these particles to a critical velocity between impacts. The advocates of the thermal theories point to the strong dependence of the dielectric strength of some materials on the temperature. They feel that breakdown will occur when the rate of heat generation within the dielectric resulting from electrical conduction or dielectric loss exceeds the rate of heat dissipation by conduction or radiation. Their theory is based upon the premise that the losses are strongly dependent on the temperature, being greater at higher temperatures. There are also many theories involving a combination of the two theories. Moon and Norcross (27) claimed that there are three types of breakdown and that the type occurring in any case depends upon the temperature. S. Whitehead and Nethercot (17) stated that the electrical theory describes breakdown at low temperatures, whereas the thermal theory describes it at elevated temperatures. This last belief is shared by many workers in the field, although some controversy exists as to the temperature at which the change takes place.

The most generally accepted mechanism of electrical breakdown is that of von Hippel (28). In this mechanism, the electron is involved and breakdown occurs when the electron is sufficiently accelerated to enable ionization by impact to occur. The electron is formed by some accidental process such as cosmic rays, photons, or radioactive emission. If this electron, accelerated by the electric field, does not acquire energy in excess of a certain value in one mean free path, then it will be trapped by the crystal lattice. This energy, lost by the electron, causes oscillation of the lattice ions. If the accelerated electron gains energy in excess of the critical amount, it will be capable of causing ionization by impact and, hence, breakdown. This theory has been successful in explaining the breakdown of such simple materials as the alkali halides but as yet has not been applied to more complicated materials. Fröhlich (29), Seeger and Teller (30), and others have modified this theory slightly and have devised equations for calculating the dielectric strength of a material from other known physical constants.

Joffé (31) proposed a theory in which the motion was that of an ion rather than of an electron; however, the ionic mobilities of solids are low, and the theory cannot satisfy the experimental results.

Smekal (32) suggested a theory in which the imperfections which are always present in a crystal structure were used to explain an ionic mobility leading to breakdown. Von Hippel (28), however, observed that breakdown follows definite crystallographic directions and does not take a random course which would be predicted by imperfections.

Hoover (33) evolved a theory on the basis that ions or free electrons present in a dielectric were always in kinetic equilibrium with the rest of the material. The position of this equilibrium varied directly with the polarization of the material. Breakdown was supposed to occur when the polarization required more ions for equilibrium than the dielectric could produce.

Thermal theories have been developed by many investigators, each starting with different assumptions and concluding with slightly different results. One of the earliest theories was that of Wagner (34), which is still considered as complete and satisfactory as those developed later. In this theory, Wagner assumed that there exist in all dielectrics imperfections or weak spots where the electrical conductivity is greater than in the rest of the dielectric. He also assumed that the electrical resistance decreases strongly with temperature increase. If his dielectric is subjected to a voltage stress, greater current will flow through the weak area than through the rest of the dielectric. Because the heat generated is proportional to the product of the current and the voltage, the weak spot becomes warmer than the rest of the dielectric. Thermal gradients and, consequently, conductivity gradients are set up. This process proceeds until the point is reached where the heat generated exceeds the heat dissipated. If the dielectric is stressed at voltages in excess of the voltage where this occurs, breakdown will result in time. This theory was also independently derived by Hayden and Steinmetz (35). Theories which are essentially the same, but which differ in some of the assumptions, have been derived by Inge, Semenov, and Walther (36) and many others. The thermal theories all are quite

effective in predicting breakdown when voltage is applied for prolonged periods of time although, even then, the time predicted tends to be much longer than is found in practice. Thermal theories have failed completely to explain breakdown resulting from short-time applications of voltage and transients.

## APPARATUS

The literature makes no mention of an apparatus for determining the breakdown gradient of dry vapor in an atmosphere of compressed nitrogen; therefore, such an apparatus had to be devised. This apparatus consisted of the following components: a source of high voltage, a high voltage voltmeter, an electrode system, a test chamber, a system for evacuating the test chamber and for supplying it with gas under pressure, and a detector to indicate breakdown.

The source of high voltage consisted of a General Electric luminous-tube type transformer. This was rated at 900 volt-amperes, with a secondary rating of 60 milliamperes at 15,000 volts. The primary was designed to operate on 110-volt, 60-cycle, a.c. current. This type of transformer was capable of withstanding a sustained short circuit without damage.

In order to make the high voltage supply continuously variable, the primary of the high voltage transformer was connected across the secondary of a General Radio Variac (an autotransformer). The Variac was operated on 110-volt, 60-cycle, a.c. current and had a maximum output of 130 volts. To make possible a finer adjustment of the voltage, a variable resistor (a Genco rheostat of the tubular type) was inserted in series with the primary of the high voltage transformer.

The high voltage voltmeter consisted of a high resistance and a microammeter. These, in series combination, were connected across the terminals of the secondary of the high voltage transformer. The voltage of the transformer secondary was calculated by assuming Ohm's law to hold.

The high resistance was composed of ten 1.5-megohm resistors made by the Continental Carbon Company. These were connected in series. Each resistor was tested for resistance in a Wheatstone bridge using 45 volts, and all were found to differ from 1.5 megohms by less than 1 per cent. This variation was within the accuracy of the bridge. Subsequent work at 300 volts gave values for the resistance as 1.5 megohms when compared with a 1.0-megohm I.R.C. precision wire-wound resistor which had an accuracy of 1 per cent. This would indicate that Ohm's law was essentially valid for these resistors between 45 and 300 volts. The average working voltage across the resistors when in use was 150 volts, which is well within this range.

The microammeter was made by the Cambridge Instrument Company and was designated as "R pattern." It had a full-scale deflection of 150 microamperes. The meter was converted to a.c. operation by the use of a full-wave rectifier of the semiconductor type. The meter was calibrated by employing it to measure the current passing through a resistor of known resistance when a known voltage was applied. An I.R.C. precision wire-wound resistor was used, which was rated at 1.0 megohm to an accuracy of 1 per cent. The voltage was measured by a General Electric voltmeter, Type P-3, with full-scale deflections of 150 and 300 volts. It had an accuracy of 0.2 per cent of full-scale value. Knowing the resistance and the voltage, one could calculate the current flowing through the resistance by means of Ohm's law.

The test chamber had to be so designed and constructed that it could be evacuated to a pressure of the order of 10 microns at a temperature of 60-70° C. and also withstand internal gas pressures of

the order of 200 pounds per square inch. The period of evacuation and heat was that for the desiccation of the samples, whereas the gas pressure was to be applied during the testing of the samples. With this idea in mind, the test chamber (Figure 1) was constructed from a 7-inch length of 3-inch seamless steel tubing having a wall thickness of 1/4 inch. The ends of the test chamber were formed by two 12-inch squares of 1/2-inch boiler plate. Vacuum seals between the plates and the tube were effected by rubber gaskets and vacuum grease. The test chamber was held together by five 1/2-inch round iron rods. One end of each rod was turned down to 3/8-inch diameter, and both ends were threaded. The 1/2-inch end was screwed into a tapped hole in the bottom plate, whereas the other end passed through a 1/2-inch hole in the top plate and was fitted with a 3/5-inch nut. By adjustment of these nuts, it was possible to obtain any desired compression of the rubber gaskets.

At a height of 4 inches on the wall of the test chamber, ten equally spaced holes were drilled using a size X drill. Into each of these holes a number 0 rubber stopper was forced as far as possible from the inside of the chamber. The portion of the stopper which protruded outside the chamber expanded sufficiently to prevent the stopper from being sucked back into the test chamber during the evacuation. Each stopper was pierced centrally with a length of No. 18 copper wire prior to its insertion in the chamber wall. This copper wire served as an electric conductor; the rubber stopper served as an insulator; together they were high voltage lead-ins. Any leaks occurring around the lead-ins were sealed with a linseed oil product which was prepared by

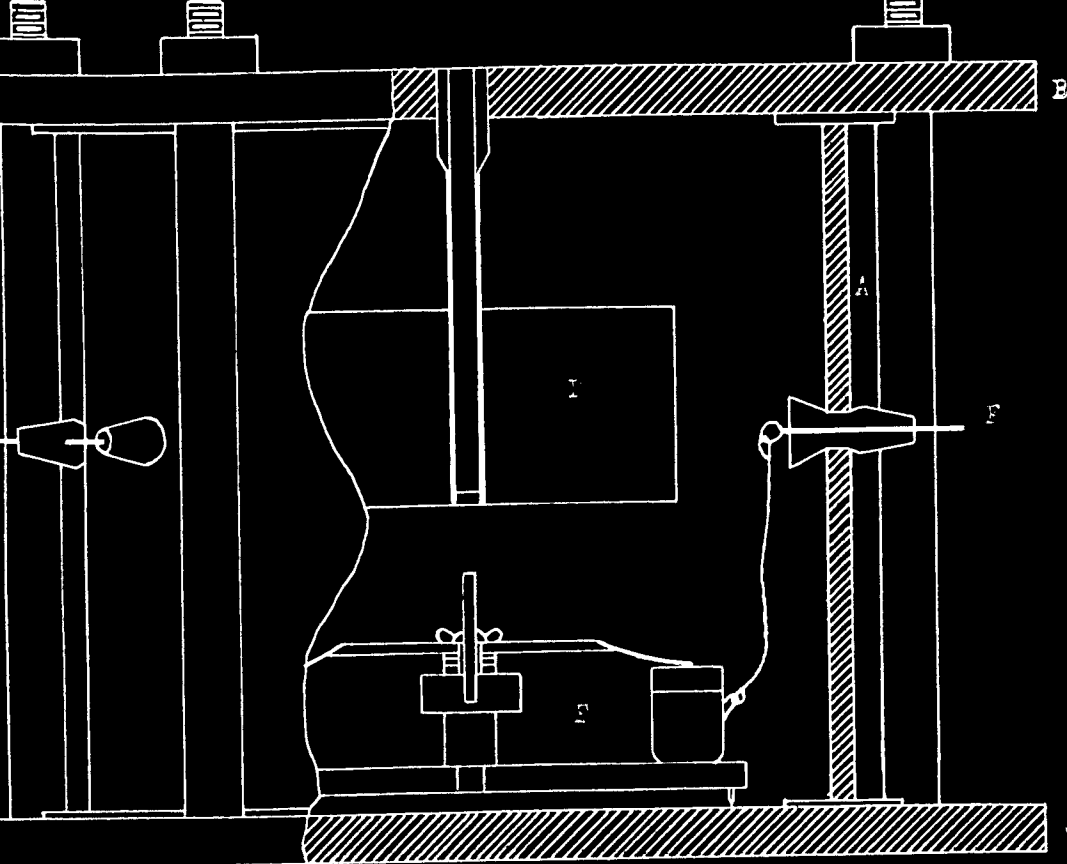


Fig. 1

Test Chamber

1-1 Visk. Fluid Detector

1-2 Visk. Fluid Detector

prolonged heating of linseed oil in the neighborhood of the flash point. This compound was extremely viscous at room temperature and retained a large measure of its viscosity at 60° C.

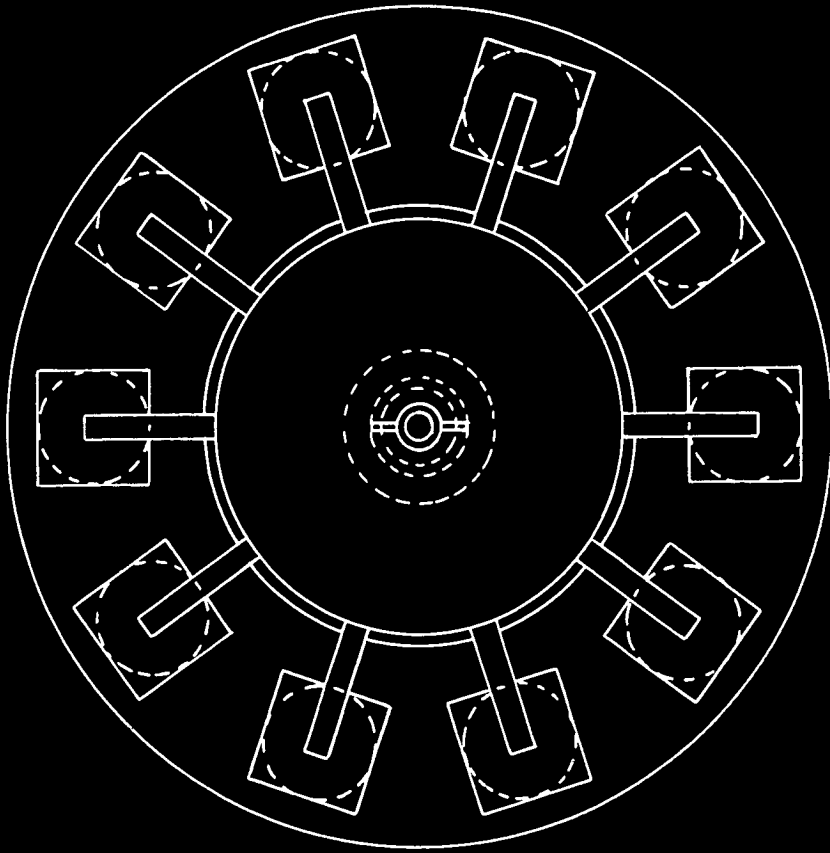
Vacuum and pressure connections to the test chamber were made through a 1/4-inch pipe which was screwed into the wall of the chamber about 2 inches from the bottom of the tube. This joint was sealed with a hard wax of the Dennison series.

A thermometer well consisting of a 4 1/2-inch length of 1/8-inch pipe was screwed into the center of the top plate of the test chamber. The joint was sealed with a hard wax. All but a short portion of the threaded end of the pipe was turned down to a wall thickness of 0.02 inch. This was done to reduce the heat transfer by conduction between the top plate of the test chamber and the bottom of the well. The bottom of the well was closed with a snug-fitting brass button which was soldered in place. To facilitate heat transfer between the lower portion of the well and the surrounding gas, ten radial fins of copper were soldered to the wall of the well. These fins were blackened with a thin coat of black lacquer. The efficiency of the thermometer well was tested by placing one of two calibrated thermometers in the well and the other in the gas directly below the thermometer well. The test chamber was then heated in various ways, and the difference between the two thermometer readings was taken as the error involved in temperature measurement of the gas by the well. Under extremely unfavorable conditions (i.e., all the heat applied to the top plate), the temperature recorded in the well was 4° C. higher than the temperature of the gas.

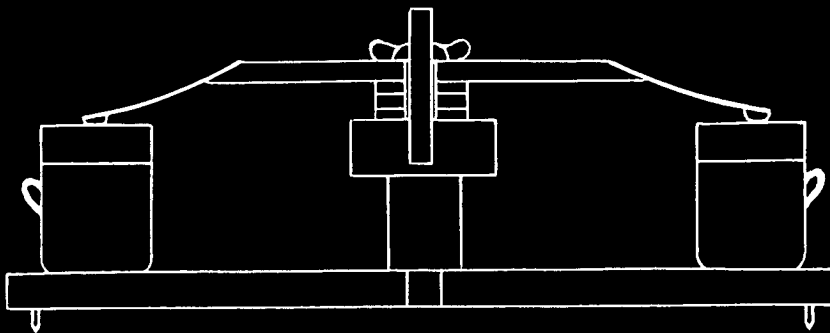
Under conditions employed during the use of the chamber (i.e., a more uniform distribution of heat), the temperature recorded by the thermometer in the well was in error less than 2° C. All these measurements were made at atmospheric pressure. The errors would probably be greater when the chamber was evacuated, since the rate of heat transfer by convection would be reduced. On the other hand, the errors would be less when the test chamber was filled with gas under pressure. Because the effect of temperature is slight during the evacuation portion of the cycle, this objection was not important.

At the time this apparatus was being designed, it was thought that the dielectric strength of paper would be very erratic and, hence, would require the testing of a number of specimens to obtain an accurate value. With this in mind and in view of the fact that the desiccation of the specimens prior to test required a long time, it was decided to design the electrode system so that a number of specimens could be conditioned at once. Consideration also had to be given to the fact that the time involved in testing the specimens increased as the first power of the number of specimens tested, whereas the accuracy of the resulting average increased only as the square root of this number. For these reasons, the number ten was decided upon as giving a satisfactory average and yet not involving an excessive amount of time.

The electrode system (Figure 2) consisted of ten small high voltage electrodes and one large common ground electrode. The ground electrode formed the base of the system. The high voltage electrodes were placed in a circle upon the ground electrode and were separated from it by the paper specimens. A spring clamping mechanism held the



Top View



Side Section

Figure 2

Electrode System

high voltage electrodes against the paper samples with a definite force.

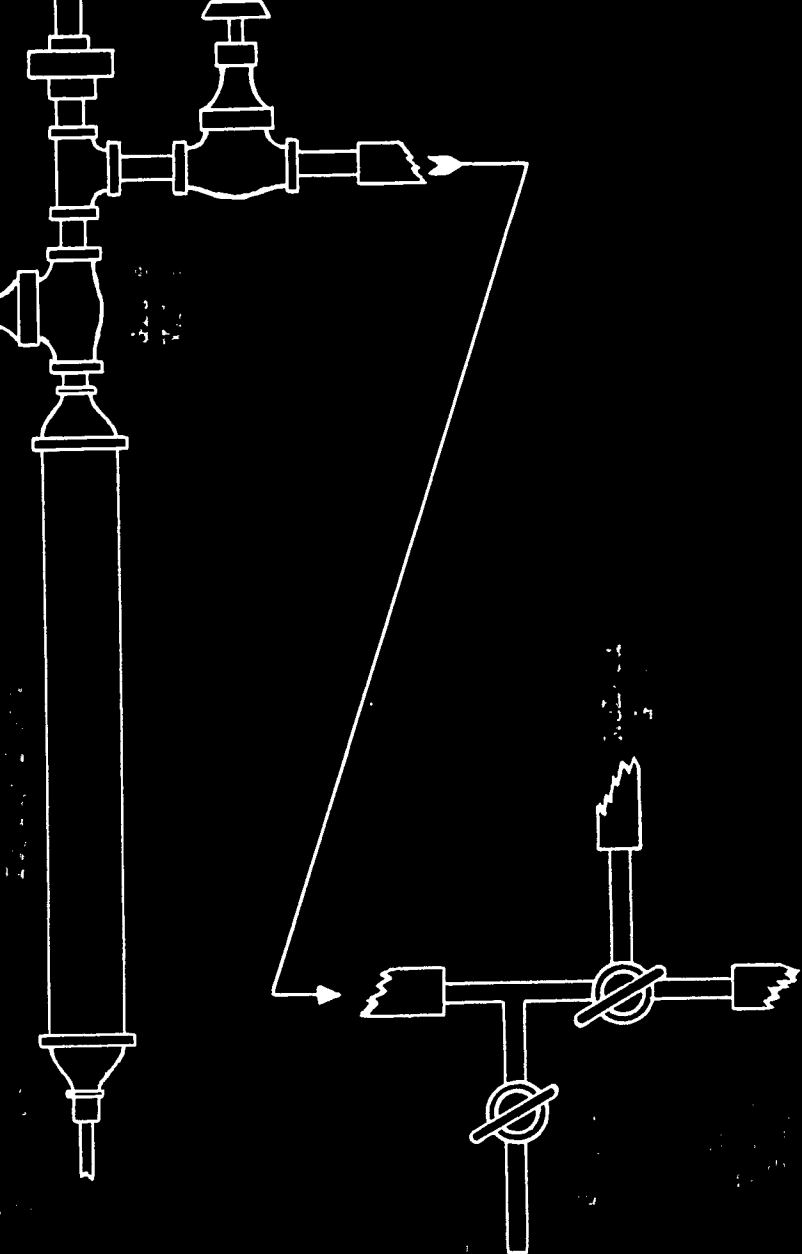
The ground electrode was made from a 5 3/4-inch disk of 1/4-inch brass. One surface was ground smooth and flat with carborundum on a plate glass surface. The final polishing was done on a cloth impregnated with carborundum. This electrode was mounted on three legs made from phonograph needles set in holes in the bottom of the electrode. These legs enabled the plate to be thermally insulated from the bottom plate of the test chamber (hence, at the temperature of the gas), and yet to be electrically connected to the bottom plate through the sharp points of the needles. A post of iron 1 inch long and 1/2 inch in diameter was screwed into the center of the top side of the electrode. A stud an inch long was put in the top of the post. This post served to support the spring clamping mechanism.

The high voltage electrodes were made from 3/4-inch lengths of 3/4-inch round brass rod. The edge of one end was turned to a 1/8-inch radius. This end was ground flat and smooth with carborundum and polished on a cloth. Before each test, each of these electrodes and the ground electrode were carefully wiped free from grease and foreign material with a soft cloth saturated with benzene. A short loop of copper wire was soldered on the side of each electrode to afford electrical connection. The high voltage electrodes were connected to the high voltage lead-ins by means of links formed of stranded wire. These were hooked to the lead-ins and were attached to the electrodes by "Pee-wee" clips. A 3/4-inch square of thick plate glass was cemented on the top of each electrode to insulate it from the clamping device.

In order to maintain a known separation between the electrodes, it was decided to hold them together with a clamping device which would compress the paper specimen with a definite pressure. This also eliminated troubles resulting from cockling of the sheet. The pressure chosen was that exerted by the foot of the ordinary caliber gage (7.5 pounds per square inch). By this choice it was possible to use the caliber of the specimen directly as the electrode separation, since the areas involved were approximately the same.

The clamping device consisted of a 3-inch disk of 1/8-inch brass. This had a central hole which fitted loosely over the stud on the ground electrode. The top edge of the disk had a 30-degree bevel. Fastened on this beveled portion, and projecting radially from it, were ten 1-inch leaf springs. A bead of solder on the projecting tip of each spring served as a contact on the glass plates of the high voltage electrodes. By tightening a wing nut over the disk on the stud, it was possible to cause a deflection of the springs. The magnitude of the force thus exerted on the electrodes could be regulated roughly by inserting washers between the disk and the top of the post, thus limiting the deflection of the springs. Fine adjustments of the forces were made by filing the solder beads. The pressure did not change appreciably with the caliber of the specimens, because the total deflection of the springs was about 1/4 inch whereas the caliber variations were only a few mils.

The system for varying the pressure in the test chamber and also for evacuating it is best understood by reference to Figure 3.



The pressure was supplied from a cylinder of compressed nitrogen. Prior to introduction into the test chamber, the nitrogen was dried by passing it through a drying train. The drying train consisted of a 16-inch length of 1-inch pipe, of which the first 6 inches were filled with Anhydron and the last 10 inches were filled with phosphorus pentoxide. Every 2 inches throughout the length of the train, plugs of glass wool were inserted to minimize channeling. The drying train and the pipe fittings connecting it to the test chamber were sealed with de Khotinsky cement; thus, entrance of moisture after the gas was dried was precluded. A 1/4-inch globe valve, having a soft rubber disk and packed with cotton waste saturated in stopcock grease, was placed in the line between the drying train and the test chamber, permitting the drying train to be shut off from the rest of the system during the evacuation of the chamber. Evacuation was obtained with a Cenco Hyvac pump. The system was sufficiently tight to permit evacuation to better than 10 microns with paper specimens in the chamber. The pressure in the test chamber during the evacuation period was determined by a McLeod gage of the compact form made by Ace Glass Inc. The scale on this gage was extended to read pressures down to 0.1 micron. The vacuum system could be shut off from the test chamber during the pressure portion of the cycle by means of a second globe valve similar to the one described above.

In order to prevent accidental contact with the high voltage, the test chamber was enclosed in a cage of 1/4-inch mesh hardware cloth. A section of the 110-volt line running to the Variac was mounted on this cage. In order to remove the cage, electrical connections to the Variac had to be broken. This prevented operation of the high voltage supply except when the cage was in place.

The test chamber was heated by three electric spotlights. In this way the complexities of a special oven were avoided.

Breakdown of the paper samples was detected by amplifying the voltage variations across a 600-ohm resistor in the ground return line from the test chamber. The amplifier was a General Radio d.c. operated amplifier. The output of the amplifier was fed into a pair of headphones. Breakdown was evidenced by a loud popping or "frying" noise easily heard above the 60-cycle hum.

## PREPARATION OF PAPER SAMPLES AND TEST PROCEDURES

### PREPARATION OF PULP

The pulp used in the formation of paper sheets for dielectric strength testing was prepared by cooking spruce chips in an indirectly heated 10-pound experimental digester by the kraft process. The cooking data are given in Table I. Two cooks were made employing identical conditions. Each cook was washed twice in the blowit under conditions of good agitation. The pulp was drained, screened through an 8-cut screen plate, pressed to a moisture content of 20-25 per cent and picked into small pieces. The pulps from the two cooks were thoroughly mixed and stored in tightly covered metal pails lined with waxed paper. During the time of storage, the moisture content of the pulp changed very little and no indications of bacterial action were observed.

### PREPARATION OF PAPER SHEETS FOR TESTING

The pulp described above was beaten or refined prior to sheet formation in the Lampen ball mill. The high degree of reproducibility of results on the Lampen ball mill, the small size of the pulp charge required, the simplicity and speed of operation, and the probable lack of contamination of the pulp through the introduction of inorganic matter during beating prompted the use of this piece of equipment.

The procedure used in processing the pulp was, in the main, that specified in Institute Tentative Method 407. Some modifications were introduced to permit more complete utilization of the pulp. A brief outline of the procedure employed follows.

TABLE I

DATA ON EXPERIMENTALLY PREPARED PULP

Wood Data

Species-----Black Spruce  
 Seasoning after cutting-----3 years  
 Chip length-----3/4 inch  
 Moisture content-----17.0%

Cooking Data

Process used-----Kraft  
 Active chemical as NaOH-----22.0%  
 Sulphidity-----33.3%  
 Water ratio-----5:1  
 Chip charge-----5150 grams  
 Maximum temperature-----180° C.  
 Time to maximum temperature-----1 hour  
 Time at maximum temperature-----3 hours  
 Pressure at blow-----50 lb./sq. in.  
 Relief continuous to 100° C., none thereafter until blow

Yield Data

	Cook A	Cook B
Weight of screened pulp, oven dry -	2060 grams	2160 grams
Yield of unscreened pulp -	41.6%	43.5%
Yield of screened pulp (oven-dry wood)	40.0%	42.5%
Screenings (total yield basis)	3.7%	2.9%
Permanganate number of mixed pulps-----	17.0	

Disintegration was accomplished by diluting 72 grams of oven-dry pulp to 2 liters with water. The mixture was disintegrated in the British disintegrator for 3000 revolutions (on the counter) with the propeller 2 inches from the bottom. The pulp was thickened on filter paper and divided into three equal parts by weight.

In beating, one portion of the disintegrated pulp (24 grams on the oven-dry basis) was diluted to 800 ml. with water and dispersed manually. This mixture was distributed about the ball, the cover put on, and the mill revolved for 12,500 revolutions or 50 minutes. The pulp was then diluted to 3840 ml.

One half of the diluted pulp was cleared at a time in the British disintegrator for 300 revolutions (on the counter) with the propeller 1 inch from the bottom.

From each portion of cleared stock, 320 ml. of pulp were removed and diluted to 1 liter for freeness for determinations on the Schopper-Riegler freeness tester. The remainder of the stock was diluted with 5 liters of water and used for forming sheets.

If more pulp was required for the preparation of any one set of sheets than was cleared at one time, the cleared pulps were mixed thoroughly prior to forming sheets.

Handsheets were prepared on the British sheet machine according to Institute Method 411. The sheets were dried in room air. During the course of the work, it was occasionally necessary to make departures from Method 411; whenever this occurred, mention will be made of the fact.

A 4-inch square was cut from each handsheet after drying which, in turn, was cut into 1-inch squares. By this method, only the central portions of the handsheets were used. The 1-inch squares were each carefully inspected both with reflected and with transmitted light, and all those containing irregularities or dirt were discarded. The accepted samples were stored in a desiccator over calcium chloride. Care was taken during the above operations to limit contact between the sheets and the hands to a practical minimum. Once in the form of the 1-inch squares, the sheets were handled only with tweezers.

The choice of 12,500 revolutions or 50 minutes for the duration of the beating process was arrived at after inspection of the strength evaluation data of the pulp as obtained by the Lampén ball mill (Table II).

TABLE II

DATA ON STRENGTH EVALUATION OF PULP WITH THE LAMPÉN MILL

Beating Time min.	Freeness S.-R. cc.	Burst* points/100 lb. ream wt.	Tear* g./100 lb. ream wt.	Density g./cm. <sup>3</sup>	Gurley Porosity sec.	Basis Weight* lb.
0	820	139	254	0.741	5.9	44.6
20	795	156	217	0.803	9.4	45.7
40	750	185	172	0.841	34	46.4
80	660	187	176	0.890	466	45.6

\* Ream size, 25 x 40—500.

DESICCATION OF SAMPLE

In most cases the samples were tested for breakdown gradient only after a period of desiccation, during which time the sample was

inside the test chamber and in position to be tested. The drying was accomplished by prolonged evacuation of the test chamber while it was at a temperature of 60-70° C. Because such a treatment results in a paper sheet of negative moisture content as determined by heating at 105° C. and because of the difficulties encountered in removing the specimens from the test chamber without absorption of moisture from the outside air, no direct tests were made of the efficiency of this method of desiccation. The method was tested indirectly, however, by desiccating samples for various lengths of time and then testing these samples for breakdown gradient. It was shown that evacuation for periods longer than 12-15 hours increased the breakdown gradient of the samples but little. Evacuation for periods shorter than 12 hours revealed a steady improvement of the breakdown gradient with an increase in the evacuation period. For the purpose of this work, it was decided to standardize on a desiccation period of 14 hours. This period was within the range for essentially constant breakdown gradient and was convenient in that the samples could be desiccated overnight.

Experiments were also carried out to test the effectiveness of flushing techniques in desiccation. The term "flushing" refers to the following operation. A reasonable vacuum was attained, dry nitrogen was admitted up to atmospheric pressure, and the chamber re-evacuated. By this method it was hoped that a part of the moisture could be removed by entrainment. It was found that flushing as many as five times in 7 hours failed to give samples with as high breakdown gradient as could be attained by simple evacuation for 14 hours.

Uncertainties as to the effectiveness of the drying train were dispelled by the following experiment. The drying train was replaced by another having twice the length and twice the diameter of the former one. This afforded eight times the volume of desiccant and reduced the velocity of flow through the desiccant to one-fourth its original value for the same volume rate of flow. This variation produced no observable change in the breakdown gradient of the desiccated samples.

#### TESTING OF SAMPLES FOR DIELECTRIC STRENGTH

The specimens to be tested were removed from the desiccator where they were stored over calcium chloride, and each square was calibrated. The specimens were placed in the electrode system and this, in turn, was placed in the test chamber. Each high voltage electrode was then connected with the appropriate high voltage lead-in. The top plate of the test chamber with its rubber gasket was bolted in place and the vacuum pump started. The preceding operations were carried out as rapidly as was consistent with accuracy, in order to minimize the absorption of moisture from the atmosphere. The protecting cage was then put in place, and the heating lamps were turned on.

After the period of desiccation was complete, the valve leading to the vacuum system was closed and the vacuum relieved with dry nitrogen. The pressure of the nitrogen within the test chamber was slowly brought to the desired magnitude by a number of small pressure steps. The pressure of the test chamber was taken to be that recorded on the calibrated pressure gage on the cylinder of compressed nitrogen. Since the

system was vacuum-tight, errors resulting from pressure drop in the connecting pipe line and drying tube were vanishingly small. The temperature of the test chamber was adjusted to the value desired for testing.

The electrical ground connection was attached to the test chamber, and the high voltage lead was connected to the desired high voltage lead-in. The protecting cage was connected to ground. The breakdown detector was turned on, and the electrical connections were made to the high voltage supply.

The high voltage was applied and increased according to a definite time schedule until breakdown occurred. The time-voltage schedule was chosen in the light of the caliper measurement taken prior to placing the specimen in the test chamber. This process was repeated for each specimen in the test chamber. In this work, the rate of voltage increase was 3 volts per mil per minute until breakdown occurred. The initial voltage was so chosen that breakdown would result in 15 to 20 minutes.

The choice of the rate of voltage increase was entirely arbitrary. It was desirable to have the rate relatively low in order that chemical or physical changes, occurring with the increase in voltage stress would have time to approach equilibrium. The rate of 3 volts per mil per minute was felt to satisfy this condition and was convenient from an experimental standpoint.

In order to obtain values for the breakdown gradient which

would be directly translatable into practice, dielectric strength tests should continue for several days or weeks. Unfortunately, such test periods were not adaptable to the time available for this work. Because the increase in time required for breakdown to occur at a given voltage varies as the fourth power of the voltage, the effects of voltages which are more than 50 volts per mil less than the value required for immediate breakdown are very slight. This was borne out experimentally. Tests were made in which the voltage was increased at the rate of 3 volts per mil per minute with the initial voltage so chosen that the breakdown occurred within 15 minutes. Tests on similar samples were then made with a starting voltage which would cause breakdown within 45 minutes. The results in the two cases were the same within experimental error.

Undoubtedly it would be most desirable to determine the entire time-voltage curve, but experimentally this would offer difficulties. After a certain length of time under a voltage stress, breakdown would occur coincident with the next voltage surge rather than when the dielectric failed at the average applied voltage. To eliminate this difficulty, a very stable high voltage source would be required. Also, the time range which would be easily measurable—a few seconds to a few hours—would correspond to a voltage range of a few volts per mil.

When breakdown occurred, a voltage surge or transient was set up in the electrical system. This transient was amplified by the breakdown detector and was heard in the headphones as a loud popping or "frying" sound. The time of the occurrence of the first transient

was considered to correspond to breakdown. Since it rarely happened that the voltage was read at the instant breakdown occurred, it was decided to calculate the breakdown voltage from the time-voltage schedule, using the time to the first transient. Because the time-voltage schedule was adhered to very closely, the errors introduced by calculating breakdown voltage in this manner were small.

After the specimens had been tested for breakdown gradient, their density was determined. The test chamber was opened, and the electrode system was removed. The dimensions of each specimen tested were then measured with a steel scale. The length of each side was taken to the nearest tenth of a millimeter. The lengths of opposite sides were averaged, and their product with the caliper of the sheet was taken as equal to the volume of the specimen. The total volume of all specimens tested under the same conditions was calculated. The specimens were dried overnight in an oven at 105° C. and weighed. The quotient of the weight of the specimens and their volume was the oven-dry density. By this method the errors arising from sheet variations were avoided, since the density measurements were made on the specimens tested. Also, by taking oven-dry density as a criterion, differences in the hygroscopicity of the sheets could not introduce error.

## EXPERIMENTAL

In this work a study was made of the following variables: gas pressure, moisture content, temperature, sheet density, and sheet thickness.

In the study of the effect of gas pressure on the breakdown gradient, the specimens to be tested were desiccated for 14 hours at 60-70° C., after which the pressure within the test chamber was raised to the desired value. The specimens were tested in accordance with the procedure outlined previously. Typical data are given in Table III and are plotted in Figure 6. Other typical plots showing the effect of gas pressure are shown in Figures 3 and 10. Increase in pressure appears to cause a marked increase in the breakdown gradient.

TABLE III

## THE EFFECT OF GAS PRESSURE ON THE BREAKDOWN GRADIENT

Tested in Dry Nitrogen at 60° C.

Gage Pressure lb./sq.in.	Sheet Caliper mils	Sheet Density g./cm. <sup>3</sup>	Breakdown Gradient volts/mil	No. of Samples Tested	Standard Error of Mean volts/mil
0	3.0	0.707	170	4	3.3
50	3.1	0.720	347	4	9.7
100	3.0	0.724	469	7	3.4
148	3.1	0.731	537	3	12.7
187	3.1	0.713	598	4	9.1

In the preliminary work involved in the standardization of the desiccation procedure, it was discovered that the dielectric strength of desiccated specimens was higher than that of undesiccated specimens.

In testing at a gage pressure of 100 pounds per square inch, this difference amounted to 40 volts per mil in 400, or 10 per cent. In the light of this finding, it was decided to investigate the effect of greater moisture contents. Because most mill humidity rooms are maintained at 50-65 per cent relative humidity and because much of the control testing of electrical papers is carried out in these rooms, it was decided to condition the samples at a humidity within this range.

This was accomplished in the following manner. A saturated solution of calcium nitrate, which will maintain a relative humidity of 50-55 per cent at 20° C., was poured in a shallow puddle on the bottom of the test chamber. The electrode system containing the sample was inserted and connected to the high voltage lead-ins, being careful not to splash any of the salt solution on the specimens. A shallow dish containing more of the calcium nitrate solution was placed on top of the electrode system. The test chamber was then sealed and allowed to stand at 20° C. for at least 6 hours to permit equilibrium to be established. At the end of the conditioning period, dry nitrogen was admitted until the desired pressure was reached. Because the nitrogen contained a negligible moisture content, no change in the relative humidity within the test chamber occurred upon this addition of gas. After the desired pressure was attained, 15 minutes were allowed to elapse prior to testing in order that any inequalities resulting from layering or incomplete mixing of the gas might be dissipated. The specimens were then tested, and the results were compared with those obtained on similar desiccated specimens. The results are listed in Table IV and are plotted in Figure 4. Increase in relative humidity is seen to cause a decrease in the breakdown gradient.

TABLE IV

## THE EFFECT OF HIGH RELATIVE HUMIDITY ON THE BREAKDOWN GRADIENT

Tested in Dry and Humidified Nitrogen at 20° C.

Aporox. Relative Humidity %	Gage Pressure lb./sq.in.	Sheet Thick- ness mils	Sheet Density g./cm. <sup>3</sup>	Breakdown Gradient volts/mil	No. of Samples Tested	Standard Error of Mean volts/mil
50	0	2.9	0.735	178	3	11.5
0	0	3.0	0.744	195	4	3.0
50	50	3.1	0.727	309	3	5.0
0	50	3.0	0.725	361	4	1.3
50	100	3.0	0.753	441	3	8.2
0	100	3.1	0.731	492	4	5.0
50	148	3.0	0.740	524	3	16.7
0	148	3.1	0.732	596	4	3.1
50	182	3.0	0.744	583	3	14.4
0	188	3.0	0.721	679	4	9.0

The effect of temperature at the time of testing on the breakdown gradient was studied by desiccating all samples according to the standard procedure at 60-70° C., and then bringing the nitrogen pressure up to 100 pounds per square inch gage. The temperature was adjusted to the desired value and the specimens were tested. During the testing, the temperature was maintained constant to within  $\pm 0.5^{\circ}$  C. except in the measurements made at 75.5° C., during which tests the temperature was maintained constant to within 1.5° C. The results of the work are shown in Table V and are plotted in Figure 5. Increase in temperature apparently causes a decrease in the breakdown gradient.

Figure 4

The Effect of Relative Humidity  
on the Gas Pressure-Breakdown  
Gradient Relation

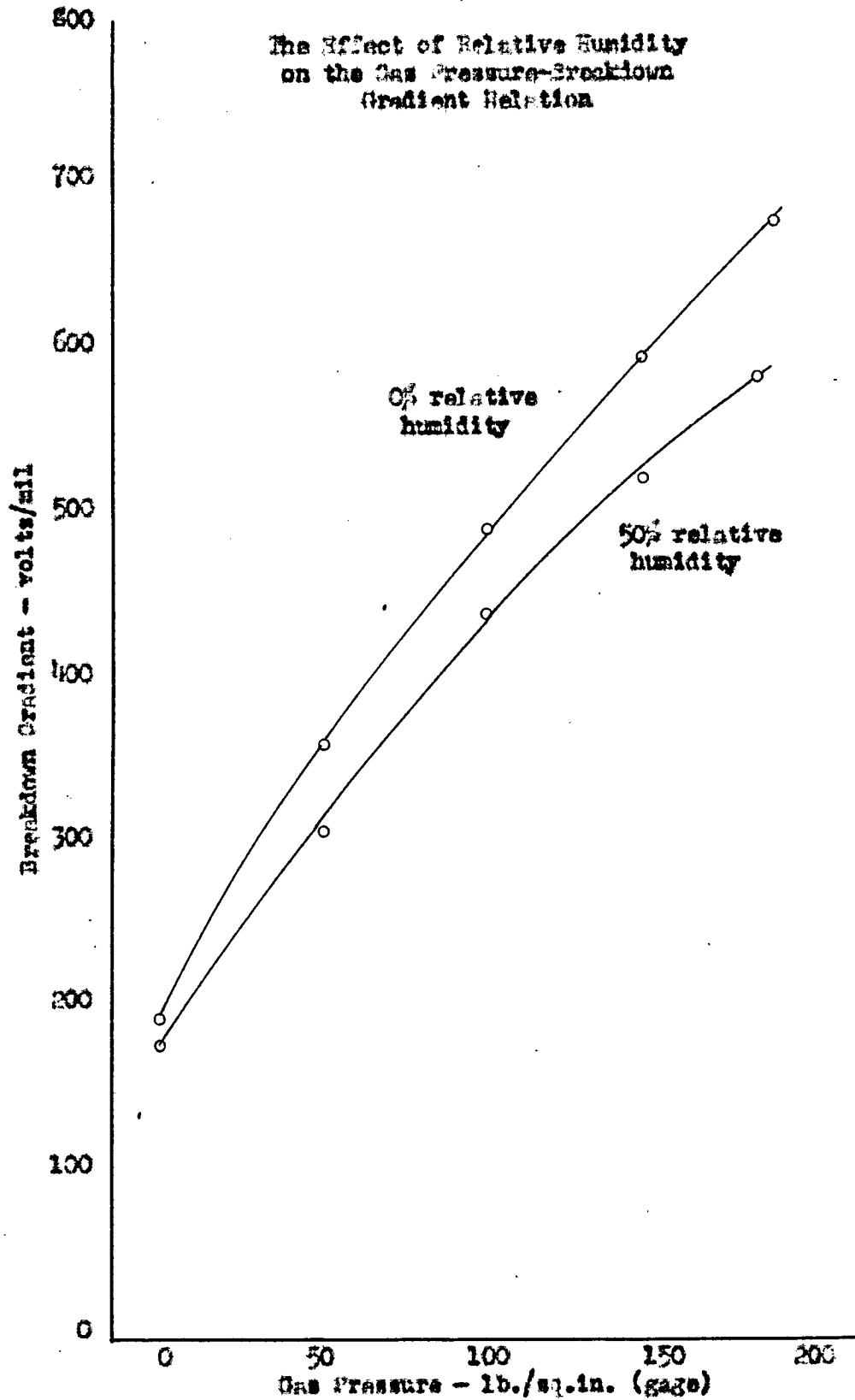


TABLE V

## THE EFFECT OF TEMPERATURE ON THE BREAKDOWN GRADIENT

Tested in Dry Nitrogen at 100 Pounds Per Square Inch Gage Pressure

Temperature ° C.	Sheet Caliper mils	Breakdown Gradient volts/mil	No. of Samples Tested	Standard Error of Mean volts/mil
20.5	3.1	482	10	3.9
40.5	3.1	455	9	3.6
60.5	3.0	441	5	2.3
75.5	3.1	410	7	1.8

The above data represent the effect of temperature at one pressure; to determine whether the effect is the same over the entire pressure range, specimens which had been desiccated according to the usual procedure were tested at five different pressures at both 20° C. and 60° C. The data are given in Table VI and are plotted in Figure 6. An increase in temperature results in a decrease in the breakdown gradient at all pressures.

A study was made of the effect of sheet density upon the breakdown gradient. Sheets were prepared having the same caliper but with densities ranging from 0.550 to 0.520 gram per cc. The difference in density was attained by various degrees of wet pressing. These sheets were desiccated and tested according to the usual procedure. All samples were tested at a gage pressure of 50 and 143 pounds per square inch, and the sheets of the highest and lowest density were tested also at 0, 100, and 185 pounds per square inch (gage pressure). The results are given in Table VII and in Figures 7 and 8. The breakdown gradient increases with a decrease in density.

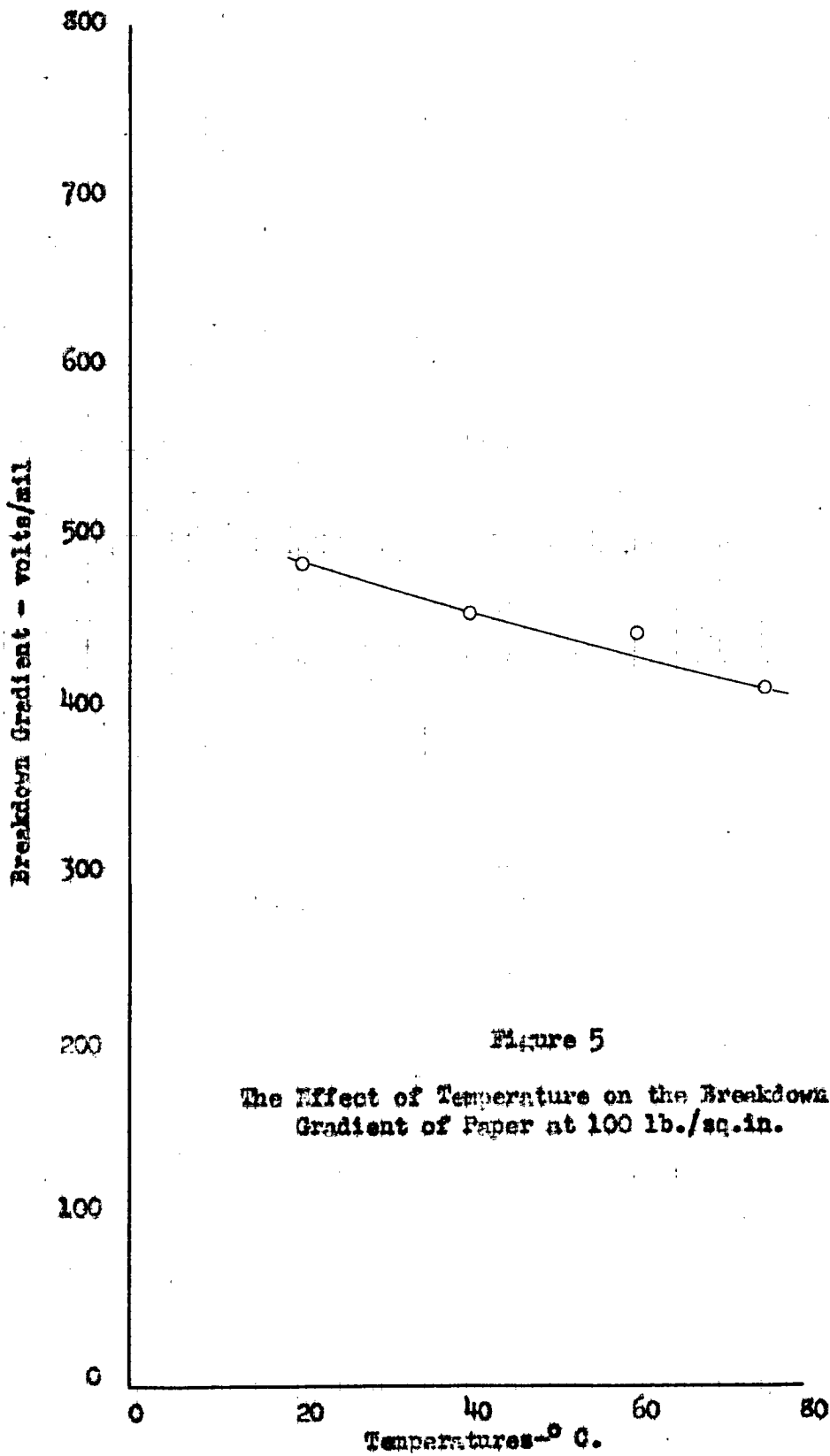


Figure 5

The Effect of Temperature on the Breakdown Gradient of Paper at 100 lb./sq.in.

TABLE VI

## THE EFFECT OF TEMPERATURE ON THE BREAKDOWN GRADIENT

Temperature ° C.	Tested at Various Pressures of Dry Nitrogen				Breakdown Gradient volts/mil	No. of Samples Tested	Standard Error of Mean volts/mil
	Gas Pressure lb./sq. in. gauge	Sheet Caliper mils	Sheet Density g./cm. <sup>3</sup>	Sheet Density g./cm. <sup>3</sup>			
20	0	3.0	0.744	0.744	195	4	3.0
60	0	3.0	0.707	0.707	170	4	3.3
20	50	3.0	0.725	0.725	361	4	1.3
60	50	3.1	0.720	0.720	347	4	9.7
20	100	3.1	0.731	0.731	492	4	5.0
60	100	3.0	0.724	0.724	469	7	3.4
20	148	3.1	0.732	0.732	596	4	3.1
60	148	3.1	0.731	0.731	537	3	12.7
20	188	3.0	0.721	0.721	679	4	9.6
60	187	3.1	0.713	0.713	598	4	9.1

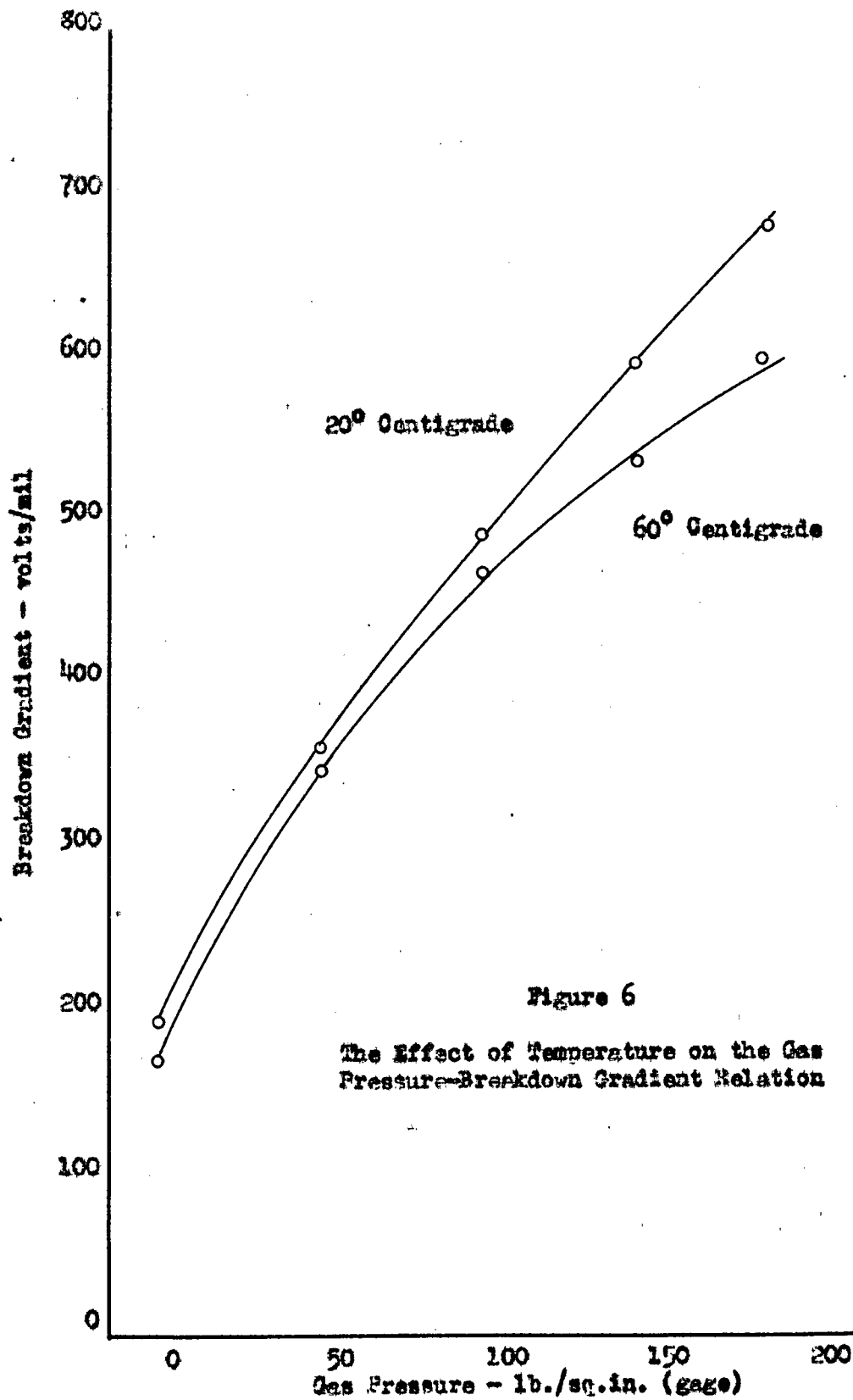


Figure 6

The Effect of Temperature on the Gas Pressure-Breakdown Gradient Relation

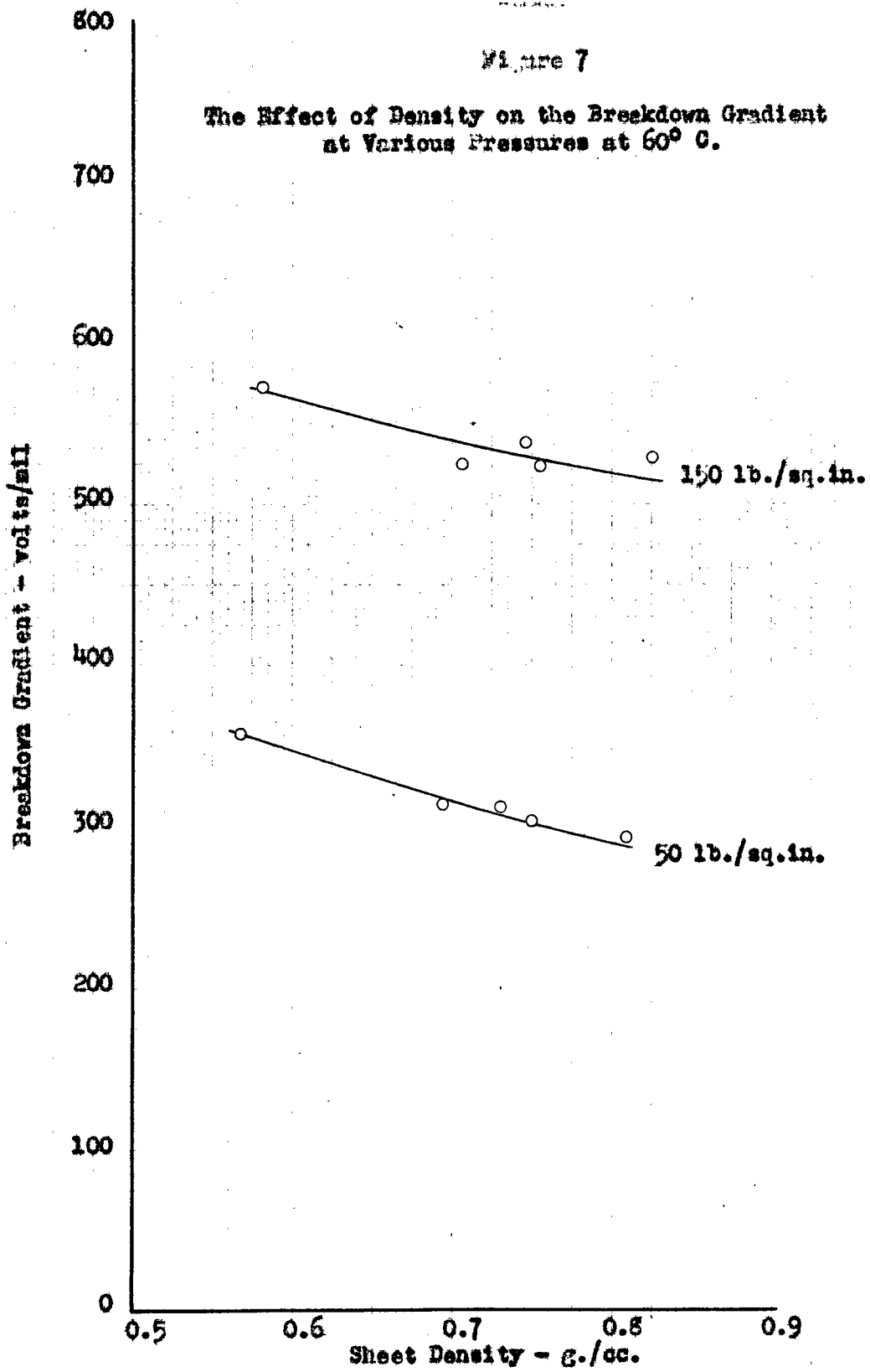
TABLE VII

## THE EFFECT OF SHEET DENSITY ON THE BREAKDOWN GRADIENT

Tested in Dry Nitrogen at 60° C.

Sheet Density g./cm. <sup>3</sup>	Gage Pressure lb./sq.in.	Sheet Caliper mils	Breakdown Gradient volts/mil	No. of Samples Tested	Standard Error of Mean volts/mil
0.555	0	2.9	161	4	10.6
0.783	0	2.9	149	4	3.3
0.569	50	2.9	357	4	8.5
0.695	50	2.9	314	4	5.3
0.730	50	2.8	311	4	9.8
0.748	50	2.7	304	4	5.0
0.809	50	2.8	294	4	5.6
0.580	100	2.8	467	3	3.5
0.826	100	2.8	423	4	2.5
0.583	148	2.8	573	4	6.8
0.715	148	2.8	524	3	6.4
0.748	148	2.7	539	4	9.8
0.755	148	2.7	523	4	9.3
0.815	148	2.8	526	4	9.8
0.586	185	2.8	683	4	6.3
0.795	185	2.9	591	4	4.4

Sheets were prepared having approximately the same density but with different thickness or caliper. Unfortunately, the thinner specimens were quite appreciably less dense than the thicker sheets. The samples were desiccated and tested in the usual manner. The results are shown in Table VIII and in Figures 9 and 10. The breakdown gradient appears to decrease with an increase in sheet thickness.



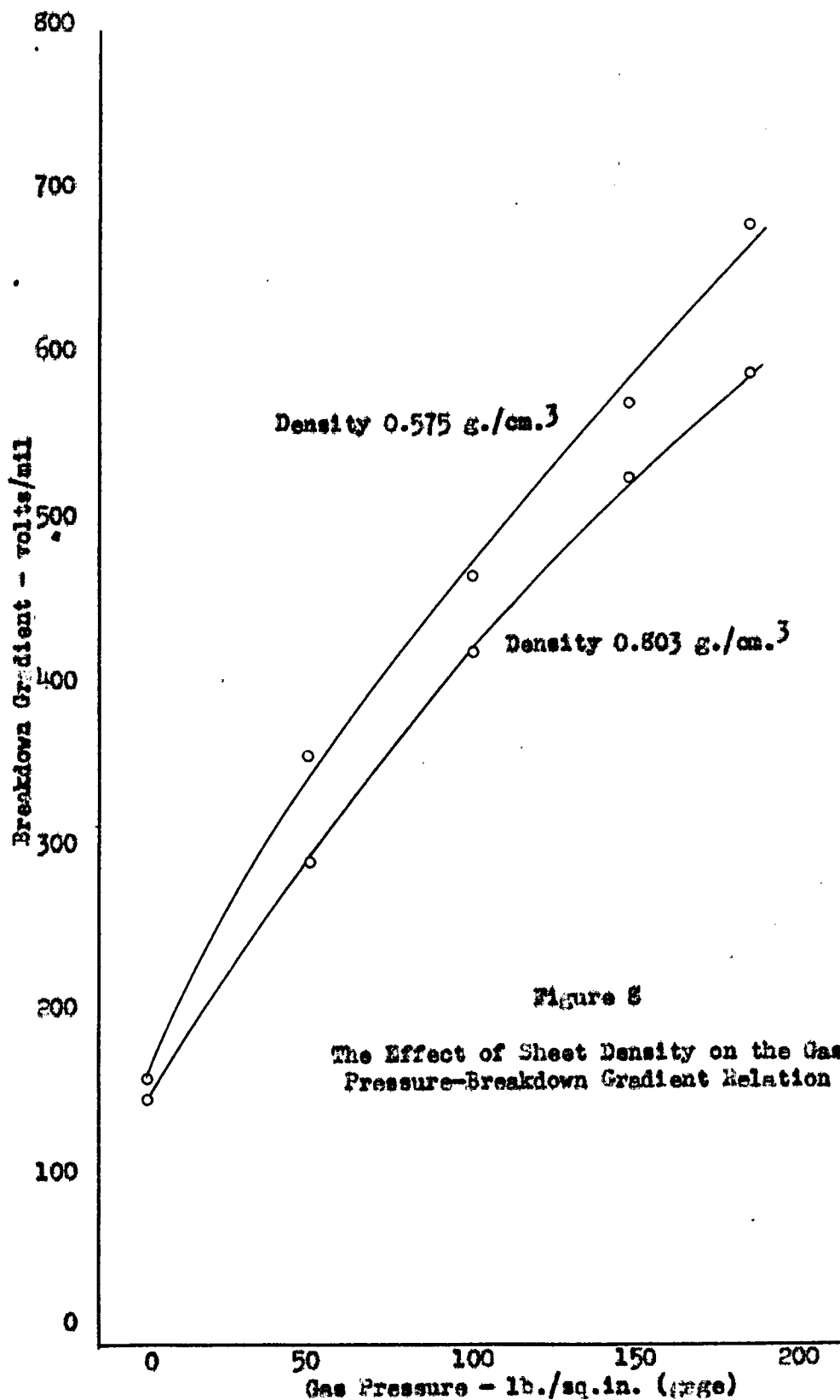


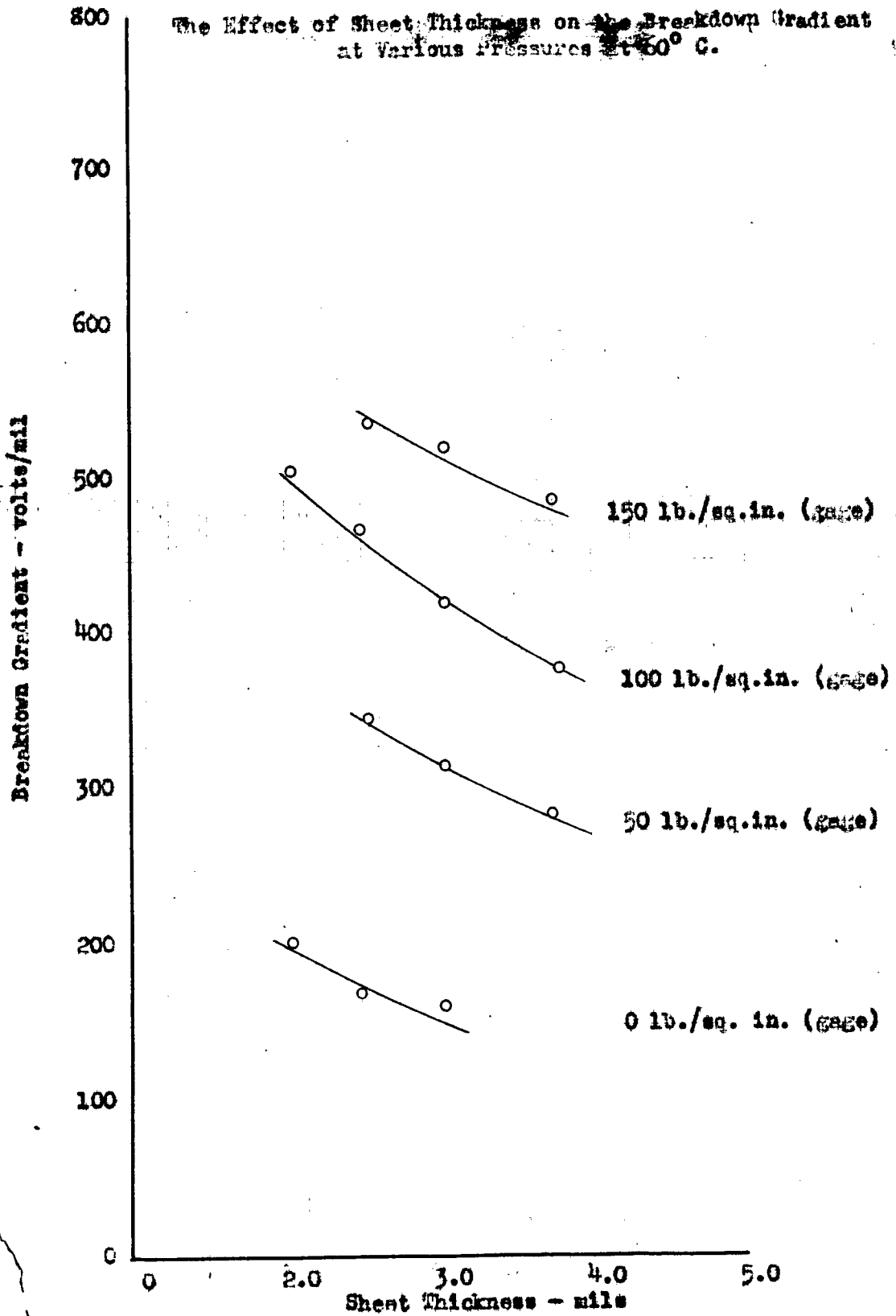
TABLE VIII

THE EFFECT OF SHEET THICKNESS ON THE BREAKDOWN GRADIENT

Tested in Dry Nitrogen at 60° C.

Sheet Caliper mils	Gage Pressure lb./sq.in.	Sheet Density g./cm. <sup>2</sup>	Breakdown Gradient volts/mil	No. of Samples Tested	Standard Error of Mean volts/mil
2.1	0	0.730	202	3	7.0
3.0	0	0.707	170	4	3.3
4.1	0	0.777	161	4	2.7
3.1	50	0.720	347	4	9.7
4.1	50	0.792	316	4	4.5
5.5	50	0.810	286	4	3.1
2.1	100	0.706	506	9	6.2
3.0	100	0.724	469	7	3.4
4.1	100	0.770	421	10	2.3
5.6	100	0.796	404	9	0.9
3.1	148	0.731	537	3	12.7
4.1	148	0.793	522	4	5.1
5.5	148	0.810	487	4	3.9
2.2	182	0.718	624	2	13.9
5.4	182	0.822	538	3	3.5
4.1	185	0.779	591	4	2.0
3.1	187	0.713	598	4	9.1

Figure 9



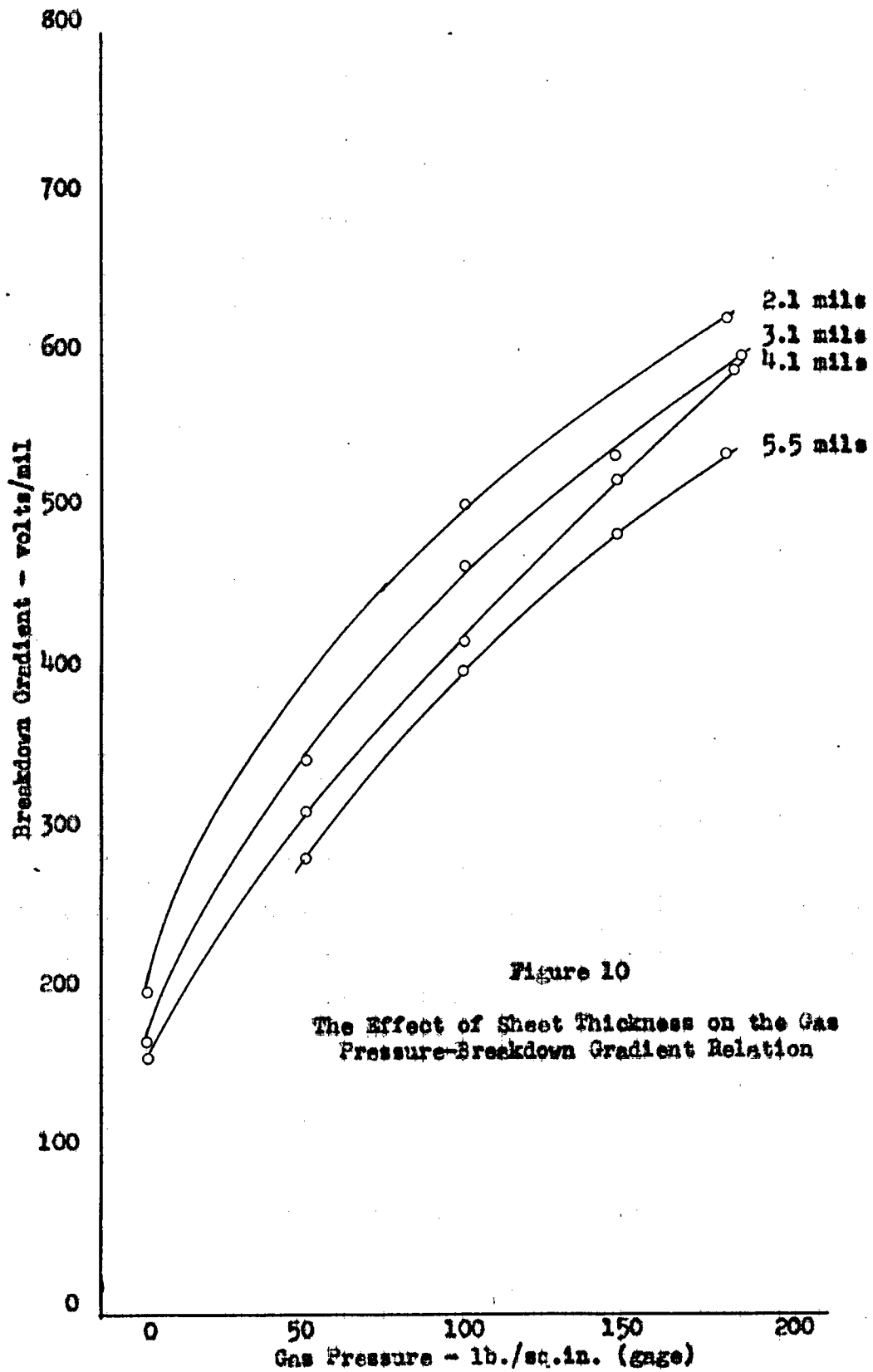


Figure 10

The Effect of Sheet Thickness on the Gas Pressure-Breakdown Gradient Relation

## DISCUSSION OF RESULTS

An examination of the data presented in the preceding section shows that each of the variables studied had an appreciable effect on the breakdown gradient. The breakdown gradient decreases with increases in the relative humidity, the temperature, the sheet thickness, and the sheet density. On the other hand, the breakdown gradient increases with increases in the pressure of the surrounding gas. The effect of gas pressure is very large as compared with the effects of the other variables. It amounted to a change in breakdown gradient of three- to four-fold when the gage pressure was changed from 0 to 200 pounds per square inch. The effects of the other variables never amounted to more than 10-15 per cent within the ranges studied. This is truly remarkable in the case of the variation of relative humidity, which has been shown to cause other electrical properties of paper (such as the dielectric loss and resistance) to change through several orders of magnitude.

In attempting to explain the behavior of paper, it must be remembered that a paper sheet is composed of two phases; a solid phase consisting of the fibrous portion of the sheet, and a gaseous phase consisting of the nitrogen which fills the interstices of the sheet and even cements the structure of the fibers themselves. Undoubtedly the dielectric properties of both phases are involved in the dielectric strength of the mixture.

The strong dependence of the breakdown gradient on the pressure of the gas phase would indicate that the dielectric strength of the gas is involved, because this is the only property of either

dielectric which varies strongly with pressure. In general, the dielectric strength of a gas varies directly with pressure for pressures of one atmosphere or more. The literature reports breakdown voltages for air of about 31 kilovolts per centimeter peak value. Converting that value to effective voltage, which was used throughout this work, the result is 55.6 volts per mil. Miner (3) stated that the dielectric strength of nitrogen is greater than the dielectric strength of air by a factor of 1.16; thus, nitrogen would have a value of 64.5 volts per mil at atmospheric pressure. If the dielectric strength of nitrogen is plotted against pressure (Figure 11), a straight line results having a slope of 4.4 volts per mil per pound per square inch. The average slope of the curve for the breakdown gradient against pressure (Figure 11) is about 2.3. The curves cross at 93 pounds per square inch pressure and 470 volts per mil.

An examination of Figure 11 reveals that the parallelism between the two curves is not very good, although they both have positive slopes and are more or less linear. The values for the dielectric strength of nitrogen used for plotting the curve were obtained from tests made on pure nitrogen in a uniform electric field. This is quite different from the present case, in which the nitrogen was not stressed by itself but in the presence of the fibrous material of the sheet. Electrical theory shows that, when voltage is applied to a mixed dielectric, an intensification of field occurs within the component having the lower specific inductive capacity. Therefore, the presence of fibers would mean that the gas would be more intensely stressed and, hence, breakdown would occur at lower pressures. It must be considered

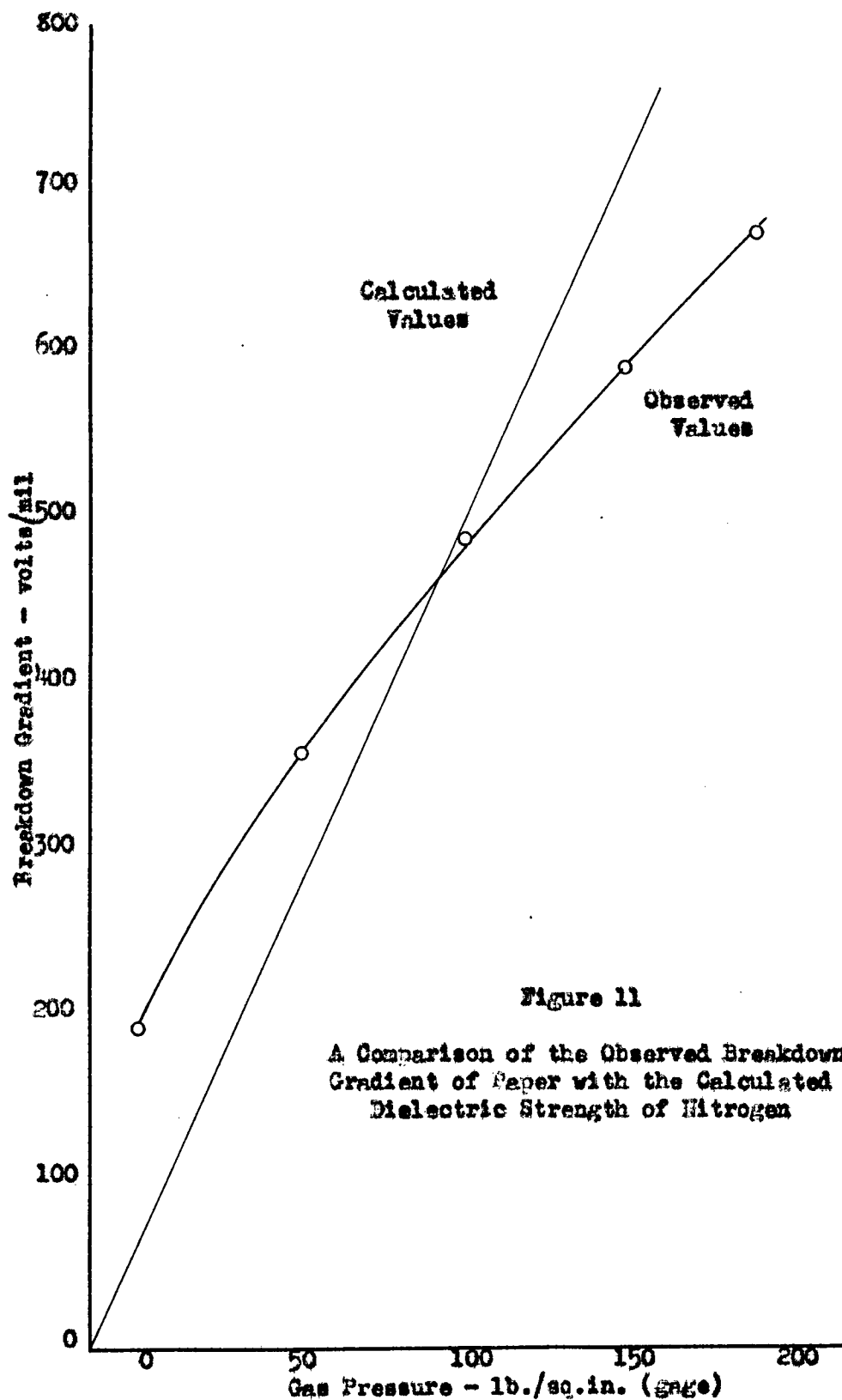


Figure 11

A Comparison of the Observed Breakdown Gradient of Paper with the Calculated Dielectric Strength of Nitrogen

also that the field within the dielectric is not uniform. The gas has a specific inductive capacity of unity, whereas the fibrous material has a specific inductive capacity of approximately six. The fibers are distributed throughout the space between the electrodes and refraction of the electric field occurs at each gas-fiber interface. The lines of electric flux tend to converge upon approaching a fiber and to diverge upon leaving it. The process of breakdown is complicated by the presence of two phases. Breakdown initiating at a point in one dielectric medium cannot proceed far without being interrupted by the presence of the other medium. This hindrance to breakdown would require higher voltages before failure.

In order to evaluate more or less quantitatively the effects of field intensification within the gas resulting from the presence of the fiber, one may consider a condenser with the space between the electrodes filled with two slabs of different dielectric materials. The specific inductive capacities of the two layers may be represented by  $\underline{K}_1$  and  $\underline{K}_2$ , and the voltages across the layers by  $\underline{V}_1$  and  $\underline{V}_2$ . The total electrode separation may be designated  $\underline{t}$ . If the total voltage across the combination is  $\underline{V}$ ,

$$\underline{V} = \underline{V}_1 + \underline{V}_2.$$

By electrical theory it can be shown that

$$\underline{V} = [4\pi\sigma(\underline{t}-\underline{d})]/\underline{K}_1 + (4\pi\sigma\underline{d})/\underline{K}_2.$$

where

$\sigma$  is the density of the charge on the electrodes, and

$\underline{d}$  is the thickness of the layer whose specific inductive capacity is  $\underline{K}_1$ .

The field ( $E_1$ ) in one of the dielectrics is equal to

$$E_1 = \frac{4\pi\sigma}{K_1}.$$

Substituting in the previous equation,

$$V = E_1 [t-d + (K_1 d)/K_2].$$

If it is assumed that breakdown initiates in medium 1 and that, once breakdown is initiated, failure of the condenser is complete, and if it is further assumed that medium 1 is a gas, then breakdown will occur when  $E_1$  exceeds some critical value  $E_1'$  or when

$$V = V_0 = E_1' [t - d + (K_1 d)/K_2].$$

From this equation, it is obvious that breakdown will occur at lower voltages than if one dielectric only filled the entire space between the electrodes; in this case the equation would be

$$V_0 = E_1' t.$$

In a sheet of paper, the fibers of the sheet are for the most part arranged so that their long axes are more or less parallel with the plane of the sheet. In passing from the top to the bottom of the sheet the point of consideration must pass through both gas and fiber—hence, two dielectrics in series. If this picture is simplified by concentrating the fibrous dielectric into one continuous layer and the gas into another continuous layer, the situation is that described above.

The thickness of such layers of dielectric can be calculated from the density of the paper sheet. If the paper sheet were composed entirely of fibrous material, it would have a density of approximately 1.5 grams per cc. The ratio of the actual density to this figure will

then give the fraction of the total plate separation occupied by the fiber. The thickness of the gas films between the sheet proper and the electrodes were automatically included in this method, because they were measured in the volume used in computing the sheet density (see page 36).

The breakdown gradient of a sheet of paper may be calculated by use of the above formula, assuming this gradient to depend solely on the gas but taking into account the effect of field intensification discussed above.  $K_1$  may be assumed to be 1.0 (this is accurate within a fraction of 1 per cent for nitrogen even at the higher pressures), and  $K_2$  may be taken as 6.0 (this agrees with the results obtained for cellulose by De Luca, Campbell, and Weiss (37)). The average density of the paper samples used in the tests plotted in Figure 11 was 0.730 gram per cc. Substituting in the formula given above (and using a value of 1 mil for  $t$ , so that  $V_c$  will be given directly in volts per mil) gives the expression

$$V_c = E_1' (0.594).$$

As previously mentioned,  $E_1'$  for a gas is a function of the gas pressure, being described for nitrogen by the equation

$$E_1' = 64.5 p,$$

where  $p$  is the gas pressure in atmospheres. The critical voltage thus becomes

$$V_c = 38.2 p.$$

This expression is plotted in Figure 12.

Inspection of Figure 12 reveals that the curve for the calculated values of the breakdown gradient for the gas in the electric field

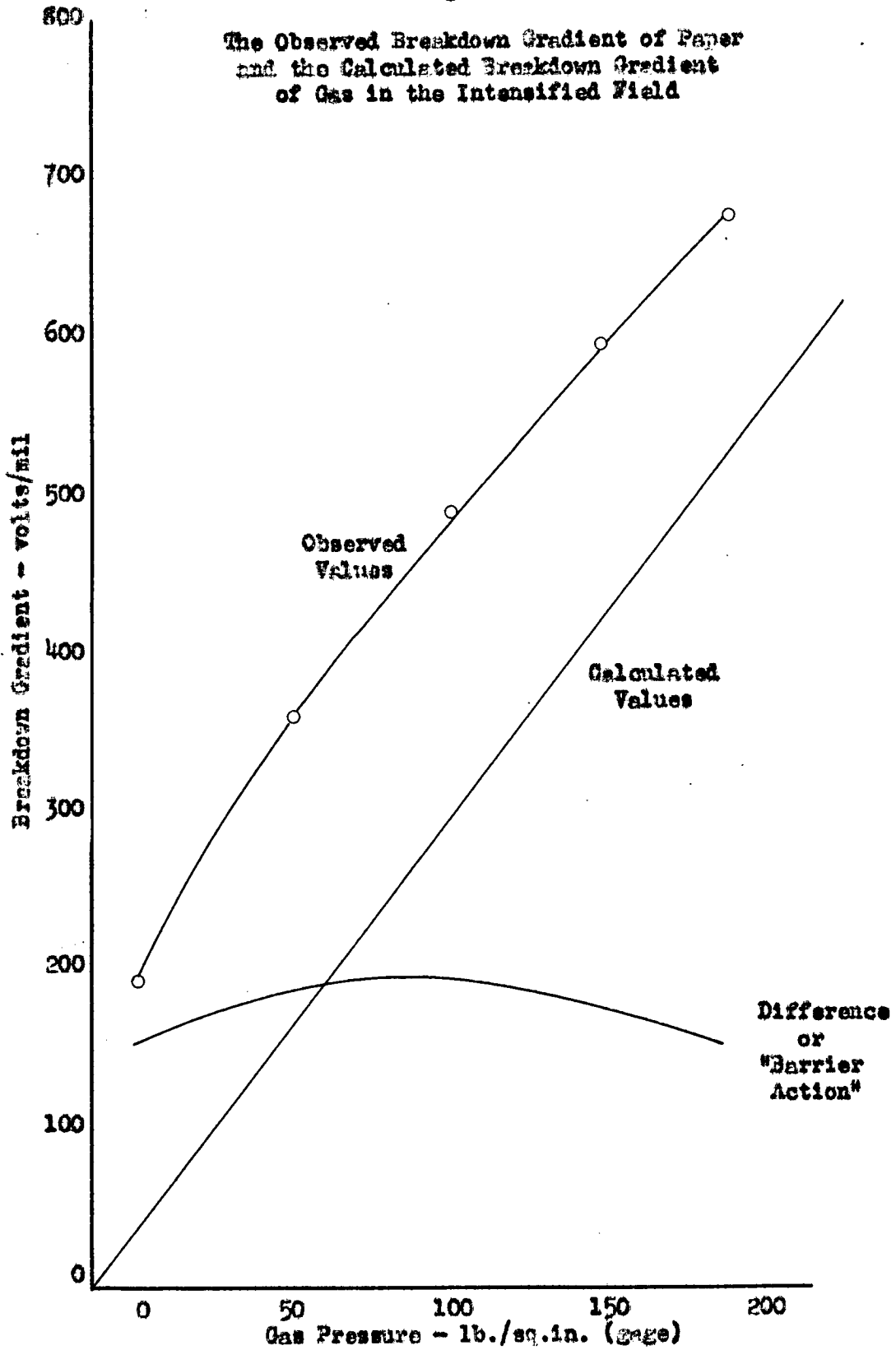
intensified by the presence of the fiber more or less parallels the curve obtained experimentally for the breakdown gradient of the paper specimens. This would indicate that, on the basis of the assumptions and the theory presented thus far, the major portion of the dielectric strength-pressure dependence can be accounted for by considering the dielectric strength of the gas phase alone in the field intensified by the presence of the fiber.

The foregoing theory has been derived on the basis of a uniform field intensified by the presence of dielectric material. In a sheet of paper, the field is nonuniform as a result of refraction of the lines of electric flux at the fiber-gas interfaces because of the difference between the specific inductive capacities of the two components. This results in local variations of the electric field within the gas phase. The field will be most intense near the fibers but will fall off to a uniform value at some distance from the fiber. The effect of this inhomogeneity on the theory advanced thus far will be slight. The only probable effect would be the lowering of the slope of the calculated curve. Whatever the effect, it will be compensated for in the theory to be presented subsequently.

If the calculated curve for the breakdown gradient in the gas (Figure 12) is subtracted from the curve of the observed data on the breakdown gradient and the difference plotted, the resulting curve is no longer strongly dependent on pressure. It is, rather, a flat curve which is concave downward. The curve has a maximum at about 80 pounds per square inch and 200 volts per mil. This portion of the

Figure 12

The Observed Breakdown Gradient of Paper  
and the Calculated Breakdown Gradient  
of Gas in the Intensified Field



total dielectric strength should be ascribed to the "barrier action" of the fibrous material. The curvature of this plot may indicate a variation of this quantity with pressure. This need not be the case, however, because higher voltages are involved in breakdown at the higher pressures and the variation might be the result of voltage changes rather than pressure changes.

In order to investigate the nature of this barrier action, it is necessary to picture what takes place within the sheet of paper as the voltage stress increases.

The paper sheet consists of fibers lying with their long axes more or less parallel with the plane of the sheet, but otherwise randomly oriented. The voids between these fibers are filled with nitrogen. Each fiber is a slightly flattened tube tapered at the ends. The internal cavity or lumen is filled with gas. The fibers range from 20 to 35 microns in diameter but, because of the heating process, considerable amounts of fibrous debris of lesser diameter are also present. The gas voids are of the same order of magnitude as the fibers, but greater variations of size are to be expected.

Both the fibrous material and the gas are very good electrical insulators at low voltage stresses. In the gas phase, ions or electrons created by radioactive materials (which are ever present), cosmic rays, photons, etc., are accelerated in the electric field toward the electrode of opposite sign. Such currents are extremely small. As the voltage approaches that described by the calculated curve in Figure 12, the current flowing in the gas becomes much more appreciable. This is due

to the fact that the electrons migrating in the electric field are being accelerated sufficiently between collisions with the molecules of the gas present to cause ionization by impact when they do collide with the gas molecules. This process yields secondary electrons which, in turn, can be accelerated and cause further ionization. The positive ions thus formed migrated in the reverse direction toward the electrode, which at that instant is acting as the cathode. In the fields involved in the present study, it is doubtful whether the positive ions are accelerated sufficiently to cause ionization by impact with gas molecules; however, in the higher voltage regions they probably do cause secondary ionization by impact with the electrodes (38).

These charged particles, being accelerated by the electric field, will impinge on the paper fibers present and will accumulate on the fiber surfaces. Electrons will collect on those surfaces which "look" at the cathode, whereas positive ions will collect on those surfaces which "look" at the anode. Because the fiber has an extremely high resistance, these charges will not neutralize each other. Since these charges are separated by only the thickness of a fiber, their effect on the electric field at any great distance from the fiber will be negligible. At distances not greater than a few fiber diameters (the width of most gas voids), the effects of these charges will be quite significant. With electrons collecting on the surfaces of the fibers facing the cathode and positive ions collecting on the surfaces facing the anode, the effects of these charges will be to nullify a portion of the field within the gas produced by the electrode system. In this way, as soon as ionization commences, surface charges will

build up sufficiently to reduce the field to the neighborhood of the ionization point.

The fact that alternating current was used throughout this study adds a few complications, but the over-all picture remains unchanged. During each half-cycle the surface charges migrate to the opposite sides of the gas voids. Those charges which are dissipated by conduction and recombination are replenished by ionization during the peak portion of the cycle. Because of the high mobilities of the charged particles and the short distances involved, equilibrium conditions are probably maintained throughout the cycle.

While the surface charges building up on the fibers and in the surrounding atmosphere are reducing the field in the gaseous phase, they are intensifying the field within the fibrous portions of the sheet. As the voltage increases, the magnitude of the space charges also increases until finally the field within the fiber exceeds its dielectric strength and breakdown occurs. Once the fiber breaks down, the charge adsorbed on and around it disappears, thus permitting breakdown in the gas to proceed.

The barrier action of the fibrous material thus consists of the ability of the fibers to retain surface charges which reduce the field within the gas and effectively prevent its breakdown. This barrier action persists until the field within the fibers exceeds their dielectric strength, at which point the insulating ability of the paper sheet collapses and breakdown occurs. Inequalities in the original field resulting from refraction of lines of electric flux will probably

cause at least local ionization to occur at voltages lower than those predicted by the calculated curve in Figure 12. This will mean slightly greater surface charges and, hence, earlier collapse of the fiber barrier.

The total field within the fiber will consist of the sum of the field resulting from the electrode system and the field resulting from the charges accumulating at its surfaces. When this total field exceeds a certain value, breakdown will occur. Since, as the gas pressure is increased, the voltages required to cause ionization are also increased, the relative portion of the critical field supplied by the electrode system becomes greater with pressure increases. Under these conditions, the contribution by the surface-charge field will be less when breakdown occurs and, therefore, the barrier action should decrease with increase in pressure. If sufficiently high pressures are attained, this barrier action should disappear completely. Such pressures were never attained in this study; however, a decrease in barrier action with an increase in pressure is readily observed in the plot of the difference between the observed and calculated values for the breakdown strength of paper and gas, respectively (see Figure 12).

The plot of the barrier action of the fibrous material as shown in Figure 12 is curved, being concave downward and having a maximum at a gage pressure of about 50 pounds per square inch. The decrease with increase in pressure can be explained, in part, by the mechanism described in the preceding paragraph. The increase with pressure at low pressures can be explained as follows. It has been shown

experimentally (2) that the dielectric strength of very thin films of gas is quite appreciably higher than that of the gas with the usual electrode spacings. This is attributed to an insufficient number of mean free paths for an electron across the film and, hence, insufficient impacts to cause the required ionization for breakdown to occur. Such very thin films exist in the lumens of paper fibers. If the field within the fiber is insufficient to cause breakdown of the gas within the lumen, then the dielectric strength of the fiber will increase with an increase in the pressure of the gas. Ultimately, however, with increase in the pressure of the gas the mean free path of an electron in the gas decreases and, consequently, the dimensions of the fiber lumen become relatively larger. As a result, the dielectric strength of the gas in the lumens becomes more nearly that of the gas outside the fiber. This decrease in the difference between the dielectric strength of the gas in the lumen and that outside the fiber will continue as the pressure increases until it finally vanishes. Above some critical pressure, breakdown of the gas within the lumen will occur before breakdown of the fibrous material. This will result in a collection of charges on the internal surfaces of the fiber and, hence, a further intensification of the field in the fibrous material. At pressures in excess of this critical pressure, the contribution of the gas in the lumen of the fiber to the barrier action of the sheet will no longer increase with pressure.

The various phenomena appearing in the study of the effect of gas pressure on the breakdown gradient have been quite completely explained by the theory just evolved. Attention is now turned to the

effects of the other variables to determine whether these effects are compatible with the theory.

The results of the investigation of the effect of relative humidity on the breakdown gradient are listed in Table IV and are plotted in Figure 4. From the curves it can be seen that, at constant pressure, the values of the dielectric strength of paper at 0 per cent relative humidity are greater than those at 50 per cent relative humidity throughout the pressure range.

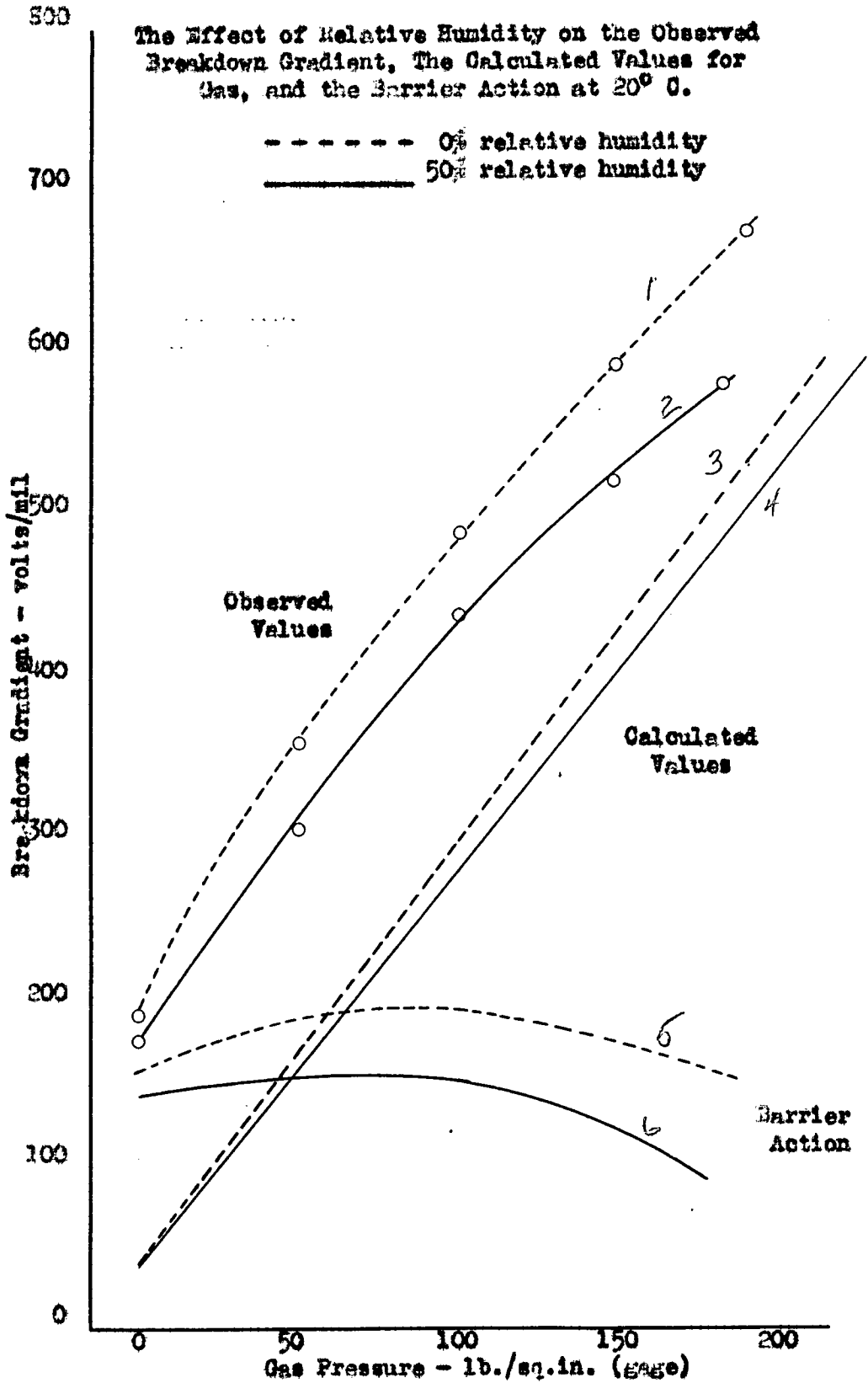
In order to evaluate the barrier action of the paper sheet at each humidity, the dielectric strength of the gas must be calculated according to the method discussed on page 56. In calculating the values for the gas at 50 per cent relative humidity, a change in the specific inductive capacity of the fiber must be assumed, because the fiber has absorbed moisture which has a specific inductive capacity of 80. In view of the fact that no data were available on this subject, a value of 8 for the specific inductive capacity of the moist fiber was assumed. The exact value of this quantity is not critical because it enters the formula only as the denominator of an additive term, the numerator of which is quite small. If the specific inductive capacity of the moist fiber were taken as being infinite, the value of the breakdown voltage for the gas as calculated would be changed by only about 10 per cent. Since the experimental work of Peak (2) showed no effect of humidity on the dielectric strength of gas in a uniform field, the previously used value of 64.5 volts per mil at atmospheric pressure was employed in the calculations. The values of the breakdown gradient

for nitrogen in the field intensified by the presence of the fiber are given in Figure 13 for both 0 and 50 per cent relative humidity. The values at 50 per cent relative humidity vary little from those at 0 per cent.

The difference between the calculated curve for the gradient for initiation of discharge in the gas and the curve for the breakdown gradient for the paper and gas is a measure of the barrier action of the fiber. This is plotted in Figure 13. The barrier action is found to vary quite considerably with humidity. The values at 50 per cent relative humidity are lower than the values at 0 per cent at the same pressures. This difference in the barrier actions at the two humidities is attributed to the great lowering of the electrical resistance of the paper fiber as its moisture content is increased. The resistance of the fiber at 50 per cent relative humidity is less than the resistance of 0 per cent relative humidity by a factor of the order of  $10^4$  or  $10^5$ . This lower resistance permits the charges accumulating on the fibers to be dissipated by conduction, and gaseous discharge occurs at a lower over-all voltage.

In general, there will be two criteria for breakdown, either of which will be sufficient. In one case, the surface charge will build up on the fibers sufficiently to prevent gaseous discharge from occurring. Breakdown will then occur when the field within the fiber, resulting from the charges on the electrodes and the surface charge on the fiber, exceeds the dielectric strength of the fiber. At this point, the charges on the fiber neutralize each other and gaseous discharge is no longer impeded. In the other case, the resistivity of the fibers is

Figure 13



low enough so that a point is reached at which insufficient charge can be maintained on the fibers to prevent breakdown of the gas. In this case, the fiber may act as a resistance in series with the discharge or the discharge may by-pass the fiber and take place wholly within the gas phase. Since the magnitude of the surface charges under any given set of conditions is dependent solely on the voltage in excess of that required for ionization of the gas in the absence of space charge, failure resulting from inability to maintain sufficient space charge will take place at lower voltages than failure resulting from the breakdown of the fibers. The condition of breakdown of the fibers will be considered as that giving rise to the upper limit for the barrier action of the paper sheet.

The effects of temperature on the breakdown gradient at constant pressure (100 pounds per square inch) are shown in Figure 5. The gradient decreases more or less linearly with temperature increase over the range from 20° C. to 75° C. No densities were obtained for these samples and, hence, the magnitudes of the barrier action in each case could not be ascertained. Figure 6 shows the effect of temperature on the breakdown gradient-pressure relationship. The values at 60° C. are lower than those at 20° C. for the same pressures.

In the calculation of the gradient corresponding to breakdown in the gas (in the field intensified by the presence of the fibers), it is necessary to use a different value for the dielectric strength of nitrogen at 60° C. than at 20° C. At constant pressure, the dielectric strength of a gas varies inversely as the absolute temperature. In

calculating the dielectric strength of the gas alone, the equation for the critical voltage at 60° C. becomes,

$$V_c = \frac{(64.5)(293.1)}{(333.1)} p [t-d + d/K_2],$$

or

$$V_c = 57.1 p [t-d + d/K_2].$$

The plot of this equation is shown in Figure 14.

The differences between the observed and calculated data fall very close together, and any differences between the two curves lie within the range of experimental error (Figure 14). It can be said that the effect of temperature on the barrier action of the fibrous material is very slight, if present at all.

The location of the maximum in the curve for 60° C. at higher pressure than the maximum in the curve for the barrier action at 20° C., if not due solely to experimental error, may be explained as follows. At the higher temperature and at constant pressure, the mean free path in the gas is longer than at the lower temperature; hence, higher pressures are necessary before the gas in the lumen can break down. For this reason, the maximum should occur at a higher pressure at 60° C. than it does at 20° C.

The effect of density on the breakdown gradient-pressure relation is shown in Figure 7. The values of the breakdown gradient for the sheet of lower density are above those for the higher density sheet at the same pressure. Because these determinations were made at 60° C. the value of 57.1 volts per mil was used for calculating the dielectric strength of the gas alone in the intensified field. The values thus calculated are shown in Figure 15.

Figure 14

The Effect of Temperature on the Observed Breakdown Gradient, the Calculated Values for Gas, and the Barrier Action

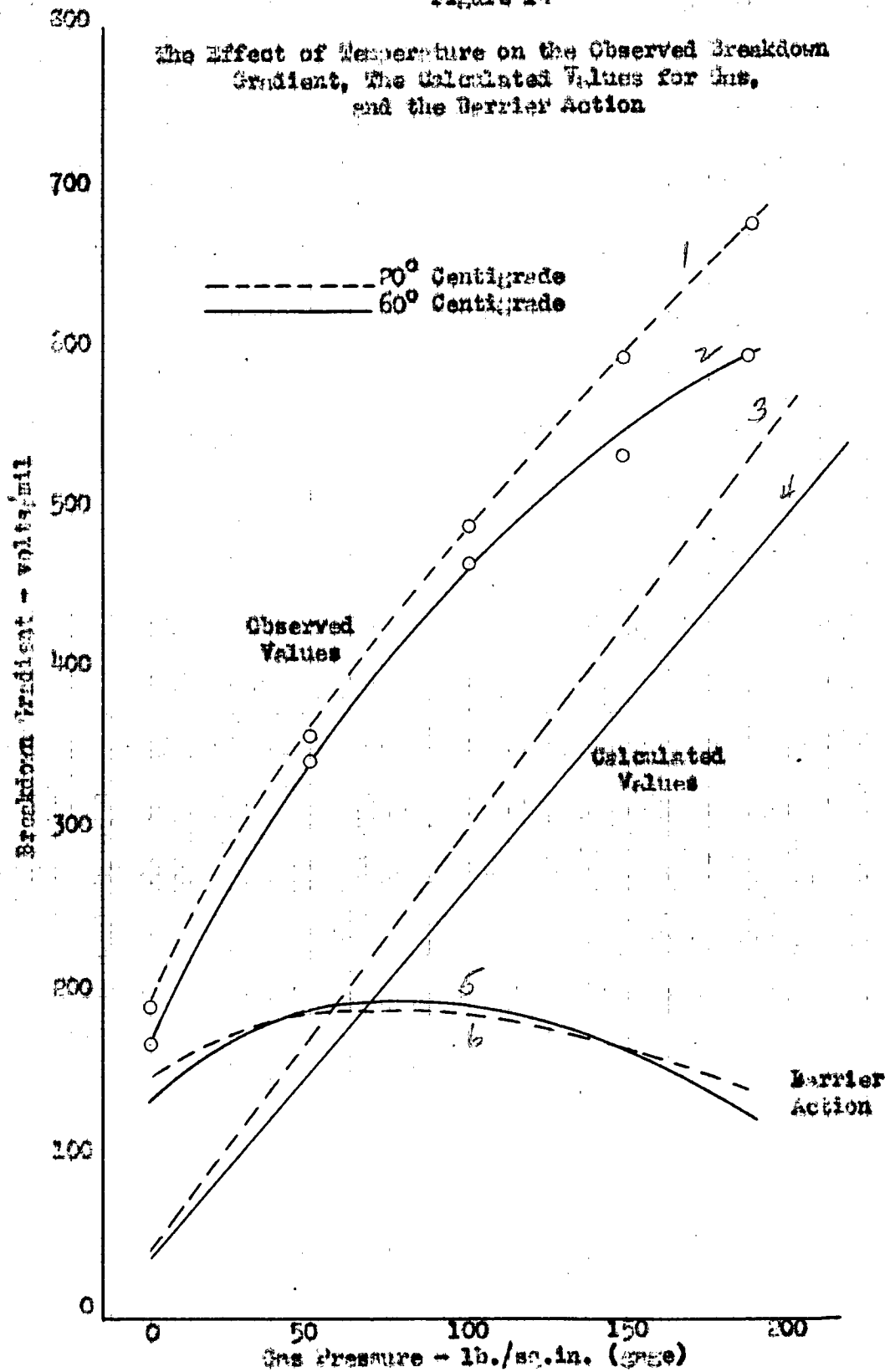
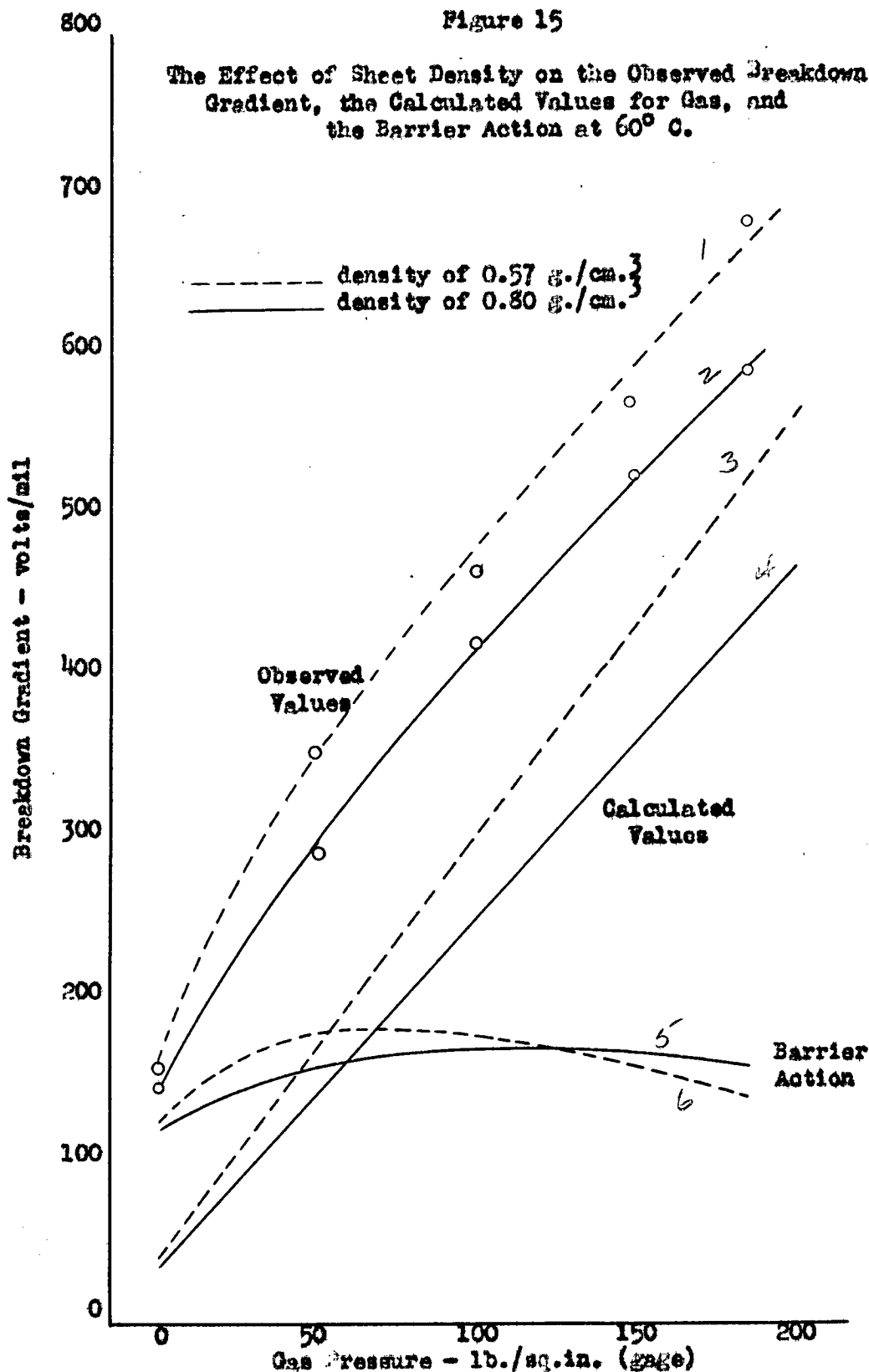


Figure 15

The Effect of Sheet Density on the Observed Breakdown Gradient, the Calculated Values for Gas, and the Barrier Action at 60° C.



The barrier action curves for the two densities (Figure 15) show that the values for the lower density sheet rise to a higher maximum at the lower pressures than those for the higher density sheets and fall off more rapidly as the pressure increases.

The relative heights of the maxima can be explained as the result of two effects. First, in the higher density sheet, less gas was present and, hence, the field within the fiber was more intense. This can readily be seen by referring to the calculations of the field within the gas presented on page 55. For this reason, the more dense sheet should break down at a lower voltage than the less dense sheet. On the other hand, however, the magnitude of the space charge necessary to prevent gaseous breakdown depends principally on the size of the gas void. Because the gas voids in the denser sheets are, on the average, smaller than those in the less dense sheets, the space charges and the resultant fields within the fibers are also smaller. The barrier action plotted in Figure 15 represents a balance of these two effects.

At the higher density, the maximum in the curve representing the barrier action of the fibrous material occurs at higher pressures than does the maximum in the curve for the lower density sheet. Because the greater density was obtained by pressing the sheet while wet, it is logical that the lumens of the fibers in the denser sheet were more reduced in size in the direction perpendicular to the plane of the sheet than were those in the fibers of the less dense sheet. The smaller the lumens, the higher the pressure required before breakdown can occur within the lumen. For this reason, the maximum in the barrier action curve occurs at higher pressures.

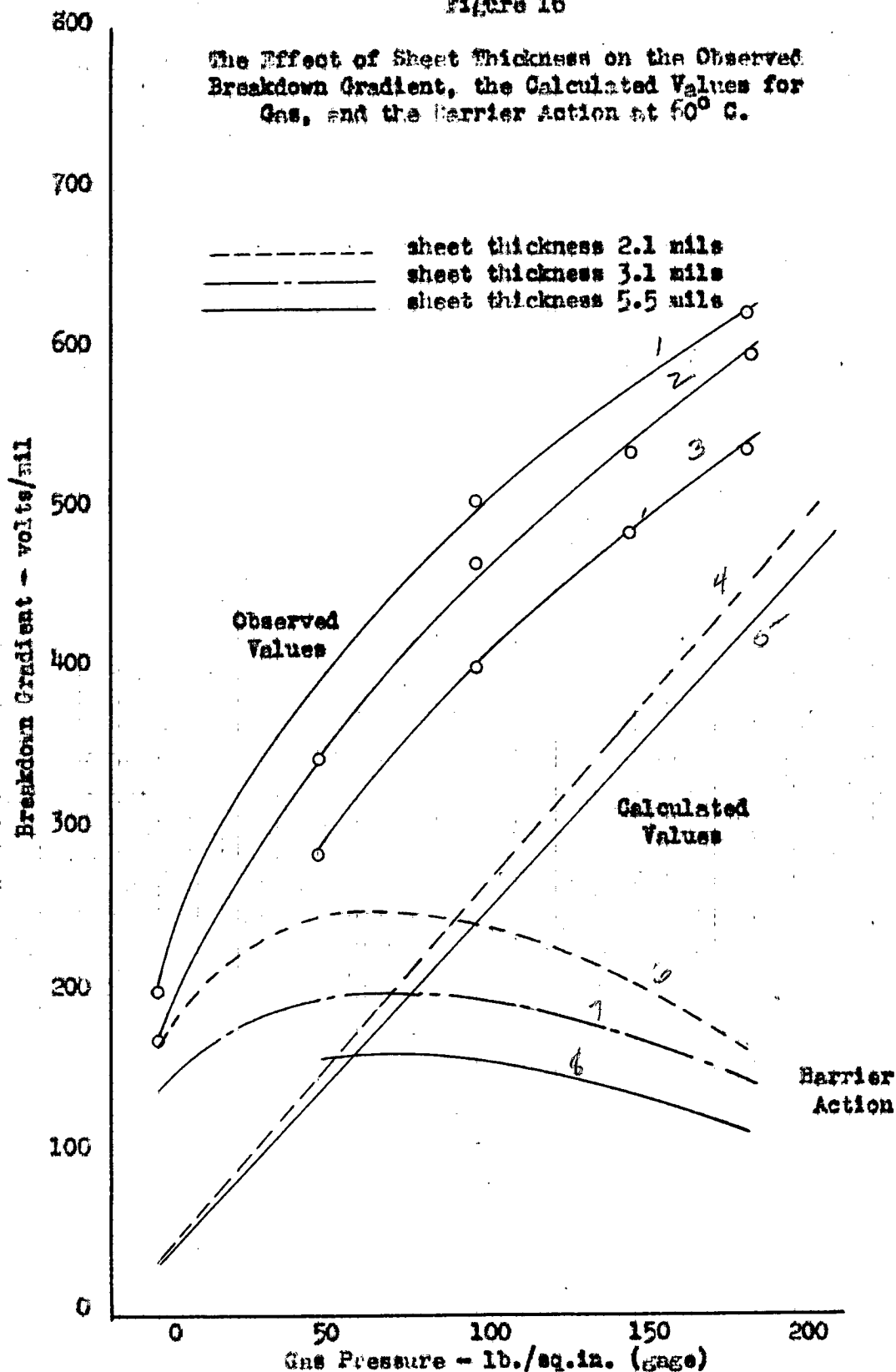
The effects of sheet thickness on the breakdown gradient are shown in Figure 9. The gradient is seen to fall off with increase in thickness. Figure 10 shows the effect of thickness on the breakdown gradient-pressure relation. The curves are more or less the same shape, with those for the greater thicknesses lying below those for the lesser thicknesses.

According to the equation derived previously, calculations were made for the gradient corresponding to breakdown in the gas (in the field intensified by the presence of the fibers). The results of these calculations, together with the differences between these values and the observed breakdown gradients, are plotted in Figure 16. The barrier action curves were of similar shape and arranged in the same order as the observed breakdown gradient curves—i.e., the greater the thickness, the lower the value of the barrier action at the same pressure.

The reason for the low barrier action with thick sheets is statistical in nature. In any path through the paper sheet in the direction of the field, there are a number of alternately placed fibers and gas voids. In the vicinity of breakdown, each fiber possesses sufficient charge at its surfaces to restrain the field within the gas voids to such an extent that further ionization of the gas occurs at a rate just necessary to replace the charge dissipated by electrical conduction through the fibers. The magnitude of the charge required will depend upon (a) the dimensions of the gas space in which the field must be neutralized, and (b) the thickness of the fiber (i.e., the

Figure 16

The Effect of Sheet Thickness on the Observed Breakdown Gradient, the Calculated Values for Gas, and the Barrier Action at 60° C.



separation of charges of opposite sign). The sizes of the gas voids and the thicknesses of the fibers are not constant but are distributed over a range of magnitudes; hence, the surface charges present on the fibers and the fields within the fibers are also distributed over a range of magnitudes. As the field within the fibers is increased, a point is reached at which the dielectric strength will be exceeded within some one fiber. Failure of this fiber is accompanied by an increase in the stress in the other fibers. The other fibers may be capable of withstanding this additional stress, in which case equilibrium will be re-established. If, however, the other fibers are not capable of withstanding the increased stress, then failure of the other fibers will take place and complete breakdown of the sheet will occur. As the thickness of a sheet is increased, the number of fibers which are to be encountered in passing from one electrode to the other also increases. With this increase comes the greater probability that, at some point within the test area, the distribution of gas voids, fiber thicknesses, and dielectric strengths is such that breakdown will occur at an exceptionally low value. For this reason, the breakdown gradient decreases with increase in sheet thickness.

## CONCLUSIONS

The first and principal conclusion to be drawn from the preceding work is that the breakdown gradient of a sheet of paper immersed in a gas is not a measure of the intrinsic dielectric strength of either the fibrous material or the gas. Rather, it is a complex phenomenon involving the dielectric strengths of both. The conditions existing prior to breakdown are primarily determined by the properties of the gas, whereas it is the failure of the fiber which finally determines breakdown. The breakdown strength of the fiber itself, however, cannot be deduced simply by dividing the total voltage applied across the electrode system by the electrode separation. This would give a value far too low. The stress on the fiber at breakdown consists of the stress resulting from charges on the electrodes plus those arising from the presence of charges on the fiber.

Most paper tested for dielectric strength is intended for use by the electrical industry after it has been impregnated with some oil or resin. Much control testing of this paper for dielectric strength is carried out on unimpregnated samples in air. In view of the theory and mechanism evolved herein, interpretation of such results in terms of use requirement of the paper is exceedingly difficult, if not impossible.

If the gas voids within a sheet of paper were to be filled with an oil, the conditions of the electric field within the sheet would be greatly changed. Even without consideration of the uncertainties of the impregnation process, this would be true. The oil,

having a specific inductive capacity of two or three times that of the gas, would bring about a more equitable distribution of the electric field. The oil would be subject to an intensified field, but not to the extent present in the gas. Accordingly, for the same applied voltage, the field within the fibrous portion would be much greater. The field would also be more nearly uniform within the oil as the refraction of the field at the fiber-oil interface would be greatly reduced.

If such an oil-filled sheet is imagined to be stressed to the vicinity of breakdown, what is taking place within the sheet? Does the oil become filled with conducting ions or electrons as a gas does, or does breakdown in an oil take place in a different manner? Do charges accumulate on the fibers and thus partially neutralize the field in the oil? Until the mechanism of dielectric breakdown of the oil can be experimentally established, these possibilities must continue to be objects of speculation.

Poor correlation between the dielectric strength of paper as tested in air and the performance of the electrical equipment fabricated from this paper is observed in practice (38). Generally, variations of the impregnating process have been assumed to account for this lack of correlation. The real trouble may lie in the fact that the mechanism of breakdown of paper in air is quite different from that of paper in oil.

Assuming for the moment that the mechanism of breakdown of paper in oil is quite analogous to that of the breakdown of paper in

air, difficulties would still be experienced in predicting the results of one test from the results of the other, because of the differences existing between the specific inductive capacities and dielectric strengths of the oil and air.

From the proposed theories and the foregoing experimental work, it is concluded that the voltage stress required to cause the dielectric breakdown of paper in a gaseous atmosphere can be divided into two parts: that required to cause ionization by impact to occur in the gas phase and that during which a surface charge resulting from such ionization accumulates on the fibers. This latter portion is culminated in breakdown, which occurs when the field within the fibers exceeds the dielectric strength of the fibrous material, or when electrical conductivity through the fiber dissipates the surface charges so rapidly that gaseous discharge is no longer inhibited. The first portion of the breakdown voltage stress is considered to be gas-dependent and will vary with any changes in the field within the gas, or with its dielectric strength. The second portion is attributed to a "barrier action" of the fiber which prevents breakdown from occurring until the apparent field in the gas has exceeded the dielectric strength of the gas by a certain amount. This barrier action is a fiber-dependent quantity, although it is complicated by the dielectric strength of the gas in the fiber lumen.

Relative humidity or moisture content has scarcely any effect on the gas-dependent portion of the breakdown voltage stress but has a marked effect on the barrier action. This is attributed to the reduction in the resistivity of the fiber, which is known to accompany

increases in humidity or moisture content. Such a reduction increases the rate of dissipation of the surface charges on the fibers to the point that gaseous discharge takes place despite the presence of the fiber.

The thickness of the test sample is another variable which affects primarily the barrier action. The effect is statistical in nature. Since the magnitude of the surface charge which collects on the fibers depends upon the size of the gas void and the thickness of the fiber, quite a spread in the distribution of voltage stresses will be present. Failure at one point within the sheet will place an increased stress on the rest of fibers lying in the same path. This increased stress may or may not cause failure to continue across the sheet. As the thickness of the sheet is increased, so also are the chances of finding an exceptionally weak spot so arranged that breakdown can occur. For this reason, breakdown gradient decreases with increase in thickness.

Gas pressure, temperature, and sheet density, on the other hand, primarily affect the gas-dependent portion of the breakdown voltage. The gas pressure and temperature changes cause variations in the density of the gas and, hence, in the dielectric strength. Changes in sheet density cause variations in the field within the gas by changing the ratio of gas to fiber present. Density, however, also has some effect on the barrier action, because the field within the fiber is also affected by changes in the fiber-to-gas ratio. At high moisture contents, where ultimate breakdown does not depend upon the

dielectric strength of the fiber, this effect on barrier action would not be as pronounced.

The barrier action of the fibrous portion of the sheet decreases with increasing pressure, and theory predicts that, at some pressure, it will vanish. At such a point, the curve of the observed breakdown gradient of paper plotted against pressure would intersect with the curve of calculated breakdown gradient corresponding to onset of discharge in the gas. This point would represent the condition of the fiber failing at the same time the gas commences to break down. From the voltage at which this intersection occurs, it would be possible to calculate the dielectric strength of the fibrous material itself. Such an intersection of curves does not occur within the range of pressure attainable with the apparatus used in this work. From an estimate based upon the curves obtained, the intersection should occur in the vicinity of 500 pounds per square inch.

### SUMMARY

An apparatus was devised and constructed in which paper could be tested for dielectric strength while well desiccated and immersed in an atmosphere of dry nitrogen under pressure. The specimens of paper were dried by evacuation at elevated temperature while in position to be tested for dielectric strength. The apparatus was so designed that ten specimens could be dried and tested without opening the test chamber.

A procedure was evolved for desiccating and testing paper with an average standard error of the mean of ten determinations of dielectric strength of 4 to 5 volts per mil.

A theory was developed describing the mechanism of dielectric breakdown of paper immersed in a gas. This theory is based on the knowledge that, when the electric field within the gas phase of the sheet exceeds a certain critical value, ionization of the gas begins to occur. Such ionization is accompanied with immediate collection of charges by the fibrous material of the sheet. Those surfaces of a fiber that face the electrode which at the instant is acting as the cathode collect electrons, whereas the opposite surfaces collect positive ions. These charges effectively cancel the field within the gas voids of the sheet which is in excess of the ionization field. While this space charge restrains the field within the gas voids, it intensifies the field within the fiber. As the surface charge on the fiber increases with voltage increase, a point is finally reached at which the dielectric strength of the fiber is exceeded, failure of the fiber results.

the surface charges on the fiber are neutralized, and complete breakdown of the sheet occurs.

The average voltage stress at breakdown, calculated as the quotient of the applied voltage by the electrode separation, was divided into two portions. One, a gas-dependent portion, was calculated as the breakdown voltage stress of the gas itself, assuming that its dielectric strength was a linear function of the pressure and that the field within the gas was that which would exist if the fiber and the gas were present as two continuous layers. The other portion was a fiber-dependent quantity which was referred to as the "barrier action" of the sheet. This was calculated as the difference between the observed values of the average stress and the stress corresponding to the onset of discharge in the gas. It represented the ability of the fibrous material to prevent gaseous breakdown despite the attainment of an average field in excess of the dielectric strength of the gas. The foregoing theory was developed from the study of data obtained in the following experiments.

The breakdown voltage of paper was found to increase markedly with increase in pressure. As would be expected, the effect of pressure was principally on the gas-dependent portion of the breakdown voltage.

Increases in relative humidity were found to decrease the breakdown voltage. This decrease was principally a fiber-dependent quantity resulting from a decrease in the electrical resistance of the fiber.

Temperature was found to have a gas-dependent effect on the breakdown voltage of paper. The breakdown voltage was reduced by temperature increases. This was attributed to a variation of gas density with temperature at constant pressure.

The breakdown voltage of paper was found to decrease with increase in the sheet density. This was principally the result of an increase in the electric field within both the fiber and the gas. Density was thus capable of causing changes in both the gas and the fiber-dependent portions of the breakdown gradient. The greatest part of its effect was on the gas-dependent portion.

Increases in sheet thickness were found to decrease the breakdown voltage of paper. The effect is primarily fiber-dependent. It is attributed to a statistical effect. As the thickness increased, the number of fibers and the gas voids to be traversed in passing from one electrode to the other also increased; hence, an increased probability that a fiber configuration having an exceptionally low dielectric strength existed.

It was concluded that the dielectric strength of paper as tested in air was distinctly different from that of paper as tested in oil. Each quantity depended upon different distributions of electrical field and different relative dielectric strengths. Even if the mechanisms might be considered identical, the drawing of conclusions concerning one of these values on the basis of experimental results on the other would be a difficult and uncertain process.

LITERATURE CITED

1. Whitehead, S., Dielectric phenomena, Vol. III. Breakdown of solid dielectrics. London, Benn, 1932.
2. Peek, F. W., Jr., Dielectric phenomena in high-voltage engineering. 3d ed. especially Chapt. VIII. New York, McGraw-Hill Book Co., 1929. 410 p.
3. Miner, Douglas F., Insulation of electrical apparatus. 1st ed. especially Chapt. II and III. New York, McGraw-Hill Book Co., 1941. 452 p.
4. Whitehead, J. B., Impregnated paper insulation. Especially Chapt. V. New York, Wiley, 1935. 221 p.
5. Clark, F. M., and Montsinger, V. M., Gen. Elec. Rev. 28:286-290 (1925).
6. A. S. T. M. Tentative Method D149-40F. A. S. T. M. Standards part III: 1141-1147(1942).
7. Cloke, Paul, Philpott, L. A., and Stetson, F. H., Annual report National Research Council, Conf. on Elec. Insulation p. 37-38(1940).
8. American Society for Testing Materials. Standards on electrical insulating materials. Especially p. 63-66. Philadelphia, American Society for Testing Materials, 1941. 448 p.
9. Farmer, F. M., Elec. World 62:1250(1913); C. A. 8:629(1914).
10. Milnor, J., Am. Inst. Elec. Eng. 32:2097(1913); quoted by (1) p. 94.
11. Kennelly, A. E., and Wiseman, R. J., Elec. World 70:1138-1141(1917); C. A. 12:332(1918).
12. Hill, Chas. F., Elec. J. 31:277-281(1934); C. A. 28:5348(1934).
13. Clark, F. M., J. Am. Inst. Elec. Eng. 44:3-10(1925).
14. Proc. Am. Soc. Testing Materials 24, pt. 1:462-650(1924).
15. Harvey, Dean, Proc. Am. Soc. Testing Materials 37, pt. 1:436-439 (1937).
16. Vogel, Trans, Am. Inst. Elec. Engrs. 43:340(1924); quoted by (1), p. 41.
17. Whitehead, S., and Nethercot, W., Proc. Phys. Soc. (London) 47:974-997(1935).
18. Whitehead, J. B., J. Am. Inst. Elec. Engrs. 42:1297-1304(1923); C. A. 18:632(1924).

19. Finch, J. M., Ind. Eng. Chem. 32:1021-1028(1940).
20. Finch, J. M., Bell Lab. Record 19:371-373(1940-41).
21. Kohmen, G. T., Ind. Eng. Chem. 31:807-817(1939).
22. Oyerant, A., Z. tech. Physik 10:328-334(1929).
23. Whitehead, J. B., Trans. Am. Inst. Elec. Engrs. 59:715-720(1940).
24. Whitehead, J. B., Elec. Eng. 59:660-663(1940).
25. Whitehead, J. B., Annual report National Research Council, Conf. on Elec. Insulation. p. 36-37(1940).
26. Ebanueli, L., High voltage cables. New York, Wiley, 1930. 107 p.
27. Moon, P. H., and Norcross, A. S., J. Am. Inst. Elec. Engrs. 49:125-129(1930).
28. Hippel, A. von, J. Applied Phys. 8:815-832(1937).
29. Fröhlich, R., Proc. Roy. Soc. (London) A160:230-241(1937).
30. Saeger, R. J., and Teller, E., Phys. Rev. 54:515-519(1938); C. A. 32:8914(1938).
31. Joffe, A. F., Trans. Faraday Soc. 24:65-72(1928).
32. Smekal, Adolf, Z. tech. Physik 8:561-586(1927).
33. Hoover, F. L., J. Am. Inst. Elec. Engrs. 45:824-831(1926).
34. Wagner, Karl Willy, J. Am. Inst. Elec. Engrs. 41:1034-1044(1922).
35. Hayden, J. L. R., and Steinmetz, Charles P., Elec. World 30:865-868(1922).
36. Inge, Lydia, Semenoff, N., and Walther, Alexander, Z. Physik 32: 273-286(1925).
37. De Luca, H. A., Campbell, W. Ford, and Morse, O., Gen. J. Research B16, no. 8:273-288(1938).
38. Loeb, Leonard B., Fundamental processes of electrical discharge in gases. Chapt. X. New York, Wiley, 1939.
39. Roman, F. L., Proc. Am. Soc. Testing Materials 30, pt. II:1012-1024(1930).