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INTRODUCTION

For many years it has been known that the complete charging and discharging of a condenser with complex dielectric involved a time element. Particularly, it was noted that a condenser could be discharged to zero potential, allowed to stand for an interval of time and a discharge then secured from the condenser. In some cases even after months a discharge could be obtained. The accumulation of such a charge on a condenser is spoken of as residual charge or dielectric absorption.

The Lyden jar was used extensively in the early work on residual charge. Physicists such as Benjamin Franklin, Faraday, and Maxwell recognized this. In fact Maxwell gives us the first attempt ever made at a theoretical explanation of the phenomena of absorption.¹ Today this is the principal theory recognized in the Physics world for this phenomena.

It was not until the day of speech communication over long distances that a study of the dielectric was given considerable attention. Theories have been developed for the explanation of dielectric absorption, some of which will be mentioned later. Even today large inconsistencies are found to exist between theory and experiment in this field of work.

There are numerous factors upon which dielectric absorption depends. Some of these are, material of dielectric, previous history, charging potential, moisture content, air content, charge time, discharge time, recovery time, and temperature.

It is the purpose of this paper to present results of experiment and to state conclusions drawn from work on temperature effects on residual charge of a paraffin paper dielectric. Through the study which has been made of this phenomenon it is felt information has been gained

which can be added to our now small understanding of absorption.

REVIEW OF LITERATURE

In accordance with fundamental theory, in which a dielectric is considered as subject to polarization but free from conductivity, if a constant potential difference E_0 is applied at time t_0 to the terminals of the condenser, then flows in the connections a "normal charging" current i_1 , which varies with time. The time variation of this normal charging current may be computed from the familiar equation

$$L \frac{d^2 i_1}{dt^2} + R \frac{di_1}{dt} + \frac{i_1}{C} = 0$$

L and R being respectively the self induction and resistance of the connections, and C the capacity of the condenser. A solution of this equation shows that $i_1(t)$ is a periodic function depending on the relation between L , R , and C .²

It is probable, however, that no dielectric exists which is entirely free from conductivity. When considering this we realize there is a conduction current i_g which must be added to i_1 . This value of i_g is dependent upon the potential difference across the plates of the condenser, and the dimensions and specific conductivity of the dielectric. In this view, when a condenser is discharged by short circuit, the difference of potential at its terminals is zero, and there is no conduction current in the dielectric. Thus the normal discharge current i_2 is the displacement current of dielectrics and it follows the same laws as i_1 , but is in opposite direction, that is, $i_2(t) = -i_1(t)$. The charge and discharge currents due to the change in the displacement in the dielectric should die out in an extremely short time interval. However, these currents persist as so called residual currents, in some cases for days or even months. These residual currents occur during both charge and discharge,

and will be designated by $i_1'(t)$ and $i_2'(t)$ respectively. The total current on charge and discharge then is

$$I_1(t) = i_1(t) + i_g + i_1'(t)$$

$$I_2(t) = i_2(t) + i_2'(t)$$

In many single dielectrics $i_1'(t) = -i_2'(t)$ and we have what is spoken of as the reversible anomalous current. In cases in which $i_2'(t)$ vanishes we speak of an irreversible anomalous current. If the current $i_1'(t)$ is of the reversible type, it builds up the stored charge

$$Q_1 = \int_0^t i_1'(t) dt$$

which may be completely recovered on a long time short circuit of the condenser.³

Many theories have been developed in an attempt to explain dielectric absorption. These theories may be classified as follows:

(1) Those in which the fundamental electric equations are retained, and the anomalies of dielectric behavior are attributed to anomalies of the structure of the dielectric medium.

(2) Those in which the departures from the fundamental laws are attributed to anomalies of dielectric displacement without reference to the nature of the underlying mechanism. Dielectric displacement is not proportional to field strength but dependent on the preceding state of the dielectric.

(3) Explanation of displacement and its anomalies traced to the motion of electrons within the atom.

(4) Explanations based on anomalies of conductivity, such as the free motion of ions, electrolytic dissociation, water in bulk or in capillary filaments.⁴

Maxwell's Theory falls into the first class of these four. He starts with the assumption that all dielectrics have both specific inductive capacity and conductivity as we know in the normal dielectrics, and that under electric force they function simultaneously and independent of each other. The assumption is justified by the experimental fact that conductivity may be observed in even the best insulators, and that poor insulators with very high conductivity also manifest specific inductive capacity. Maxwell first explores the question as to whether a normal dielectric, that is, one possessing specific inductive capacity and conductivity, can of itself manifest the characteristic phenomenon of absorption. Making use of Poisson's equation $\Delta^2 v - 4\pi\rho = 0$ and the equation of continuity of current flow, he shows that in a homogeneous dielectric no residual charge can appear. Maxwell shows that a dielectric which consists of a mixture of two or more different materials, even though under our closest observation it may appear to be homogeneous, may show the phenomena of absorption. The dielectric, therefore is to be thought of as a conglomeration or mixture of different normal dielectrics, that is, dielectrics having in general different values for dielectric constant (K) and specific conductivity (λ). He shows that a variation of the values of these constants, among the several constituent materials, is sufficient to account for dielectric absorption, but if the dielectric has the same values of K and λ throughout, absorption cannot appear.⁵

The Maxwell Theory of dielectric absorption is widely accepted in the field of Physics today. The chief disadvantage that the theory suffers is that not only has it no quantitative nor exact experimental confirmation, but many experiments appear to offer contradiction.⁶

Under the second classification we find the theory of Hopkinson. He proposes as an explanation that the dielectric consists of a mixture and that the components have different rates of approaching complete polarization and decay. Hopkinson develops an equation for the residual potential of a dielectric, analogous to the equation for the angular twist of a torsion thread under a succession of couples of various magnitudes and direction. Each couple applied for some time is supposed to cause an initial, and a sustained, gradual yield with time, that is, an increase of angular displacement, and the decay of this is reflected in subsequent twisting couples. Hopkinson's formula is substantially as follows:

$$D(t) = \frac{K}{4\pi} E(t) + \int_0^t E(t-u) \cdot \phi(u) du$$

This formula states that the actual displacement $D(t)$ in a dielectric at any instant t is made up of two terms. The first is the normal displacement as determined by the dielectric constant of the medium and by the instantaneous value of the voltage $E(t)$ in accordance with fundamental theory. The second term is the sum of the residual effects of all foregoing values of E considered as a function of an elapsed time u . The equation has the important property of showing the variation of the displacement when the electric field strength has varied in the past in accordance with any given function of the time $E(t)$. Every such residual effect of foregoing values of E decreases with the elapsed time u in accordance with a definite function $\phi(t)$ and the single residual effects are superimposed of each other. Hopkinson concludes from many experiments that his equations are only roughly approximated, but they are quite sufficient to support his principal conclusion that the effects on a dielectric of past and present electromotive forces are superposable.⁷

Under the second classification of theories may also be mentioned that

of Pellat. He proves experimentally that dielectrics subjected to electric force show an initial instantaneous polarization to which is added an additional polarization which changes with time. This second variable component polarization leads to the usual residual phenomena. He therefore proposes to account for these phenomena qualitatively and quantitatively by making an assumption as to the law followed by the variation of the polarization time. The law he proposes is that the second or variable part of the polarization leads to a final value which is proportional to the applied electric force, and that its rate of change is always proportional to its difference from its final value.⁸

The theory by Decombe on dielectric absorption is based on atomic structure. Decombe, in seeking an explanation of the heating of condensers, notes the remarkable and very general fact that most thermodynamic modifications are inseparable from noticeable electric phenomena. Thus, mechanical deformations are always accompanied by both heat and electricification; capillary deformation, shock, cleavage, etc., all result in both heat and electric manifestation. It is in terms of motions and deformations of electrons within the atom that Decombe concludes offers and explanation for dielectric absorption.⁹

We now come to the theories based on anomalies of conductivity. In reality there are no theories in this class sufficiently developed to merit the name. There are, however, many peculiarities of dielectric conductivity, which indicate departures from fundamental laws, and in which the time enters as a factor. It has often been suggested that dielectric absorption is due to a varying conductivity resulting from a motion of variable changes in "ions" within the dielectric. In the case of solids there are

obvious difficulties in this point of view. Instinctively, one thinks of the conductivity of solid dielectrics as being of the same general nature as that in metals, into which an influence of time does not enter. Experimental investigations as to the exact nature of the conductivity of solid dielectrics are very difficult. As a consequence, principal attention has been directed to those other forms of conductivity which are found in liquids and gases, and in which the relation between current and electromotive force vary with time. Many composite solid dielectrics reveal an irreversible anomalous current which does not reappear on discharge. This property is also possessed by most liquids. Moreover, it is their only prominent anomalous property, residual charge being entirely absent. It has been noted that this current does not obey Ohm's law, and that the apparent conductivity falls off with increasing voltage. This is also the case in an ionized gas, and this has led to the suggestion that conductivity of both liquid and solid dielectrics is of the same nature as that in gases. In spite of the fact that experimental data is far from complete as connected with conductivity, there is evidence that absorption and conductivity are definitely related properties.¹⁰

Although every effort is made to reduce the chemical and physical properties of paper insulation to those pertaining only to the cellulose of wood pulp fiber, it nevertheless results that the electrical properties of the purest paper are not those commonly expected in a single substance, and the behavior of the best, purest, and driest paper is highly complex. The explanation is to be found in the fibrous structure of the paper which results first in a mesh-like combination of air and fiber, and second in a microscopic structure possessing the finest filaments and channels with

consequent pronounced capillary properties. Such a structure is avidly absorbent of both gas and thin liquids such as water, and it is practically impossible to extract completely the air and moisture from the paper before impregnation. In spite of the fact that the electrical conductivity of dry paper is extremely small and difficult to measure, under alternating stress it shows a definite dielectric loss and phase difference. These are due to the presence of dielectric absorption, in some way resulting from residual moisture.¹¹ It is known that further elimination of moisture reduces both conductivity and dielectric absorption in insulating materials.

The apparent power factor is very sensitive to slight residual moisture changes, and particularly so at the higher values. Taking into account the whole range studied, there is an increase of fifteen times in power factor as against a corresponding increase of five times in residual moisture content. Absorption contributes the greater proportion of this increase.¹²

Whitehead records an observation showing increase in capacitance with temperature. His work was with a cylindrical condenser and he believes this increase was largely due to thermal expansion of the electrodes.

The dielectric constant of paper in the range from twenty-five to seventy degrees centigrade is independent of the temperature; that of the oils decreases in normal relation to the density. In combination the dielectric constant of impregnated paper varies with temperature only as affected by the density of the oil. The dielectric constant may, however, increase as the result of oxidation of the oil.¹³

Dielectric loss in the paper is closely associated with moisture content. In very dry paper the loss is due almost entirely to absorption. Dielectric loss in oils is of pure conduction or leakage type. The conductivity is

due to ions of which the origin in commercial oils is largely moisture, oxidation, or entrained impurities. The conductivity which determines the loss is that associated with a very short time interval after the application of continuous voltage. Longer time measurements indicate lower conductivities because, of the original number of ions, some have been divided into space charges with resulting counter polarization, and some have discharged at the electrodes. A measure of the total number of ions present is to be found in the product of the initial conductivity and the viscosity. This product is a measure of the free ion content or electrical purity of the oil.¹⁴

Before a thorough understanding can be had of the electrical properties of insulation, it is indeed necessary that there be much development in the understanding of dielectric absorption.

INVESTIGATION

The subject investigated in this experiment was one of temperature effects on the residual charge of a paraffin paper condenser with varying charge time, discharge time, and recovery time.

This work was carried out with nine Western Electric, type 1370-A, Condensers. These condensers were connected in parallel so as to give a maximum capacity. They were charged with a dry cell of which the charging potential was 1.52 volts. A constant check was kept on the voltage of this cell.

Three temperatures were extensively studied in this investigation. These temperatures were room temperature (approximately 16° C.), zero degrees centigrade, and minus seventy degrees. Ice was used in cooling the condensers to zero degrees. Solid carbon dioxide mixed with alcohol was used to secure the temperature minus seventy-degrees centigrade. The alcohol was used so as to have better contact with the condensers thus insuring greater uniformity of temperature.

In order to secure uniform temperatures it was necessary to place the condensers in a well insulated box. The condensers were insulated with approximately two inches of rockwool and an inch air space on all sides. They were enclosed in a metal container equipped with a resistance thermometer. The resistance thermometer provided a means of determining the temperature of the condensers. This thermometer was made of several meters of very fine copper wire.

The thermometer was calibrated from 47.0°C to -1.0°C. The data for the calibration curve was obtained by using a mercury thermometer and an ohmmeter. With the equipment used the temperature could easily be deter-

mined within an error considerably less than one degree. A maximum variation in temperature of four degrees is recorded in the data taken at room temperature. The calibration curve for the thermometer is shown in figure 1.

In working with ice and dry ice practically no variation in temperature was recorded. To insure uniform cooling of the condensers no readings were until the condensers had been cooled a minimum of four hours.

It was found necessary to completely seal the condensers when working at low temperatures in order to remove factors arising from the condensing of moisture from the air on the condensers and connections.

An automatic timing system was used in timing the charge time, discharge time, and recovery time. A picture of this apparatus is shown in figure 2. By means of the selector and the Cenco impulse counter any variation in time of charge, time of discharge, and time of recovery desired could be obtained. The timing device was arranged so that the condenser was charged for a definite time, discharged on short circuit for a definite time, allowed to stand on open circuit for a definite time (recovery time), and then was discharged through a ballistic galvanometer. The circuit of the automatic timing system is shown in figure 3.

The ballistic galvanometer provided a means of measuring the residual charge. The constants of the galvanometer used were:

Sensitivity-- $.002$ microcoulombs/mm.

C. D. R. X.-- 9000 ohms.

Resistance-- 2070 at 25°C .

Period -- 27.2 seconds when connected to condensers.

In the operation of the timing system the electrical impulse for the

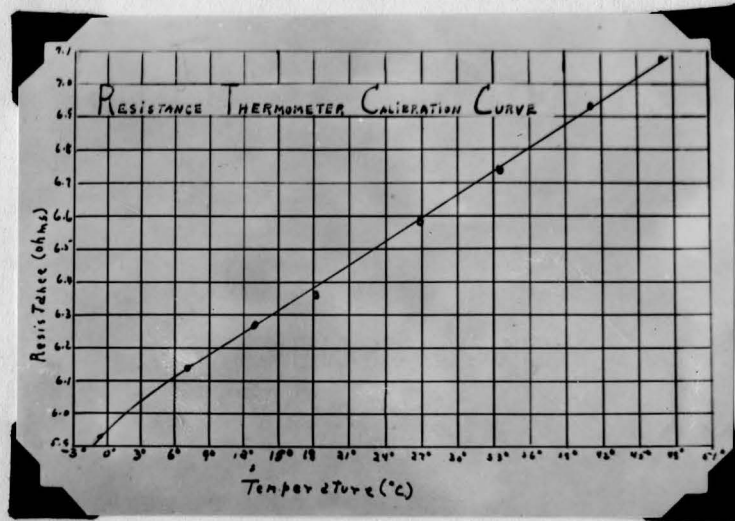


Fig. 1 Resistance Thermometer Calibration Curve

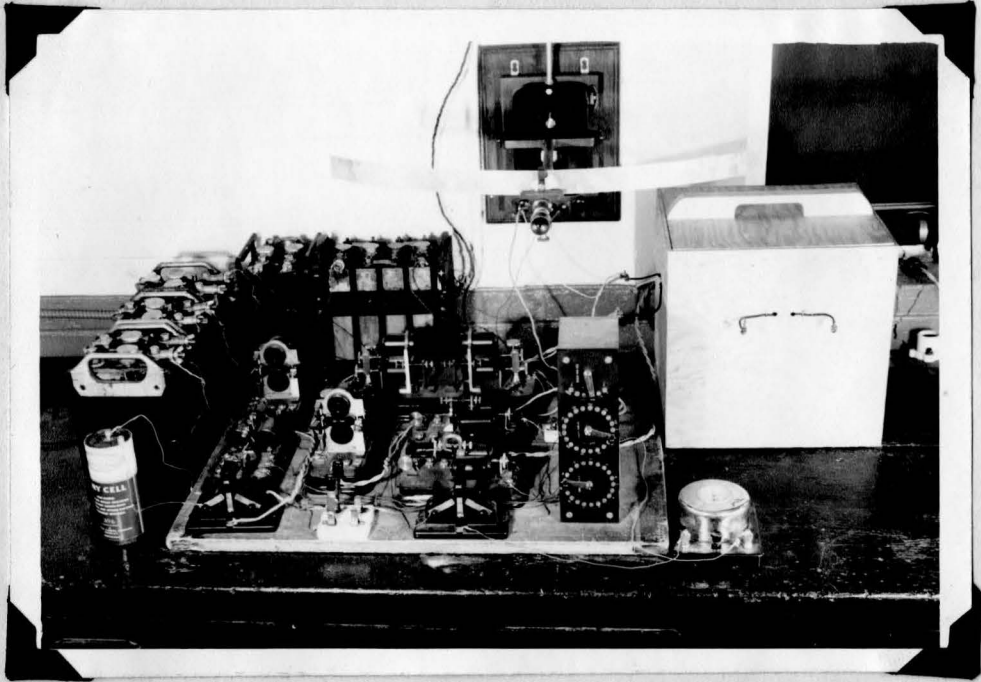


Fig. 2 The Automatic Apparatus

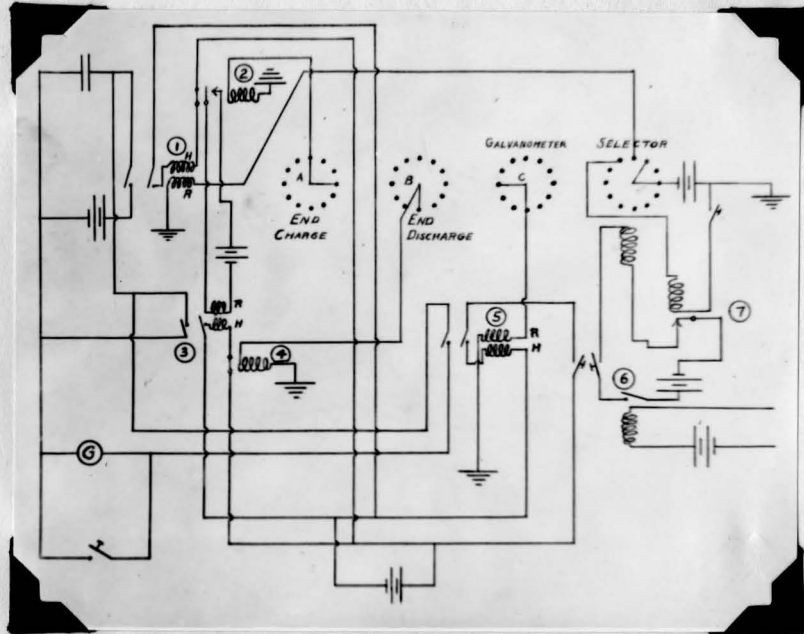


Fig. 3 Wiring Diagram

relays were timed by a clock. The clock was constructed such that its pendulum made contact each time it passed through the midpoint of its swing. The interval between each contact was one second. The clock was operated by a relay and two Edison cells. A picture of the clock is shown in figure 4. In order to secure consistent readings throughout this work it was necessary to duplicate conditions as nearly as possible. The resistance thermometer served as an indicator of constant temperature. Condensation of moisture caused trouble until this factor was removed by sealing the condensers in a metal box. Since timing was taken care of entirely by the automatic equipment, there was very little source of error. It was found that the readings could be duplicated with a high degree of accuracy.

In the work no reading of less than 25 ms. was considered sufficiently accurate to record. Readings were taken at spaced intervals of time varying charge time, discharge time, and recovery time, from one to sixty seconds. The charge time was varied eight times, discharge time ten times, and recovery time nine times. All possible combinations of these were taken for the three temperatures. The value of each reading recorded is an average of two readings. A total of approximately nine hundred points are recorded in the Appendix II. It was found these readings could be duplicated within an error of one percent at the time and later within an error of four percent.

Curves were plotted in which the charge time t_c , the discharge t_d , and the recovery time t_r , were independently treated as variables, and plotted against the residual charge q . The equations of these curves were suggested from the work of Simmons "A Study of Dielectric Absorption."¹⁵

Plotting t_c against q , holding t_d and t_r constant gives curves as represented in figures 5, 6, and 7. In these curves it is seen that the



Fig. 4 The Mercury Timer

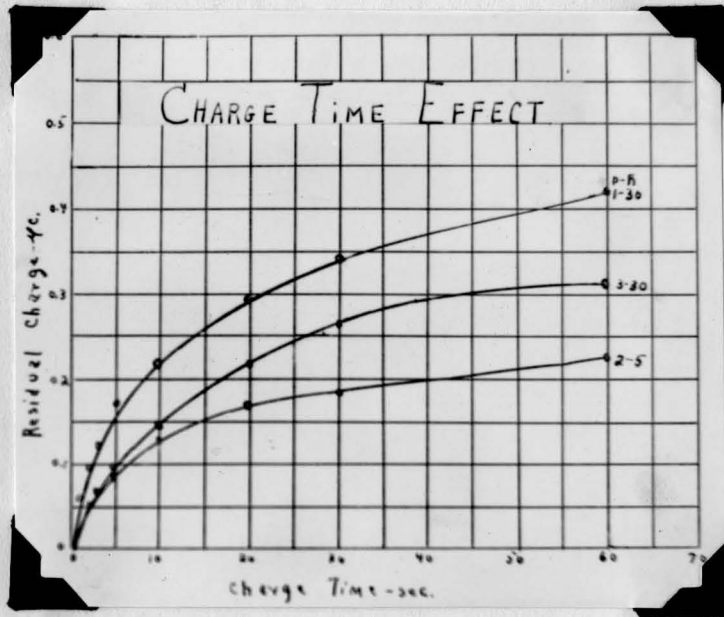


Fig. 5 Curves of Charge Time Effect at Room Temperature

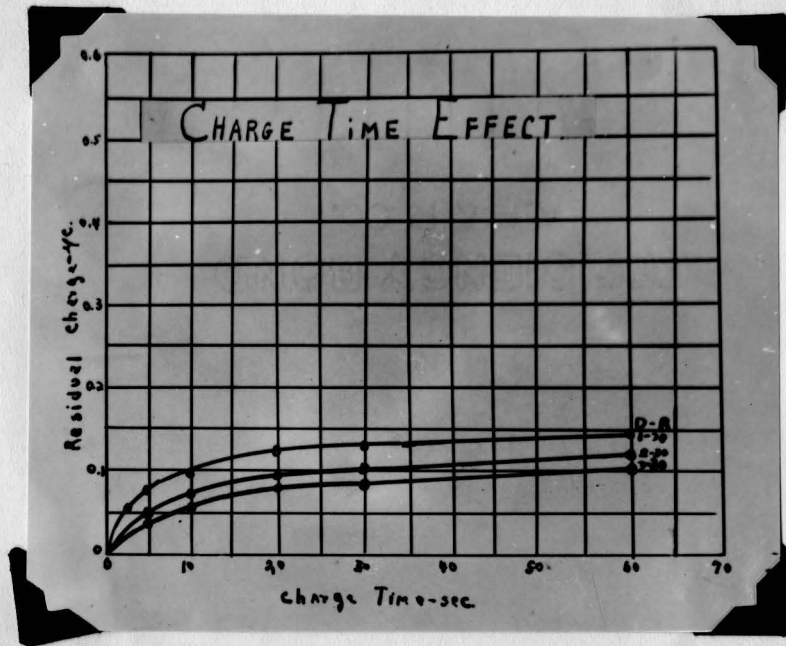


Fig. 6 Curves of Charge Time Effect at Zero Degrees Centigrade

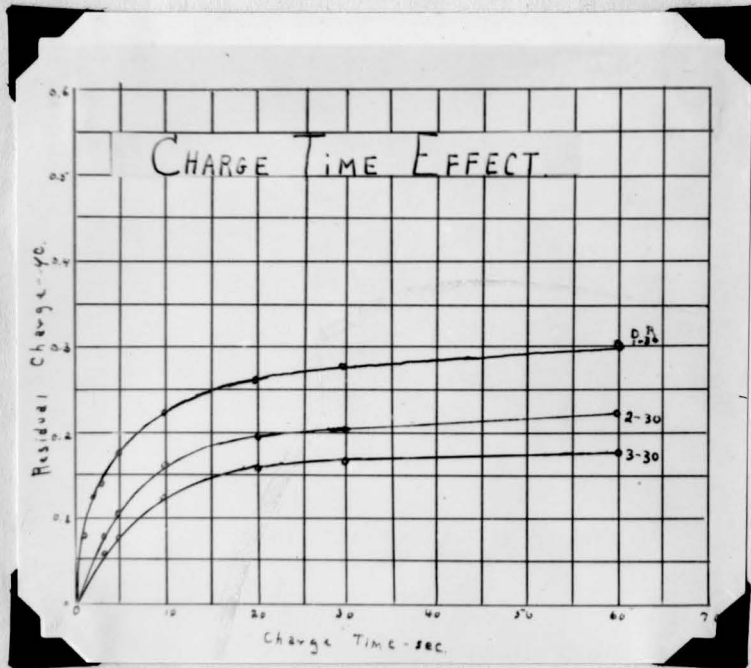


Fig. 7 Curves of Charge Time Effect at Minus Seventy Degrees Centigrade

residual charge at zero degrees is much less than at room temperature or minus seventy degrees centigrade, in which t_d and t_r are the same for all three temperatures. This information indicates that there is a temperature for minimum residual charge somewhere between room temperature and minus seventy degrees.

The equation $q = \frac{1}{\alpha + \beta(t_c - 1)}$, where α and β are constants, was tested as representing these curves. Two points were selected on a particular curve from which α and β could be determined. Having determined α and β , other points on the curve were tested. The calculated values and the observed values agreed within experimental error for all three temperatures. However, α and β differed for each curve, indicating that α and β are function of t_r and t_d .

As a sample calculation suppose we use the charge time effect curve for room temperature for which $D = 1$ and $R = 30$. Here q is 0.293 for $t_c = 20$ and $q = 0.377$ for $t_c = 40$. α and β as calculated are respectively, 1.86 and 30.4. As a check to see if this equation did represent the curve other points were tested. For $t_c = 30$, $q = 0.348$ from calculation and 0.344 from experiment. This is an error of 1.1%. For $t_c = 60$, $q = 0.422$ from calculation and 0.424 from experiment. This represents an error of 0.5%. All curves examined did not agree with as high accuracy as this, but the error did remain within experimental error. From the several curves tested it is felt that the equation $q = \frac{1}{\alpha + \beta(t_c - 1)}$ does represent the relation between residual charge and charge time for this work.

If we plot curves showing discharge time effects, keeping t_c and t_r constant, we obtain curves as represented by figures 8, 9, and 10. An equation of the form $q = n + kt_d$, where n and k are constants, was found to represent these curves for all three temperatures. n and k were found to

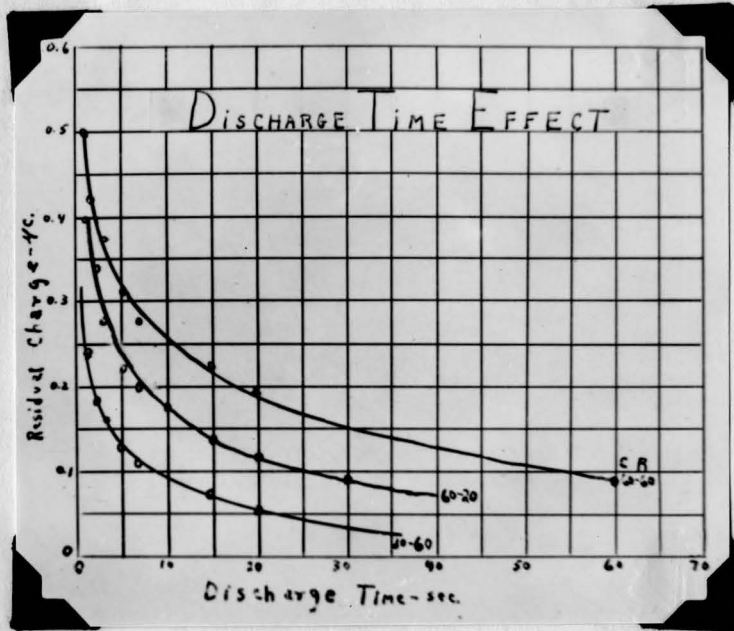


Fig. 8 Curves of Discharge Time Effect at Room Temperature

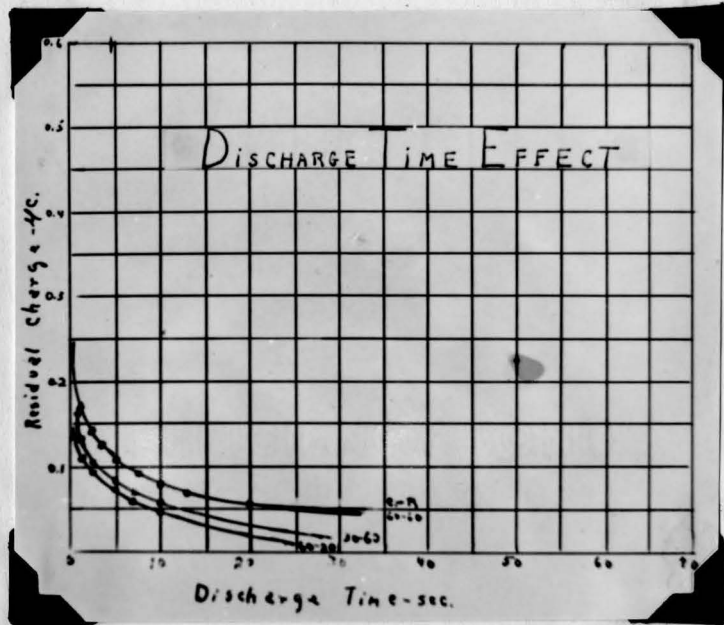


Fig. 9 Curves of Discharge Time Effect at Zero Degrees Centigrade

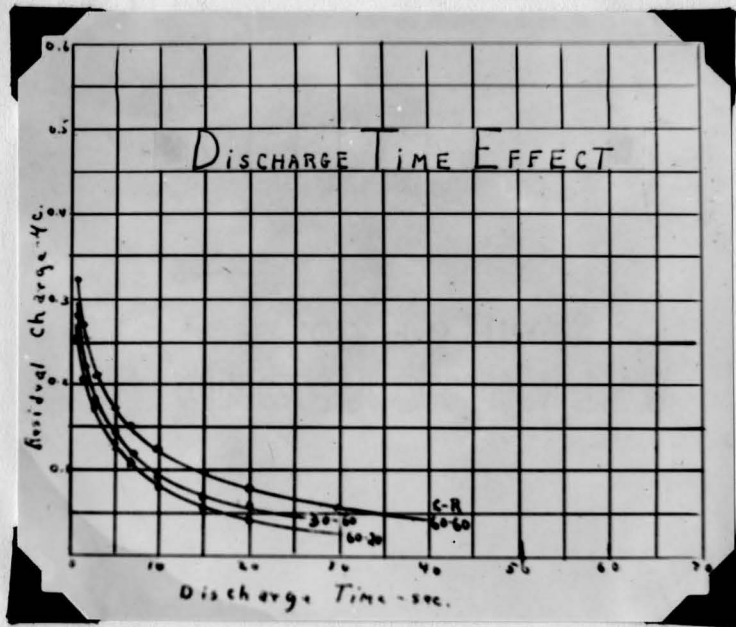


Fig. 10 Curves of Discharge Time Effect at Minus Seventy Degrees Centigrade

differ for each curve and thus it may be concluded that n and k are functions of t_c and t_r . Here also it is noted that the residual charge for the same t_c and t_r is smallest for zero degrees and highest for room temperature.

As a sample calculation suppose we use the discharge time effect curve for dry ice with $t_c=60$ and $t_r=60$. Two points were chosen on the curve and n and k calculated. n was found to be 3.30 and k was 0.469. As a check $t_c=10$ and $t_r=15$ were substituted in this equation. The error between the calculated values and measured values of q were 1.6% and 1.0% respectively. Similar accuracy was found in testing other curves. It is concluded that $q = \frac{1}{n + kt_c}$ is an equation which represents the discharge time effect curve for the temperatures tested in this work.

In figures 11, 12 and 13 are shown the curves in which t_r is treated as a variable and t_d and t_c are constant. Here the dotted line represents $t_r=0$. During the time required for the galvanometer to reach a maximum deflection the condenser had a chance to accumulate an additional residual charge. This time between discharge and the reading of the galvanometer was one fourth of the period or 6.8 seconds on the graph. These curves were then extended through the origin as shown in the graphs. This being the same type curve as that for the charge time effect it suggests an equation of the form $q = \frac{1}{a + b(t_r - 1)}$. This equation was tested and found to fit the curve within an error of 5% for all three temperatures. Here also a and b differ for each curve, and are thus functions of t_c and t_d .

In a sample calculation for the curve for dry ice in which $C=30$ and $D=2$, a was found to be 4.10 and b was 29.0. For two of the points on this curve the error between the calculated and observed values of q were 4.3%

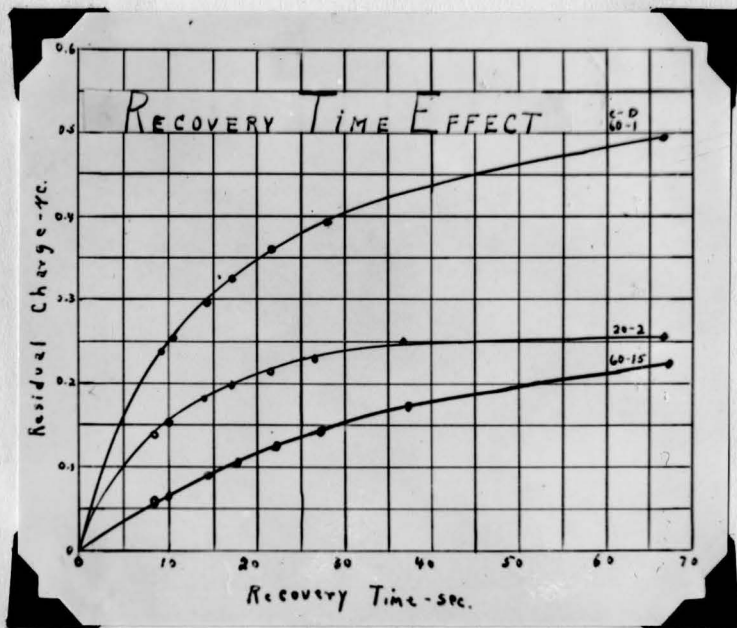


Fig. 11 Curves of Recovery Time Effect at Room Temperature

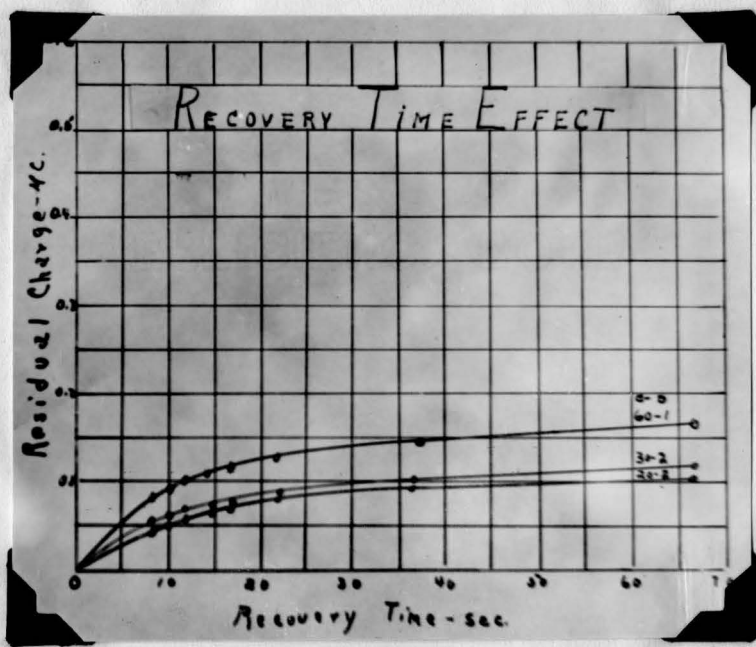


Fig. 12 Curves of Recovery Time Effect at Zero Degrees Centigrade

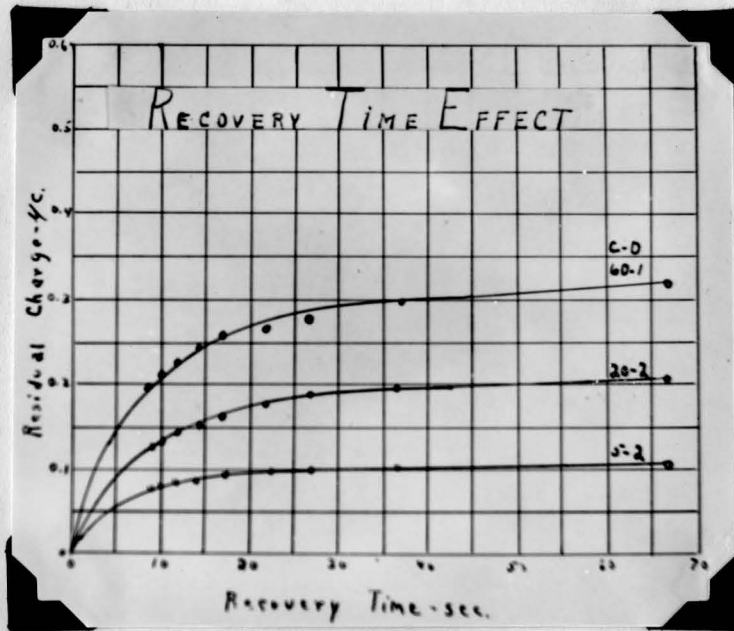


Fig. 15 Curves of Recovery Time Effect at Minus Seventy Degrees Centigrade

and 0.9%.

Time prevented the carrying out of this experiment for more than the three temperatures. However, an attempt was made to determine whether zero degrees actually was a temperature of minimum residual charge. A graph of the results obtained on this work is shown in figure 14. Here the residual charge was measured at fifteen minute intervals with t_g , t_d , and t_r constant, as the condensers were cooled from room temperature to -70°C . Of course the resistance thermometer could not be used in determining the temperature of the condensers while this change of temperature was taking place since the thermometer measured the temperature of the air surrounding the condensers. The curve does show, however, that a minimum exists in the vicinity of zero degrees. The fact that the minimum does not drop as low as that measured for these conditions at zero degrees is explained on the basis of the nonuniformity of temperature throughout the condensers. This does support the view that a minimum exists near zero degrees centigrade. The curve also indicates a maximum between zero degrees and minus seventy. When steady temperature conditions exist, the curve flattens out as expected.

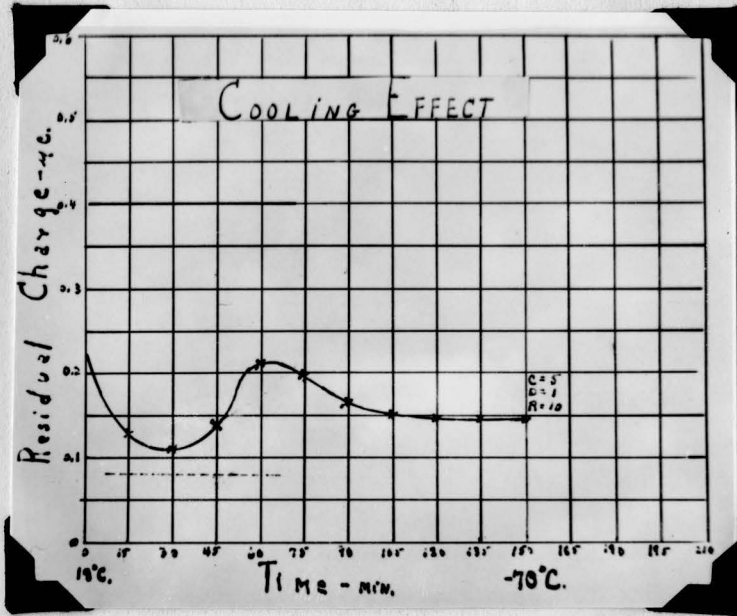


Fig. 14 Curve of Cooling Effect

ACKNOWLEDGMENTS

I wish to express sincere thanks to Dr. F. B. Hynes for his guidance during this experiment and for the use of the automatic timing system which he devised, and to Dr. F. L. Robeson, who constructed the clock used in carrying out this work.

DISCUSSION

From the investigation it is seen that a point of minimum residual charge exists between room temperature and -70°C . In spite of fact that time prevented further investigation to determine if this minimum does exist at zero degrees, there is evidence in favor of this. In the graph of figure 14 there is shown a minimum residual charge condition approximately thirty minutes after cooling with dry ice. The fact that this value does not fall to as low value as that previously determined for the same t_c , t_d , and t_r , is a point which favors this view. Naturally, since the temperature is not uniform in the condensers, if a minimum does exist at zero degrees, then in the process of cooling, such a minimum would not be expected to be as low as that recorded at zero degrees.

In the charge time effect curve it is seen that as t_c increases the residual charge reaches a constant value. Under such conditions the dielectric absorption has reached a saturation value. With this condition the only current flowing in the circuit would be that of conduction through the dielectric.

The discharge time effect curves show a decrease in residual charge as t_d increases. This is to be expected since the condensers have been drained of a large proportion of their charge. Under very large discharge time, little or no charge is recorded since the dielectric has returned toward its original state before recharging. However, it must be remembered as previously stated that the complete discharging of a condenser in some cases may necessitate months.

The recovery time effect curves display an increase in the recovery of the residual as t_r increases. An extension of recovery time, after a

certain point, does not result in further increase of residual charge is shown by the flattening of the curves.

It is felt that Pellat's theory, as discussed heretofore, offers the best explanation for the characteristic curves. The flattening of the charge time effect curves represents a condition of maximum displacement of ions from their normal positions. The rate of return of the ions to their normal position would be represented by an equation of similar form. This one finds to be the case, the equations differing only in values of constants. The decrease in residual charge as t_d increased in the discharge time effect shows a decrease of displacement. This displacement would approach zero as t_d increased.

The decrease of residual charge in going from room temperature to zero degrees may be explained on the ion displacement theory. It is accepted that the activity of ions is decreased as temperature is lowered. It seems logical that the maximum displacement of the ions would be decreased under this condition. If such is the condition, then the residual charge would be decreased.

As for an explanation of the increase in residual at $-70^{\circ}\text{C}.$, this does not seem to follow directly from this theory. A possible explanation lies in the change of the spacing between the condenser plates. Such a change would be brought about by contraction of the metal case container of the condenser. This change would result in an increase in the capacity of the condenser. Considering residual charge as proportional to the capacity of the condenser, it follows that the residual charge would be increased.

It is true the factor of contraction does enter also for cooling from room temperature to zero degrees. However, here the contraction is small as compared to that when the temperature is changed from zero degrees to

-70°C.

There are two points suggested from this work that should be investigated further. The one of these is to determine if zero degrees is a temperature of minimum residual charge. The second is a study of the maximum residual charge condition evidenced in figure 14.

It is indeed evident that considerable research remains to be carried out before a full explanation of dielectric absorption is to be had. To have theory and experiment in this field is indeed a challenge which the physicists must meet.

CONCLUSIONS

The following are the conclusions reached in this paper:

1. When all other factors affecting the residual charge in dielectrics are held constant, then, in general,

$$q = \frac{1}{\alpha + \beta t_c^1}, \text{ when } t_c, t_d, \text{ and } T \text{ are constant,}$$

$$q = \frac{1}{n + kt_d}, \text{ when } t_c, t_r, \text{ and } T \text{ are constant,}$$

$$q = \frac{1}{a + bt_r^1}, \text{ when } t_c, t_d, \text{ and } T \text{ are constant,}$$

where, q is the residual charge

t_c is time of charge

t_d is time of discharge

t_r is the time of recovery after discharge

T is the temperature in degrees Centigrade

α and β are functions of t_d , t_r , and T

n and k are functions of t_c , t_r , and T

a and b are functions of t_c , t_d , and T .

2. There exist a point of minimum residual charge between 18°C . and -70°C . This minimum is in the vicinity of 0°C .

APPENDIX I

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9. Ibid, pp. 60-61
10. Ibid, pp. 70-71-72
11. Whitehead, Impregnated Paper Insulation, John Wiley & Sons, Inc., London, 1935, pp. 13-14
12. Ibid, p. 32
13. Ibid, p. 105
14. Ibid, pp. 181-182
15. Simons, J. W., A Study of Dielectric Absorption, Thesis for Master of Science Degree, Virginia Polytechnic Institute, 1939.

APPENDIX II

Herein is given data taken during this experiment under conditions as stated in the investigation.

The symbols used have the following meanings:

T is temperature in degrees centigrade.

C is charge time in seconds.

D is discharge time in seconds.

R is recovery time (not corrected) in seconds.

S is galvanometer deflections observed, in millimeters, the average of two readings for each point.

The galvanometer constant for converting the deflection readings to microcoulombs is .002 microcoulombs/mm.

-38-

T = 14°C.

C = 1

Date: 1/8/42

R	D = 1	S
	-	
7	-	25
10		26.3
15		27
20		29.5
25		30
30		31

for D = 2 or over, all readings were less than 25

T = 14°C.

C = 2

Date: 1/8/42

R	D = 1	S	R	D = 2	S	R	D = 3	S
1		35		-			-	
3		37		-			-	
5		39.2	5		26		-	
7		42.2	7		27.2		-	
10		42.5	10		28.9		-	
15		44	15		30.7		-	
20		46.5	20		31.5		-	
25		47.2	25		32.2		-	
30		48.4	30		33	30		25

for D = 5 or over, all readings were less than 25

T = 14°C.

C = 3

Date: 1/8/42

R	D = 1	S	R	D = 2	S	R	D = 3	S	R	D = 5	S
1		45	1		30	1		-		-	
3		47.5	3		32.2	3		-		-	
5		52.5	5		34.7	5		25.2		-	
7		53.2	7		36.5	7		27.2		-	
10		56.5	10		38.5	10		29.2		-	
15		59.7	15		41	15		31		-	
20		60	20		43	20		33.2		-	
25		60.5	25		43.7	25		34.1		-	
30		62	30		44.7	30		35	30		25
						60		37.5	60		26

for D = 7 or over, all readings were less than 25

T = 17°C.

C = 5

Date: 1/9/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	61.5	1	42.2	1	32	-	-	-	-
3	66.5	3	46	3	35	-	-	-	-
5	69.2	5	49.2	5	38	5	25	-	-
7	73	7	51.7	7	40.5	7	27.2	-	-
10	76.2	10	55	10	44	10	29.7	-	-
15	81	15	58.7	15	47	15	33	15	25
20	85	20	62	20	49.7	20	35	20	27.3
25	86.5	25	63.7	25	51.2	25	36.8	25	28.7
30	86.7	30	65.5	30	52.7	30	38.5	30	30.2
60	93.5	60	70	60	57.2	60	42.2	60	34.5

D = 10

R S

for D = 15 or over, all readings were less than 25

60 28

T = 16°C.

C = 10

Date: 1/9/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	73.2	1	53.3	1	42.5	1	30.7	-	-
3	78.2	3	57.7	3	45.5	3	33.5	3	25.5
5	84.2	5	62.3	5	49.7	5	37	5	28.2
7	87.8	7	66.5	7	54	7	41	7	31.2
10	93.2	10	71.2	10	58.5	10	44.7	10	34.7
15	101	15	77.5	15	64	15	49.1	15	39.7
20	103.5	20	82	20	68.2	20	53.7	20	43.2
25	108	25	84.5	25	72	25	56	25	46
30	109.5	30	87	30	73.7	30	58.7	30	48
60	118	60	95	60	82.5	60	66.7	60	56.5

D = 10

R S

D = 15

R S

D = 20

R S

10 26.5
15 30.2
20 33
25 35.5
30 38.2
60 46

25 25
30 27.1
60 34

60 26

for D = 30 or over, all

readings were less than 25.

AC

T = 17°C.

C = 20

Date: 1/10/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	91	1	71.5	1	58.7	1	44.2	1	35.7
3	98	3	77.5	3	63.7	3	48.2	3	38
5	105.7	5	84.2	5	71	5	53.5	5	42.5
7	112.5	7	90.7	7	75.5	7	58	7	48
10	120.5	10	98.2	10	84	10	64.7	10	54.5
15	129.5	15	108	15	94	15	73	15	60
20	136.2	20	115.2	20	100	20	79.7	20	66
25	143.2	25	121	30	110.7	30	89	30	75.5
30	147	30	125.5	60	125	60	105.2	60	91
60	162	60	141.2						

D = 10		D = 15		D = 20		D = 30	
R	S	R	S	R	S	R	S
1	26.2						
3	28.5						
5	31.6						
7	34.8						
10	39.5	10	28	15	26.5	30	25.5
15	46	15	33.5	20	30.5	60	35
20	51.5	20	38.5	30	36.2		
30	59	30	45	60	47.2		
60	74	60	58.1				

for D = 60 or over,
all readings were
less than 25

T = 17°C.

C = 30

Date: 1/12/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	97.7	1	79.7	1	68.5	1	58.7	1	48.2
3	109	3	87	3	74.5	3	63.5	3	52.5
5	117	5	94.7	5	83	5	70.4	5	58.2
7	125	7	102	7	88.5	7	77	7	63.1
10	134	10	112.5	10	98.7	10	85.4	10	71.7
15	146.2	15	125	15	111	15	97.5	15	83.2
20	156.5	20	137	20	120	20	106.5	20	91.7
30	171	30	148.5	30	133.8	30	121.2	30	106.4
60	193	60	169	60	157.5	60	145.5	60	128

-41-

C = 30

(continued)

D = 10		D = 15		D = 20		D = 30		D = 60	
R	S	R	S	R	S	R	S	R	S
1	32.5	-	-	-	-	-	-	-	-
3	34.6	-	-	-	-	-	-	-	-
5	38.6	5	28	10	27.4	15	26.2	60	28.4
7	43.2	7	31	15	33.7	20	30.7		
10	46.7	10	35	20	39	30	38		
15	56.2	15	42	30	47	60	52.5		
20	63.5	20	48	60	62				
30	74.5	30	57.4						
60	92	60	73						

T = 18°C.

C = 60

Date: 1/15/42-1/17/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	117	1	96	1	78.5	1	56	1	48
3	126.5	3	104.9	3	86.7	3	59.5	3	51.5
5	137.5	5	114.9	5	94	5	66	5	58
7	147.2	7	124.5	7	102	7	73.5	7	63.6
10	162	10	137.2	10	113	10	82	10	72.5
15	179.8	15	154.3	15	127.7	15	96.7	15	84.8
20	193.2	20	167.2	20	140.1	20	107	20	95
30	212.5	30	176.2	30	157.9	30	123	30	111.5
60	249.6	60	208.5	60	189	60	152.5	60	138.5

D = 10		D = 15		D = 20		D = 30		D = 60	
R	S	R	S	R	S	R	S	R	S
1	41	1	32	1	26	-	-	-	-
3	43	3	34.5	3	28	-	-	-	-
5	50.5	5	38.8	5	31.5	7	25	30	29.2
7	56	7	43.2	7	35.2	10	30.5	60	44.5
10	64.5	10	50.4	10	41	15	37.1		
15	76	15	61.4	15	50	20	43.2		
20	86	20	70	20	58.4	30	54.5		
30	102	30	84.2	30	72	60	77		
60	130.9	60	111.2	60	97.6				

42.

T = 0°C.

C = 3

Date: 2/5/42

D = 1	
R	S

10	26
15	26.7
20	27.5
30	28.1
60	30.5

for D = 2 or over, and for C = 2 or less, all readings were less than 25.

T = 0°C.

C = 5

Date: 2/5/42

D = 1		D = 2	
R	S	R	S

1	27
3	28.2
5	29.5
7	30.8
10	33
15	33.8
20	35.1
30	37
60	37.6

30	25
60	27.2

for D = 3 or over, all readings were less than 25.

T = 0°C.

C = 10

Date: 2/5/42

D = 1		D = 2		D = 3		D = 5	
R	S	R	S	R	S	R	S

1	32.5
3	35.1
5	37
7	39.2
10	41.9
15	43.5
20	45.5
30	48
60	51

5	26
7	27.5
10	29.8
15	32
20	33.8
30	35.9
60	38.5

15	25
20	27.7
30	29
60	32.1

60	25
----	----

for D = 10 or over, all readings were less than 25.

-43-

T = 0°C.

C = 20

Date: 2/5/42-2/7/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	37	1	26.9	-	-	-	-	-	-
3	40.7	3	29.8	-	-	-	-	-	-
5	43.9	5	32.4	5	25.7	15	25.3	30	25.5
7	46.2	7	34.4	7	27.5	20	27.7	60	30.9
10	49.9	10	37.5	10	30.2	30	30.9		
15	53.4	15	41	15	33.6	60	36		
20	55.9	20	43.3	20	36				
30	59.8	30	47.3	30	39.6				
60	65.6	60	52.7	60	45				

for D = 10 or over, all

readings were less than 25.

T = 0°C.

C = 30

Date: 2/8/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	39.8	1	29	3	25.2	-	-	-	-
3	43.5	3	31.9	5	27.8	10	25.4	20	26.4
5	47.4	5	34	7	30	15	29.1	30	29.5
7	49.8	7	36.6	10	33.2	20	31.1	60	36.1
10	52.5	10	40.3	15	37.4	30	35.2		
15	56.7	15	44.5	20	40.5	60	42		
20	60.6	20	47.4	30	44.7				
30	65.2	30	51.9	60	51.8				
60	72.4	60	58.7						

D = 10

R S

60 30

for D = 15 or over, all readings were less than 25.

Ab.

T = 0°C.

C = 60

Date: 2/8/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	42	1	31	1	26	-	-	-	-
3	46.9	3	34	3	28.5	-	-	-	-
5	50	5	37.1	5	31.5	7	26	10	25
7	53	7	40.8	7	33.7	10	29.3	15	28.9
10	57.9	10	44.8	10	37.8	15	34.2	20	32.2
15	63	15	49.7	15	42.6	20	37.5	30	37.5
20	67	20	54.1	20	46.8	30	43.5	60	47.2
30	73	30	60.4	30	52.4	60	53.2		
60	82.9	60	71.6	60	62.5				

D = 10		D = 15		D = 20	
R	S	R	S	R	S
-	-	-	-	-	-
20	26.7	60	33.2	60	28.2
30	31.5				
60	40.7				

for D = 30 or over, all readings were less than 25

T = -70°C.

C = 1

Date: 2/27/42

D = 1	
R	S
1	36
3	41.4
5	38.5
7	38.6
10	43.6
15	39.9
20	40.5
30	40.5
60	40.9

for D = 2 or over, all readings were less than 25.

-45-

T = -70

C = 2

Date: 2/27/42

D = 1		D = 2	
R	S	R	S
1	51.4	1	25.5
3	53.5	3	27.4
5	58.5	5	28.5
7	56.1	7	29.4
10	60.5	10	30.5
15	61	15	31.1
20	61.8	20	31.5
30	62.2	30	32.5
60	61.7	60	33

for D = 3 or over, all readings were less than 25.

T = -70°C.

C = 3

Date: 2/ 27/42

D = 1		D = 2		D = 3	
R	S	R	S	R	S
1	59.5	1	30.7	-	-
3	62.6	3	33	-	-
5	64.5	5	34.7	10	25.9
7	66.1	7	36.2	15	27
10	66.6	10	37.3	20	28
15	68	15	39	30	28.4
20	68.1	20	40.1	60	30.1
30	69.1	30	40.8		
60	71.5	60	42.5		

for D = 5 or over, all readings were less than 25.

T = -70°C.

C = 5

Date: 2/27/42

D = 1		D = 2		D = 3		D = 5	
R	S	R	S	R	S	R	S
1	67.2	1	38.4	1	25.4	-	-
3	71	3	41	3	27.2	-	-
5	74.1	5	43.5	5	29.3	60	25.5
7	76.5	7	45.4	7	31.4		
10	81	10	47.4	10	33		
15	83.2	15	49.5	15	35		
20	84.4	20	50.5	20	35.7		
30	86.1	30	52.2	30	37.3		
60	88.2	60	54.1	60	38.9		

for D = 7 or over, all readings were less than 25.

-46-

T = -70°C.

G = 10

Date: 3/ 23/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	81.7	1	59	1	41.2	1	25.2	-	-
3	91.7	3	62.2	3	44.7	3	27.7	-	-
5	96.1	5	66.2	5	48	5	30.2	10	25.2
7	98.2	7	70.5	7	50.7	7	32.1	15	27.5
10	99.5	10	73.2	10	54.7	10	34.6	20	29.5
15	102.2	15	78	15	58	15	37.7	30	32.2
20	105.2	20	79.5	20	61	20	40	60	35.5
30	112	30	82.7	30	63.2	30	42.5		
60	115	60	87.7	60	67.5	60	47		

D = 10	
R	S
-	-
60	25.7

for D = 15 or over, all readings were less than 25.

T = -70°C.

G = 20

Date: 3/ 23/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	95	1	65.5	1	48	1	31	-	-
3	98.2	3	69	3	52.5	3	34.1	-	-
5	108.2	5	73.5	5	57.1	5	37.5	5	27
7	112.9	7	79.2	7	60.2	7	40	7	29.7
10	115.2	10	84.2	10	65.5	10	43.7	10	32.5
15	120	15	89	15	69.7	15	48	15	36.2
20	125	20	92.9	20	74.7	20	51.5	20	39.5
30	129.2	30	98.5	30	79.5	30	57	30	43.7
60	136.5	60	104.2	60	86.5	60	63	60	50

D = 10		D = 15	
R	S	R	S
15	26.5	60	27.2
20	28.9		
30	32.2		
60	38.2		

for D = 20 or over, all readings were less than 25.

-47-

T = -70°C.

C = 30

Date: 3/23/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	97	1	65	1	49.2	1	33	1	25
3	105.6	3	70.2	3	53.5	3	36.3	3	27.2
5	111	5	75.2	5	58.7	5	39.7	5	30
7	116.9	7	80.5	7	63.5	7	43.4	7	32.8
10	119	10	85.7	10	67.2	10	47.2	10	37
15	124.7	15	93.2	15	73.5	15	53.6	15	41.2
20	130.5	20	97	20	78.8	20	57.5	20	46.2
30	139	30	102.2	30	84.5	30	63.2	30	50.7
60	146.5	60	114.3	60	93.2	60	72.7	60	59.4

D = 10		D = 15		D = 20	
R	S	R	S	R	S
-	-	-	-	-	-
10	27	30	28.1	60	27.6
15	31.1	60	35.5		
20	34.6				
30	39.1				
60	45.9				

for D = 30 or over, all

readings were less than 25.

T = -70°C.

C = 60

Date: 3/30/42

D = 1		D = 2		D = 3		D = 5		D = 7	
R	S	R	S	R	S	R	S	R	S
1	98.7	1	66	1	51.2	1	36.6	1	28.3
3	106	3	71.3	3	55.5	3	39	3	30.7
5	116	5	76.7	5	60.2	5	43.7	5	34.1
7	121.2	7	82.2	7	64.5	7	46.3	7	37.7
10	129.7	10	89	10	70.7	10	53.2	10	42.5
15	132.5	15	97.2	15	79	15	60	15	49.7
20	139	20	103	20	87.2	20	66.5	20	54.5
30	150.7	30	112.7	30	92.5	30	74.3	30	62.1
60	163.5	60	127	60	108.9	60	88.7	60	76.2

C = 60(continued)

D = 10		D = 15		D = 20		D = 30	
R	S	R	S	R	S	R	S
-		-		-		-	
5	25.6	25	27.5	30	30.2	60	29
7	28.9	20	31.3	60	39.5		
10	32.7	30	37.2				
15	38.5	60	49				
20	42.7						
30	50.2						
60	62.5						

for D = 60, all readings were less than 25.

Temperature	Resistance Thermometer Resistance(ohms)
27	6.58
33.5	6.74
41	6.93
47	7.08
18.5	6.35
13	6.27
7	6.14
-1	5.93

Temperature- Charge Data

C = 5

D = 1

R = 10

Time(minutes)	S
0	103.5
15	62
30	54.5
45	93.5
60	109
75	96
90	79.5
105	75.5
120	73.5
135	73.5

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