A STUDY OF ELECTRET PROPERTIES WITH VACUUM TUBE ELECTROMETER

A Thesis

Presented to

the Faculty of the Department of Physics

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

---

by

James Sophocles Pappas

June 1952

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ABSTRACT

It was the purpose of this study (1) to develop a vacuum tube electrometer for rapid determinations of relative characteristics of electrets; (2) to establish the effectiveness of this instrument by verifying an earlier claim that the time required for the reversal of charge on an electret increased with the temperature of the molten mixture components.

Electrets were made from Carnauba wax rosin mixtures and the effective surface charge on the electrets measured by means of a vacuum tube electrometer. The method used was the discharge of a capacitor across a high resistance (10^{11} ohms) in the grid circuit.

Curves were plotted of proportional values of effective charge versus time and the decay characteristics studied. Definite reversal times were obtained for some electrets. The reversal times for other electrets could not be obtained because of the malfunctioning of this type of instrument in relative high humidities. However, by taking the average values for the data and constructing a smooth curve through these points, an indication of the

reversal times increasing with increasing temperatures was obtained.

Electrets yielding homocharges were made with electric fields of 7-8 kv/cm, which was in contradiction to an earlier report that the electric field must be greater than 10 kv/cm. However, this was in good agreement with the values of electric fields as used by other workers.

The electrometer was calibrated with a known condenser, and an approximate value of 3 esu/cm^2 was calculated for the effective surface charge density of the electret. This is in agreement with the value of from 0.4-10 esu/cm^2 reported in the literature.

It is concluded that with proper atmospheric moisture control, that the vacuum tube electrometer is capable of rapidly indicating substances which make electrets (yielding a homocharge). Very possibly, through ingenious methods, the meter could be calibrated quite accurately to read values of the effective surface charge densities.

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CHAPTER I

THE PROBLEM AND DEFINITIONS OF TERMS USED

There have been very few papers published on the electret, the earliest of which was written in 1925, shortly after the discovery of the electret. An electret is a dielectric exhibiting anomalous effects, the explanation of which has not yet been satisfactorily expounded. In reviewing the scant literature on the subject many diverse opinions about the electret in general were encountered.

1. THE PROBLEM

Statement of the problem. It was the purpose of this study (1) to develop a vacuum tube electrometer for rapid determinations of relative characteristics of electrets; and (2) to establish the effectiveness of this instrument by verifying an earlier claim that the time required for the reversal of charge on an electret increased with increased

temperature of the molten mixture components.[1]

Importance of the study.

> A number of commercial and scientific researchers have followed in the footsteps of Eguchi and Gemant, and at this writing a variety of electret production projects are rumored and reported to be underway throughout the United States. It is impossible to assess the value of these rumors and reports, probably due to the need for trade secrecy in most cases; but it is a rather well-known fact that electret experimentation has recently been accelerated in numerous colleges, universities, and governmental research organizations. Therefore, it would seem at best that the debut of electrets as commercial products will not be long delayed.[2]

Considering the need of the vast amount of research and experimental investigations of materials from which to fabricate electrets, there appears to be a definite advantage to have a means of rapidly determining whether or not an electret has been prepared successfully, and whether or not the substance being considered will yield a homocharge. In the study

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[1]W. M. Good and J. D. Stranathan, "An Improved Method of Making Permanent Electrets and Factors Which Affect Their Behavior," Physical Review, 56:810-13, October, 1939.

[2]Thomas A. Dickinson, "Ceramic Electrets," Ceramic Industry, 52:64, May, 1949.

of charge recovery curves (e. g. irradiation of the electret with x-rays) it is advantageous to have a measuring instrument with a rapid response.

The experimental results of the investigations on the electret obtained by earlier investigators will have to be duplicated by others before being generally accepted; thus in the attempt to develop a measuring device a verification of earlier results should be of value.

2. DEFINITIONS OF TERMS USED

Electret. The term "electret" was coined by Oliver Heaviside to denote a permanently electrified substance exhibiting electrical charges at its extremities. At the ordinary meeting of the Physico-Mathematical Society of Japan, in the year 1920, the name "Permanent electret" or simply "electret" was given to the special dielectric which retained a net electric moment after the externally applied polarizing field was removed. This special dielectric was prepared by Eguchi from a molten mixture of equal

parts by weight of Carnauba wax and resin. Ten per cent beeswax was added to some mixtures.[1] An electret in many respects is the exact electric counterpart of a permanent magnet.[2]

Carnauba Wax. "Waxes are usually mixtures of higher alcohols of the methyl alcohol series ($C_nH_{2n+1}OH$) with esters of these same alcohols and the fatty acids; in some waxes higher paraffin hydrocarbons are also present."[3] Carnauba wax is extracted from the leaves of a Brazilian palm. It has an exceptionally high melting point (83°C to 86°C) and is largely $C_{25}H_{51}COOC_{30}H_{61}$.

Heterocharge. Using the terminology originated by Gemant and appearing in numerous papers on electrets, a charge on the electret surfaces of the opposite sign to that of

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[1]M. Eguchi, "On the Permanent Electret," Philosophical Magazine, 49:178-92, January, 1925.

[2]A. Gemant, "Electrets," Physics Today, 2:8, March, 1949.

[3]James B. Conant, Albert H. Blatt, The Chemistry of Organic Compounds (New York: The Macmillan Company, 1947), p.217.

the adjacent polarizing electrode is called a heterocharge. The heterocharge which initially appears on the electret is not strange and is simply explained in terms of the orientation of dipoles in an electric field wherein charges of opposite sign attract each other.

Homocharge. A charge on the electret surfaces of the same sign as that of the adjacent polarizing electrode is called a homocharge. In a number of materials, the initial heterocharge declines, a reversal of polarity takes place, and a homocharge builds up. The explanation of the phenonomenon of the subsequent appearances of the homocharge on the electret has yet to be established.[4]

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[4]F. Gutmann, "The Electret," Reviews of Modern Physics, 20;467-70, July, 1948.

CHAPTER II

REVIEW OF THE LITERATURE

Eguchi, a Physics Professor at the Higher Naval College, Tokoyo, Japan published the first paper on an electret in the year 1925. Since the publication of Eguchi's paper, there have been relatively few papers on electrets. Most of these papers established experimental facts, with approximately only four presenting theories. However, as yet, none of the theories have been universally accepted.[1]

The literature contains numerous variations in opinions and many disagreements of the methods of preparing electrets as well as the factors which affect their behavior. Consequently the present investigator has elaborated many points in detail to emphasize the importance and need

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[1] F. Gutmann, "The Electret," Reviews of Modern Physics, 20:467-70, July, 1948.

of much further research on the electret.

Known Substances capable of yielding electrets. Hydrocarbon compounds having a finite dipole moment tend to develop homocharges but, non-polar hydrocarbons, which have been investigated, such as paraffin wax, will not develop permanent charges and thus, will not yield electrets. The electrification of an electret is not merely a surface effect but also a volume effect. The homocharge appears in compounds containing esters and/or alcohols; however, in many substances there is no sign of any decay of the primary heterocharge.

Figure 1 shows the characteristics of various substances. Gutmann has divided these substances into two classes: those capable of permanent volume polarization and those giving surface charges only.[2]

Mikola subdivided electrets into two classes:

1. Those substances of comparatively high conductivity yielding heterocharges only.

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[2] Ibid., p.468.

2. Those substances of a much lower conductivity capable of developing homocharges.[3]

Gemant stated that dipolar constituents with a high degree of hardness at room temperature are necessary for the preparation of electrets; however, he was not certain as to whether these two conditions, orientability and hardness, were sufficient. As other possible materials from which to prepare electrets, he suggested synthetic plastics, thermo-plastics, thermosetting plastics and glasses - especially high electrical resitivity glasses, such as are used in the manufacture of fiber glass for electrical purposes. More recently, Gutmann says," It was thought that only hard and brittle substances are suitable to become electrets, but it has been found that some very soft and low melting carnauba waxes also form electrets."[4]

Padgett[5] is of the opinion that the

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[3]Loc. cit.

[4]Ibid., p.459.

[5]Edward Padgett, "Improved Electrets," Radio Electronics, 20:20-23, April, 1949.

preparation of electrets from the mixtures as used by early workers is unsatisfactory, because beeswax is relatively soft and so complex, physically and chemically, that it is unstable, is subject to decomposition by light, and precipitates out of the wax mixture. He used equal parts of carnauba wax and Hercules Hydrogenated rosin (Staybelite resin). "Hydrogenation of rosin eliminates the difficulties mentioned above. Splendid semi-plastic electrets can be made from 45% carnauba wax, 45% hydrogenated rosin, and 10% ethyl cellulose."[6] Padgett found that the density of surface charge varied from 0.25 to 4.00 statcoulombs per square centimeter. He then states that Eguchi and Genant working under ideal laboratory conditions found the relative density of surface charge to be approximately 6 statcoulombs per square centimeter; yet, he claims, "New compounds produce electrets with better stability and higher surface charge."[7] In considering the

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[6] Ibid., p.21.

[7] Ibid., p.20

relatively small magnitudes of the surface charge densities measured by Padgett as compared to the results of other workers, the present investigator is not of the opinion that the implication of a higher surface charge density in the above quotation is wholly justified.

From Dickinson's[8] research on electrets, he claims that unsaturated polyesters appear to have the most desirable features for the manufacture of electrets. He states that it is alleged that Gemant, working with the Detroit Edison Company, has done some work on ceramic electrets.

In a more recent paper Dickinson states that glass is considered particularly well adapted to the fabrication of electrets and gives a number of reasons.[9]

Actually there are no indications in the

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[8]Thomas A. Dickson, Electrets (Alhambra, California: Plastics Research Company, 1948)

[9]Thomas A. Dickinson, "Ceramic Electrets," Ceramic Industry, May, 1949, p.62.

paper that he prepared electrets from glass. Footnotes in this republished paper, resulting from rebuttals by the readers, state:

> Experts assert that there is a considerable gap between wax and glass that should be supported with experimental evidence relating to ceramic materials.
>
> Organic electrets mentioned here are non conductors of electricity at both room temperature and in the range at which orientation of the particles take place. Insofar as commercial glass and other inorganic ceramic materials become good conductors at high temperatures, the small residual charge that is "frozen" in is of relatively short duration, and of little consequence.[10]

Dickinson further states:

> It is quite possible that many electret materials can be compounded with ferrous oxides or assembled as a series of non-ferrous parts so that they can duplicate the fundamental manifestations of permanent ferromagnets; further, it is a well-known fact that they can be compounded or assembled so as to exert magnetic influences as many non-ferrous substances.
>
> In the manufacture of glass electrets, it seems rather evident that quartz materials (such as the soda lime combinations) should play a leading role. However, it is entirely possible that other glasses which are more compatible with metallic oxides will meet the majority of specifications.[11]

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[10] Ibid., p.63.

[11] Ibid., p.64.

Dickinson lists other ceramics which he claims may find uses in the fabrication of electrets.

(1) Fireclays - where ultra-high temperature resistance is essential.

(2) Clays with "non-metal" ferrous components such as iron oxide - where low cost substitutes for alloy ferromagnets are desired. Materials in this category, Dickinson claims, may in some instances, be molded like pottery and charged after firing by insertion in an electromagnetic coil rather than by the conventional electret charging method.

(3) Porcelain - where the natural transparency of glass is non-essential, or where maximum chemical inertness is desired.

Gemant[12] also mentioned plastics of high softening point, glass, ceramics - especially barium-titanate ceramics - as promising materials from which to prepare electrets. However, no indications in the literature were

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[12] A. Gemant, "Electrets," Physics Today, 2:8-13, March, 1949, p.13.

found of any of the above suggested materials having been successfully used to make electrets.

The charge on electrets. The average surface charge density reported to have been attained on the surface of the electret was from 5-10 esu/cm^2, without any sign of decay of the homocharge over a period of years. The time required for the reversal of polarity appears to have been from one to fourteen days. Eguchi observed no evidence of decay of the homocharge after three years when the electret was kept in a dry atmosphere and the surfaces short-circuited with a keeper (i.e. wrapped in a metal foil). An electret which has lost its charge by adsorption of moisture on its surface will regain the charge by drying in a desiccator. Gemant made electrets which showed no sign of decay over a period of twelve years.[13]

Eguchi made the following observations on the electret.[14] The manner of growth of the

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[13] A. Gemant, Physics Today, p.8.

[14] M. Eguchi, "On the Permanent Electret," Philosophical Magazine, 49:187, 1925.

charges on both surfaces and their values do not vary much when the method of preparation is modified in certain ways; e. g., when both electrodes are completely insulated from the earth, or when either one of the electrodes is completely earthed and the other insulated. Using a bunsen flame, he melted some of the surface of an electret which, after cooling and drying, regained its original charge. The surface charge disappeared when washed with various reagents such as water, acids, alkalis, absolute alcohol, ether and benzene; but the electret always recovered sometime after the dielectrics were completely dry. If the surface layer were removed by planing or cutting, the remainder was still an electret. When the carnauba wax and rosin mixture was solidified first and then put under an electric field, the surfaces displayed some weak residual charge, "...their intensity and durability were of very small order quite incomparable with those of the electret."[15] When an electret was placed in an oppositely

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[15] Loc. cit.

directed electric field for thirty minutes, the surfaces obtained moderately large surface charge densities of signs respectively opposite to the signs of the initial charges. This reversed charge decayed rapidly and the electret regained its original charge.

Gutmann found that the decay of the homocharge is not a continuous process, but takes place in discontinuous jumps. He claimed that the process of decay itself, as well as the magnitude and frequency of these discontinuities, were considerably speeded up by irradiating the electret in a supersonic sound field of approximately 700 kc and of rather appreciable intensity.

Effects of mixing the components on the behavior of the electret. The electret behavior depends markedly upon the details of preparation of the carnauba wax-rosin mixture. Stranathan and Dodds[16] investigated the effects of varying the method of mixing the electret components and the effects of different molten mixture temperatures on the resulting charge density. They used

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[16] W. J. Dodds and J. D. Stranathan, "Electrets from Dry-mixed Components," Physical Review, 60:360, August, 1941.

"Selected Flora" carnauba wax and a special grade rosin, pulverized with a mortar and pestle and sifted through sieves, which yielded strong, smooth, physically uniform electrets having characteristics more easily reproducible than could be obtained using the usual methods.

Equal parts of the pulverized rosin and carnauba wax were mixed in a mechanically driven mixer, the time of mixing being the same in all cases. The desired amount of dry mix was weighed out in a tinned pan and placed in an electrode and tank system immersed in an oil bath. The melting and cooling times for the electrets were carefully controlled, and a uniform procedure adopted for all electrets. They stated that stratification into two component layers occured during melting if the particles were too large, and small bubbles, probably of air, appeared on the surface of the electret when the particles were too small. "Preliminary work indicates a slight particle-size effect on the shape of the reversal curve."[17] Stranathan

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[17] Ibid., p.360.

and Dodds stated that the reversal-times of electrets prepared in this manner were considerably shorter than many of those reported in the literature for electrets of similar composition. They concluded that the shorter reversal time was due to the grade of carnauba wax and rosin used rather than to the method of manufacture.

Temperature considerations in making electrets. The temperature (above the melting point of the carnauba wax and rosin mixture) is a factor in the behavior of the electret, though the final surface charge density is independent of the excess temperature and attains approximately the same final value.[18] Thus, in the process of melting the mixture, it is sufficient to raise the temperature to the melting point. Dodd and Stranathan claimed that the time required for reversal of charge on the electret increases with increasing temperatures above the

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[18] W. M. Good and J. D. Stranathan, "An Improved Method of Making Permanent Electrets and Factors Which Affect Their Behavior," Physical Review, 56:810-13, October, 1939.

melting point, and that the reversal time approaches a lower limit which is that time characteristic of an electret of pure carnauba wax. They also report that there is evidence that prolonged heating or vigorous stirring of the wax mixture at lower temperatures accomplishes to a lesser degree what is accomplished by higher temperatures during the initial melting.

The cooling time of the electret under the applied charging field was investigated by Good and Stranathan. Using a cathode container (iron cylinder) in oil bath, the hot oil was drawn off at 75°C and the electret further cooled by the addition of cold oil. The rapidly cooled electrets reversed the sign of the charge and also attained the same final charge in a shorter time than when waiting for the hot oil to cool. However, when water was used, instead of cold oil, and, the electret cooled to room temperature in thirty minutes the rapid cooling did not yield an electret. Electrets cooled in the air were full of cracks and easily broken; whereas, those cooled within

the iron cylinder were uniform and smooth. As an explanation, the investigators say, "... the phenomena are no doubt connected with the temperature gradient within the cooling electret."[19] Extending the cooling time in the electric field beyond a day produced little effect. Below this there existed a range of cooling times vital to the behavior of the electret.

Gutmann obtained his best results when the substance was thoroughly fluid at the melting point and the polarizing field removed once the wax had thoroughly solidified but still remained at an elevated temperature.

Johnson and Carr[20] conducted a series of experiments in which the electric field was applied to the wax mixture at different temperatures and allowed to remain until the wax cooled to room temperature. Another series of experiments was made in which the electric field was

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[19] Ibid., p.813.

[20] O. J. Johnson and P. H. Carr, "Some Experiments on Electrets," Physics Review, 42:912, December, 1932.

applied when the wax was molten, but was removed from each successive sample when it had cooled to a temperature lower than that at which the field was removed from the preceding sample. The strengths of these electrets were measured and the investigators concluded, "Results indicate that the molecules of the wax mixture become fixed in their polarized positions, so that random reorientation is negligible at a temperature definitely lower than the temperature at which solidification takes place."[21]

Importance of the electrodes in making electrets. The electrode material used in making electrets was reported by Gutmann as being an important factor.[22] Nickel electrodes yielded a small charge which decayed to zero in a few months. Using tin electrodes without applying a polarizing field, electrets were obtained having a charge of two thirds the magnitude of those similarly prepared when using an applied electric field, and with no decay of charge over a period of six months. He stated that

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[21] Loc. cit.

[22] Gutmann, Op. cit., p.459.

there is an important difference between electrified bodies prepared by the latter methods and the true electret prepared with an electric field at an elevated temperature. "The electrification of the true electret is a volume effect, extending through the whole of its mass while the charge appearing without either the thermal or electrical part of the preparation are purely surface charges."[23]

Most workers used tin-foil electrodes because they strip easily from the wax mixture. Good and Stranathan reported that tin seemed to be the most satisfactory electrode material, and that it showed less evidence of electro-chemical activity than any other materials used. They used a tinned pan for the bottom electrode and a solid tin disk turned on a lathe, polished with carbon tetrachloride and rouge, for the top electrode. A new pan was used and the top repolished in preparing each electret. The temperature of the oil bath was kept below 90°C, for at temperatures greater than this the tin showed

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[23] Loc. cit.

evidence of chemical action.

Franklin claims that he has produced electrets having a heterocharge without the homocharge by insulating the electret material from the electrodes with sulfur disks during polarization.[24]

Strength of the polarizing electric field used in preparing electrets. Gutmann claimed that electrets prepared with electric fields less than ten kilovolts per centimeter produced hetrocharges only, which decayed slowly to a permanent value within ten to twenty days. "First investigators all applied fields in excess of 10 kv/cm, but Thiessen and co-workers found that electrets can also be prepared with lower fields."[25] Johnson and Carr state that they made electrets - after the manner of Eguchi - using carnauba wax and rosin in electric fields as small as a few hundred volts per centimeter. However, Gutmann said that the important difference is that electrets prepared with an electric

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[24]A. D. Franklin, "The Heterocharge of Carnauba Wax Electrets," Physical Review, 78:342, May, 1950.

[25]Gutmann, Op. cit., p.460.

field less than 10 kv/cm gives a heterocharge only.[26]

If the figures given in Padgett's paper are correct, the present investigator calculated his electric field to have been around 7 to 8 kv/cm, yet his published twelve-week curve shows a definite reversal of charge. Gemant states, "To make an electret the molten wax is put in a moderately strong direct current field, perhaps five thousand volts per centimeter."[27] Bearing in mind that Padgett used slightly different components, there appears to be a lack of definite knowledge of the question of polarizing field strength effects.

Dickinson[28] stated that he used either alternating or direct current in the polarizing process that, as a rule, the direct current was preferable because it formed distinguishable positive and negative charges, whereas the alternating current produced charges of the

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[26] Loc. cit.

[27] Gemant, Physics Today, Op. cit., p.9

[28] Dickinson, Ceramic Industry, Op. cit., p62.

same sign on each surface, one stronger than the other. "This statement is challenged by an expert in the field who says that only direct current is applicable."[29] The latter statement is the editor's note on a republication of Dickinson's paper.

The electric field of the electret.

The electric field intensity near the surface of the electret was reported as high as 20 kv/cm. Gemant[30] attempted to analyze mathematically the effects of the free ions present in the atmosphere on the electric field of the electret. The results of his derivations, based upon simple considerations, were in apparent contradiction to the experimental findings. Phenomena along these lines would be encountered in the consideration of the possibility of the use of electrets in vacuum discharge tubes.

The assumption of Gemant's problem - a mathematical analysis of the field of an

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[29] Loc. cit.

[30] A. Gemant, "Field of Electrets in the Presence of Gaseous Ions," Physical Review, 61:79, January, 1942.

electret in a space of finite ion concentration - was that "The Calculation is based on the type of double-layer as first concerned by Gouy for electrolytic solutions. It can be applied to this case as well."[31] The basic idea is that ions of a charge opposite to a given charged surface will accumulate in the neighborhood, while ions of the same charge will be repelled. When equilibrium is reached, the ions are acted upon by electrical and diffusion forces of equal magnitude and opposite direction. Thus, for a positive electret surface negative ions will accumulate near the surface, shielding the field outside the double layer formed by the positive electret charge and the negative ionic charge.

However, from experimental findings, the field of electrets is appreciable even in the presence of gaseous ions. Gemant stated that it is quite likely that the field will diminish with increasing concentration of the ions and that "Experiments will have to establish the

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[31] Loc. cit.

relation, field versus ion concentration."[32] With this relationship known, an electret combined with a measuring device may be usable as a quantitative indicator for the ion concentration of the atmosphere or any closed space.

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[32] Ibid., p.82.

CHAPTER III

MEASURING INSTRUMENT THEORY

An absolute determination of the effective charge on the surface of an electret can be obtained by means of a quadrant electrometer; and, thus the effective surface charge density, the ratio of the total effective charge on one surface of an electret to the area of that surface, can be calculated for purposes of comparison. However, for many investigations on the electret, it is sufficient to measure relative changes in the effective surface charge density. An instrument satisfying the requirements for the latter type of measurements was used in the present investigation. For this purpose an electron tube electrometer was used.

An electrometer utilizing an electron tube is identical in utility with a quadrant electrometer or a gold-leaf electroscope with an indicating scale, for they are all constant potential measuring devices which are not supposed to take current from the source of potential being measured. An electron tube, in principle, is an electrostatic device because

the operation of the tube depends only upon the grid potential.[1]

> By the simplest definition, a three element electron tube is a device in which the current flowing from cathode to anode is controlled by the potential of a grid to which no current flows. Under this definition, an operating triode would show no change of plate current if the grid lead were disconnected; for, if no current flows to or from the grid, its potential will not change. Tubes which can do this are called electrometer tubes.[2]

Special tubes can be obtained which are essentially electrostatic in character after special considerations have been given to the prevention of electrons from leaking at the tube base, to internal ionization, and a number of other extremely important points in the manufacture of such tubes. Ordinary vacuum tubes fail even to approach the requirements of an electrometer. "The word 'electrometer' is properly applied only where it refers to a tube or circuit in which the control element may

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[1]John A. Victoreen, "Electrometer Tubes for the Measurement of Small Currents," Proceedings of the I. R. E., Vol. 37, No. 4, April, 1949, p. 433.

[2]Loc. cit.

have an input leakage resistance of the order of 10^{16} ohms or grid current of 10^{-15} amperes.[3] Currents as small as 10^{-17} amperes may be measured with vacuum tube electrometers.[4]

A number of methods are available for the measurement of small currents by the use of an electron tube. One method, and the method used in the present investigation is to measure the potential difference produced when there is a current through a very high resistance. The size of the resistor that can be used, and the resulting sensitivity obtainable, are limited by the leakage resistance of the grid. A 10^{11} ohm resistor was used as shown in the circuit diagram of Figure 4. Thus for an input signal of 10^{-11} amperes the corresponding potential difference would be 1 volt. This potential difference across the high resistance in series with the grid bias can be indicated on the plate current

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[3] Loc. cit.

[4] Herbert J. Reich, Theory and Applications of Electron Tubes, (New York and London: McGraw-Hill Book Company, Inc., 1944), p. 613.

microammeter when a vacuum tube with a high transconductance - the ratio of the change in plate current to the change in grid voltage - is used.

An electrometer triode, number VX-5803, manufactured by the Victoreen Instrument Company, was used in the modified Soller[5] circuit of Figure 4. The use of this circuit, and the theory upon which the method was based, was an outgrowth of an earlier unsuccessful attempt to obtain data using the circuit of Figure 3, taken from Victoreen's[6] paper with an added variable measuring capacitor C_m and a d'Arsonval galvanometer arrangement with a balancing circuit. The latter circuit, with the exception of the galvanometer, was mounted in a grounded metal case made from surplus equipment - with a few small holes in the sides and a cover which did not permit complete light - shielding within the case. "Photo-

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[5] J. Barton Hoag, Electron and Nuclear Physics (Toronto and New York: D. Van Nostrand Co., Inc., 1948), pp. 404-35.

[6] Victoreen, Op. cit., p.438

electric currents may be prohibitive when even a small amount of light strikes the tube."[7] These small cracks very convincingly verified the above statement. Extreme care was not exercised in the selection of materials for the input circuit, the results of which was a very unstable plate current.

> When leakage currents of the proper order are not obtained with good electrometer tubes, it is almost certain that external causes are responsible. A fingerprint on the treated surface of the glass may cause endless trouble until removed with absolute ethyl or methyl alcohol and the surface carefully dried. Small pieces of lint give considerable difficulty. The surface of the grid resistor used always should be suspect. Resistors having values up to 10^{14} ohms are available for this type of service; and, because their surfaces have been similarly prepared, they should be handled with great respect. All other insulation which may be used in connection with the grid circuit is equally important. It is recommended with emphasis that only pure polystyrene be used and that its surface be optically polished and cleaned only with absolute methyl or ethyl alcohol. Some grades of polystyrene contain other materials and these are unsuitable for this service. Capacitors suitable for use in the grid circuit may be made from thin, pure polystyrene,...[8]

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[7] Victoreen, Op. cit., p. 437.

[8] Ibid., p. 438.

Many of the connections, including the ground wire contact to the metal case, were mechanical connections on the first attempted circuit. This proved to be far from satisfactory, for the slightest motion of a human body standing near the instrument caused large erratic drift of the plate-current meter needle due to the stray fields set up by the difference in body potential with respect to ground. Carefully soldered contacts eliminated this difficulty.

The sensitivity of this type of circuit is limited in part by fluctuations of battery voltages and by difficulties in balancing the steady component of plate current.[9] The stability of a. d. c. circuit can be no better than the stability of its power source. When cathode, grid, and plate are supplied by dry cells, economy requires that a potential decrease of at least 20 per cent be permitted during the life of the batteries.[10] Old dry

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[9]Reich, Op. cit., p. 614.
[10]Victoreen, Op. cit., p. 436.

cells were used at first, the results of which were a stable meter on some days and then on other days a very troublesome drift of the plate current rendering measurements impossible. The d'Arsonval galvanometer was far too sensitive and the damping too slow to be used in this arrangement. The outcome was a series of thirteen electrets, prepared under different conditions, which could not be utilized in the investigation.

Using the circuit of Figure 4 built with due consideration to all of the aforementioned sources of trouble, the data were improved. These earlier difficulties aided in clarifying the theory upon which the present data were based. With the measuring capacitor C_m short-circuited, an electret was placed between the brass plates and the upper plate was lowered to the contact position with the electret. Charges, equal in magnitude and opposite in sign, were induced upon the plates through the short-circuit path, grounded to the instrument case. When the short was broken and the plates separated a small distance, work had been done in overcoming the electrostatic force of

attraction between the charge on the upper plate and the charge on the surface of the electret facing the upper plate. Thus, the difference in potential between the surfaces has increased.

The charged condenser would now discharge completely were it not for the permanent effective charge on the surface of the electret which continues to exert its force of attraction on the charge of the upper plate.

For relatively small distances and small plate separations, the electric field between the plates would be uniform. However, it was assumed that the separations were large enough to disrupt the uniform field such that some of the lines of force no longer ended on the upper plate; consequently, a fraction of the charge on the upper plate discharged through the high resistor. The corresponding change in the difference of potential of the grid with respect to the filament and the resulting change in plate current was indicated on the plate current microammeter. From the deflection of the ammeter, whose circuit was previously calibrated with a potentiometer,

the potential difference across the resistor could be read from the curves. The relation $C = Q/V = a/4\pi d$ (for air) was used, where C is the capacitance of the parallel plate measuring condenser - other input capacitances were neglected, such as the interelectrode capacitances, since their consideration would merely change the relative measures by a constant factor - a is the area of the plate (same as that of the electrets), d is the distance separation between upper electret surface and upper plate, V is the difference in potential measured from the curves. Since the actual difference in potential between the plates $\overline{V}$ would be $kV = \overline{V}$, where K is a constant - for only a fraction of Q is discharged - the above expression can be solved for Q. Thus

$$\frac{Q}{V} = \frac{Q}{K\overline{V}} = \frac{a}{4\pi d}$$

$$\frac{Q}{K} = \frac{a\overline{V}}{4\pi d} = \frac{h\overline{V}}{\pi d}$$

$$\frac{Q}{K} = \frac{h\overline{V}}{d} \qquad \text{Eq. 1}$$

or where $h = a/4$, a constant since a is a constant area.

Therefore Q/k, which is a proportional value of the effective charge on the electret, can be plotted against time and the decay characteristics studied.

CHAPTER IV

PROCEDURE

The electrets were made in a manner following Padgett. The block-diagram of the apparatus is shown in Figure 2, the details of which are reported by A. O. Clauset in his masterb thesis, University of Houston, 1952.

The vacuum tube electrometer, the theory of which is reported in Chapter III, was used to obtain the σ/k data. The details of making the measurements are given below. Throughout the discussion the symbols referred to are those of Figure 4.

The plate current ammeter M_2 was calibrated in terms of the observed deflection of the indicating needle for the corresponding known applied voltage as determined by a Leeds and Northroup potentiometer. The calibrating difference of potential was applied across the condenser leads, with the plates sufficiently separated to eliminate the capacitor effects. Three deflections-vs-voltage curves (Figures 7-9) were then constructed for the three sensitivity ranges of the ammeter. M_2 was

calibrated from left to right, for each of the three ranges, using the balancing-circuit resistors R_1 and R_2 to obtain the zero points for the different ranges.

Before the filament switch S_1 was turned on, care was taken to have plate current switch S_2 off so that there would be no positive elements within the tube before the filament had reached emission temperature. The filament current of 10 milliamperes was adjusted by R_5 and maintained at this value throughout the measurements.

After the filament had warmed up for approximately thirty minutes, the plate current switch S_2 was turned on. After the proper range - range C - 0-150 microamperes was selected, the zero-signal operating plate current of 100 microamperes was obtained by adjustment of R_4 with the two balance potentiometers R_1 and R_2 at maximum resistance and the shorting switch S_3 shorted.

An electret was then placed between the plates of the measuring capacitor C_m. The top plate was screwed down to the contact position with the upper surface of the electret, and the

separation d_o read on the vernier. The balance circuit was used to obtain a zero point on the plate ammeter for the sensitivity range used, as determined by the magnitude and direction of the deflections of the ammeter caused by a plate separation of about 1 to 1.5 mm. The upper plate was then separated from the upper surface of the electret, after the shorting circuit had been broken, to a distance d_e, as read from the vernier. The corresponding maximum deflection was read on M_2.

The deflection was due to the partial discharge of the measuring capacitor through the high resistor R_1 giving a change in grid potential. The measurement was taken for each surface of an electret and curves constructed of value of charge vs time.

The data on the electrets were taken approximately every twenty-four hours, and calculations made using the following method. The reading m_o of the meter M_2 was read with the electret in C_m, in contact with both plates and the shorting switch S_3 open. The reading m_e was read as the maximum deflection when the plates were then separated a distance d, where

$d = d_e - d_o$. For the observed deflections, the corresponding potential difference was read from the calibration curves of Figures 7-10, depending upon the sensitivity range used (Table no. 10 was used for all calculations after April 23, 1952, at which time a replacement tube was installed).

Thus, by Eq. 1 ,

$$\frac{Q}{k} = \frac{a}{4} \frac{V}{(d_e - d_o)(300)}$$

$$\frac{Q}{k} = \frac{2.68}{4(300)} \frac{V}{(d_e - d_o)}$$

$$\frac{Q}{k} = 2.23 \times 10^{-2} \frac{V}{(d_e - d_o)}$$

Where the area of the plates $a = 2.68 cm^2$.

CHAPTER V

ANALYSIS OF THE DATA

The curves of Figures 11-17 show the results of attempts to compare electrets made under similar conditions except for the molten mixture temperatures. The published curves of other investigators show a decrease of the heterocharge to the cross over point, and then a steady build up of the homocharge with time. The methods of the present study did not yield smooth curves. These fluctuations appear to have been caused by variations in humidity.

No measurements could be obtained for the four days from April 19 to April 22. The weather was rainy during the greater part of this time. The instrument would not respond to electrets; it had lost its sensitivity, and was extremely unstable. Many hours of efforts to attempt to restore the instrument to operating condition failed. The installation of a new vacuum tube did not alter the operation of the meter. With time (after a period of four days) the instrument finally resumed its functioning, seemingly of its own accord.

During this period, a number of electrets reversed signs, with the result that these critical points for the curves were missed. This period is indicated on the curves for electrets (Figures 11, 14, 15, 16 and 17) which were being measured during this time by the symbol H_1.

Further evidence pointing toward humidity conditions as the source of trouble was shown again at a later date, May 16 to May 19, during a less severe rain spell. The instrument would indicate the presence of charges, but of a very diminished magnitude. Many electrets appeared to have lost their charge. The desiccant in the desiccator was good; and the electrets would pick up scraps of paper, indicating that they were still charged. A small flood light was directed into the opened instrument, from ten to fifteen minutes, to heat the circuit. After the parts were dried in this manner, the instrument responded nicely; giving a meter deflection of the order of magnitude of from 20 to 25 deflections for electrets which had shortly before given from 1 to 2 deflections. This

sensitive response of the meter persisted for about thirty minutes at the most, at which time it had again resumed its sluggish condition. This period is indicated on the curve for the electret of Figure 6 by the symbol H_2.

These difficulties led to a further investigation of the electrometer. The humidity was varied by spraying water around the laboratory and measurements taken on a given electret stored in a desiccator. Figure 18 shows the measured value of Q/k versus relative humidity. For the change in relative humidity from 61 % to 65 %, the value of Q/k decreased by approximately 80 %.

Table VIII obtained from the Weather Bureau, gives the humidity data for the months of April and May as measured at the Houston, Texas Airport Station. The days of previously mentioned difficulties correspond excellently with the high relative humidity days, thus indicating the extreme sensitivity of the electrometer to atmospheric conditions. This accounts for the variations from a smooth curve obtained in the present investigation.

Figures 12 and 13 show cross-over at some

time between eight and ten days. This reveals that for a change in temperature from 150°C to 235°C, the reversal times differ by an amount less than two days and that the reversal does not take place before eight days. In considering the initial Q/k values at time t = 0 for these two electrets, Number 2, made on April 28 when the relative humidity was 41% indicates a slightly larger effective charge on both surfaces than does number 3 - made on April 30 when the relative humidity was 51%. Since there was little difference in the electric field strengths used, this appears to be an effect of humidity or possibly in part due to the higher molten mixture temperature. These two electrets indicate a net positive charge after the reversal point.

Electrets number 1, 4, and 5 of Figures 10, 14, and 15 reversed signs during the high humidity days when the instrument would not measure. Therefore, all that has been indicated with respect to the time of reversal is that all three electrets reversed signs before 9 days, that Number 1 reversed before 8 days, and that Number 5 reversed before 6 days. Number 5

was made from a molten mixture of 100°C and Numbers 1 and 4 were made at 180°C. By constructing the curves through the average points, one finds that the shapes of the curves - without substantiating points - appear to indicate that the electret made with the low temperature crossed over first. This conclusion is only indicated, not proved.

The initial Q/k values of numbers 4, 1, and 5 decrease in the order listed. The respective relative humidity for these days (April 14, 15, and 17) were 38%, 57%, and 63% respectively. Electret number 4 has the highest initial effective charge and was made with the lowest electric field strength of these three electrets. Thus it appears that the chief factor affecting the initial charge is the effects of humidity on the instrument and the electret rather than the polarizing electric field used. This does not indicate that the electric field strength is not a factor.

Electret Numbers 6 and 7 of Figures 16 and 17 did not give a reversal of sign. Number 6 was made with an electric field of 5.33 kv/cm

and number 7 was made at 7.14 kv/cm. This failure to reverse sign was probably due to the low electric field. However, electric fields below 10 kv/cm did yield reversals, which was contrary to Gutmann's claim, but in good agreement with Padgett and Gemant.

Electrets 1 to 5 gave reversals of sign and a homocharge in accordance with the definition. But electret 6 and 7 did not give a reversal of sign. However, the sign of the effective charge indicated on these two electrets were in contradiction to all previous reports on electrets. They were made by the usual methods, except the electrodes were aluminum. A violation of normal polarization effects was indicated.

The bottom surface of the electret solidified in contact with the anode should show an initial negative charge, but these two indicated positive charges. The electric field strengths were low. Gutmann claims that a homocharge is not obtained with less than 10 kv/cm. The literature reviewed contains no reports of reversals before one day. Yet, these two electrets had the sign of a homocharge.

It is possible that the reversal occured immediately after removal of the electric field, for the measurements were taken as soon as possible after the electric field was removed.

An attempt was made to determine the magnitude of the effective surface charge densities obtained. An electret was placed in the instrument and the data of Table IVX obtained. The upper plate was lowered to the contact position with the electret and the usual measurement taken. The plates were separated 1.3 mm and the corresponding deflection noted. Next the upper plate was brought down to a position of 0.2 mm above the upper surface of the electret while the shorting switch was in contact. After removing the short, the upper plate was cranked back to the same height above the electret surface as before, with a resulting decreased deflection. This was continued in increments of 0.2 mm up to 1.0 mm separations. It was found that when the upper plate was separated from an initial position 1.0 mm above the electret that the meter deflection was only 15% of the initial deflection resulting from the contact position.

Thus it appears that the effective field of the electret falls extremely rapidly with distance and is almost ineffective at 1.0-1.5 mm from the surface of the electret.

The meter was then calibrated with an 88 micromicrofarad condenser charged with various known potential differences and discharged across the high resistor (10^{11} ohms). The plates were separated approximately 8 cm during this calibration. Figure 19 shows the meter deflection versus known charge. Q was obtained as follows:

$$Q(\text{esu}) = C(\text{cm})\ V(\text{volts})\ 1\ \frac{\text{statvolt}}{300\ \text{volts}}$$

$$C = 88\times10^{-12}\ f \times 9\times10^{11}\ \frac{\text{cm}}{f} = 79.2\text{cm}$$

$$\therefore\ Q(\text{esu}) = \frac{79.2}{300}\ V(\text{volts})$$

$$Q(\text{esu}) = 0.264V$$

Where V is known.

Considering Table I, on April 30, electret Number 1 gave a deflection of 20 divisions for a plate separation of 1.8 mm. From Figure 19, 20 deflections is caused by approximately 11.5 statcoulombs. Since 1.8 mm is greater than

1.0 mm, thus separation was beyond the distance for 85% decrease in induction. Therefore for the electret area of 2.68 cm^2

$$11.5(esu) \times 0.85 = 9.78(esu)$$

and

$$\frac{Q}{a} = \frac{9.78(esu)}{2.68(cm^2)} = 3.64\frac{(esu)}{cm^2}$$

The effective surface charge density on the electret is of the order of magnitude of 3.5 esu/cm^2, which is in agreement with the values reported in the literature of from 0.4-10 esu/cm^2.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions. The effectiveness of this instrument in studying the characteristics of electrets has been considerably obscured by atmospheric moisture conditions. Definite reversal times were determined on some electrets, however, at most it can only be said that the investigation indicated an increase in reversal time with increased molten mixture temperatures. Relative humidity appears to be one of the chief factors affecting the accuracy of the instrument.

Electrets exhibiting reversals of effective charge were obtained using an electric field from 7-9 kv/cm. For electric fields slightly below these values, a reversal sign was not observed. The sign of the effective charge on these latter electrets, as indicated by the instrument, was in contradiction to the reports of the literature. However, for those electrets yielding a homocharge, the signs of the effective charge on the surfaces were in agreement with electret theory.

The magnitude of the effective surface charge density was of the order of 3 esu/cm^2 which agrees with previously reported values.

Recommendations. It is entirely possible that through ingenious methods an electron tube electrometer could be calibrated to yield fairly accurate absolute values of effective surface charge densities. The electrometer could achieve this only under atmospheric moisture controlled conditions. With these controls the electrometer could be used to obtain data rapidly to study quantities of substances being tested for the electret effect. Further investigations could possibly reveal that electrets made with low field intensities, or due to the other conditions, have a reversal point immediately after being made.

FIGURE 1*

CHARACTERISTICS OF VARIOUS SUBSTANCES

Substances capable of permanent volume polarization		Substances giving	
Yielding heterocharges only	Yielding also Homocharges	Surface charges only	No permanent charges
Acidic groups	Carnauba wax	Cetyl alcohol	Paraffin wax
Glass	Beeswax	Cetyl Palmitate	Palmitic acid
Resin	Polar hydrocarbons	Non-polar Hydrocarbons	Stearic acid
Sulfur	Esters	Stearanilide	1,8-Dinitronaphthalene
	Alcohols	Seekay wax	
	Asphaltos		

*F. Gutmann, "The Electret," Reviews of Modern Physics, 20:468, July, 1948.

FIGURE 2

ELECTRET OVEN ARRANGMENT

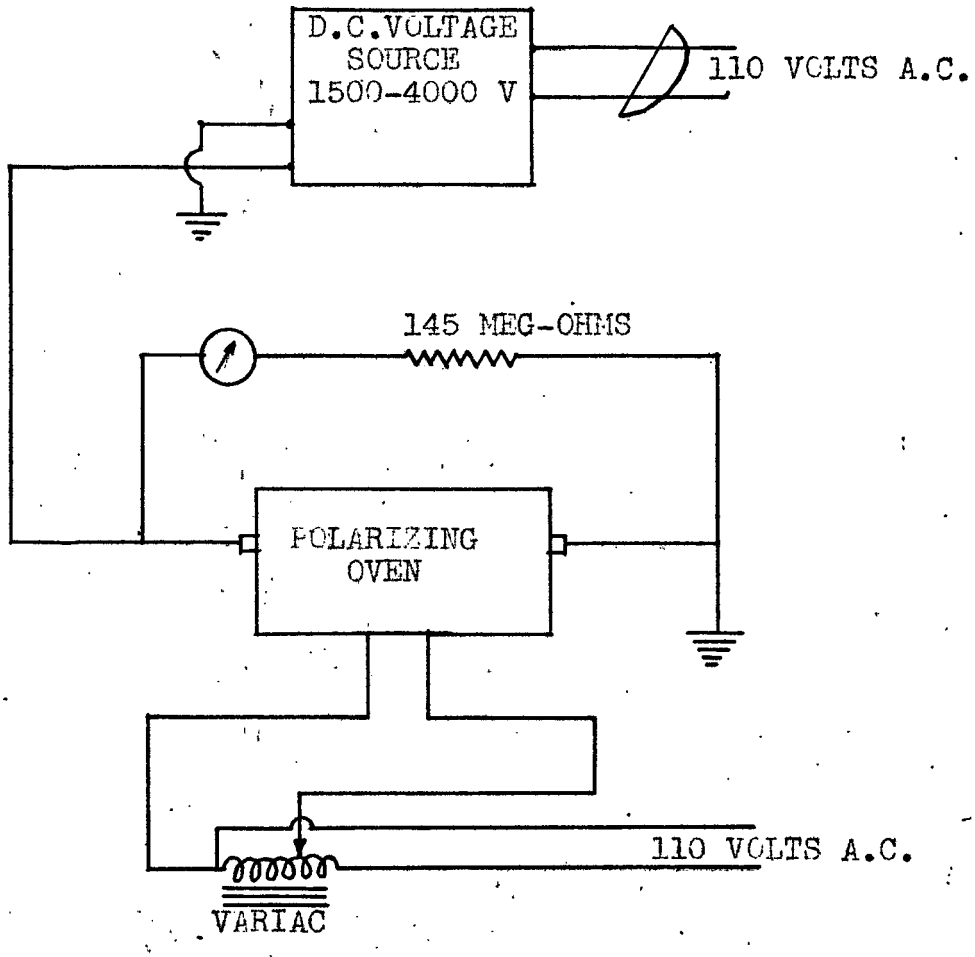


FIGURE 3

FIRST ATTEMPTED VACUUM TUBE ELECTROMETER CIRCUIT

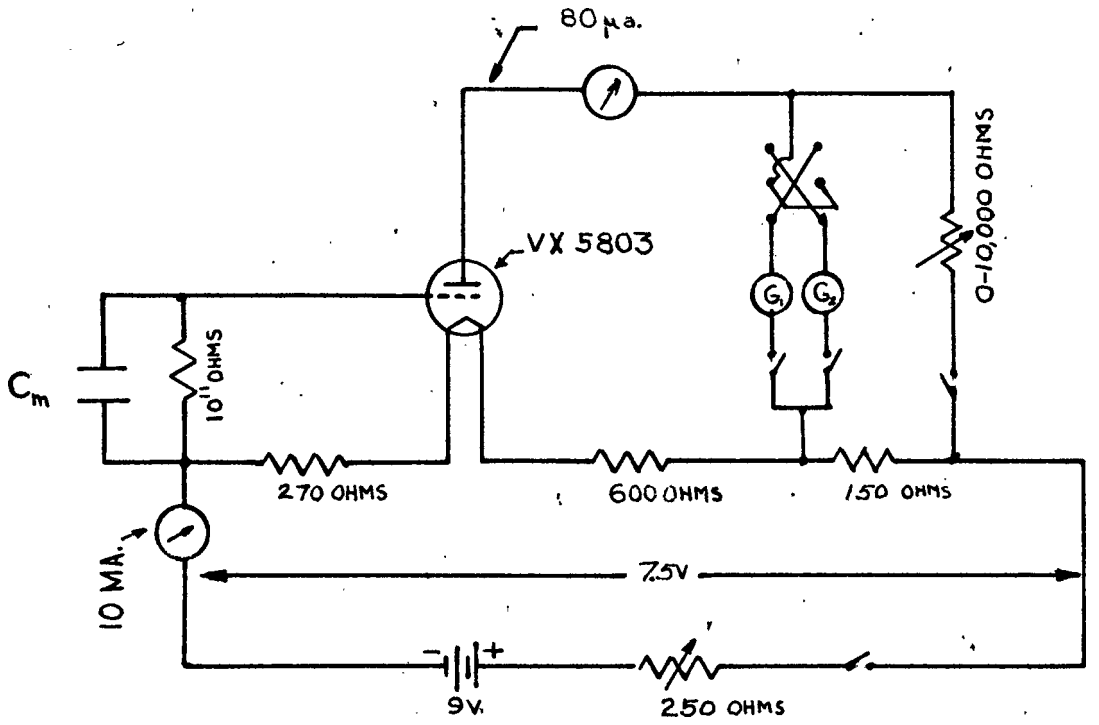


FIGURE 4

VACUUM TUBE ELECTROMETER CIRCUIT USED TO OBTAIN DATA

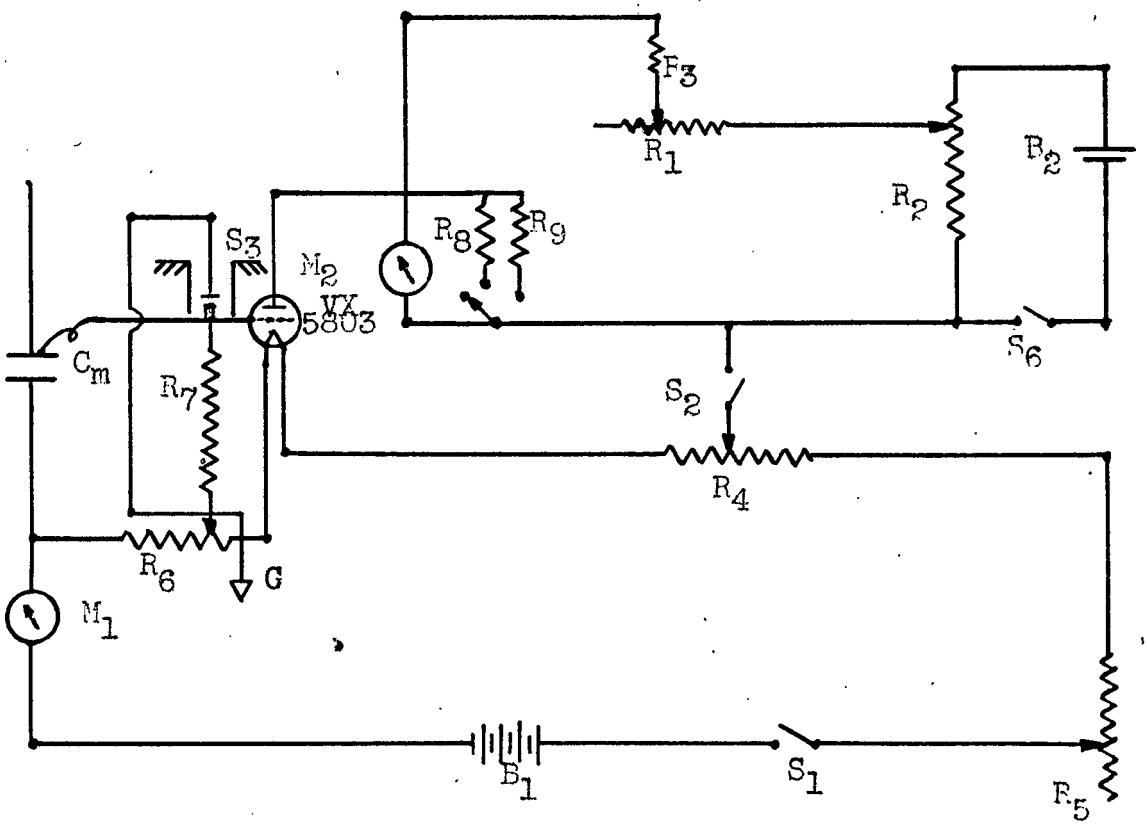


FIGURE 5

KEY TO SYMBOLS FOR VACUUM TUBE ELECTROMETER CIRCUIT OF FIGURE IV

R_1 - 2500 ohm wire-wound potentiometer.

R_2 - 100 ohms.

R_3 - 1300 ohms.

R_4 - 1000 ohm wire-wound potentiometer (normally set at 750 ohms).

R_5 - 350 ohm wire-wound potentiometer (normally set at 250 ohms).

R_6 - 250 ohm wire-wound adjustable resistor (normally set at 170 ohms).

R_7 - Grid resistor, 10^{11} ohms.

R_8 - Shunt for 0-100 μa range, approximately 1300 ohms.

R_9 - Shunt for 0-150 μa range, 285 ohms.

B_1 - Dry cells, 12 volts.

B_2 - Dry cells, 1.5 volts.

C_m - Measuring capacitor

VX5803 - Victoreen electrometer triode

S_1 - S. P. S. T. toggle switch.

S_2 - S. P. S. T. toggle switch.

S_3 - Shorting switch

S_4 - Plate current sensitivity selector switch, range a, 0-50 μa.

S_5 - Plate current sensitivity selector switch, range b, 0-100 μa.

M_1 - Filament circuit ammeter, 0-15 ma.

M_2 - Plate current microammeter.

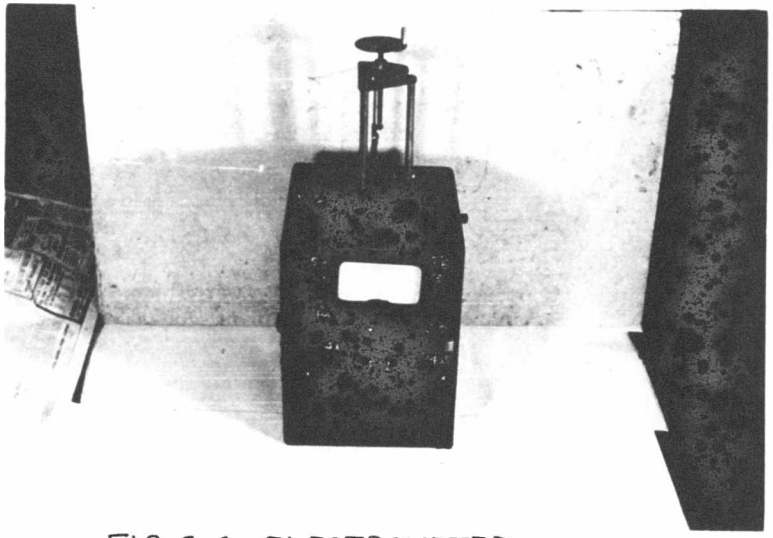


FIG. 6-A ELECTROMETER

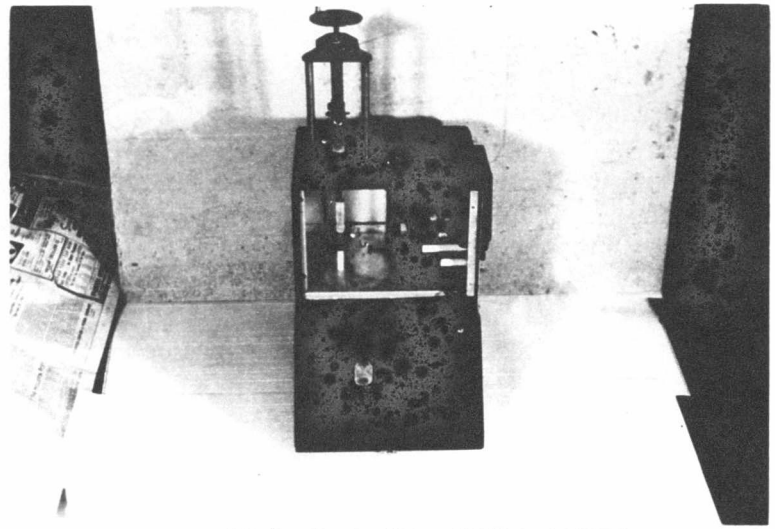
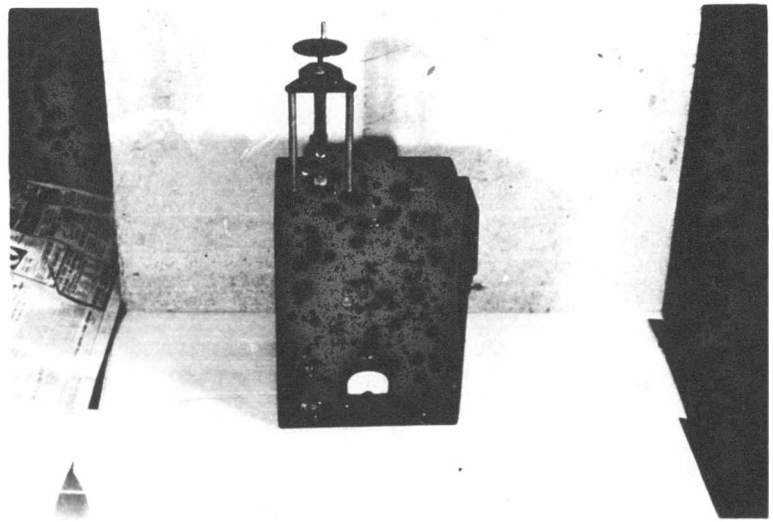


FIG. 6-B ELECTROMETER

FIG 6-C OVEN

FIG. 6-D ELECTROMETER



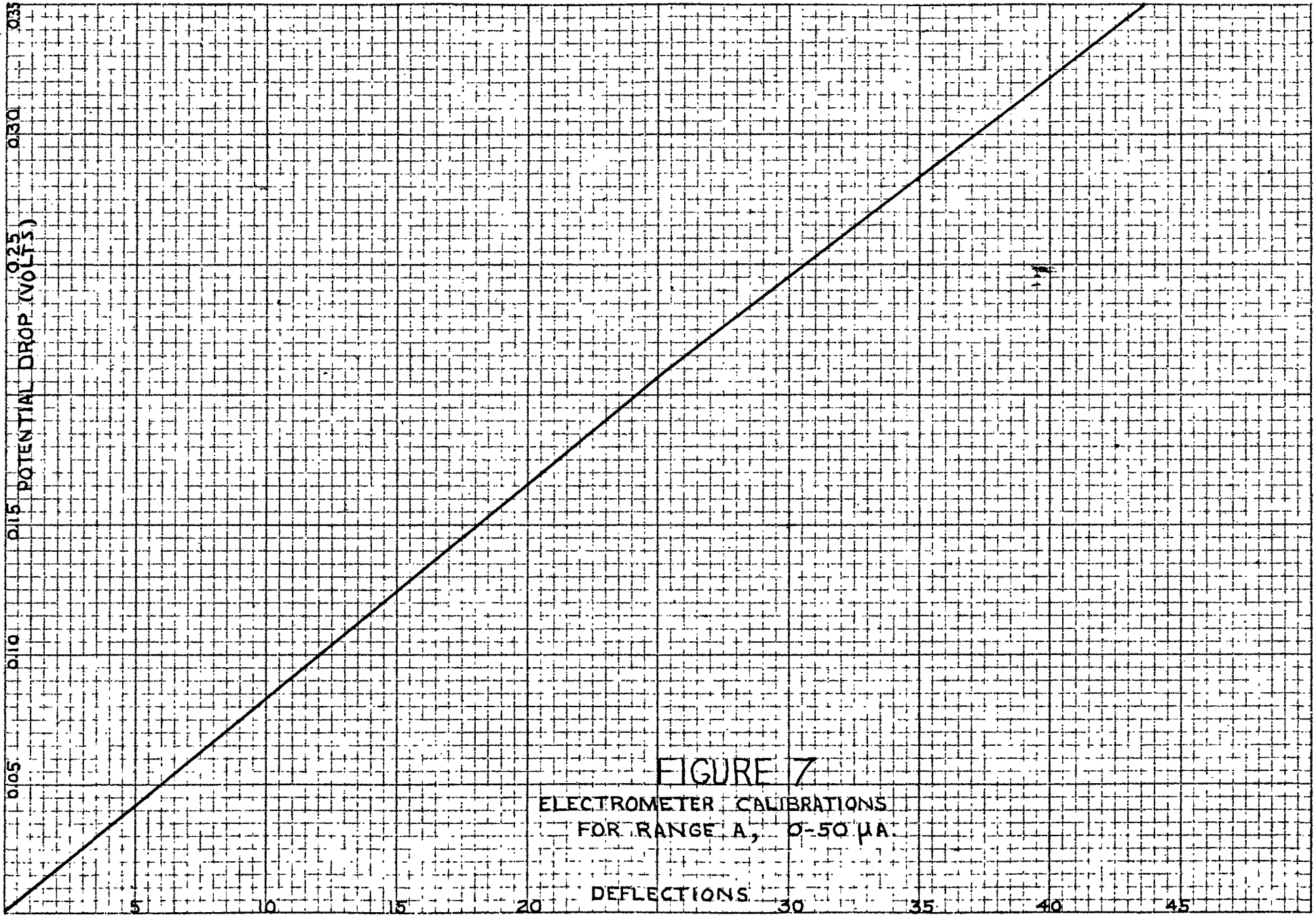


FIGURE 7

ELECTROMETER CALIBRATIONS FOR RANGE A, 0-50 μA.

FIGURE 8

ELECTROMETER CALIBRATION
FOR RANGE B, 0-100 μA.

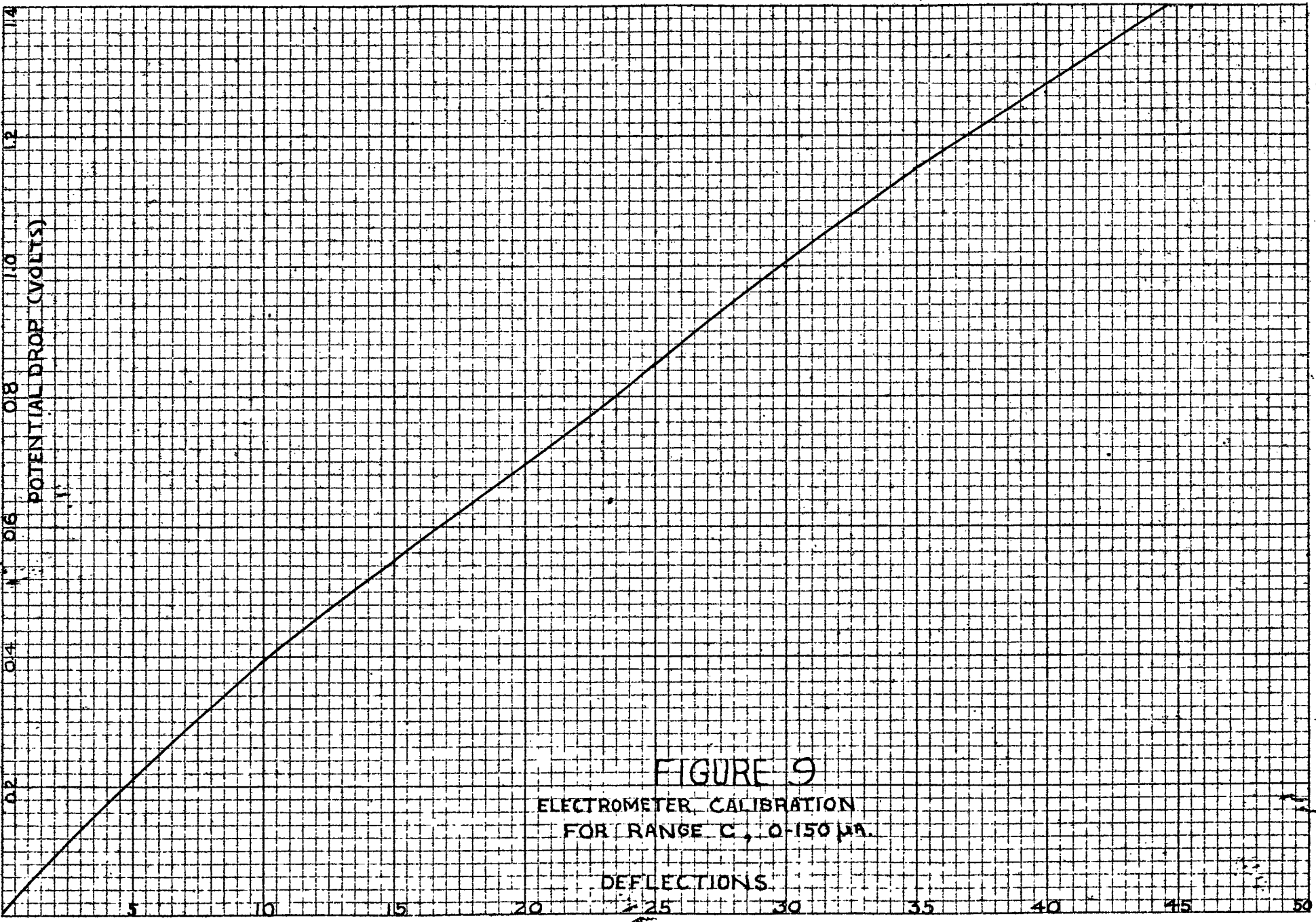
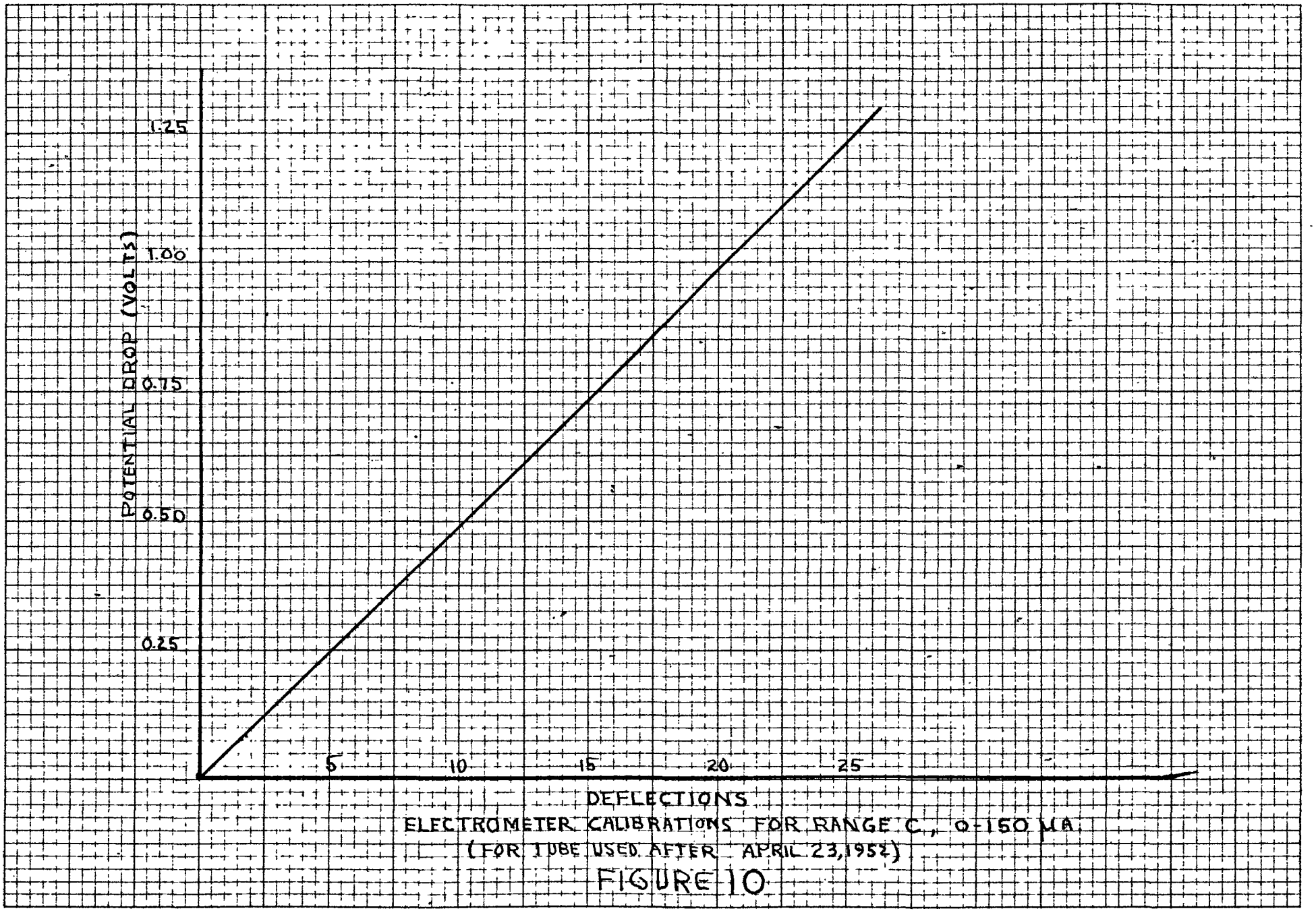


FIGURE 9

ELECTROMETER CALIBRATION

FOR RANGE C, 0-150 μa.



ELECTROMETER CALIBRATIONS FOR RANGE C, 0-150 μA
(FOR TUBE USED AFTER APRIL 23, 1952)

FIGURE 10

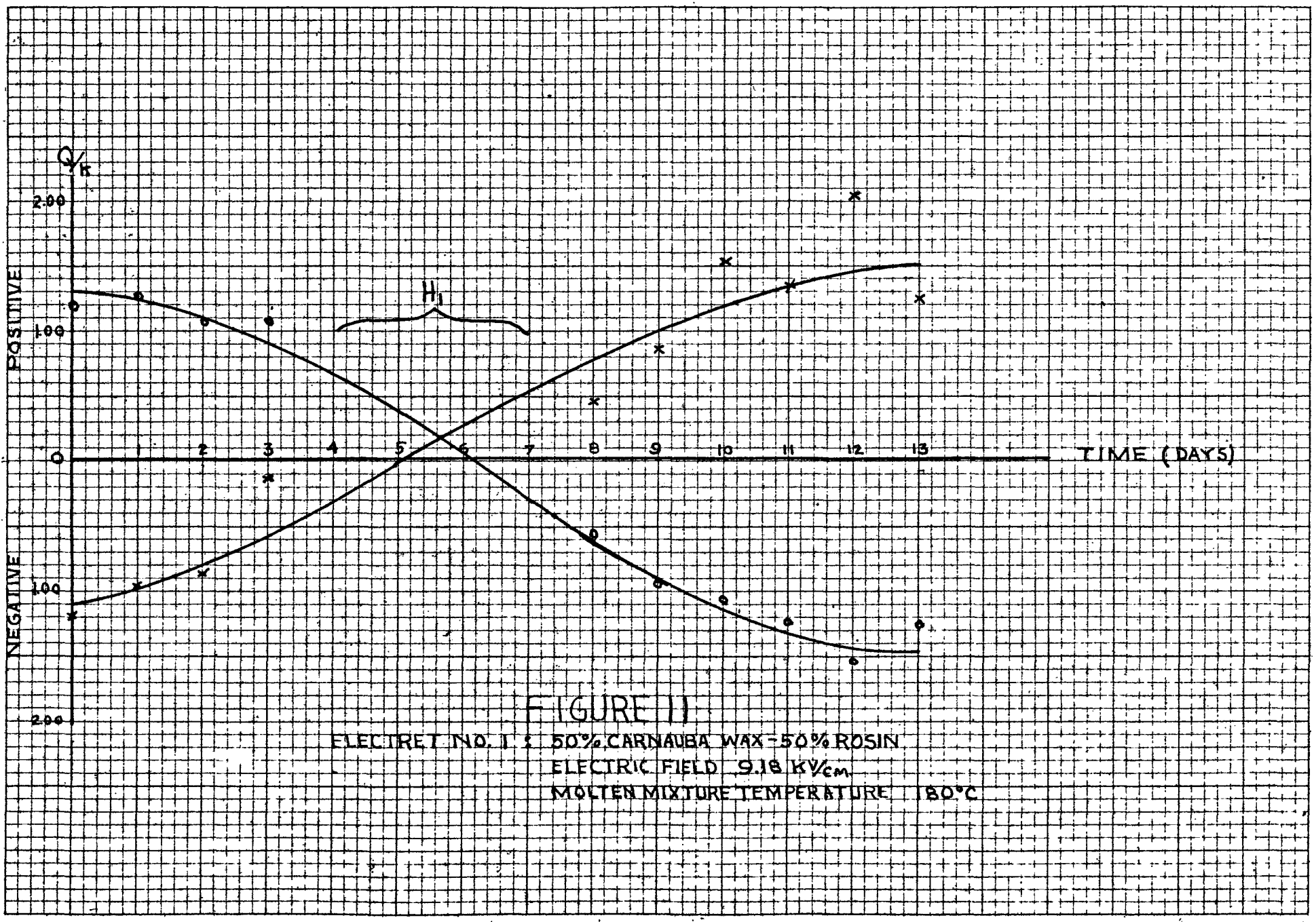


FIGURE 11

ELECTRET NO. 1 : 50% CARNAUBA WAX - 50% ROSIN
ELECTRIC FIELD 9.18 KV/cm.
MOLTEN MIXTURE TEMPERATURE 180°C

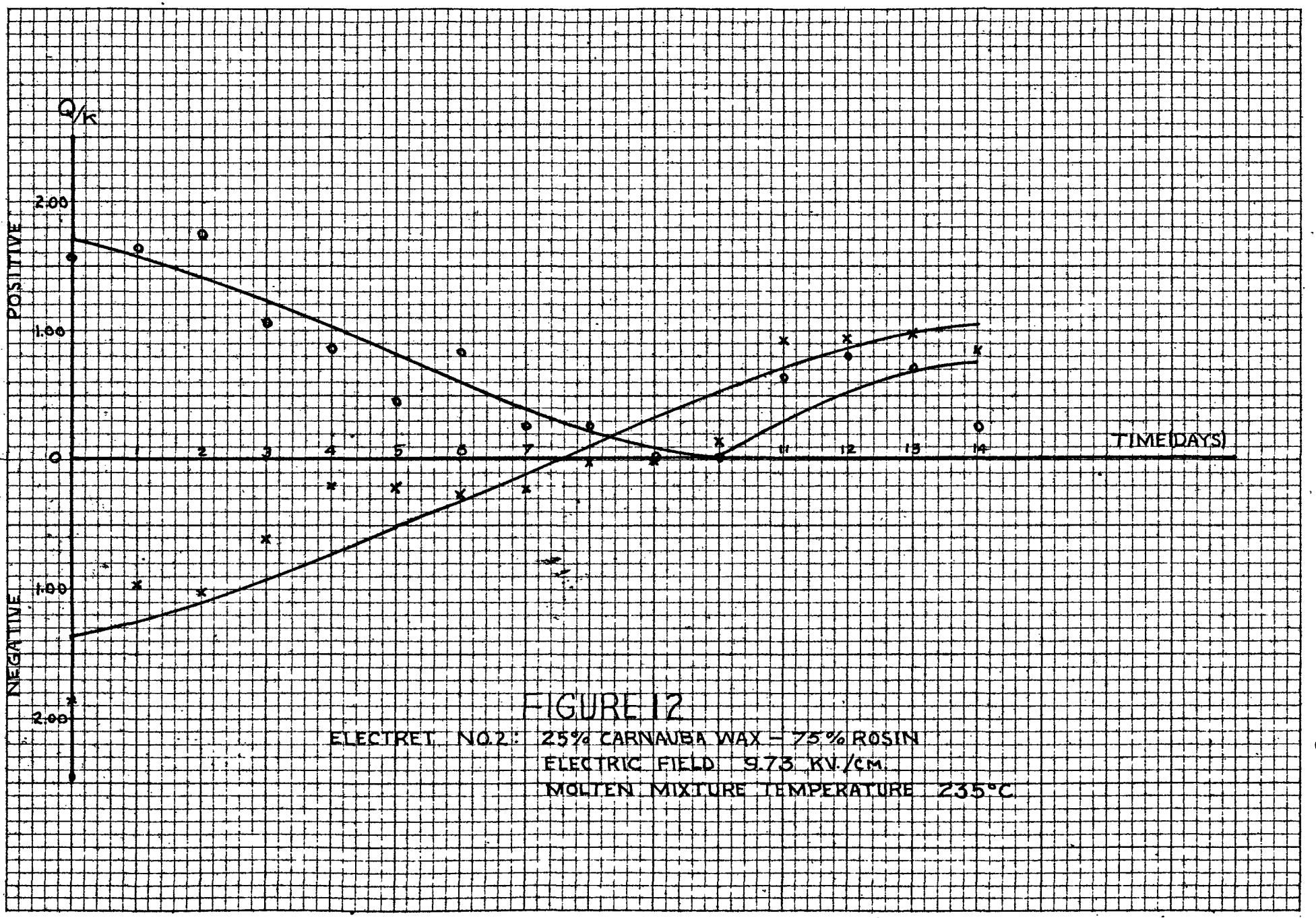


FIGURE 12

ELECTRET NO.2: 25% CARNAUBA WAX – 75% ROSIN
ELECTRIC FIELD 9.73 KV./CM.
MOLTEN MIXTURE TEMPERATURE 235°C

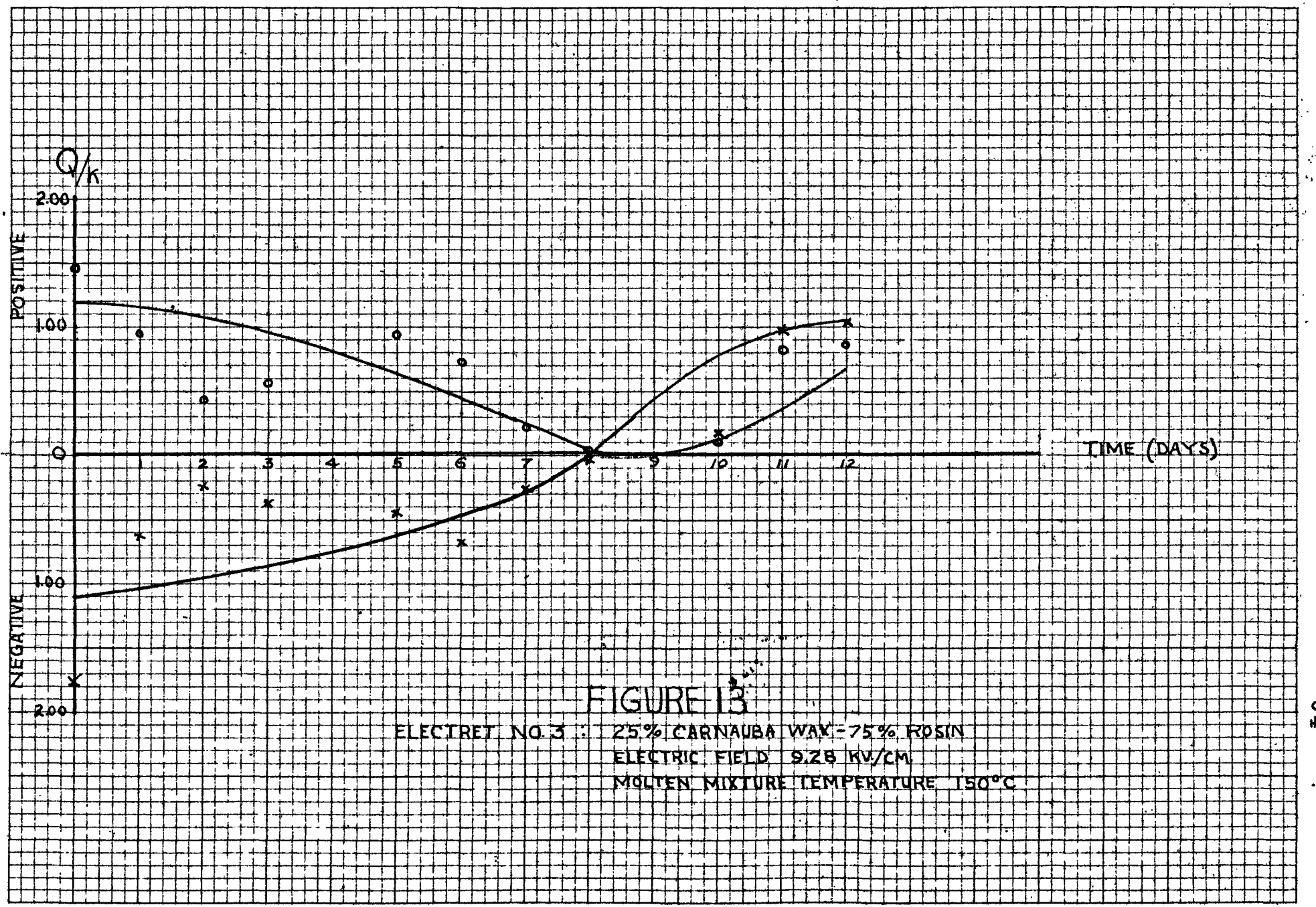


FIGURE 13

ELECTRET NO 3 : 25% CARNAUBA WAX - 75% ROSIN
ELECTRIC FIELD 9.28 KV/CM
MOLTEN MIXTURE TEMPERATURE 150°C

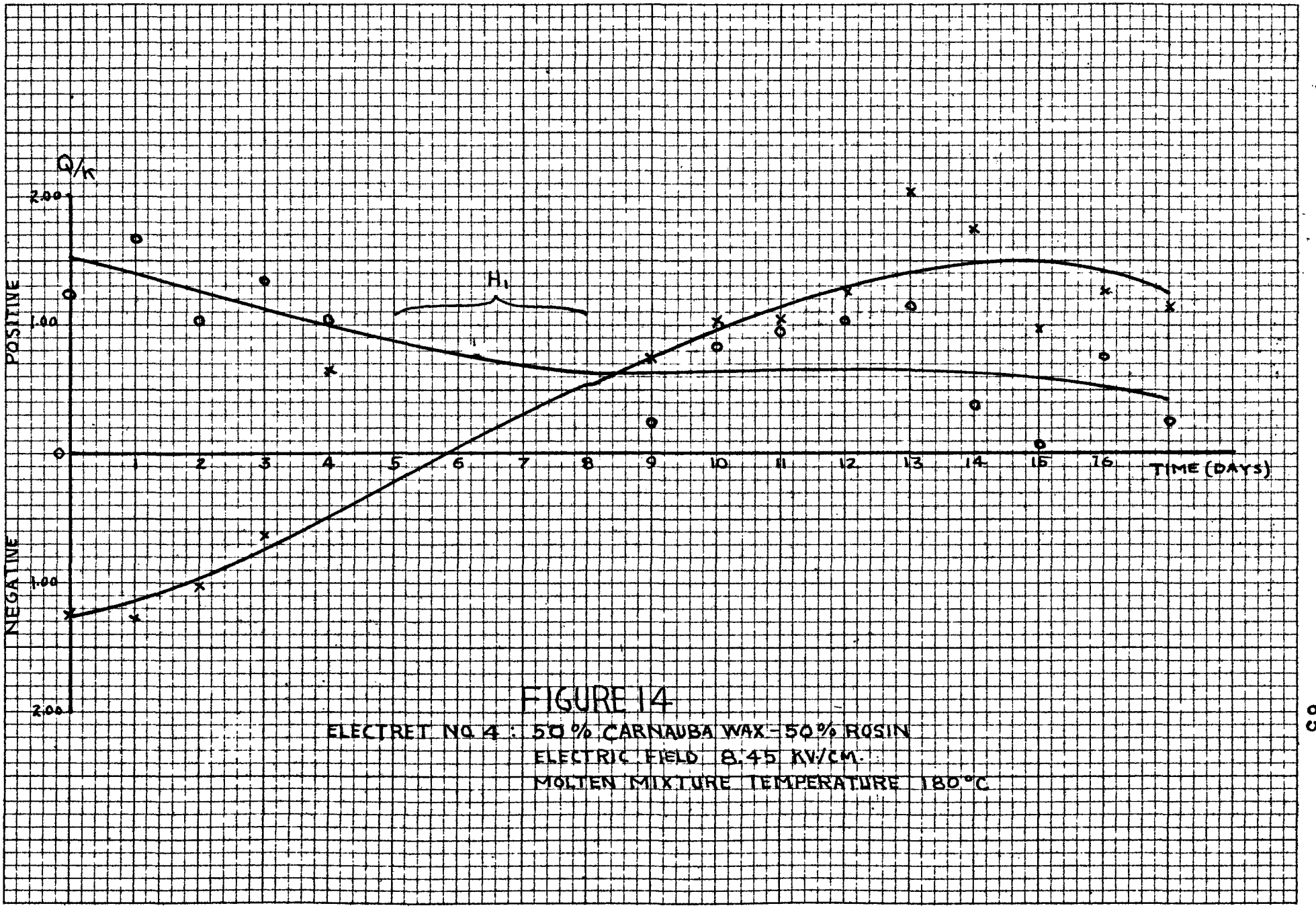


FIGURE 14

ELECTRET NO. 4 : 50% CARNAUBA WAX - 50% ROSIN
ELECTRIC FIELD 8.45 KV/CM.
MOLTEN MIXTURE TEMPERATURE 180°C

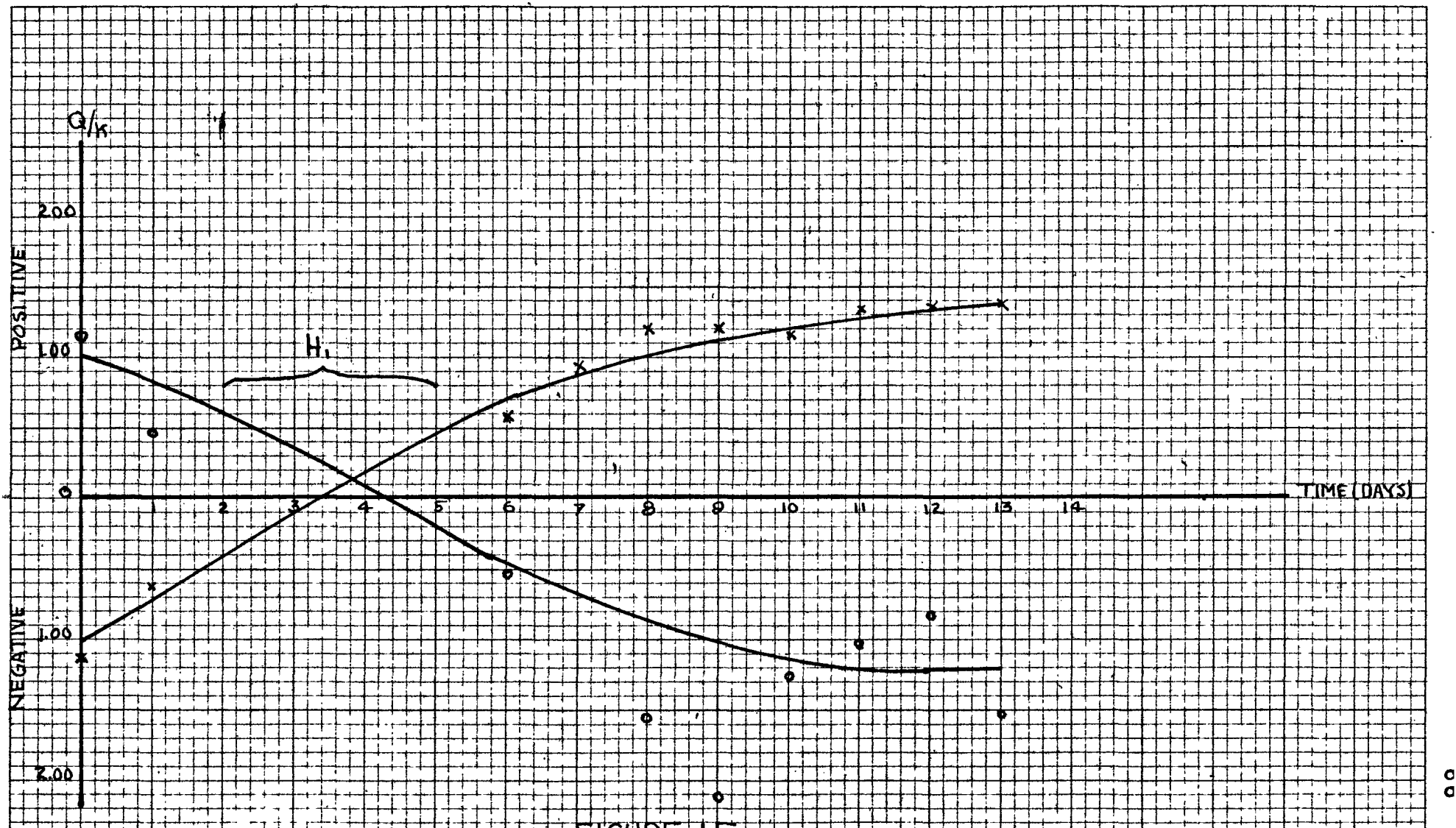


FIGURE 15

ELECTRET NO. 5 : 50% CARNAUBA WAX - 50% ROSIN
ELECTRIC FIELD 8.65 KV/CM.
MOLTEN MIXTURE TEMPERATURE 100°C

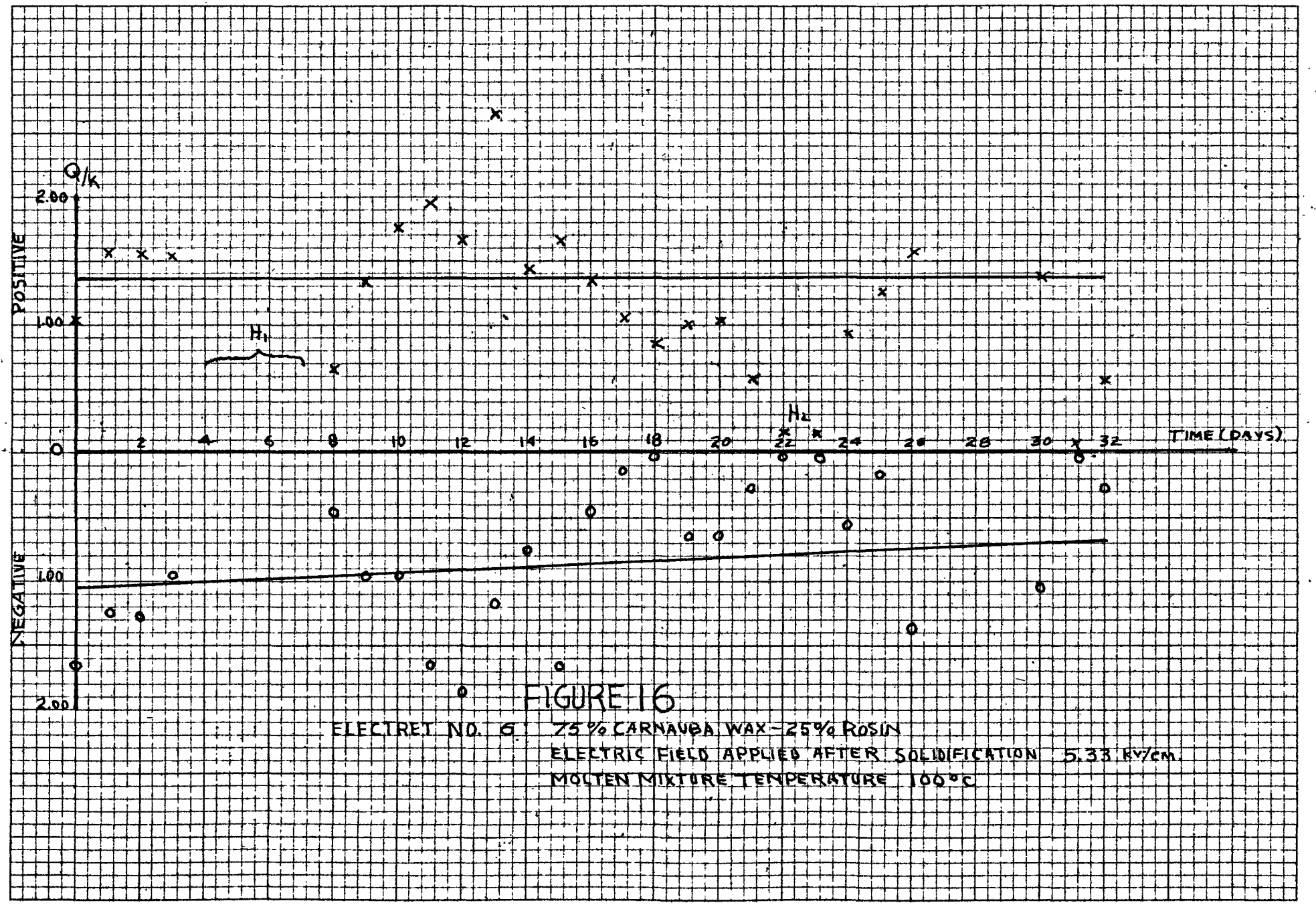


FIGURE 16

ELECTRET NO. 6 75% CARNAUBA WAX - 25% ROSIN

ELECTRIC FIELD APPLIED AFTER SOLIDIFICATION 5.33 KV/cm.

MOLTEN MIXTURE TEMPERATURE 100°C

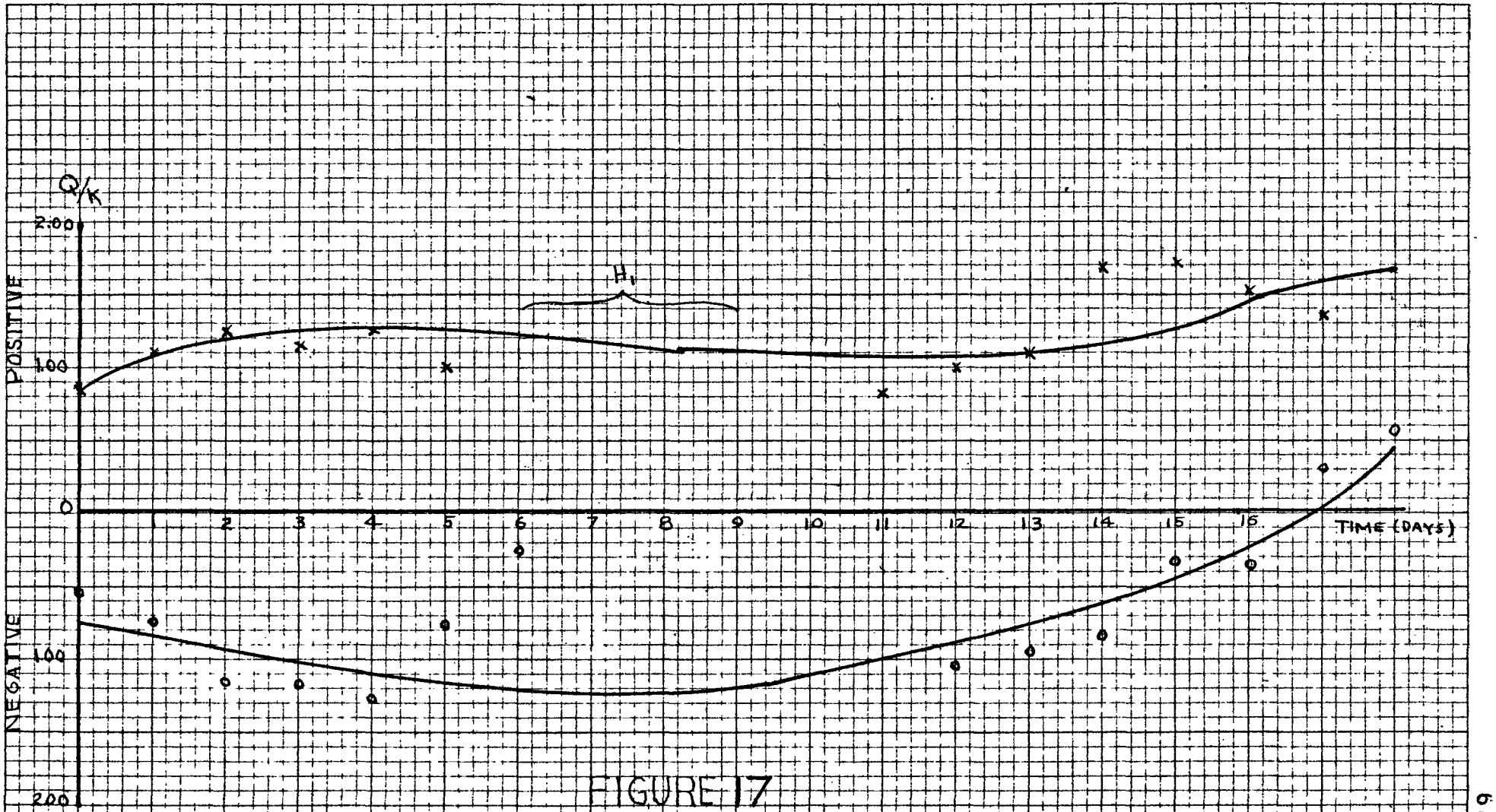


FIGURE 17

ELECTRET NO. 7 : 75% CARNAUBA WAX - 25% ROSIN
ELECTRIC FIELD 7.14 KV/CM.
MOLTEN MIXTURE TEMPERATURE 175°C

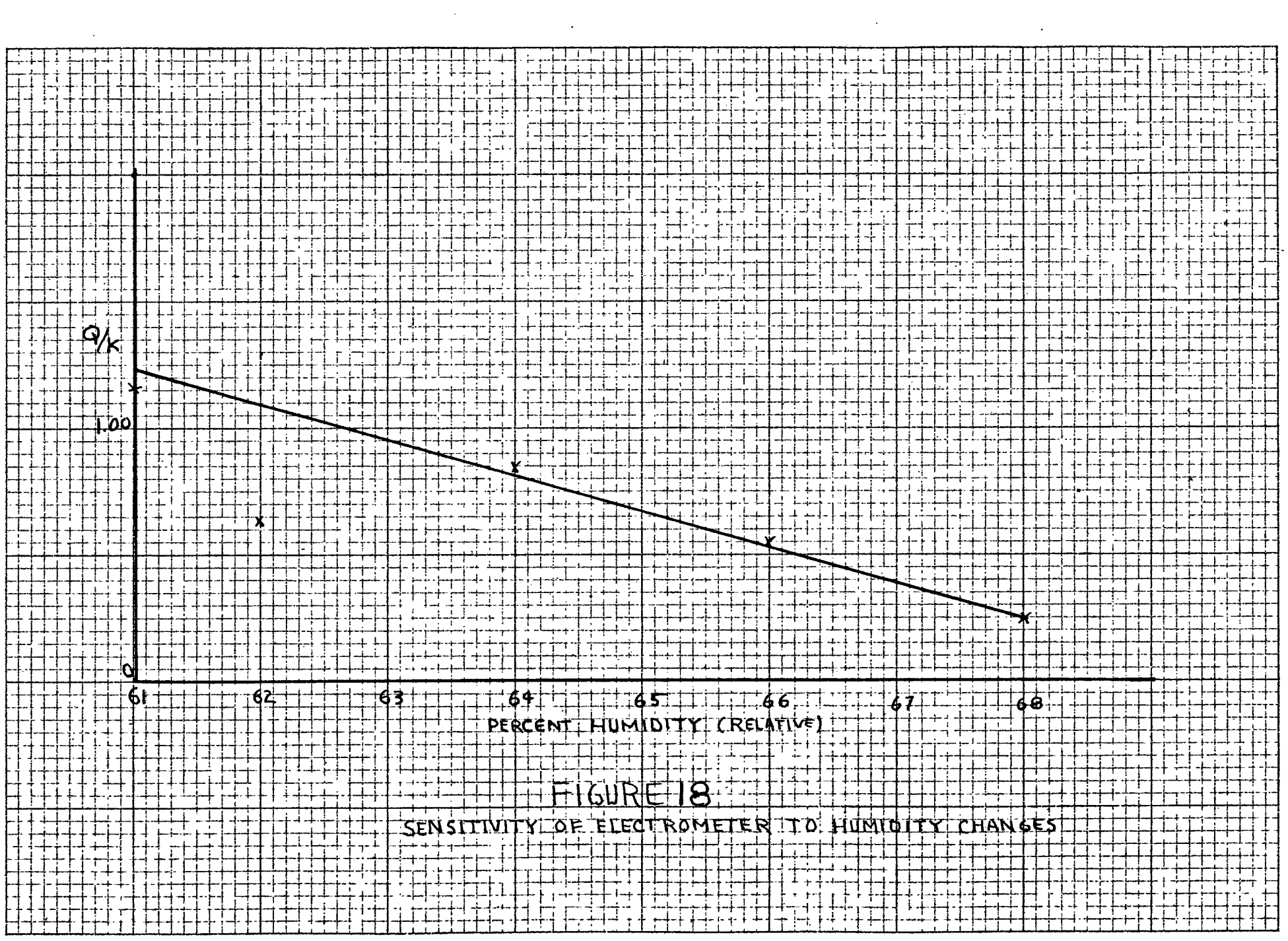


FIGURE 18

SENSITIVITY OF ELECTROMETER TO HUMIDITY CHANGES

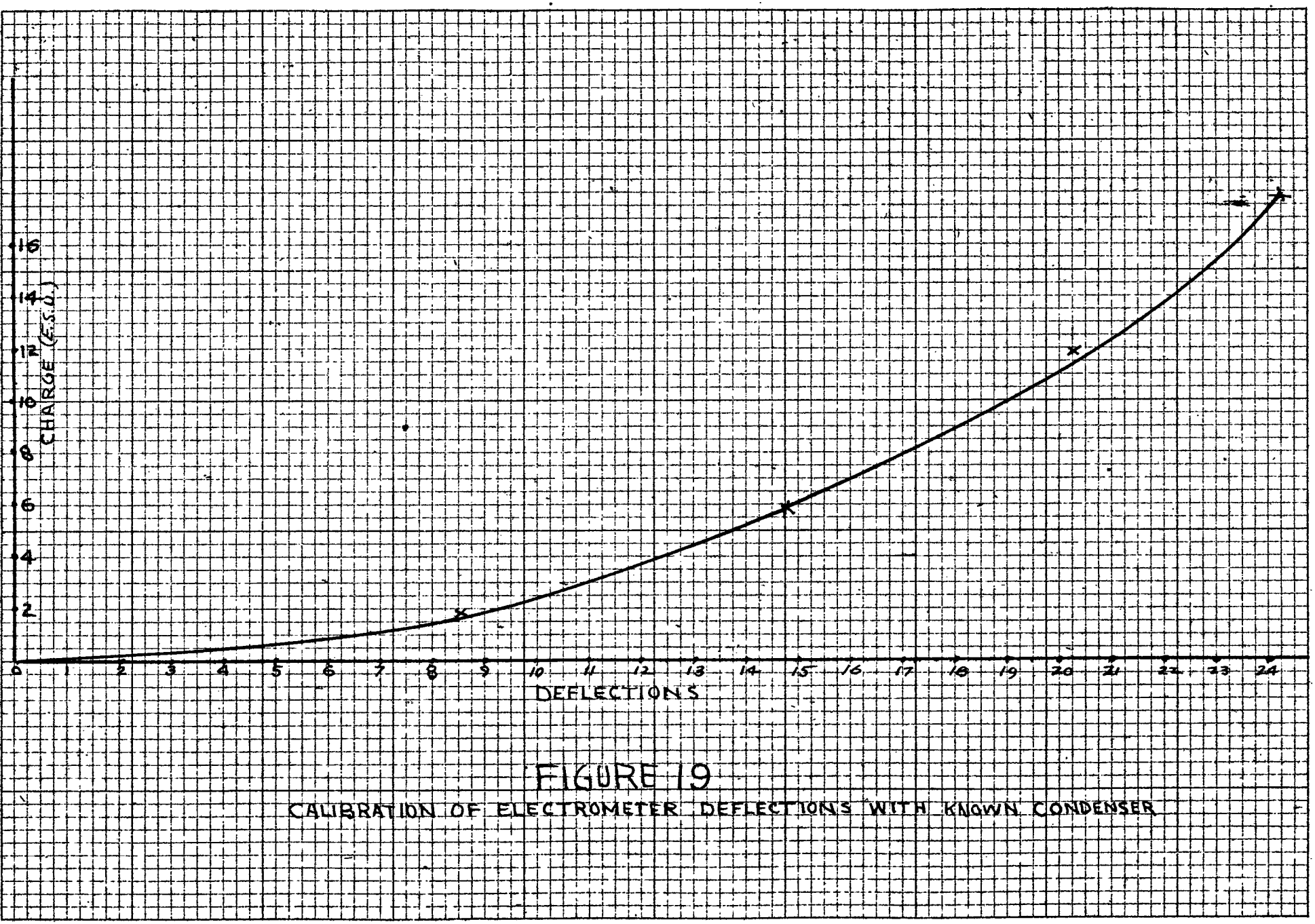


FIGURE 19

CALIBRATION OF ELECTROMETER DEFLECTIONS WITH KNOWN CONDENSER

TABLE I

Electret No. 1 50% Carnauba wax - 50% Rosin
Made 4-15-52
Polarizing Voltage 2.7 kv
Polarizing Electric Field 9.8 kv/cm
Thickness 0.294 cm
Range C

Date	S	d_o cm	d_e cm	m_o	m_e	$q/k(10^{-2})$
4-15	B	8.25	8.09	15.0	47.5	-1.41
4-15	B	8.25	8.06	15.0	46.0	-1.13
4-15	T	8.21	8.07	0	22.0	+1.28
4-15	T	8.22	8.07	0	22.0	+1.19
4-16	B	8.28	8.10	16.0	43.0	-0.99
4-16	B	8.28	8.09	15.0	43.0	-0.98
4-16	T	8.22	8.07	0	24.0	+1.28
4-17	B	8.20	8.04	16.0	37.0	-0.91
4-17	B	8.20	8.08	15.0	35.0	-0.74
4-17	T	8.22	8.07	0	20.0	+1.09
4-17	T	8.23	8.06	0	22.0	+1.05
4-18	B	8.29	8.15	15.0	19.0	-1.12
4-18	B	8.29	8.15	15.0	19.0	-1.15
4-18	T	8.19	8.05	16.0	20.5	+1.21
4-18	T	8.19	8.04	14.0	20.0	+1.09
4-23	B	8.10	7.93	18.0	16.0	+0.48
4-23	T	8.12	8.08	18.0	24.0	-1.77
4-24	B	8.11	7.92	1.0	17.0	+0.87
4-24	T	8.11	7.96	17.0	29.0	-0.94
4-25	B	8.16	8.02	21.0	1.0	+1.51
4-25	T	8.19	7.95	15.0	35.0	-1.09
4-26	B	8.10	7.95	4.0	23.0	+1.33
4-26	T	8.18	8.05	14.0	29.0	-1.22
4-27	B	8.15	8.02	0	25.0	+2.03
4-27	T	8.18	8.02	13.0	36.0	-1.52
4-28	B	8.10	7.93	5.0	25.0	+1.24
4-28	T	8.17	8.03	16.0	33.0	-1.28
4-29	B	8.13	7.93	8.0	20.0	+0.63
4-29	T	8.09	7.93	18.0	22.0	-0.26
4-30	B	8.13	7.95	3.0	23.0	+1.17
4-30	T	8.17	8.04	14.0	16.0	-0.33

Symbols: S - Surface B - Bottom T - Top

TABLE II

Electret No. 2 25% Carnauba - 75% Rosin
Molten Mixture Temperature 235°C
Polarizing Voltage 3kv
Polarizing Electric Field 9.73 kv/cm
Thickness 0.308 cm
Range C

Date	S	d_o CM	d_e CM	m_o	m_e	$Q/k(10^{-2})$
4-28	B	8.18	8.02	17.0	45.0	-1.85
4-28	T	8.18	8.02	1.0	25.0	+1.58
4-29	B	8.16	8.02	18.0	39.0	-0.98
4-29	T	8.15	8.02	0.0	20.0	+1.62
4-30	B	8.15	8.03	15.0	44.0	-2.55
4-30	T	8.18	8.03	0.0	25.0	+1.76
5-1	B	8.16	8.02	17.0	23.0	-0.60
5-1	T	8.16	8.01	0.0	15.0	+1.06
5-2	B	8.18	8.02	16.0	19.0	-1.98
5-2	T	8.18	8.04	6.0	11.0	+0.36
5-3	B	8.18	8.00	16.0	19.0	-0.21
5-3	T	8.15	8.00	8.0	15.0	+0.49
5-4						
5-4						
5-5	B	8.15	7.99	17.0	21.0	-0.26
5-5	T	8.19	8.02	4.0	17.0	+0.81
5-6	B	8.15	7.99	17.0	21.0	-0.27
5-6	T	8.19	8.02	4.0	17.0	+0.81
5-7	B	8.18	8.02	13.0	13.0	0.0
5-7	T	8.18	8.02	6.0	8.0	+0.27
5-8	B	8.17	8.03	18.0	18.0	0.0
5-8	T	8.10	8.01	11.0	11.0	0.0
5-9						
5-9						
5-10	B	8.17	8.01	6.0	2.0	+0.14
5-10	T	8.17	8.01	0.0	0.5	+0.03
5-11	B	8.18	8.02	2.0	16.0	+0.95
5-11	T	8.18	8.02	7.0	13.0	+0.67

TABLE III

Electret No. 3 25% Carnauba wax - 75% Rosin
Molten Mixture Temperature 150°C
Polarizing Voltage 3KV
Polarizing Electric Field 9.28 kv/cm
Thickness 0.308cm.
Range C

Date	S	d_o cm	d_e cm	m_o	m_e	$q/k(10^{-2})$
4-30	B	8.08	7.92	15.0	42.0	-1.78
4-30	T	8.14	7.95	2.0	28.0	+1.44
5-1	B	8.08	7.91	17.0	27.0	-0.62
5-1	T	8.11	7.92	3.0	20.0	+0.95
5-2	B	8.13	7.95	14.0	18.0	-0.23
5-2	T	8.15	7.97	6.0	13.0	+0.41
5-3	B	8.08	7.92	15.0	21.0	-0.40
5-3	T	8.11	7.93	6.0	16.0	+0.59
5-4	B					
5-4	T					
5-5	B	8.09	7.90	17.0	28.0	-0.45
5-5	T	8.13	7.92	4.0	22.0	+0.95
5-6	B	8.09	7.92	14.0	23.0	-0.68
5-6	T	8.12	7.93	8.0	21.0	+0.72
5-7	B	8.13	7.93	20.0	25.0	-0.26
5-7	T	8.12	7.92	3.0	7.0	+0.21
5-8	B	8.13	7.92	17.0	16.5	-0.03
5-8	T	8.12	7.92	2.0	2.5	+0.02
5-9	B					
5-9	T					
5-10	B	8.10	7.93	4.0	7.0	+0.18
5-10	T	8.13	7.92	19.0	17.0	+0.10
5-11	B	8.12	7.93	2.0	20.0	+0.99
5-11	T	8.13	7.92	2.0	18.0	+0.83
5-12	B	8.10	7.90	2.0	22.0	+1.06
5-12	T	8.15	7.93	2.0	21.0	+0.87

TABLE IV

Electret No. 4 50% Carnauba wax - 50% Rosin
Made 4-14-52
Molten Mixture Temperature 180°C
Polarizing Voltage 2.7 kv
Polarizing Electric Field 8.45 kv/cm
Thickness - 0.319 cm
Range C

Date	S	d_o cm	d_e cm	m_o	m_e	$\sigma/k(10^{-2})$
4-14	B	8.26	8.10	16.0	14.7	-1.28
4-14	B	8.26	8.08	16.0	47.0	-1.14
4-14	T	8.23	8.08	0	23.0	+1.24
4-14	T	8.23	8.08	0	22.0	+1.19
4-15	B	8.28	8.12	16.0	46.0	-1.25
4-15	B	8.28	8.13	16.5	46.0	-1.30
4-15	T	8.28	8.17	0	23.0	+1.69
4-15	T	8.28	8.19	0	24.0	+2.14
4-16	B	8.28	8.13	16.0	40.0	-1.08
4-16	B	8.28	8.11	15.0	40.0	-0.99
4-16	T	8.19	8.07	0	23.0	+1.54
4-16	T	8.19	8.03	0	19.0	+1.02
4-17	B	8.30	8.16	16.0	30.0	-0.70
4-17	B	8.30	8.16	16.0	28.0	-0.61
4-17	T	8.31	8.18	0	21.0	+1.32
4-17	T	8.31	8.15	0	22.0	+1.37
4-18	B	8.31	8.12	0	14.5	+0.66
4-18	T	8.31	8.16	0	19.0	+1.05
4-23	B	8.21	8.05	0	10.0	+0.74
4-23	T	8.21	8.04	3.0	6.0	+0.22
4-24	B	8.11	7.91	0	20.0	+1.06
4-24	T	8.20	8.04	0	14.0	+0.93
4-25	B	8.11	7.92	1.0	20.0	+1.06
4-25	T	8.11	8.01	2.0	11.0	+0.95
4-26	B	8.20	8.05	7.0	25.0	+1.27
4-26	T	8.15	8.04	4.0	14.0	+1.06
4-27	B	8.20	8.07	0	25.0	+2.03
4-27	T	8.16	8.02	0	15.0	+1.13
4-28	B	8.23	8.08	0	25.0	+1.76
4-28	T	8.15	7.98	16.0	10.0	+0.37
4-29	B	8.21	8.05	0	13.0	+0.99
4-29	T	8.20	8.05	4.0	5.0	+0.01
4-30	B	8.13	7.96	4.0	27.0	+1.28
4-30	T	8.17	8.01	4.0	17.0	+0.76
5-1	B	8.19	8.05	2.0	17.0	+1.13
5-1	T	8.19	8.08	4.0	7.0	+0.29
5-2	B	8.15	7.95	3.0	8.0	+0.26
5-2	T	8.18	8.03	4.0	5.0	+0.14

TABLE V

Electret No. 5 50% Carnauba wax - 50% Rosin
Made 4-17-52
Molten Mixture Temperature 100°C
Polarizing voltage 2.5 kv
Polarizing electric Field 8.65 kv/cm
Range C

Date	S	d_o CM	d_e CM	m_o	m_e	$\sigma/k(10^{-2})$
4-17	B	8.24	8.06	16.0	47.0	-1.13
4-17	B	8.23	8.06	16.0	46.5	-1.09
4-17	T	8.22	8.05	0	21.0	+1.01
4-17	T	8.22	8.05	0	24.0	+1.13
4-18	B	8.08	7.90	16.0	32.0	-0.63
4-18	B	8.08	7.90	15.5	31.0	0.60
4-18	T	8.25	8.05	16.0	30.0	+0.49
4-18	T	8.25	8.05	15.0	29.0	+0.49
4-23	B	8.14	7.99	0	9.0	+0.59
4-23	T	8.14	8.03	16.0	24.0	-0.51
4-24	B	8.12	7.96	0	13.0	+0.91
4-24	T	8.15	7.96	17.0	39.5	-0.70
4-25	B	8.16	8.01	3.0	20.0	+1.20
4-25	T	8.15	8.00	15.0	37.0	-1.56
4-26	B	8.17	7.98	3.0	24.5	+1.20
4-26	T	8.15	8.03	15.0	39.0	-2.11
4-27	B	8.03	7.84	1.0	24.0	+7.84
4-27	T	8.03	7.88	17.0	35.0	-1.27
4-28	B	8.14	8.00	0	18.0	+1.34
4-28	T	8.03	7.88	9.0	24.0	-1.06
4-29	B	8.15	8.00	3.0	27.0	+1.35
4-29	T	8.15	7.98	15.0	27.0	-0.81
4-30	B	8.12	7.94	2.0	25.0	+1.36
4-30	T	8.14	8.00	15.0	35.0	+1.52

TABLE VI

Electret No. 6 75% Carnauba wax - 25% Rosin
Made 4-15-52
Molten Mixture Temperature 100°C
Polarizing Voltage 2.7 kv
Polarizing Electric Field 5.33 kv/cm
Thickness 0.319 cm
Range C

Date	S	d_o CM	d_e CM	m_o	m_e	$\sigma/k(10^{-2})$
4-15	B	8.18	8.05	0	15.0	+0.99
4-15	B	8.18	8.06	0	14.0	+1.02
4-15	T	8.19	8.05	14.0	47.0	-1.56
4-15	T	8.18	8.04	10.0	46.0	-1.73
4-16	B	8.19	8.06	0	29.0	+1.75
4-16	B	8.19	8.05	0	28.0	+1.58
4-16	T	8.16	7.98	16.0	47.0	-1.13
4-16	T	8.16	8.00	16.0	46.0	-1.25
4-17	B	8.18	8.02	0	32.0	+1.56
4-17	B	8.18	8.04	0	31.0	+1.73
4-17	T	8.18	7.99	11.0	48.0	-1.27
4-17	T	8.18	8.05	11.0	41.0	-1.57
4-18	B	8.19	8.06	0	25.0	+1.55
4-18	T	8.18	8.04	16.0	35.0	-0.94
4-23	B	8.09	7.93	4.0	14.0	+0.66
4-23	T	8.09	7.92	16.0	24.0	-0.49
4-24	B	8.09	7.90	1.0	26.0	+1.35
4-24	T	8.09	7.92	16.0	31.0	-0.93
4-25	B	8.06	7.91	0	25.5	+1.79
4-25	T	8.10	7.92	17.0	33.0	-0.94
4-26	B	8.09	7.93	0	29.0	+1.91
4-26	T	8.08	7.94	13.0	35.0	-1.66
4-27	B	8.08	7.91	0	30.0	+1.67
4-27	T	8.09	7.94	16.0	42.0	-1.83
4-28	B	8.09	7.95	0	29.0	+2.18
4-28	T	8.08	7.92	16.0	34.0	-1.18
4-29	B	8.06	7.91	2.0	23.0	+1.48
4-29	T	8.08	7.91	12.0	23.0	-0.73
4-30	B	8.06	7.92	5.0	27.0	+1.65
4-30	T	8.07	7.92	13.5	37.0	-1.65
5-1	B	8.06	7.91	4.0	22.0	+1.36
5-1	T	8.09	7.92	12.0	19.0	-0.46
5-2	B	8.05	7.93	0	12.0	+1.06
5-2	T	8.10	7.94	12.0	14.0	-0.13

(TABLE VI, Electret No. 6)

Date	S	d_o CM	d_e CM	m_o	m_e	$q/k(10^{-2})$
5-3	B	8.05	7.90	5.0	10.0	+0.84
5-3	T	8.10	7.90	15.0	16.0	-0.04
5-5	B	8.08	7.89	3.0	21.0	+1.00
5-5	T	8.09	7.90	17.0	28.0	-0.61
5-6	B	8.08	7.91	3.0	20.0	+1.06
5-6	T	8.08	7.90	14.0	25.0	-0.65
5-7	B	8.08	7.90	3.0	13.0	+0.59
5-7	T	8.09	7.92	18.0	22.0	-0.25
5-8	B	8.08	7.91	4.0	7.0	+0.19
5-8	T	8.08	7.90	13.0	14.0	-0.06
5-9	B	8.04	7.90	4.0	6.0	+0.15
5-9	T	8.10	7.91	5.0	4.0	-0.16
5-10	B	8.09	8.01	0	7.0	+0.93
5-10	T	8.00	7.92	18.0	22.0	-0.53
5-11	B	8.08	7.90	2.5	24.0	+1.26
5-11	T	8.09	7.90	6.5	10.0	-0.19
5-12	B	8.09	7.90	2.0	30.0	+1.55
5-12	T	8.10	7.92	13.0	36.0	-1.35
5-16	B	8.13	7.96	2.0	24.0	1.37
5-16	T	8.12	7.95	17.0	38.0	-1.01
5-17	B	8.13	7.95	15.0	16.0	+0.06
5-17	T	-	-	-	-	-
5-18	B	8.12	7.92	15.0	28.0	+0.59
5-18	T	8.13	7.92	15.0	17.0	-0.20

TABLE VII

Electret No. 7 75% Carnauba wax - 25% Resin
Made 4-11-52
Molten Mixture Temperature 175°C
Polarizing Voltage 1.7 kv
Polarizing Electric Field 7.14 kv/cm
Thickness 0.236 cm
Range C

Date	S	d_o CM	d_e CM	m_o	m_e	$\sigma/k(10^{-2})$
4-11	B	8.25	8.08	0	12.0	+0.85
4-11	B	8.25	8.08	0	16.5	+0.74
4-11	T	8.21	8.04	16.0	30.0	-0.58
4-11	T	8.22	8.05	16.0	29.0	-0.54
4-12	B	8.26	8.09	0	23.0	+1.09
4-12	B	8.26	8.09	0	23.0	+1.09
4-12	T	8.25	8.09	16.0	33.0	-0.82
4-12	T	8.25	8.10	16.0	31.0	-0.72
4-14	B	8.27	8.09	0	27.0	+1.19
4-14	B	8.25	8.09	0	29.0	+1.41
4-14	T	8.25	8.09	16.0	44.0	-1.17
4-14	T	8.25	8.09	16.0	44.0	-1.17
4-15	B	8.27	8.09	0	27.0	+1.19
4-15	B	8.27	8.08	0	28.0	1.16
4-15	T	8.22	8.07	14.0	40.0	-1.19
4-15	T	8.22	8.07	14.0	40.0	-1.19
4-16	B	8.27	8.11	0	27.0	+1.33
4-16	T	8.27	8.09	14.0	40.0	-0.99
4-17	B	8.25	8.06	0	28.0	+1.16
4-17	T	8.27	8.01	16.0	40.0	-0.62
4-18	B	8.25	8.08	0	20.5	+0.99
4-19	T	8.27	8.07	16.0	23.0	-0.25
4-23	B	8.16	8.00	4.0	17.0	+0.81
4-23	T	8.17	8.05	9.5	20.0	-0.88
4-24	B	8.14	7.96	0	20.0	+0.10
4-24	T	8.14	8.00	16.5	29.0	-0.10
4-25	B	8.15	8.00	0	19.0	+1.17
4-25	T	8.15	8.03	17.0	25.0	-0.98
4-26	B	8.16	8.04	0	20.0	+1.76
4-26	T	8.19	8.08	17.0	26.0	-0.85

(TABLE VII, Electret No. 7)

Date	S	d_{oCM}	d_{eCM}	m_o	m_e	$S/k(10^{-2})$
4-27	B	8.18	8.02	4.0	30.0	+1.72
4-27	T	8.18	8.01	16.0	21.0	-0.31
4-28	B	8.18	8.02	7.0	25.0	+1.01
4-28	T	8.18	8.03	14.0	19.0	-0.35
4-29	B	8.17	8.02	4.0	16.0	+0.85
4-29	T	8.17	8.04	18.0	14.0	+0.30
4-30	B	8.16	8.00	2.0	21.0	+1.19
4-30	T	8.16	8.02	2.0	12.0	+0.59

TABLE VIII

Relative Humidity Data, U. S. Weather Bureau,
Airport Station,
Houston, Texas

April 1952

Day	Humidity(%)	Day	Humidity(%)
1	59	16	59
2	55	17	63
3	94	18	76
4	35	19	90
5	31	20	90
6	51	21	86
7	62	22	92
8	68	23	58
9	79	24	43
10	69	25	55
11	97	26	27
12	68	27	41
13	49	28	41
14	38	29	52
15	51	30	51

May 1952

Day	Humidity(%)	Day	Humidity(%)
1	60	12	41
2	49	13	42
3	65	14	54
4	51	15	68
5	38	16	75
6	43	17	85
7	67	18	97
8	65	19	74
9	72	20	51
10	55	21	66
11	24	22	80

TABLE IVX

Decrease of Effective Field of Electret
With Distance From Surface

d_1	d_e	$d_e - d_1$	m_1	m_e	$m_e - m_1$
RUN #1					
8.19	8.06	13	3	18	15
8.17	8.05	12	3	14	11
8.15	8.05	10	6	15	9
8.13	8.05	8	10	16	6
8.11	8.05	6	12	16	4
8.09	8.05	4	11	13	2
8.07	8.05	2	9	11	2
RUN #2					
8.19	8.06	13	11	23	12
8.17	8.05	12	10	22	12
8.15	8.05	10	8	16	8
8.13	8.05	8	7	14	7
8.11	8.05	6	7	12	5
8.09	8.05	4	7	10	3
8.07	8.05	2	5.5	8	2.5
RUN #3					
8.19	8.06	13	7	20	13

TABLE X

Data For Calibration of Instrument
With 88$\mu\mu f$ Condenser

m_o	m_e	$m_e - m_o$	Volts	Q(esu)
0	23.5	23.5	67.5	
0	25.0	25.0	67.5	
0	24.0	24.0	67.5	
	AVG	24.2		17.9
0	20.0	20.0	45.0	
0	20.5	20.5	45.0	
	AVG	20.25		11.9
0	14.0	14.0	22.5	
0	16.0	16.0	22.5	
0	14.0	14.0	22.5	
	AVG			5.95
0	9.0	9.0	6.0	
0	8.0	8.0	6.0	
0	8.5	8.5	6.0	
	AVG	8.5		1.59

BIBLIOGRAPHY

Conant, James B., and Albert H. Blatt, The Chemistry of Organic Compounds. Third edition; New York: The Macmillan Company, 1947. 665 pp.

Dickinson, Thomas A., "Ceramic Electrets," Ceramic Industry, 52:62-4, May, 1949.

Dickinson, Thomas A., Electrets. Alhambra, California: Plastics Research Company, 1948. 32 pp.

W. J. Dodds, and J. D. Stranathan, "Electrets from Dry-Mixed Components," Physical Review, 60:360, August 1941.

Eguchi, M., "On the Permanent Electret," Philosophical Magazine, 49:178-92, January

Franklin, A. D. "The Heterocharge of Carnauba Wax Electrets," Physical Review, 78:342, May, 1950.

Gemant, A., "Field of Electrets in the Presence of Gaseous Ions." Physical Review, 61:79-83, January, 1942.

Good, W. M., and J. D. Stranathan, "An Improved Method of Making Permanent Electrets and Factors Which Affect Their Behavior," Physical Review, 56:810, October, 1939.

Gutmann, F., "The Electret," Reviews of Modern Physics, 20:467-70, July, 1948.

Hoag, Barton J., Electron and Nuclear Physics. New York and London: McGraw Hill Book Company, Inc., 1944. 522 pp.

Johnson, O. J., and P. H. Carr, "Some Experiments on Electrets," Physics Review, 42:912, December, 1932.

Padgett, Edward, "Improved Electrets," Radio Electronics, 20:20-23, April, 1949.

Reich, Herbert J., Theory and Applications of Electron Tubes. Second edition; New York and London: McGraw Hill Book Company, Inc., 1944. 716 pp.

Victoreen, John A. "Electrometer Tubes for the Measurement of Small Currents," Proceedings of the I. R. E., vol. 37, No. 4, 1949, 10 pp.