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The relation of certain preparation conditions to the characteristics of copper oxide rectifiers

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THE RELATION OF CERTAIN PREPARATION CONDITIONS TO THE CHARACTERISTICS OF COPPER OXIDE RECTIFIERS.

BY

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I. INTRODUCTION

A. Discovery and Nature of Copper Oxide Rectifiers

Credit for the discovery and preliminary development of the copper oxide rectifier is given to Mr. L. O. Grondahl (Grondahl 8)*.

The copper oxide rectifier consists essentially of a piece of copper, usually a flat disc, upon which a coating of the red cuprous oxide, Cu_2O, has been formed by a suitable heat treatment. Electrical contact with the outside surface of the cuprous oxide is usually obtained by coating it with graphite and pressing against it a disc of soft lead. With the lead as one electrode and the original copper (mother copper) underneath the oxide as the other electrode, the rectifier is formed. When a voltage is applied across these electrodes such that the current would tend to flow through the cuprous oxide from the lead electrode to the mother copper, the electrical resistance opposing the flow of current is of the magnitude of from ten to fifty ohms per square inch of cuprous oxide surface. With the voltage drop in the opposite direction the cuprous oxide rectifier presents a resistance of thousands of ohms per square inch of oxide surface.

The rectifying action appears to take place at the surface of contact between the mother copper and the oxide coating, and it is

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* Reference numbers refer to corresponding numbers in the Selected Bibliography, page 186.

not greatly affected by the type of electrode used to make contact with the outer surface of the cuprous oxide. Lead serves well as the contacting electrode because it is soft and under pressure it sinks into the minute hollows of the cuprous oxide and makes electrical contact with the whole of the outside cuprous oxide surface.

B. Uses and Advantages in the Use of the Copper Oxide Rectifier

In its usual commercial form the copper oxide rectifier unit consists of a lead washer about one-sixteenth inch in thickness and from one to three inches in diameter and a copper washer of equal size coated with cuprous oxide on one side only. These units may be stacked to give a series connection suitable to the voltage on which they are to be used. The units are strung on the shaft of a bolt, and a pressure of thousands of pounds is applied to them by the tightening of the nut at the end of the bolt. The rectifier thus formed is permanent, movable, and easy to handle.

The copper oxide rectifier has a negative resistance coefficient. With increasing temperature the rectification ratio decreases, and at 300° C. the rectifying properties are destroyed entirely. Consequently the voltage rating of a unit is determined largely by the cooling facilities provided for it.

The copper oxide rectifier has several industrial uses. It was once extensively used in "trickle" chargers for radio batteries. It forms an excellent source of direct current for the excitation of dynamic loud speakers in a-c. radio receivers. This rectifier is used in control apparatus, as a by-pass for dynamo field switches, and in those other numerous circumstances where a dependable rectifier of stable characteristics and moderate current capacity is required. One of the more recent uses for the copper oxide rectifier is in electrical instruments which are suitable for use in both a-c. and d-c. circuits.

Briefly, the advantages in use of the copper oxide rectifier over other rectifiers are: It is rugged and stands handling and shipping well; it is dry and requires no attention after it is installed; it has no moving parts and makes no noise in operation; it produces excellent rectification with little reverse current; it operates electronically and not electrolytically - consequently it requires no reforming period at the start of each electric cycle; it can be connected readily to any number of phases and requires no intervening transformers; it may be used with any frequency. Grondahl reports experiments with this rectifier at frequencies up to three million cycles per second (Grondahl 10).

C. Characteristics of Copper Oxide Rectifiers Inviting Investigation

Several diverse theories have been presented, but none of them satisfactorily explains all of the characteristics of the copper oxide rectifier. The influencing factors in the formation of the rectifier units are numerous. It is not possible commercially to produce a number of rectifiers whose characteristics are nearly enough alike that they may be said to be identical.

The purpose of the investigation reported herein was to determine the influence exerted by certain of the variables in the preparation of copper oxide rectifiers and to consider the various theories in relation to the effects thus determined.

II. REVIEW OF PREVIOUS THEORIES AND INVESTIGATIONS

A. Introduction

It is interesting to note that each investigator attempting to establish a quantitative theory or to derive a mathematical expression for the volt-ampere characteristic of the copper oxide rectifier is driven to the conclusion that as yet neither the quantitative theory nor the mathematical expression has been discovered which can be applied successfully to the whole of the volt-ampere characteristic.

In the following discussion there will be used the customary designation of the direction of current flow, namely: electron transfer from the copper to the cuprous oxide is in the "conduction" direction, and the current constituted by this electron transfer is "forward" current; conversely, electron flow from the oxide to the copper is in the "blocking" direction, and current flowing in the blocking direction is designated as "reverse" current. "Rectification ratio" is the ratio of the forward current to the reverse current at some specified voltage.

B. Presentation of Theories

1. Theory of Wagner

Wagner assumes (Wagner 33) that the transfer of electrons from the cuprous oxide to the copper is brought about by singly charged positive copper ions in the cuprous oxide giving up an electron to a doubly charged positive ion in the copper according to the equation:

$$Cu^{+}_{(o)} + Cu^{++}_{(c)} \rightarrow Cu^{++}_{(o)} + Cu^{+}_{(c)}, \qquad (1)$$

where the subscripts (o) and (c) indicate respectively the location of the copper ion to be in the oxide and in the mother copper. Since the number of singly charged copper ions in the cuprous oxide is practically equal to the number of lattice ions and scarcely can be increased, the existence of a saturation current is to be assumed. With a very strong field (10^7 volts per cm.) other sources of electrons from the cuprous oxide are brought into action, and the current is not limited to the saturation value predicted by mode of transfer indicated in equation 1. In the conduction direction the number of electrons is essentially proportional to the concentration in the oxide of doubly charged copper ions as electron catchers. Consequently the number of electron transfers per unit time can be increased proportionally to the increase of the number of doubly charged copper ions in the boundary layer.

Upon the foregoing assumptions Wagner derives for the current density the expression:

$$\frac{i}{q} = k_2 e\left(e^{\frac{eV}{kT}} - 1\right) \qquad (2)$$

where $\frac{i}{q}$ = current strength per square cm.,

k_2 = proportionality factor,

e = elementary charge,

V = Boltsmann's constant,

T = absolute temperature,

and current in the forward direction is assumed positive.

Equation 2 is found to deviate from the experimental data for very small voltages and for voltage gradients at the contact between copper and oxide of more than 10^7 volts per cm. This derivation assumes that at the contacting lead electrode the forced electron emission takes place at very small voltages for a current flowing in the forward direction, but at the inner contact between the cuprous oxide and the mother copper a much higher voltage of 10^7 volts per cm. is required to cause this forced electron emission. Such an assumption seems difficult to justify when the contacting electrode is made of copper, for in such a case a symmetrical condition with respect to the cuprous oxide is formed, and there is left no explanation for the asymmetrical conduction properties of such a rectifier.

2. Theory of Slepian

Slepian assumes (Slepian 31) the action of the copper oxide rectifier to be of the same nature as the action of a vacuum tube rectifier. For a vacuum tube rectifier it is necessary that the electrodes be separated by an insulator having a thickness of less than a thousand molecules. One electrode must be an opulent source of electrons and the other capable of releasing only a few or no electrons at all. Current flows when the voltage drop moves electrons through the insulator from the better electron source to the other electrode, while a voltage in the opposite direction can produce only a very small current if any at all. In the copper oxide rectifier the mother copper is considered to be an abundant source of electrons, while the cuprous oxide is the electrode whose supply of removable electrons is limited. In order to provide the insulating layer separating these two electrodes, Slepian assumes that at the layer of contact between the mother copper and the cuprous oxide the molecules exist in a structural form which is not normal and that in this abnormal condition the molecules have a high electrical resistance which gives the effect of the required insulating layer.

3. Theory of Nordheim

Nordheim states (Nordheim 16) that there are two conditions necessary for the existence of a rectifier such as the copper oxide rectifier. He specifies that there must be a surface of contact between a conductor and a semi-conductor and that this contact must have a high electron transfer resistance. Of the electrons having an energy sufficient to bring them across this high resistance, the supply in the semi-conductor, the cuprous oxide, is limited, while in the conductor, the mother copper, the supply is extremely copious. Using these assumptions as a basis he derives from the considerations of wave mechanics the equation for current

$$i = DC\sigma(\epsilon^{\frac{\phi}{KT}} - 1) \qquad (3)$$

where D = proportion of electrons possessing sufficient energy to penetrate the boundary layer,

C = practically a constant varying only slightly with T,

σ = the conductivity of the semi-conductor,

ϕ = voltage applied to the rectifier,

K = a constant,

and T = absolute temperature.

4. Theory of Schottky

In Schottky's original theory (Schottky 26, pg. 87), rectification was simply a contact phenomena depending upon the difference of the work functions of the electron transfers from the copper to the cuprous oxide and from the cuprous oxide to the copper. This theory differs from the previous ones in that Schottky does not consider the limitations of the supply of electrons but only the energies required for their transportation from one electrode to the other.

5. Theory of Leblanc

Both the partial pressure of the electron atmosphere at the surface of a metal and the electrostatic field established by the positive ions remaining in the metal are different for different metals. Consequently, when two unlike metals are brought nearly into contact, a flow of electrons from one to the other takes place until the electronic partial pressures are equal in the plane of equal electrostatic fields between the metals. This electron flow establishes a potential difference between the conductors which is designated as the contact potential. Leblanc suggests (Leblanc 14) that in the formation of oxide on the copper it is possible for a eutectic mixture of copper and cuprous oxide to occur, and that this eutectic mixture will act as a second conductor and establish a contact potential with the copper. He offers this contact potential as the cause of the rectification in the copper oxide rectifier.

6. Theory of Kost

Kost heats a strip of copper by passing an electric current through it (Kost 13). The strip is hottest in the center; consequently the thickness of the cuprous oxide layer varies from a maximum at the center to a minimum at the ends. The rectification properties are not constant but vary with the thickness of the oxide layer. From this fact Kost concludes that rectification is a property of the crystal formation rather than of the boundary layer between the oxide and the copper since the crystal structure could vary with different thicknesses of the oxide while the contact layer must be uniform throughout the length of the oxidised copper strip.

7. Theory of Leo

Leo finds that cuprous oxide has the property of retaining electrons, when bombarded by them, like a condenser of high capacitance and poor insulation (Leo 15). He suggests that the retention of the electrons gives a negative space charge which may be a contributing factor to the characteristics of the blocking layer.

8. Theory of Waibel

Waibel shows that the rectification afforded when a piece of etched massive cuprous oxide is pressed against a clean metal is of the same type as that of the cuprous oxide rectifier in which the oxide is grown on the copper itself (Waibel 34). He believes this evidence to support Schottky's theory that the rectification is caused by the differences of exit work of electrons from the conductor and semi-conductor.

9. Theory of van Geel

For his derivation van Geel assumes that not only the outer exit work function, which was considered by Schottky, but also the inner exit work as defined by Sommerfeld is necessary for consideration in the current equation for the copper oxide rectifier (van Geel 7). Upon this assumption he derives the equations for the current:

$$I = AF^2 e^{\frac{-B}{F}} \qquad (4)$$

or

$$I = CF^{3/2} \qquad (5)$$

Equation 5 is the equation to be used when space charge effects are present, and equation 4 assumes the existence of no space charge. A, B, and C are constants of the materials used on either side of the dielectric, and F is the field intensity at the emitting surface. The theory of van Geel is much like that of Slepian in that they assume that the currents flowing through the blocking layer are cold emission currents from the metal electrode and the semi-conductor.

10. Theory of Pélabon

For the mechanism of the rectification of copper oxide rectifiers Pélabon proposes an explanation based on electrolysis at a poor contact (Pélabon 18, 19 and 21). For such a conduction it is necessary to have an asymmetrical condenser having a metal and a semi-conductor as the electrodes and a semi-insulator as the dielectric. In the copper oxide rectifier Pélabon specifies as the electrodes the mother copper and a mixture of cuprous oxide (Cu_2O) and cupric oxide (CuO). He states that the border layer or dielectric between these electrodes is a layer of submicroscopic thickness consisting of almost pure cuprous oxide containing but little of the cupric form. When a reverse current is flowing, the negative oxygen ions, O^{--}, move through the semi-insulator to the surface of the conductor and form there a negative space charge which repels the electrons from the semi-conductor. For a forward current the negative oxygen ions flow easily through the semi-insulator and are absorbed in the semi-conductor. Here no space charge is formed and current flows readily.

11. Theory of Grondahl

Grondahl's theory is perhaps best presented in his own words: "One of the present writers has proposed a theory based on the fact that the copper and the oxide are in very intimate relationship. The transfer of an electron from copper to oxide, or vice versa may take place without passing through the whole potential drop represented by the electron affinity of either substance, but only through a potential drop corresponding to their difference. Under this condition it is conceivable that even at room temperature and without any application of an e.m.f. a great number of electrons are able to escape from the copper and into the copper oxide. The copper then serves the same purpose as the hot wire filament in a vacuum tube, and maintains an atmosphere of electrons in the oxide in excess of the normal amount. On account of the short distance between electrodes, the comparatively large area, and also probably assisted by the dielectric constant of the oxide, the resistance to the flow of electron current in the direction from the copper to the oxide is small.

"When the e.m.f. is applied in the opposite direction, there is a tendency to drive the electrons back into the copper. This is opposed by the ready diffusion of electrons from the copper into the oxide so that the electrons become concentrated near the surface of the copper. The resultant gradient in electron concentration in the oxide produces a potential gradient which opposes the flow of electrons in the direction from oxide to copper. This theory seems to fit the voltage resistance curves very well." (Grondahl 10).

12. Theory of Jacquelet

Jacquelet shows (Jacquelet 12) that the coefficient of thermal expansion for copper between 0 and 1000° C. is 19×10^{-6}, while that of cuprous oxide is never more than one tenth as much; and, moreover, this coefficient for cuprous oxide varies with different temperatures and becomes zero and even negative. Consequently, when a layer of cuprous oxide is formed on the expanded surface of a copper disc above 1000°C., and then the unit is suddenly cooled, the copper surface tends to contract much more than does the area of the cuprous oxide surfaces. The result of this action is that the crystals of the cuprous oxide suffer a considerable distortion.

Jacquelet pictures the conductivity of semi-conductors as being produced by the contact with each other of the metalic atoms of the molecules of the semi-conductor. The distortion described above lowers the resistance of the cuprous oxide layer because by this distortion either more of the copper atoms are brought into contact or, if they are vibrating, more copper atoms make contact and for longer periods of time than they do in the normal condition of the oxide. A voltage strain in the forward direction further decreases the resistance by adding to the strain imposed by the quenching of the rectifier, while a voltage strain in the reverse direction increases the resistance because it tends to return the cuprous oxide crystals to their normal condition.

13. Theory of Wilson

Wilson uses the new quantum mechanics to consider the conditions of electron flow between the semi-conductor and the metal (Wilson 35). He finds that as yet not enough is known of certain properties of the semi-conductor and of its contact with the metal to substantiate an exact development; however, from more general principles he is able to derive for the current the expression;

$$I = K_1 \left[e^{\alpha \frac{\epsilon V}{KT}} - e^{-(1-\alpha)\frac{\epsilon V}{KT}} \right] \qquad (6)$$

where V = voltage drop from metal to semi-conductor,

ϵ = electronic charge,

K_1 and K are constants,

T = absolute temperature,

and α is independent of V and lies between 1 and 1½.
Of this theory the author states (Wilson 35, pg. 498), "The difficulties in the way of a complete theory of the transmission coefficient are considerable, but the crude theory seems adequate to explain a large part of the phenomena."

Wilson agrees with Schottky that the difference of the effects of the contacts at the two surfaces of the cuprous oxide are caused by a difference in the physical condition and type of contact the oxide surface makes with the metal touching it. Wilson says (Wilson 35, pg. 489), "In any crystal rectifier there are always two contacts to consider, the two at the boundaries of the semi-conductor. One of these contacts is always supposed to have a negligible rectifying effect. The justification for this is difficult to find. If the contacts are very dissimilar, then there is a rectifying effect, but, as we shall see later, the direction of easy flow is determined more by the nature of the dissimilarity than by its magnitude."

C. Report of Previous Investigations

1. Effect of temperature change on rectifier characteristics

The effect of temperature variations upon the characteristics of copper oxide rectifiers has been investigated by Leblanc (Leblanc 14), Kost (Kost 13), Irion (Irion 11), Demontvignier (Demontvignier 2), and others. They found that an increase of temperature lowers both the forward and reverse resistances, but the reverse resistance suffers the greater proportional decrease; consequently, with increasing temperature the rectification ratio decreases. If the copper oxide rectifier is heated to about 300°C. it loses its rectification properties, and both the forward and the reverse resistance are greatly increased.

2. Effect of contacting electrode on rectifier characteristics

The most thorough investigation of the effect of the contact electrode upon the characteristics of the copper oxide rectifier was made by Schottky and his coworkers (Schottky 27, 28, and 29). They found that practically the only effect the contacting electrode has upon the conductivity of the rectifier is one of simple contact resistance which is merely added alike to both forward and reverse resistances of the rectifying section of the unit. The surface of the cuprous oxide is not smooth; the more the contacting electrode is capable of sinking into the hollows and making a more complete contact with the whole of the oxide surface, the less the contact resistance becomes. For this reason soft lead or mercury under pressure are found to be good contacting electrodes.

3. Chemical composition and crystal arrangement of the oxide layer

A decided difference of evidence and opinion exists concerning the form and material of the blocking layer at the surface of the mother copper.

Pélabon (Pélabon 21) made a chemical analysis of the oxide layer and found that below an outside surface of black cupric oxide exists a mixture of cuprous and cupric oxides; this mixture varies from the pure cupric oxide on the outside surface to pure cuprous oxide at the surface of the mother copper.

Scharf and Weinbaum (Scharf 25) have made a photomicrographic study of the same question. They used an acid to etch away the oxide layer to different depths and disclosed successively layers of fine grained cupric oxide, a mixture of fine grained cupric and course grained cuprous oxide, and the course grained cuprous oxide which is the final layer before the mother copper is reached. These authors concluded that their investigation results support the theory of Pélabon. Their pictures show no correspondence in position between the individual cuprous oxide crystals and the copper crystals on which they are formed, but that one cuprous oxide crystal may rest upon parts of two or more copper crystals.

Torres, however, (Torres 32) conducted a photomicrographic study similar to that of Scharf and Weinbaum and came to entirely contradictory conclusions. He found that rectification is unimpaired when only the pure cuprous oxide crystals form the whole of the oxide layer. Further, his photographs show that the contour of each cuprous oxide crystal corresponds to the copper crystal below it.

Jacquelet (Jacquelet 12) used chemical analysis to find results agreeable to those of Torres, namely: the rectifying layer consists of pure cuprous oxide and there is no evidence of the presence of cuprous and cupric oxide mixtures in the rectifying zone.

Dubar (Dubar 6) used chemical analysis and found the presence of no cupric oxide in the cuprous oxide layer.

4. Capacitance measurements of the blocking layer

Schottky and Deutschmann (Schottky 27) made use of an a-c. capacitance bridge to determine the capacitance of the blocking layer of the copper oxide rectifier. With temperatures from -73° to 20°C. and frequencies from 800 to 2500 cycles, capacitance measurements were determined which gave the apparent thickness of the blocking layer values from $3x10^{-6}$ to $3x10^{-8}$ cm.

5. Type of contact at the blocking layer

Schottky, Störmer, and Waibel (Schottky 28) constructed a rectifier with a copper plate as one electrode and a graphite layer as the other with massive cuprous oxide between the electrodes. In this combination rectification occurred at the copper-cuprous oxide surface. When polished or sand blasted massive cuprous oxide was used, rectification was quite small. If the cuprous oxide surface next to the copper electrode had been etched with nitric or sulphuric acid, rectification was relatively much greater. These results seem to indicate, as do the micrographic results of Scharf and Weinbaum (Scharf 25) and those of Torres (Torres 32) that large grained surfaces, such as those of the cuprous oxide produced by etching are required in the semi-conductor in order that good rectification may be produced.

D. Discussion of Theories

Any explanation, such as that of Wagner, which is based primarily upon the difference of the properties of the materials used as electrodes on each side of the cuprous oxide must necessarily fail when rectification is obtained with the same material, namely copper, is used for both electrodes. Rectification does occur when copper is used for the contacting electrode, and one is driven to seek a difference in the physical state of the copper electrodes or of the two surfaces of the cuprous oxide as an explanation of the asymmetrical conduction of an apparently symmetrical system.

In all of the theories in which the limitation of reverse current is attributed to the cold emission properties of the semi-conductor, it is required that the value of the reverse current approach a limit. Consequently, these derivations do not hold for higher values of the applied voltage since at higher voltages the reverse current is not only not limited but increases with increasing voltage at a higher rate than does the forward current.

Nordheim states that present theories of rectification appear fairly good but that none are fully satisfactory. He suggests that the main fault seems to be that no one has yet given an exact model of the semi-conductor and its contact with the metal (Nordheim 16, pg. 434).

Of Schottky's theory of rectification based on the exit work energy of the electrons, Grondahl has to say; "Schottky's theory (Schottky 26, pg. 87), involving the work required to carry an electron across the boundary between two substances, also fails to give a satisfactory explanation as it is probable that the electron affinity of the copper is greater than that of the copper oxide." (Grondahl 10). In a more recent article Schottky himself expresses doubt of the adequacy of the present day theories (Schottky 29, pgs. 838-839).

The theory of Leblanc and that of Pélabon depend for their establishment upon the supposition of a eutectic mixture of the cuprous and cupric oxides within the layer effective in rectification. The presence of this eutectic mixture is found by Pélabon (Pélabon 21) and by Scharf and Weinbaum (Scharf 25). Its presence is denied by Jacquelet (Jacquelet 12), by Torres (Torres 32), and by Dubar (Dubar 6). Schottky's experiments (Schottky 28) of producing rectification with massive cuprous oxide pressed against a copper electrode also deny the necessity of a eutectic mixture of cuprous and cupric oxides to produce rectification.

Scharf and Weinbaum (Scharf 25) find that there is no orientation of the cuprous oxide crystals in the copper oxide rectifier, and these results discredit the theory of Kost who attributed rectification to the crystal structure of the cuprous oxide. Results similar to those of Kost were obtained in the investigation later described, and they will be explained by the use of Jacquelet's theory.

The equations derived by Nordheim and Wagner required a saturation current in the reverse direction, and it will be shown later that these equations do not hold for voltages higher than six to eight volts.

Although, as Jacquelet himself states (Jacquelet 12, pg. 371), the theory which he proposes scarcely seems susceptible of a mathematical expression for the purpose of verification, this theory explains remarkably well almost all of the phenomena exhibited by copper oxide rectifiers.

When two copper discs are placed back against back and heated in this position, oxygen is excluded from one side of each; it results that each is coated with cuprous oxide on one side only. If such discs are quenched suddenly, they have rectifying properties; and it is invariably found that the discs, which were flat previous to the quenching, have become curved. This curvature is caused by the unequal contraction of the copper and the cuprous oxide layer. If, however, the discs are allowed to cool slowly in air or in an inert atmosphere, they are not deformed and they have only the slightest trace of rectifying properties (Jacquelet 12). Thus it appears that in the slow cooling the cuprous oxide crystals can flow on the copper disc and adjust themselves to the changing area of copper surface. Dubar observes (Dubar 5) that a rectifier heated to 300°C. loses its high conductivity in the forward direction. Apparently at this temperature the firmness of contact between the cuprous oxide and the copper is lessened to such an extent that the strain, previously imposed by the quenching of the unit, is removed. Dubar reports (Dubar 3) that cuprous oxide formed by chemical means on copper when it is cold gives no rectifying properties. Such an oxide layer would suffer no mechanical strain in its formation.

It has been observed by van Geel (van Geel 7, pg. 772, fig. 3c) that the reverse current of a copper oxide rectifier appears to be the sum of two currents obeying different laws. Figure 1 is an illustration of these current curves. Curve a represents the shape of the reverse volt-ampere characteristic. It can be seen that this characteristic is the sum of curves b and c. Curve b is evidently a saturation current, and it very well may be the cold emission saturation current required by Wagner and Nordheim. Then curve c would represent the current carried through the semi-conductor by the copper atom contacts in the strained lattice.

With temperature variation, the amplitude of oscillation of the metal atoms in a semi-conductor varies. Jacquelet assigns to the contacts made in these oscillations the current carrying properties of semi-conductors. With temperature variation there is a variation of cold emission currents. And with temperature variation the mechanical strain upon the cuprous oxide crystals is changed by the difference of expansion or contraction of the copper and the cuprous oxide. As the temperature is lowered, the forward and reverse resistance of the copper oxide rectifier are found to increase. This decrease in conductivity can be assigned to the decrease in the conductivity of the semi-conductor and to the decrease of the cold emission currents. But with decreasing temperature, the rectification ratio is found to increase, This change is undoubtedly

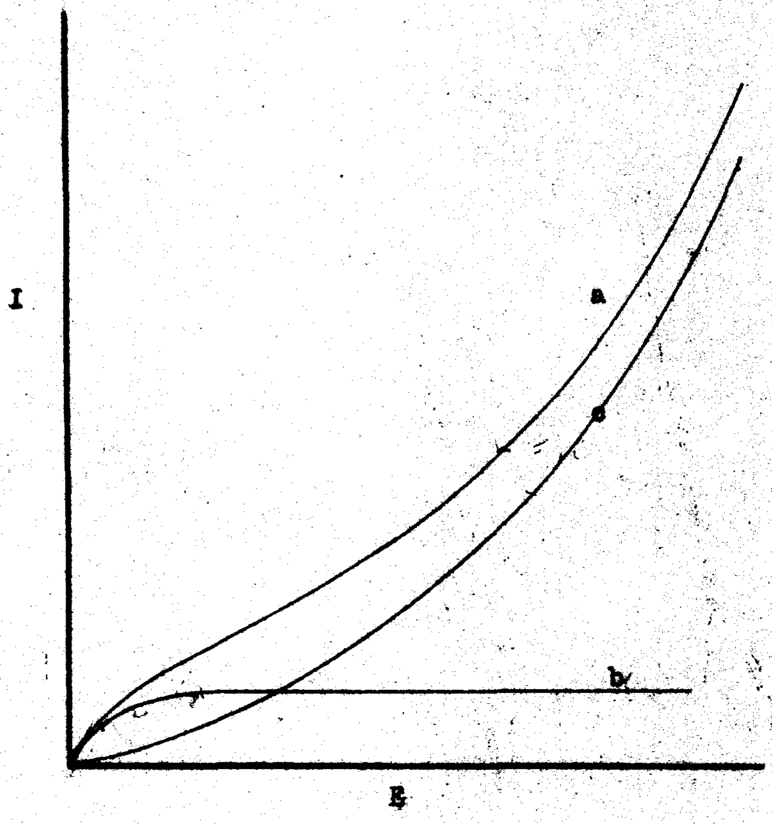


Figure 1. Reverse Current-Voltage Characteristic

due to the increase of the strain imposed on the cuprous oxide by a continued contraction of the mother copper. The experimental work described later will be shown to be consistent with the requirements of Jacquelet's theory.

Sacerdote (Sacerdote 23, pg. 108) has shown the presence of a slight hysteresis loop in the volt-ampere characteristic of a copper oxide rectifier. A copy of his illustration of this hysteresis loop is shown in figure 2. Neither the emission theories of Wagner, Nordheim, and Slepian, nor the exit work theory of Schottky could be used to account for the existence of this phenomena. According to Jacquelet's theory, however, a voltage drop in the rectifier causes a shifting of the atoms in the cuprous oxide crystals. Then - if this movement of the atoms were not frictionless - upon removal of the voltage, they would not completely recover from this displacement; and a hysteresis loop would result much as does the magnetic hysteresis loop of iron.

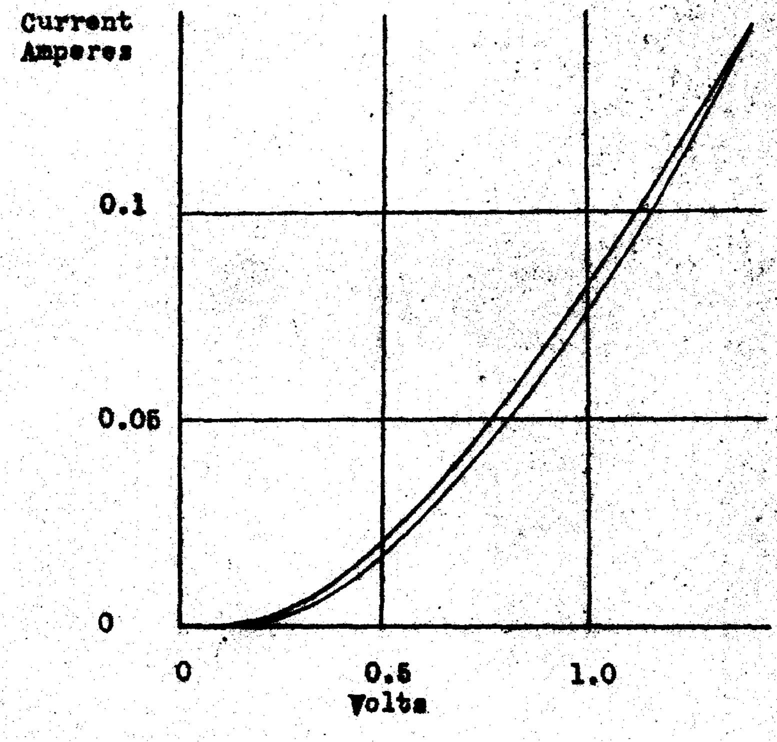


Figure 2. Hysteresis Loop of a
Copper Oxide Rectifier

III DESCRIPTION OF APPARATUS AND PROCEDURE IN INVESTIGATION

A. Presentation of Objectives in the Investigation

In the preceding section are listed thirteen theories of the mechanism of the copper oxide rectifier. Yet none of the thirteen authors gave a complete description of the exact procedure by which they prepared the rectifiers which were used in their experimental work. Contradictory evidence was offered in the investigation of the chemical constitution and physical construction of the cuprous oxide layer. Each individual observation reported may have been correct, and the apparent discrepancies may be the result of actual differences in the construction of the copper oxide rectifier specimens examined by the investigators. These differences of physical and chemical nature in individual rectifiers would be the result of unlike procedures in the preparation of the rectifiers.

It is apparent that the influence of each preparation condition upon the characteristics of copper oxide rectifiers must be determined quantitatively before a satisfactory quantitative theory can be stated for the rectifiers. The statement is made (Jacquelet 12) that the characteristics of the rectifiers are dependent upon the purity of the copper, time and temperature of heating, rate of cooling, temperature of cooling, and the amount of rolling the copper has previously experienced. There has been no publication of any data showing the kind and magnitude of the effect of any preparation condition upon the rectifier characteristics. Therefore it was proposed to investigate as nearly quantitatively as possible the variation produced in the rectifier characteristics by a difference in the temperature and nature of the quenching bath and by a difference in the length of the time of heating. It was concluded that the information procured in such an investigation would be a definite step toward the isolation of, and the determination of the effect of, the many influencing variables in the preparation of the rectifiers. The ultimate object of the entire investigation in this field would be the formation of a complete and satisfactory quantitative theory for the mechanism of copper oxide rectifiers.

According to Jacquelet's theory, rectification is the result of a mechanical strain imposed on one side of the cuprous oxide layer by the greater contraction of the copper with which it makes contact. Then one should be able to determine whether or not this theory is correct by finding the effect produced upon the rectifying properties of the oxide rectifier in the artificial change of this strain. Therefore, it was proposed to use the method of bending the rectifier unit. When the copper strip is bent, the outside surface area is increased while the inside surface area is decreased. Therefore, if a rectifier is formed with cuprous oxide layers on both sides, and the specimen is bent, any mechanical strain of contraction of the oxide layer would be decreased on the outside oxide layer and increased on the inside oxide layer. Then, if

Jacquelet's theory is correct, the rectifying ability of the outside rectifier should decrease while that of the inside rectifier should increase, providing, of course, that in the bending procedure other effects are not introduced which would mask the ones it is desired to consider.

In the course of the making of these bending experiments, it is necessary that the lead contact electrode be removed and replaced several times. It was found that the mere removal and replacement of the lead electrode would often-times have the effect of changing the conductivity of the rectifier by as much as twenty per cent., even if the pressure holding the lead electrode in place were always just the same. Therefore, it became necessary to have a permanent contact on the cuprous oxide surface. Various methods of holding the contact electrode in place so that it would not be moved about on the oxide surface when the unit was moved in the bending device were tried, but none of them were successful. An attempt was made to electroplate a copper electrode on the outer surface of the cuprous oxide. However, it was found that, due to the uneven surface and consequent uneven thickness and conductivity of the cuprous oxide, the electroplated electrode was not solid, but was formed only in the hollows of the cuprous oxide surface. Also the contact resistance of this electroplated electrode increased continually from the time it was first produced. After various other attempts, a method suggested by Jacquelet (Jacquelet 12) gave successful results. This method consists of quenching the rectifier unit in alcoholic solutions instead of water. The outside surface of the cuprous oxide is reduced to copper by the chemical reaction:

$$Cu_2O + CH_3OH \rightarrow 2Cu + HCHO + H_2O. \qquad (7)$$

This reaction takes place only while the copper strip is hot; consequently only a very thin layer of the cuprous oxide is reduced before the unit is cooled below the temperature at which the reaction can occur. The reduced copper surface thus formed gives no rectifying action against the cuprous oxide on which it is formed, and it serves as an electrode whose contact resistance with the cuprous oxide is unvarying.

B. Preparation of the Rectifier Units

An electric furnace was used to heat the copper. This furnace consisted of a single layer of chromel wire wrapped fairly closely about a vertical tube of ceramic material which was fifteen inches in length and two and one-fourth inches of inside diameter. The heat insulation about the outside of the tube had a thickness of approximately four inches, making the outside diameter of the furnace near ten inches. Inside the heating tube was placed a tube of quartz two inches in outside diameter and extending five inches above and three inches below the ends of the furnace. The temperature of the furnace was determined by the use of a chromel-alumel thermocouple which was placed inside the quartz tube about half way between the ends of the furnace cylinder. Leads from this thermocouple were connected to a millivoltmeter. This temperature registering unit was calibrated by the use of a potentiometer and the known temperature-voltage characteristics of the chromel-alumel junction. The temperature was controlled by the use of a rheostat placed in series with the furnace and a 220 volt a-c. source of energy. After a little practice, it was found possible to maintain the furnace temperature within two or three degrees Centigrade of a desired value.

Harddrawn copper was procured in sheets 0.031 inches thick. These were cut with a stamp press into segments 1x1½ inches. It was found that after the quenching the oxide had often chipped away at the edges of the copper. If the edges were slightly rounded by filing before the unit was heated, this chipping could be avoided entirely. The copper unit was suspended in the furnace by means of a suitable length of No. 26 bare copper wire which was attached to the copper piece by means of a small hole drilled in the center of one end of it.

The quartz heating tube of the furnace was closed by means of a flat slab of ceramic material placed against the bottom of the tube and by a cylindrical plug of the same material fitted into the top of it. Two plugs were used alternately, and a small hole was drilled through each along its axis. Through this hole the copper wire holding the copper segment was passed and clamped on the top of the plug. Thus, when a copper segment was to be heated, the plug in the top of the furnace was removed. The copper segment was lowered into the quartz heating tube, and the plug from which it was suspended closed the top of the quartz tube. This exchange was always made as quickly as possible in order that the furnace temperature would have no opportunity to be lowered by a current of cold air.

Care was taken to have the suspension wire always the proper length in order that the copper unit to be heated would hang in the furnace at the level of the thermocouple. This precaution was necessary to insure that all units would be heated at the same temperature since the temperature was known to vary along the length of the heating tube.

Previous to heating, the copper segment was cleaned in methyl alcohol and washed in ether. It was then etched for eight seconds in concentrated nitric acid and washed in running water. Before it was placed in the furnace it was again cleaned in methyl alcohol and washed in ether. Care was taken during this preparation that the copper section was not touched against anything which might vary the surface conditions.

Once the specimen was placed in the furnace, the time of heating was measured by the use of a stop watch. A bowl of the quenching liquid was placed just below the ceramic board at the bottom of the quartz tube. When the time of heating had expired, this insulating slab was removed, and at the same time the suspension wire was released from the top of the plug, allowing the copper unit to fall into the quenching liquid. The distance of fall was just twelve inches. Consequently the heated unit did not cool enough to allow the change of the red cuprous oxide to the black cupric oxide to occur.

The quenching bath consisted of a known mixture of methyl alcohol in water. This solution was maintained at a predetermined temperature up to the time of the quenching. 500cc. of quenching liquid were used for each copper unit.

In commercial preparation the rectifier units are subjected to certain stages of heat treatment before and after quenching. These heat treatments were not employed in the present investigation because it was thought that their use might hide the effects whose determination was sought.

When the rectifiers were removed from the quenching solution, they were always found to be covered with an outside layer of copper reduced from the cuprous oxide except for an occasional edge or corner where the red cuprous oxide would show through.

At the end of the unit containing the hole, the outside copper and the cuprous oxide layers on each side were removed by filing across a strip about three-eighths inch wide. It was found that the cuprous oxide would often not cover the edges of the copper. Apparently at the temperature at which it was formed the cuprous oxide was fluid enough to flow away from the edges because of the force of surface tension. Consequently the outside copper would often be in contact with the mother copper at the edges of the unit, and it was necessary to remove the outside copper from the edges by scraping. These exposed edges were covered by insulating tape. The rectifier unit then consisted of an inch strip of copper one and one-half inches long with a layer of cuprous oxide on each side extending from one end to within three-eighths inch of the other end. On the outside of each layer of cuprous oxide was an electrode consisting of an exceedingly thin layer of copper covering the cuprous oxide up to about one-sixteenth inch of each edge.

C. Construction and Use of Testing Circuit

The conductivity and rectification of a copper oxide rectifier vary greatly with temperature change. Therefore there were two requirements of the testing apparatus: first, the rectifier must be in a constant temperature oven in order that its temperature would not be varied by an external influence; second, the length of the time during which currents were passed through the rectifier must be so short that there would be no noticeable change of temperature of the unit caused by the electrical energy expended in it.

The constant external temperature was obtained by placing the rectifier in a box constructed of three-ply wood and maintained at a constant temperature by thermostatic regulation. Carbon lamps were used as the heating elements, and an electric fan in the box circulated the air rapidly about. The temperature could be maintained practically constant with a variation of less than 1/10°C. from the desired reading. The temperature used throughout the investigation was the arbitrarily chosen one of 32°C.

The wiring diagram is shown in Figure 3. The constant temperature box, *F*, is designated by dashed lines. The rectangles *g* and *g* are copper electrodes which are used to make contact with the outside reduced copper on the cuprous oxide layers. The shaded sections are a cross section of the cuprous oxide layers, and the mother copper is represented by the segment between them.

The circle D represents an insulating disc which was attached to the rotating part of an automatic telephone dial. The section marked e was of copper and was set into the insulating disc D. When a voltage-current reading was to be made, the disc D was turned back a quarter cycle from the position shown in the diagram. Then switch S_1 was closed and the disc D released. When the contactor e reached the brushes marked 1 and 2, the current circuit was completed through one side of the rectifier. As the contactor e passed under the brushes 3 and 4, the condensers C_1 and C_2 were charged. When the contactor e passed on beyond brush 5, it broke the current circuit; and when it reached the position at which it stopped, it made contact between the two brushes a and a causing either one or the other of the condensers to discharge into the ballistic galvanometer G. The condenser C_1 was charged proportionally to the voltage drop across the rectifier, and the reading given when it was discharged into the galvanometer indicated the voltage which had been impressed on the rectifier. The condenser C_2 always was given a charge in proportion to the amount of the voltage drop across the resistance R, and consequently the energy it gave to the galvanometer indicated the amount of current which had been flowing through the rectifier circuit.

For two successive readings of the dial D, switch S_2 was thrown first in the upward then in the downward position, and the two readings of the galvanometer were deflections proportional to the voltage and the current respectively. The direction of the

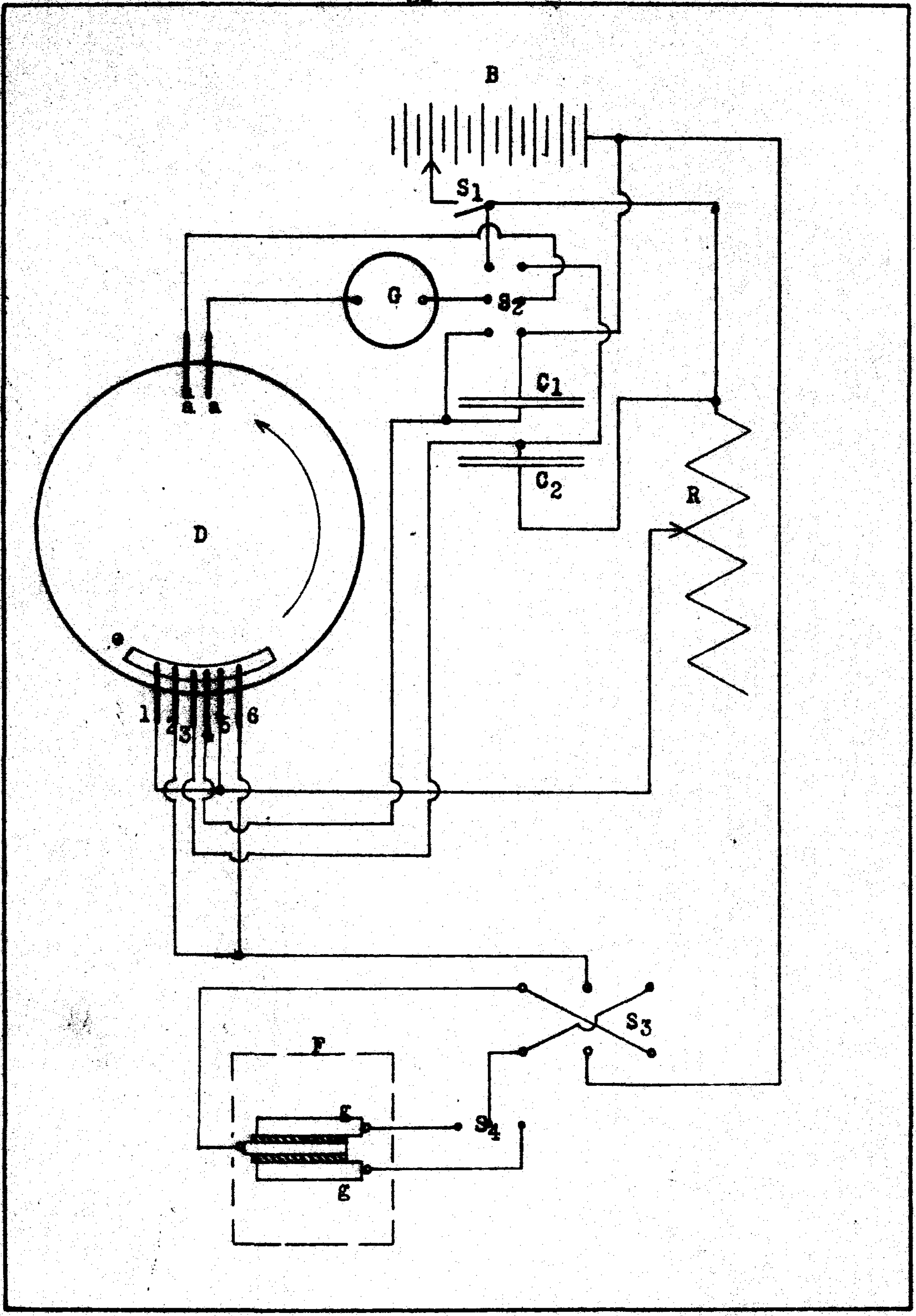


Figure 3. Wiring Diagram

current flow through the rectifier, whether forward or reverse, was controlled by the reversing switch $\underline{S_3}$. The position of the double throw switch $\underline{S_4}$ determined whether the current flowed between the mother copper and the upper electrode $\underline{g}$ or between the mother copper and the lower electrode $\underline{g}$.

The automatic telephone dial was used to turn the disc $\underline{D}$ because it has a constant speed of rotation and gives repeatable conditions of condenser discharge. Actually two condensers were used interchangeably for $\underline{C_1}$; one of 0.2 m.f. capacitance recorded the lower voltages, and one of 0.005 m.f. capacitance recorded the higher voltages. Also, two switches were provided for short-circuiting one or two sections of the resistance $\underline{R}$ in order that a readable deflection of the galvanometer could be obtained for large as well as for small currents.

As a voltage source thirty-six Edison storage cells were used connected in series. Variation of the voltage was obtained by connecting the circuit across different numbers of these cells. All the lines in the galvanometer circuit were shielded to prevent erratic readings due to stray fields.

To calibrate the galvanometer deflection, a rheostat of high current capacity was substituted for the rectifier unit. A suitable ammeter was inserted in the circuit. Then for a certain setting of the rheostat and a fixed voltage, the current flowing was read on the ammeter scale. Then the dial $\underline{D}$ was caused to rotate as in the taking of readings of rectifier currents, and the corresponding deflection on the galvanometer for the discharge of condenser $\underline{C_2}$

was observed. Similarly, a voltmeter was connected across the terminals of the switch $\underline{S_3}$, and voltage deflections of the galvanometer from the condenser $\underline{C_1}$ were observed for various voltage drops. Curves plotted between the currents and corresponding current deflections and between voltage readings and corresponding voltage deflections of the galvanometer could then be used to translate the many recorded deflections into the indicated volts and amperes.

D. Description of the Bending Apparatus

It was found that in order to make an appreciable change in the rectification of a unit, it required bending far beyond the elastic limit of the copper. Therefore none of the methods based upon elastic bending could be used. The method finally employed was one in which the rectifier was placed between two block electrodes whose surfaces were concave and convex. A sufficient pressure to bend the rectifier unit into conformity with the shape of the electrodes was applied. The radius of curvature of each of a pair of electrodes was not the same but differed by the thickness of the rectifier unit. Pressure was applied to the electrodes by means of weights suspended on a lever arm whose fulcrum rested on the top electrode. A cross section drawing of the bending apparatus is shown in Figure 4.

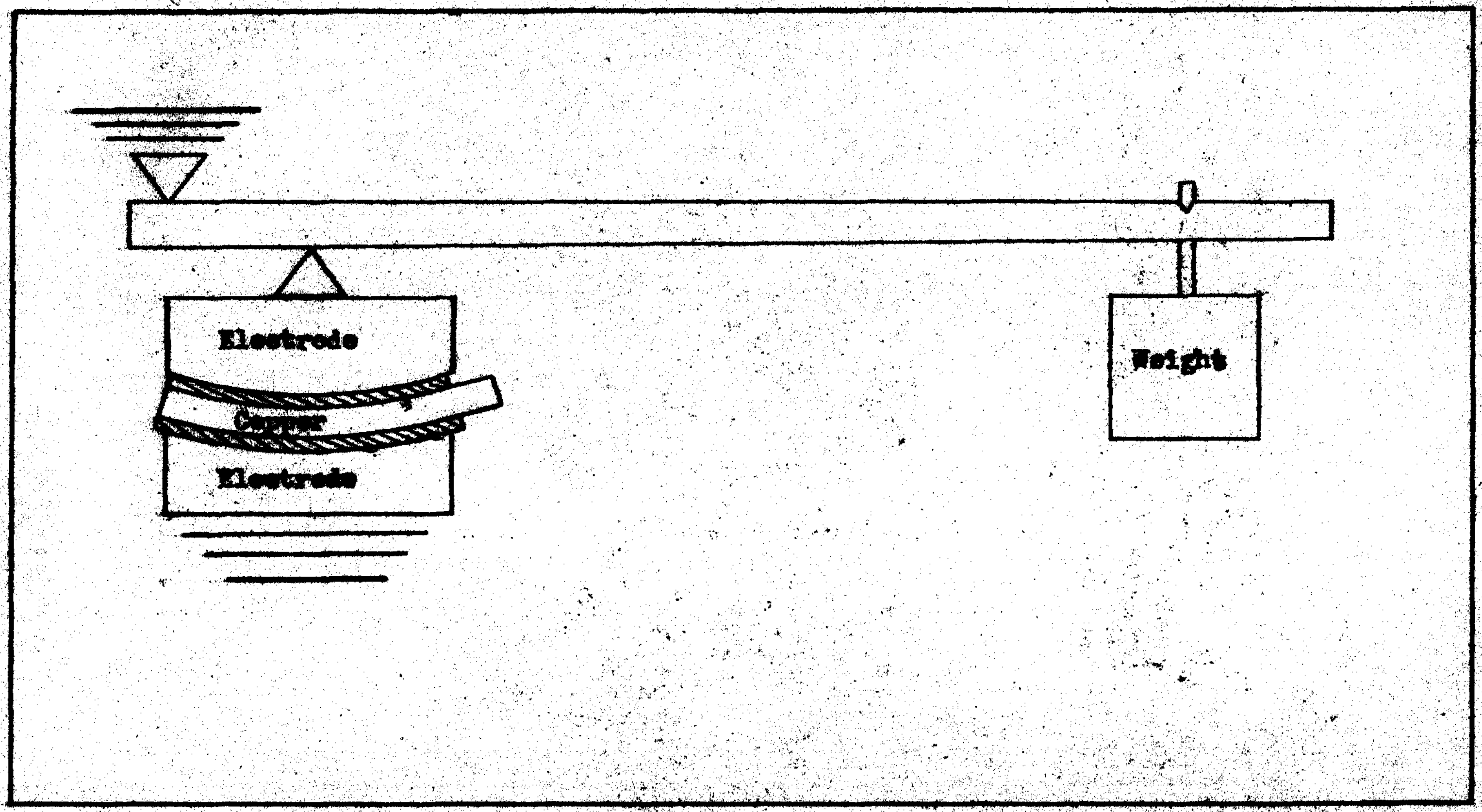


Figure 4. Diagram of Bending Apparatus

IV PRESENTATION OF DATA AND DISCUSSION OF RESULTS

A. Presentation of Data

1. Discussion of the accuracy of the data

The measurement of deflections by means of condenser discharge into a ballistic galvanometer and the subsequent translation of the deflection readings into terms of volts and amperes is not direct. The probable error of the recorded volts and amperes was determined by the method which is described below. A rheostat was substituted for the rectifier in the circuit of Figure 3. With a fixed voltage the rheostat connection was varied until a desired current was to be read on the ammeter in the circuit. Then with the same rheostat setting and a constant voltage twenty consecutive current deflections were recorded, and by the use of the calibration curves they were translated into terms of amperes. The probable error, e_p, was calculated by the equation

$$e_p = 0.6745\sqrt{\frac{1}{19}\sum_{e=1}^{e=20} e^2} \qquad (8)$$

where e is the individual difference between the ammeter reading and the reading translated from the deflection value. An illustration of the probable error calculation is given on the next page in Table 1, where

I_a = the current read on the ammeter,

and I_d = current evaluated from the galvanometer deflection.

Table 1

I_a(ma.)	I_d	e	e^2
80.00	79.78	0.22	0.0484
80.00	79.95	0.05	0.0025
80.00	80.01	0.01	0.0001
80.00	80.01	0.01	0.0001
80.00	80.01	0.01	0.0001
80.00	79.95	0.05	0.0025
80.00	79.88	0.12	0.0144
80.00	80.04	0.04	0.0016
80.00	80.04	0.04	0.0016
80.00	80.01	0.01	0.0001
80.00	80.01	0.01	0.0001
80.00	80.04	0.04	0.0016
80.00	80.02	0.02	0.0004
80.00	80.04	0.04	0.0016
80.00	80.04	0.04	0.0016
80.00	80.04	0.04	0.0016
80.00	80.04	0.04	0.0016
80.00	79.98	0.02	0.0004
80.00	80.04	0.04	0.0016
80.00	80.04	0.04	0.0016

$$e_p = 0.0447 = 0.056\%,$$

and $$e_m = 0.22 \quad = 0.375\%,$$

where $\underline{e_m}$ is the maximum recorded error.

The values $\underline{e_p}$ and $\underline{e_m}$ for five values of the current were calculated by the above procedure. These values are given in Table 2. In each case twenty observations were made.

Table 2

I_a(ma.)	e_p	e_m
8.00	0.336%	0.963%
50.00	0.123%	0.546%
80.00	0.056%	0.375%
567.0	0.119%	0.252%
1000.	0.132%	0.384%

From the values given in Table 2, it is to be estimated that in the range from 10 to 1000 milliamperes the probable error is below 0.5%. For readings below ten milliamperes the error would be approximately inversely proportional to the magnitude of the reading. For the voltage readings, all deflections of the galvanometer were on the scale within the range corresponding to that of the current readings between 10 and 1000 milliamperes, consequently the magnitude of the probable error of all the voltage readings is below 0.5%.

In Figure 5 are shown the photographs of two oscillograms taken of the forward current through a rectifier. The specimen used here was No. 98, side A. For the oscillogram numbered 1, the current was 235 milliamperes at 11.97 volts. Oscillogram 2 was taken with a recorded current of 2219 milliamperes at 45.40 volts. The half sine wave at the bottom of each oscillogram is a sixty cycle timing wave. It can be seen that the rectifier current of oscillogram 1 remains zero until the circuit is closed by the turning of the dial D of Figure 3. Then the current rises almost instantly to its maximum value and remains constant until the circuit is opened when the contactor e of Figure 3 leaves brush 5. But in the oscillogram 2 of Figure 5 the forward current through the rectifier is not constant, but it increases continually during the time that the circuit is closed. When the circuit is opened it has attained a value greater than its original value by the amount represented by the height of the current trace above the horizontal dashed line. The time that the

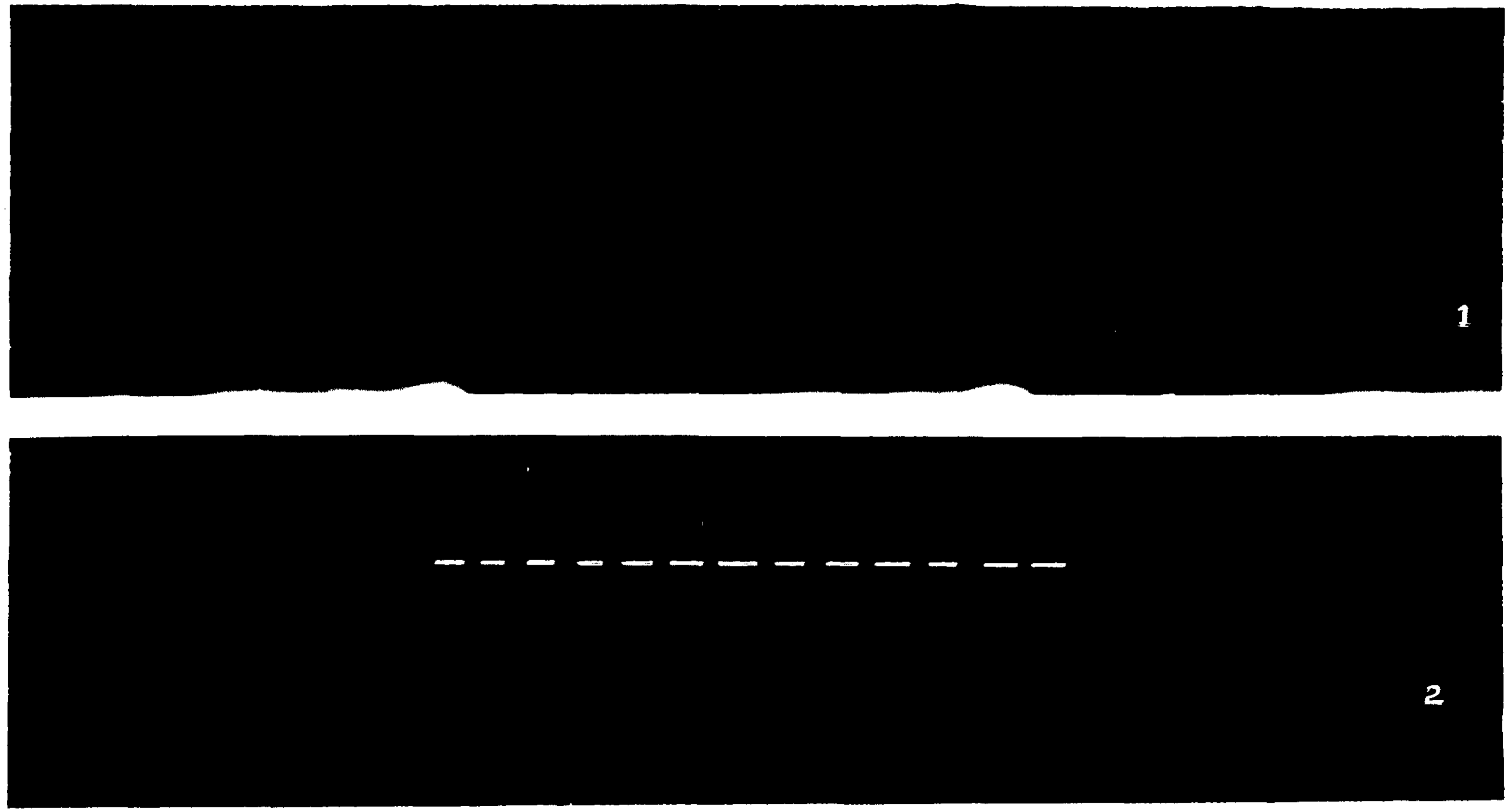


Figure 5. Oscillograms of Current through Testing Circuit

current is allowed to flow through the rectifier is approximately fifteen cycles or one-fourth of a second. Yet in that short length of time the heat generated by the large current in the rectifier is enough to raise its temperature sufficiently to increase its conductivity about forty per cent.

The data were to be taken for various rectifiers at a fixed temperature, namely 32°C.; for high current densities an error in the data will be present due to the change in the conductivity which was caused by the heating of the rectifier by the excessive current. Consequently, for high current values, the error of the recorded current readings will be much larger than that indicated from the calculation of Table 2.

For the experiment to determine whether or not the reduced cuprous oxide electrodes had a contact potential which would vary with a change of pressure upon the rectifier, rectifiers 81A and 81B were used. These rectifiers had been quenched in a methyl alcohol solution. The current-voltage characteristics were determined with the rectifier under pressures of 25, 425, and 925 pounds. Within the experimental error limits no differences of voltage-current functions were observed for the different pressures. Between each set of readings, the rectifier was removed and replaced. The reduced oxide electrode is not affected by pressure and handling.

2. Tabulation of data

All readings were taken with the rectifier at a temperature of 32°C. and under a pressure of 825 pounds. For the rectifiers which had been quenched in a methyl alcohol solution and had an electrode of reduced cuprous oxide the characteristics did not vary with any change of the pressure of the electrodes which were used to make contact with the outside copper layer. However, for the rectifiers which had been quenched in water, contact with the cuprous oxide must be made with soft lead, and this contact resistance varies greatly with increase of the pressure up to a pressure of near eight hundred pounds per square inch. In order that the conditions of measurement might be uniform the same pressure of 825 pounds was used for all rectifiers.

Forty-three rectifier specimens were prepared under various conditions. A rectifier was formed on each side of each specimen. The specimens were designated by numbers, and the rectifiers on the two sides of the specimen are distinguished one from the other by the letters A and B. Thus the two rectifiers formed on specimen 100 are 100A and 100B.

Tables 3 and 4 show approximately the variation of the conditions of preparation of the several rectifiers. The exact data of preparation are given later with the characteristics of the individual rectifiers. All the specimens considered in the present investigation were heated at temperatures between 1017° and 1022°C. The numbers are specimen numbers. Tables 3 and 4 are on the following page.

Table 3
(Time of Heating 180 seconds)

Quenching Solutions	Quenching Temperatures							
	-°C.	0°C.	5°C	10°C.	20°C.	40°C.	65°C.	93°C.
500cc. H_2O		90	91	92	111	112	113	114
487.5 cc. H_2O 12.5 cc. CH_3OH	82		83	84-89	118	120	116	
475 cc. H_2O 25 cc. CH_3OH	100		101	102	122	121	117	
450 cc. H_2O 50 cc. CH_3OH	103	104	105	106	123	125	119	
400 cc. H_2O 100 cc. CH_3OH	107	108	109	110	124			

Table 4
(Quenching solution 12.5cc CH_3OH in 487.5 cc. H_2O at 9°C.)

Time of Heating (Seconds)	Specimen Number	Time of Heating (Seconds)	Specimen Number
120	94	240	99
150	93	300	96
180	84-89	360	98
210	95	450	97

It is to be noted that six specimens, 84 to 89 inclusive, were prepared under the same conditions in order that it might be seen how much variation would occur in their characteristics due to uncontrolled and unknown influences in their preparation.

In Appendix I are given Tables 9 to 140 inclusive which contain the data of the forward and reverse current-voltage characteristics for all the rectifiers shown in Tables 3 and 4 except those on the seven specimens quenched in water. In these tables the voltage readings are designated by E; I represents the observed currents in milliamperes, and I_c in milliamperes is the calculated current for the corresponding voltage. The source of the empirical equations giving the calculated currents is discussed in the following section.

3. Presentation of current-voltage equations

The primary object in the making and testing of the specimens shown in Tables 3 and 4 was an attempt to find, if possible, a relation of the characteristics of these rectifiers to the variables in the preparation conditions. Since the characteristic of each rectifier consists of a forward and a reverse current-voltage curve, at first it might appear difficult to find a means of visualizing a variation with an independent variable of a series of curves. If an equation could be found such that by the adjustment of its constants it could be made to approximate the characteristics of all the rectifiers, then these constants plotted against the independent variable of the preparation condition change would give the desired result.

Following the usual procedure for finding simple empirical equations, the curves of I-E, I-logE, logI-E, and logI-logE were plotted for both forward and reverse currents for several rectifiers picked from the extremes and means of the columns of Tables 3 and 4. The only curves having a significant shape were the logI-logE functions.

For the forward current, the points of the logI-logE curve fell along a straight line except for the last one or two points. When the oscillograms of the current, shown in Figure 5, were taken, the cause of the last one or two points being above the straight line was quickly understood. For, as it has been explained, the larger currents heat the rectifier enough to make an appreciable decrease of conductivity even in the time of one-fourth second required to make the reading. Curves a of Figures 6, 8, 10, and 11 show the straight line logI-logE curves for four rectifiers. In Appendix II are shown the logI-logE curves for the forward current of sixty-six of the rectifiers shown in Tables 3 and 4. From the uniformity of these curves it was concluded that the forward current-voltage characteristic of all these rectifiers could be represented by the equation

$$I = CE^{D} \qquad (9)$$

where D is a constant whose value is the slope of the straight line in the logI-logE curve, and C is a constant whose logarithm is the number at which this straight line crosses the vertical axis of this graph. In Appendix I are given the values of the calculated current, I_c, compared with the observed current readings for the corresponding voltages. It is to be seen that the agreement between these values is quite good except for the top value of current. This deviation has been accounted for in the heating of the rectifier by the large current. A visual representation of the agreement between the observed and calculated values is given by the curves c of Figures 7, 9, 10, and 11 in which the plotted points are the

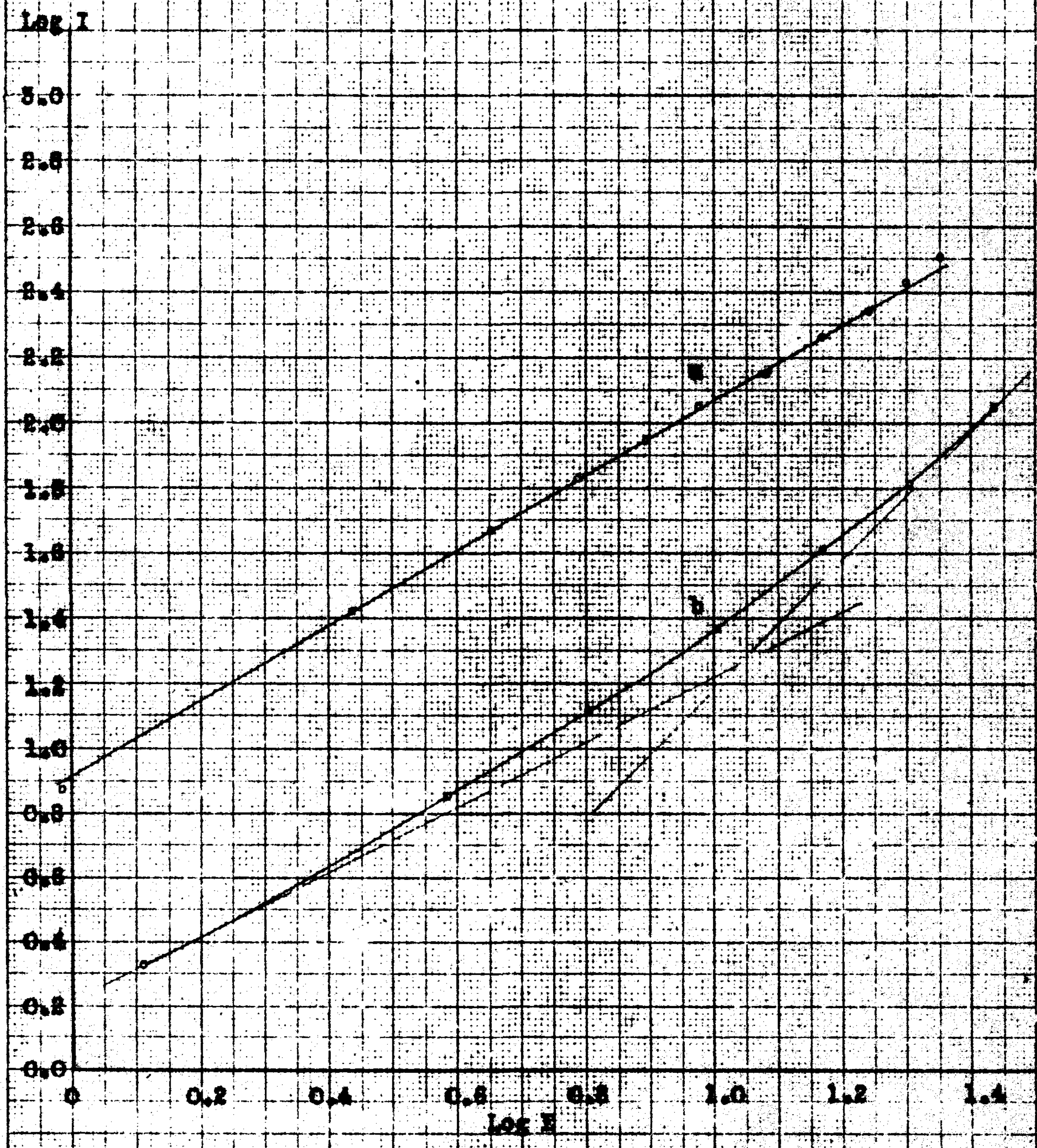


Figure 6. Current-Voltage Logarithm Curves for Rectifier 39A

Form E-3

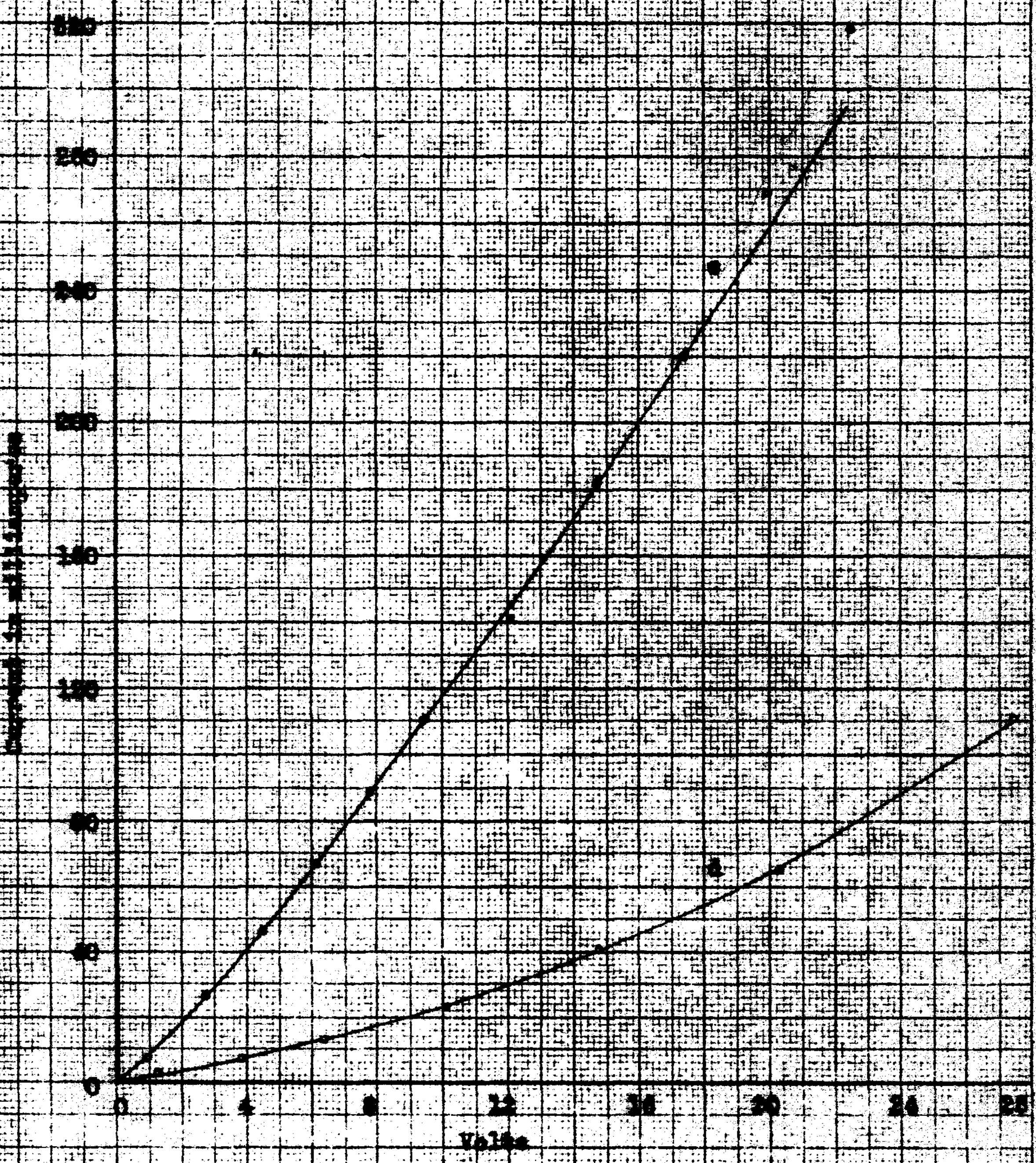


Figure 7. Current-Voltage Curves of Rectifier 30A

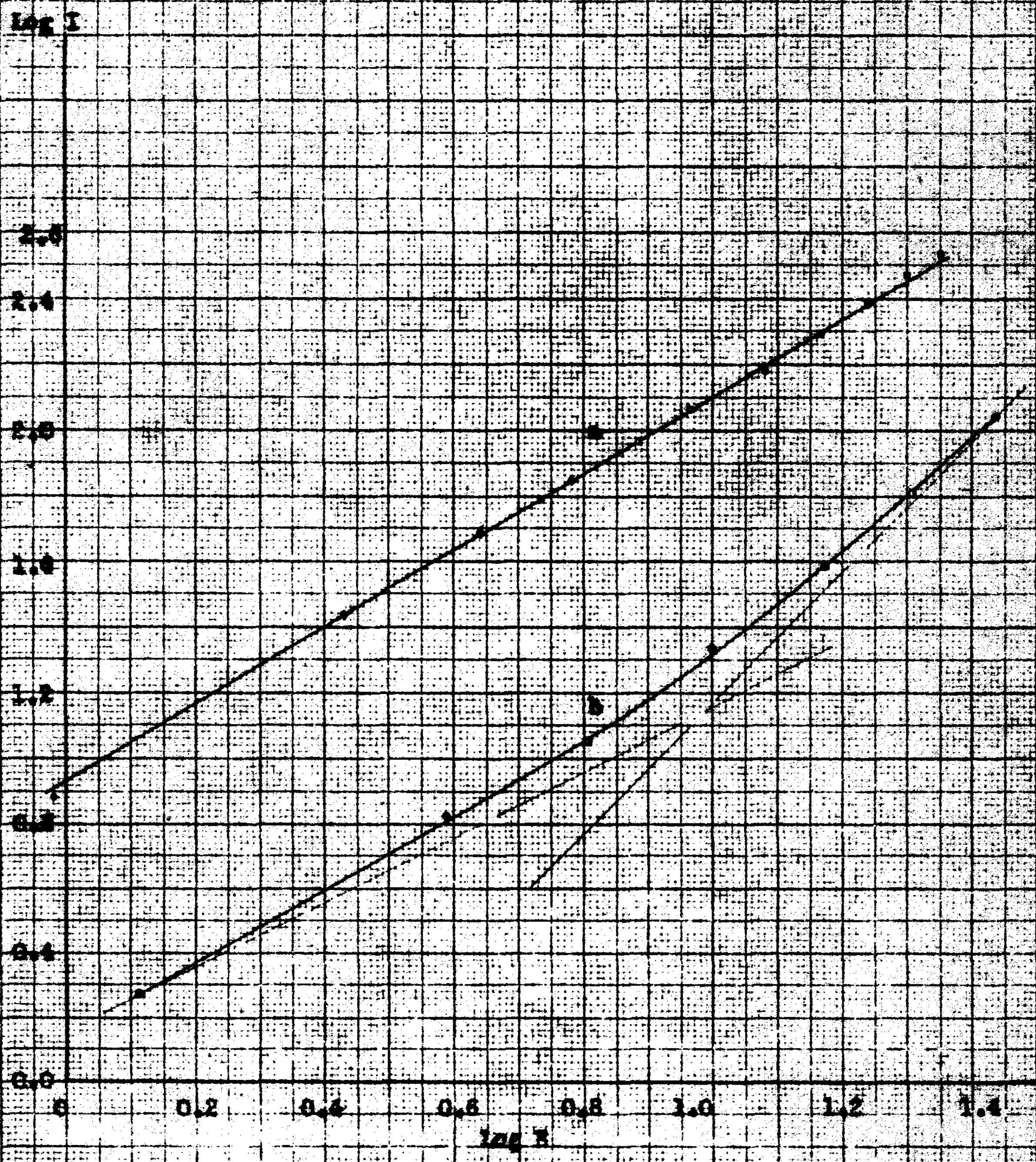


Figure 8. Current-Voltage Logarithm Curves for Rectifier [illegible]

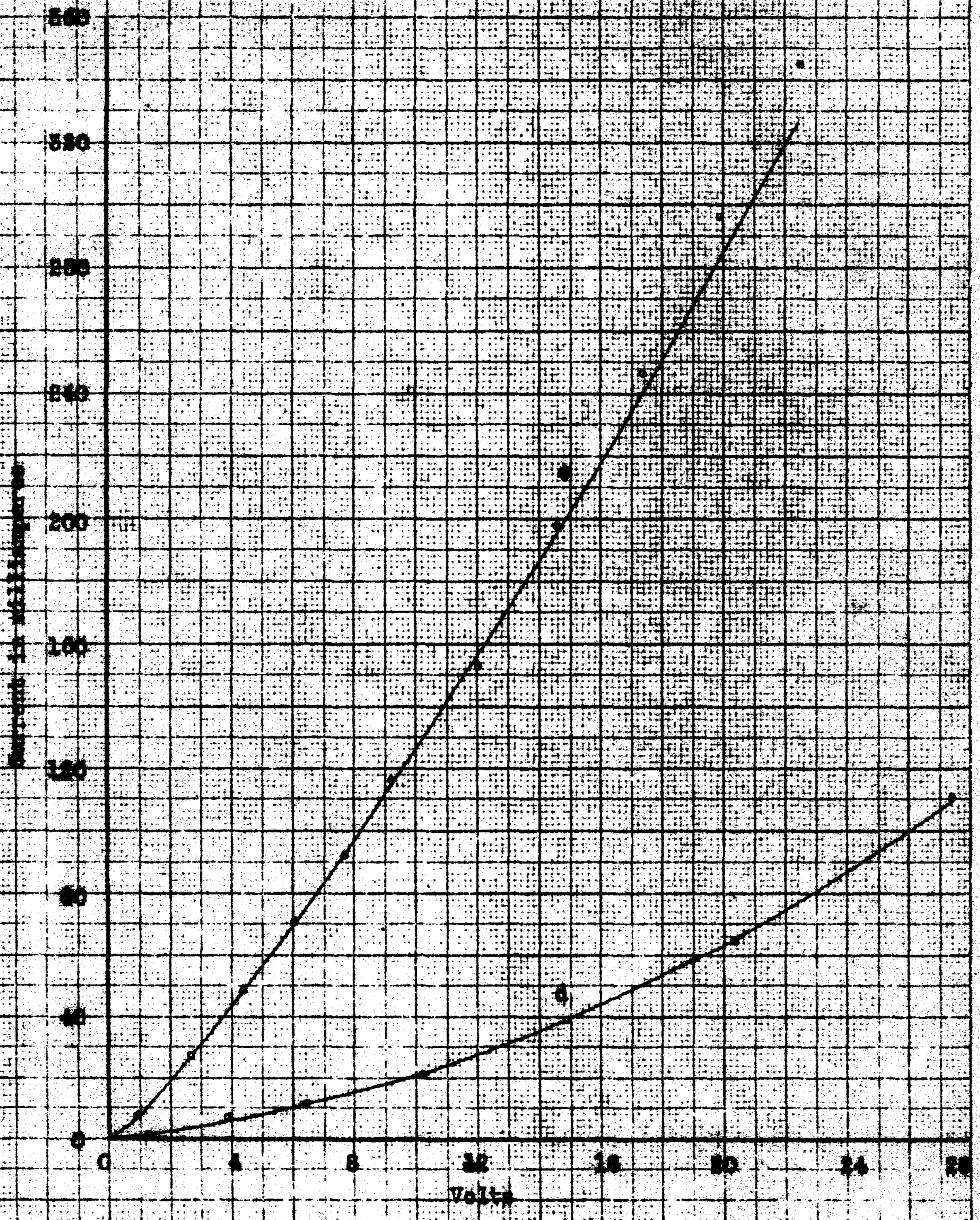


Figure 2. Current-Voltage Curves of Rectifier 398

Form E 3

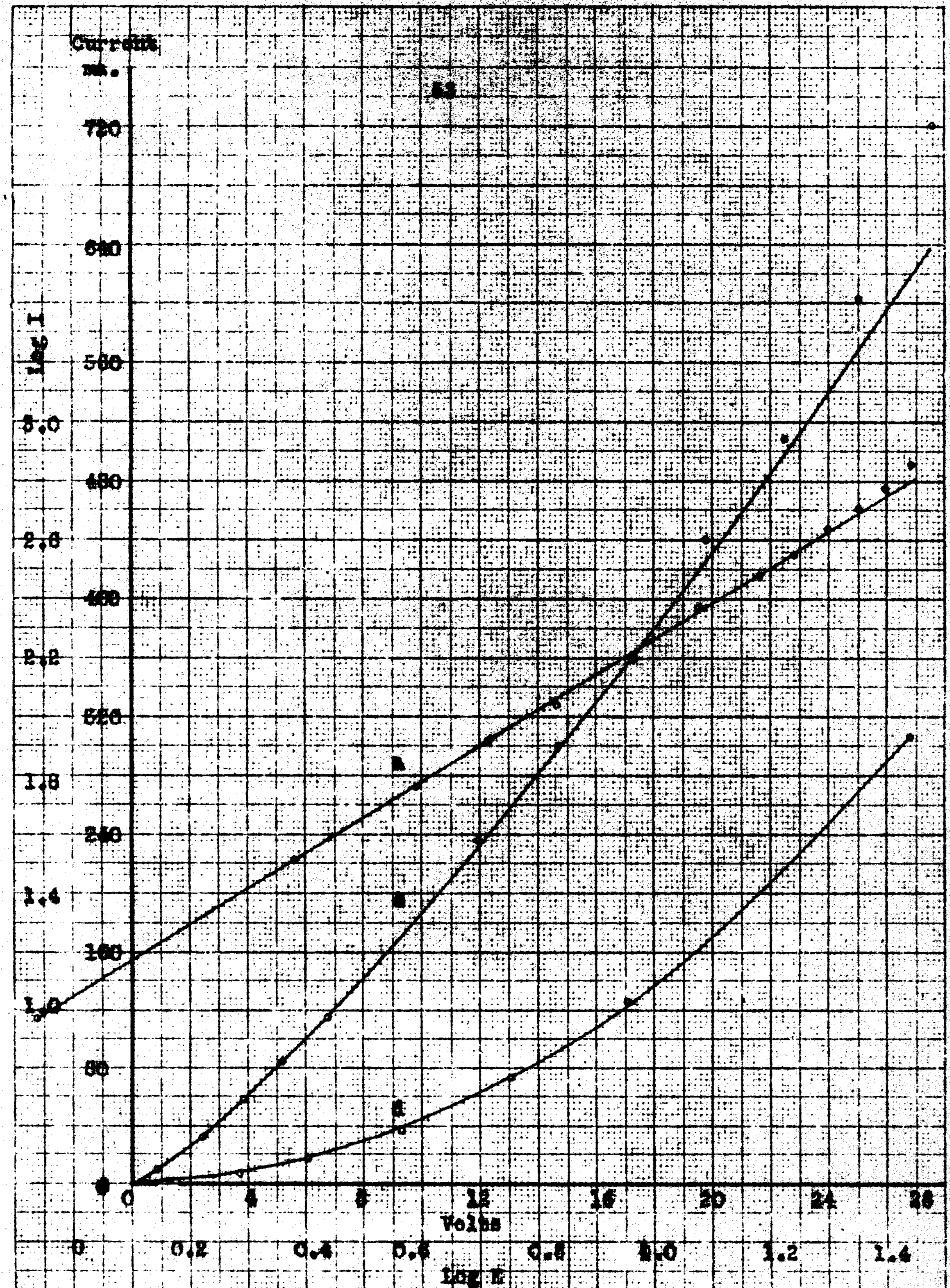


Figure 10. Current-Voltage Curves of Rectifier 98A

Form E-3

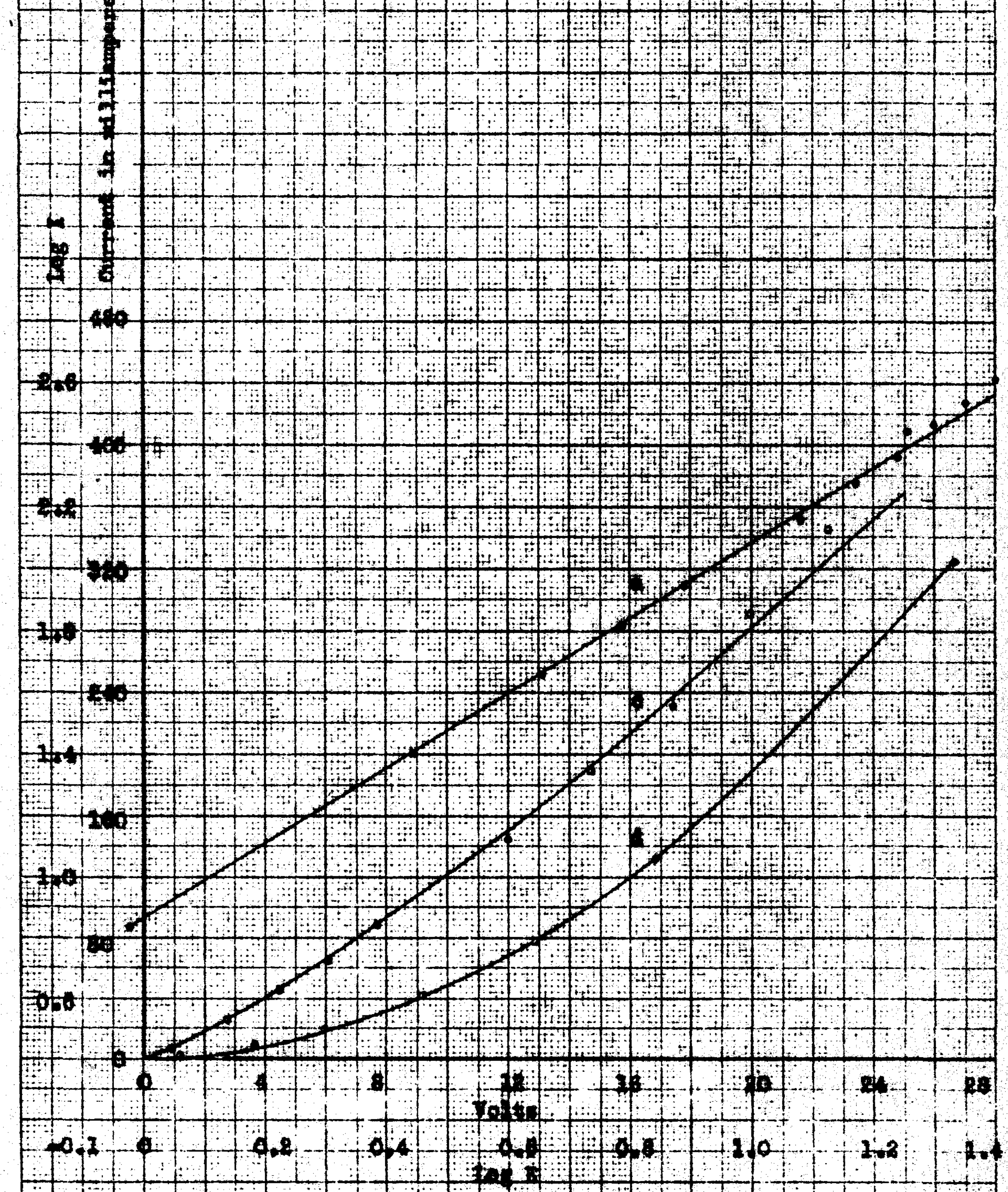


Figure 11. Current-Voltage Curves of Rectifier 98B

observed values and the adjacent curve is the calculated function.

The shape of the logI-logE curves was not a straight line for the reverse current. In each case the values of log I plotted against log E formed a curve always concave upwards. However, it was noted that the slope of each of these curves had a value slightly more than one at the bottom, and at the top it was always a little less than two. The curves b of Figures 6 and 8 are illustrations of the log curves for the reverse currents. The dashed lines drawn to the bottom and top of these curves are lines whose slopes have values of one and two respectively. If the logI-logE curve had been a straight line with a slope of one, the equation of the function would have been $I = AE$; should the logI-logE curve have been a straight line having a slope of two, the equation would have been $I = BE^2$. It was concluded that the reverse current could be represented by an equation combining the two functions, namely

$$I = AE + BE^2. \qquad (10)$$

For lower values of voltage the first term of the right side of Equation 10 predominates, and consequently the slope of the log curve is near the value of one. As the voltage is increased, the term BE^2 becomes the predominating one, and the slope of the log curve is found to approach the value of two. In the tabulated data given in Appendix I it is to be observed that the calculated values of the current, I_c, are very close to the observed values. Also it may be seen that the first two or three observed values are always high. This is the same effect of an apparent additional saturation current which was noticed by van Geel and is shown in

Figure 1. The values of the constants A and B given in Appendix I are calculated by the use of least squares; were it not for the effect of this additional saturation current, the observed points would fall even more closely to the calculated curve. For some of the reverse currents, the highest recorded value of current is sometimes obviously a little high, while for other specimens it is quite correct. The high reading of the largest current is probably due to instantaneous heating as in the case of the forward current. Curves d in Figures 7, 9, 10, and 11 show the agreement between the calculated curve and the observed reverse currents for rectifiers 89 and 98.

In the data of Appendix I the fact may be observed that often for two rectifiers in which nearly the same amount of energy is expended in heating the rectifier during the time in which the reading is taken, the error of observation, i.e., the amount the observed current is above the calculated value, may be for one rectifier three or four times that for the other. If the same amount of energy is expended in two rectifiers, the increase of temperature in each should be approximately the same, but the conductivity-temperature function for the two may be quite different, and the result will be that the same change in temperature during the time the reading is being made does not necessarily produce the same error in the observed current.

Figure 10 shows that for higher voltages the reverse current increases more rapidly with increasing voltage than does the forward current; the reverse current then might become equal to or greater than the forward current for voltages near forty volts or more. The best rectification is obtained with small voltages, not over six volts, where the ratio of the forward current to the reverse current is often more than one thousand for rectifiers which have been given the proper heat treatment.

4. Measurement of the cuprous oxide layer thickness

The thickness of the oxide layer was measured on four rectifiers which had been heated for different lengths of time. The edges of each rectifier were filed and polished. When the polished surface was observed in a microscope, the boundaries of the copper and the oxide could be distinguished very well. The microscope was calibrated, and the thickness of the oxide layer could be observed at any point by moving the cross hair of the microscope between the clearly defined edges. The rectifiers used for this measurement were quenched in water. Three or four readings were taken on each side of each one. It was observed that the thickness of the cuprous oxide layer is variable, especially for the ones which had been heated for longer times. Table 5 gives the results of the thickness measurements. The rectifiers shown in Table 5 were heated between 1015° and 1025°C., and they were quenched in water at 10°C. Table 5 is on the following page.

Table 5

Specimen	Side	Time of Heating (Seconds)	Thickness (mm.)	Average Thickness of all Readings on One Rectifier
5	A	120	0.0368	0.0316
			0.0346	
			0.0353	
	B		0.0233	
			0.0280	
			0.0342	
			0.0288	
6	A	180	0.0519	0.0521
			0.0515	
			0.0527	
	B		0.0470	
			0.0519	
			0.0577	
7	A	240	0.0865	0.0681
			0.0816	
			0.0865	
	B		0.0536	
			0.0478	
			0.0527	
10	A	300	0.0816	0.0712
			0.0742	
			0.0766	
			0.0709	
	B		0.0544	
			0.0618	
			0.0791	

5. Presentation of bending data

For the experiment in which the rectification ratio is determined for the rectifiers on the two sides of a piece of copper as it is bent in arcs having different radii of curvature, specimen

81 was used. This specimen was selected because the rectifiers on the two sides of it had current-voltage characteristics nearly alike. This rectifier had been prepared by the method used for those shown in Tables 3 and 4. It was heated for 180 seconds and quenched in a 10% solution of methyl alcohol in water at 6°C. Readings were taken so that the forward and reverse currents could be determined for 3.50 and 7.50 volts. Rectifier 81A was on the inside of the arc of the copper segment as it was bent, and consequently, rectifier 81B was on the outside. The forward and reverse currents and the rectification ratios for both rectifiers are given in Table 6 for 3.50 volts and in Table 7 for 7.50 volts. The rectification ratio is given as I_2/I_1.

Table 6
($E = 3.50$ volts)

	81A (inside)			81B (outside)		
Radius of Curvature in Inches	Reverse Current I_1(ma.)	Forward Current I_2(ma.)	$\frac{I_2}{I_1}$	Reverse Current I_1(ma.)	Forward Current I_2(ma.)	$\frac{I_2}{I_1}$
∞	5.82	98.10	16.85	5.88	80.7	13.72
20.0	5.89	97.4	16.80	5.97	79.5	13.30
15.0	5.72	96.5	16.87	5.97	79.3	13.28
12.5	5.83	94.7	16.22	6.42	78.3	12.18
10.0	5.82	93.7	16.10	6.62	78.3	11.80
7.5	5.83	93.5	16.05	6.48	78.3	12.07
5.0	5.48	89.5	16.30	5.96	75.2	12.60
4.0	5.28	89.5	17.25	6.95	75.7	10.90
3.0	5.59	88.4	15.80	6.84	76.6	11.10
2.0	5.66	91.3	16.10	38.7	83.0	2.40

Table 7
(E 7.50 volts)

	81A (inside)			81B (outside)		
Radius of Curvature in Inches	Reverse Current I_1(ma.)	Forward Current I_2(ma.)	$\frac{I_2}{I_1}$	Reverse Current I_1(ma.)	Forward Current I_2(ma.)	$\frac{I_2}{I_1}$
∞	14.58	225.0	15.43	14.40	192.3	13.33
20.0	14.85	233.0	15.65	14.08	190.0	13.50
15.0	14.58	227.0	15.60	14.08	189.0	13.42
12.5	14.85	222.	14.95	15.80	188.0	11.90
10.0	14.65	223.	15.22	16.65	187.5	11.28
7.5	14.83	220.	14.83	16.45	187.0	11.35
5.0	14.22	214.	15.03	15.22	184.5	12.11
4.0	13.82	214.	15.45	17.90	185.	10.32
3.0	14.28	212.	14.85	17.66	188.	10.63
2.0	14.85	220.	14.83	91.0	203.	2.30

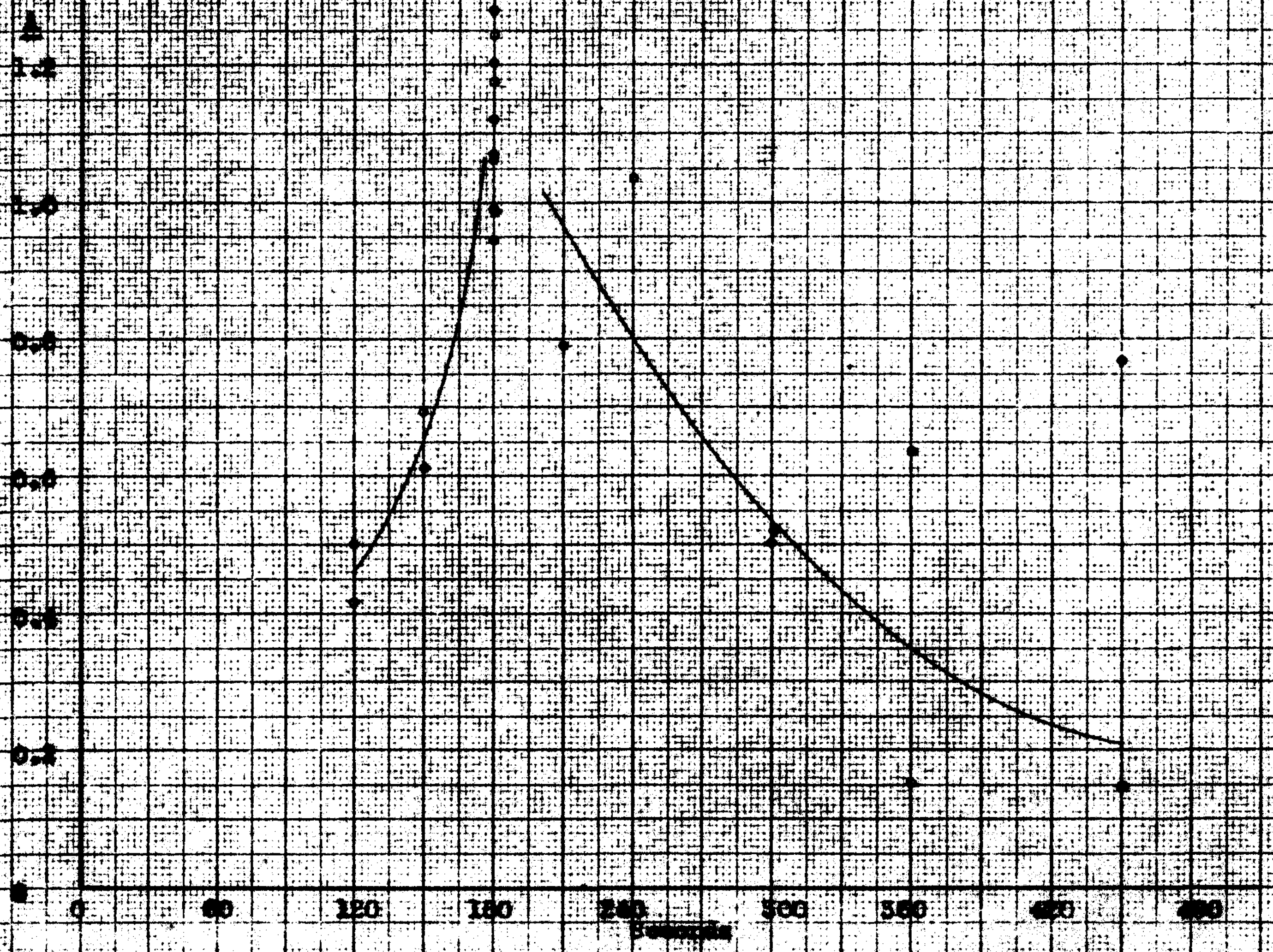


Figure 12. Variation of Constant A with Time of Heating

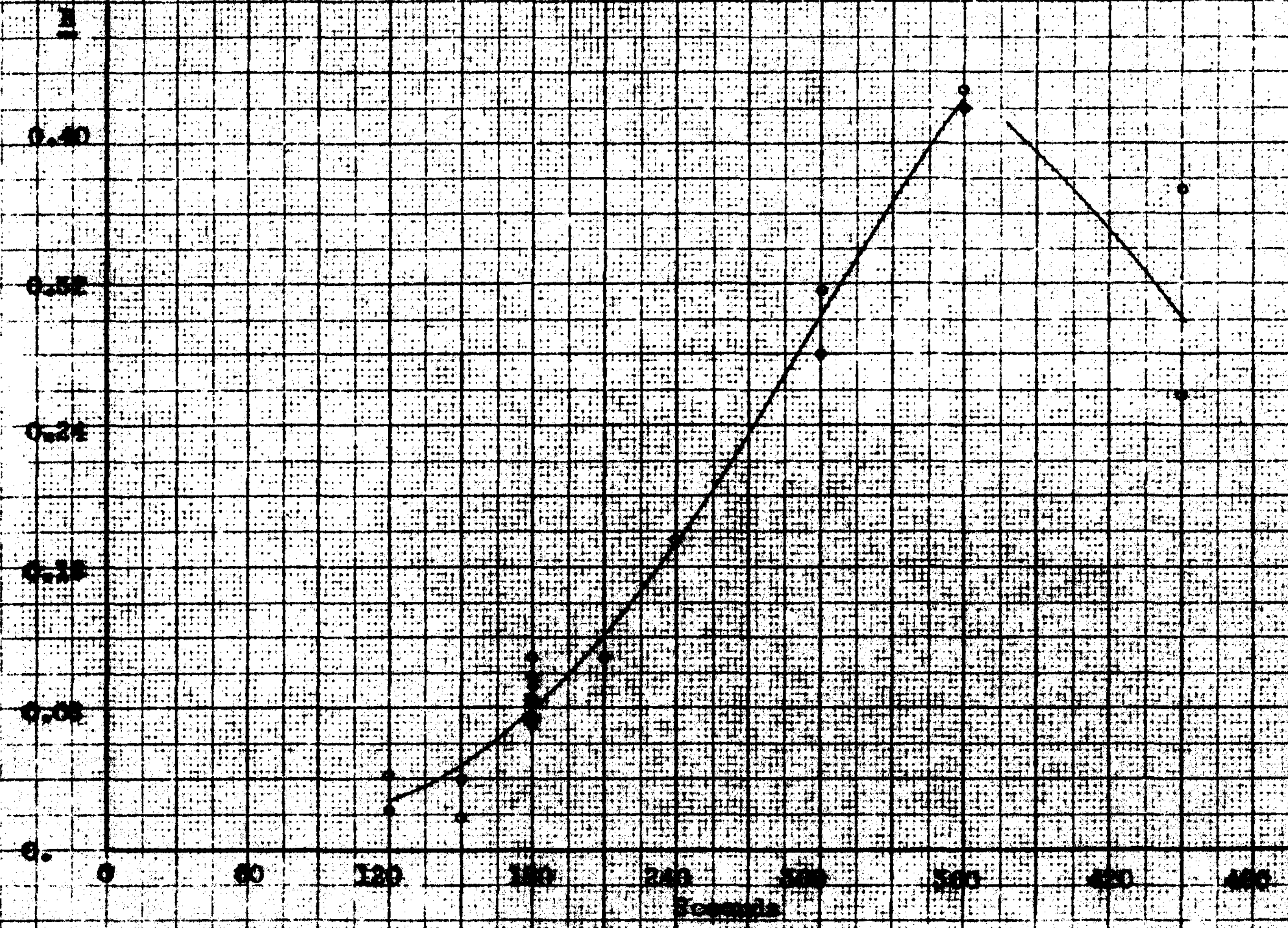


Figure 15. Variation of Constant K with Time of Heating

Form F-3

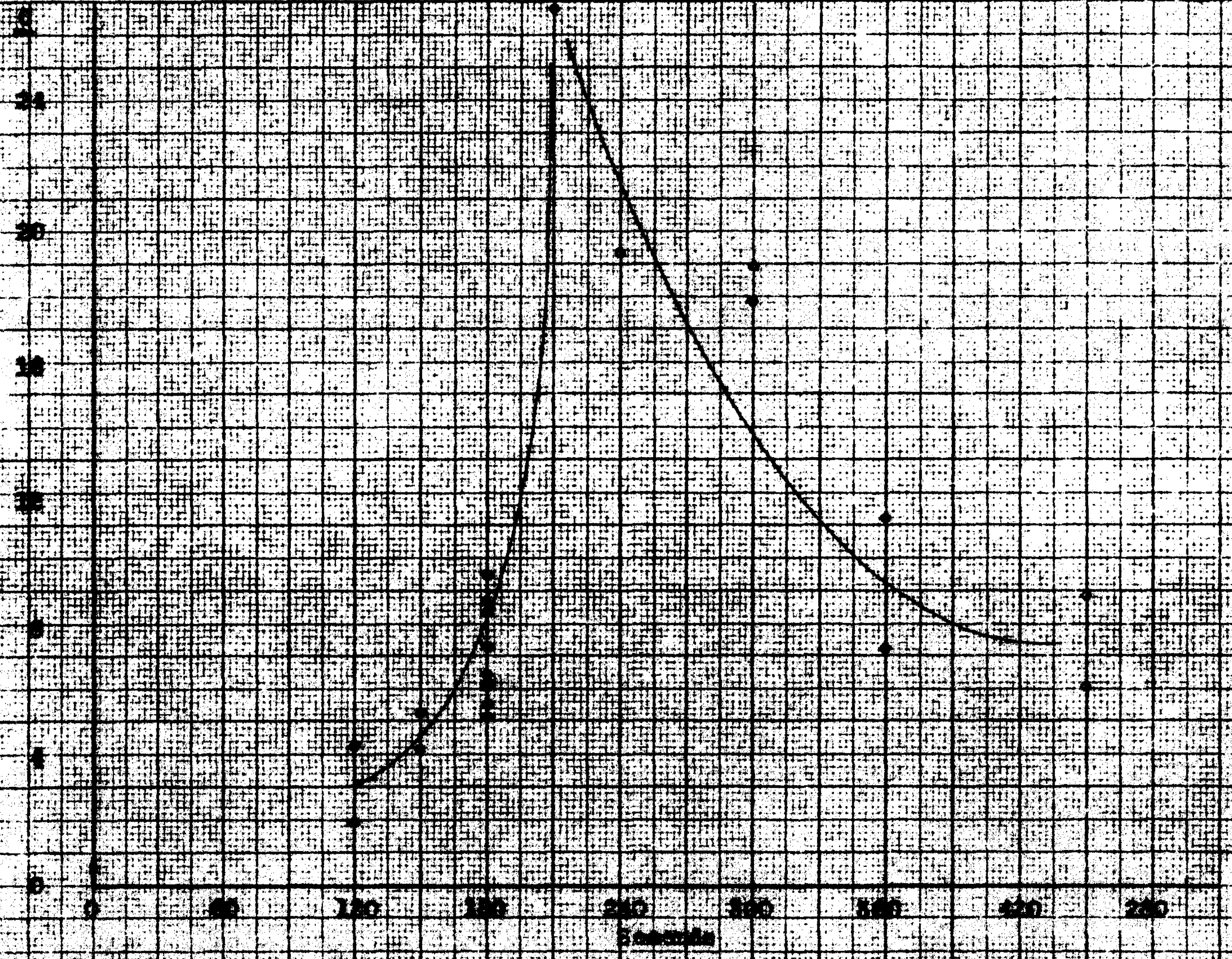


Figure 14. Variation of Constant C with Time of Heating

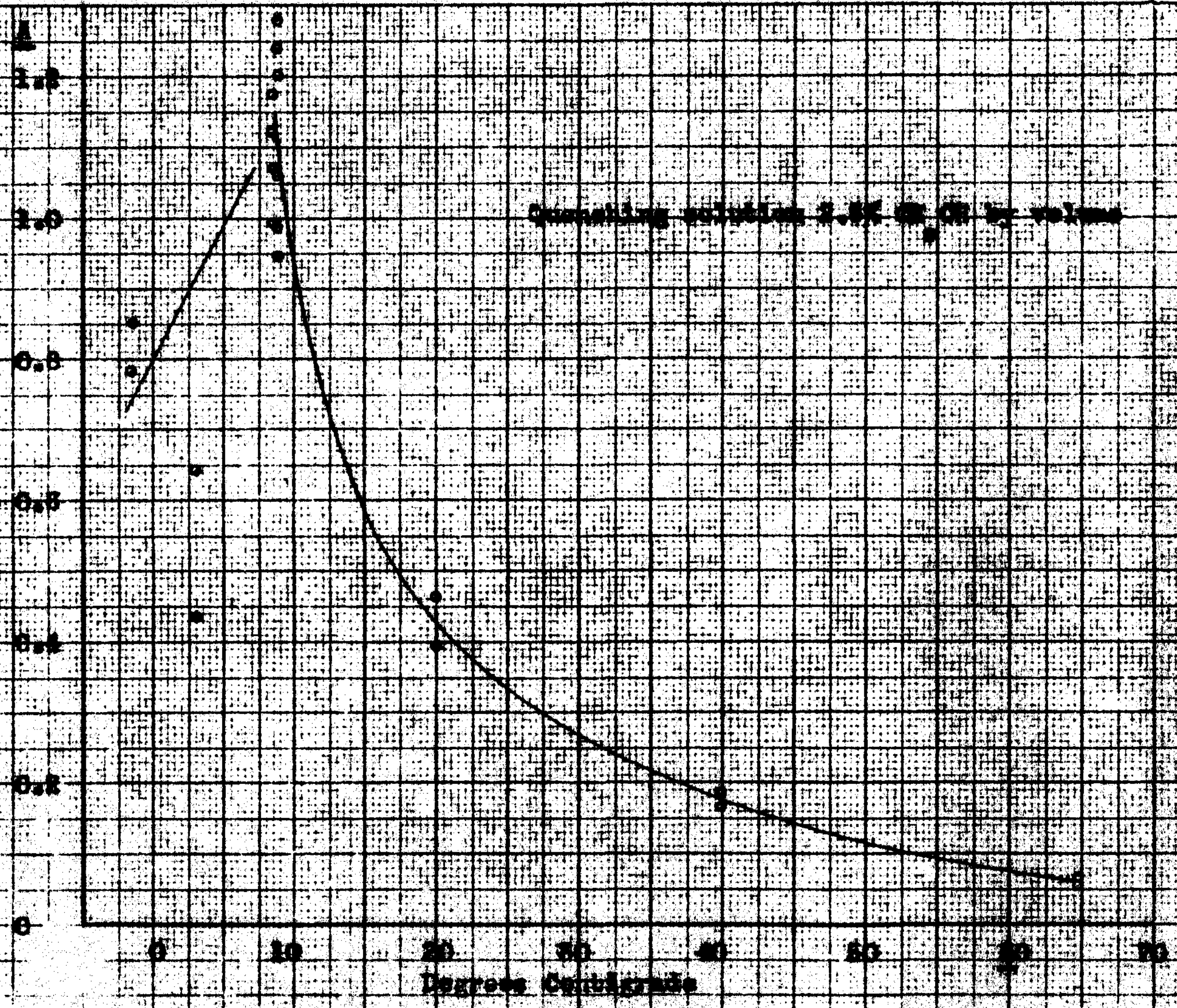


Figure 15. Variation of Constant A with Quenching Temperature

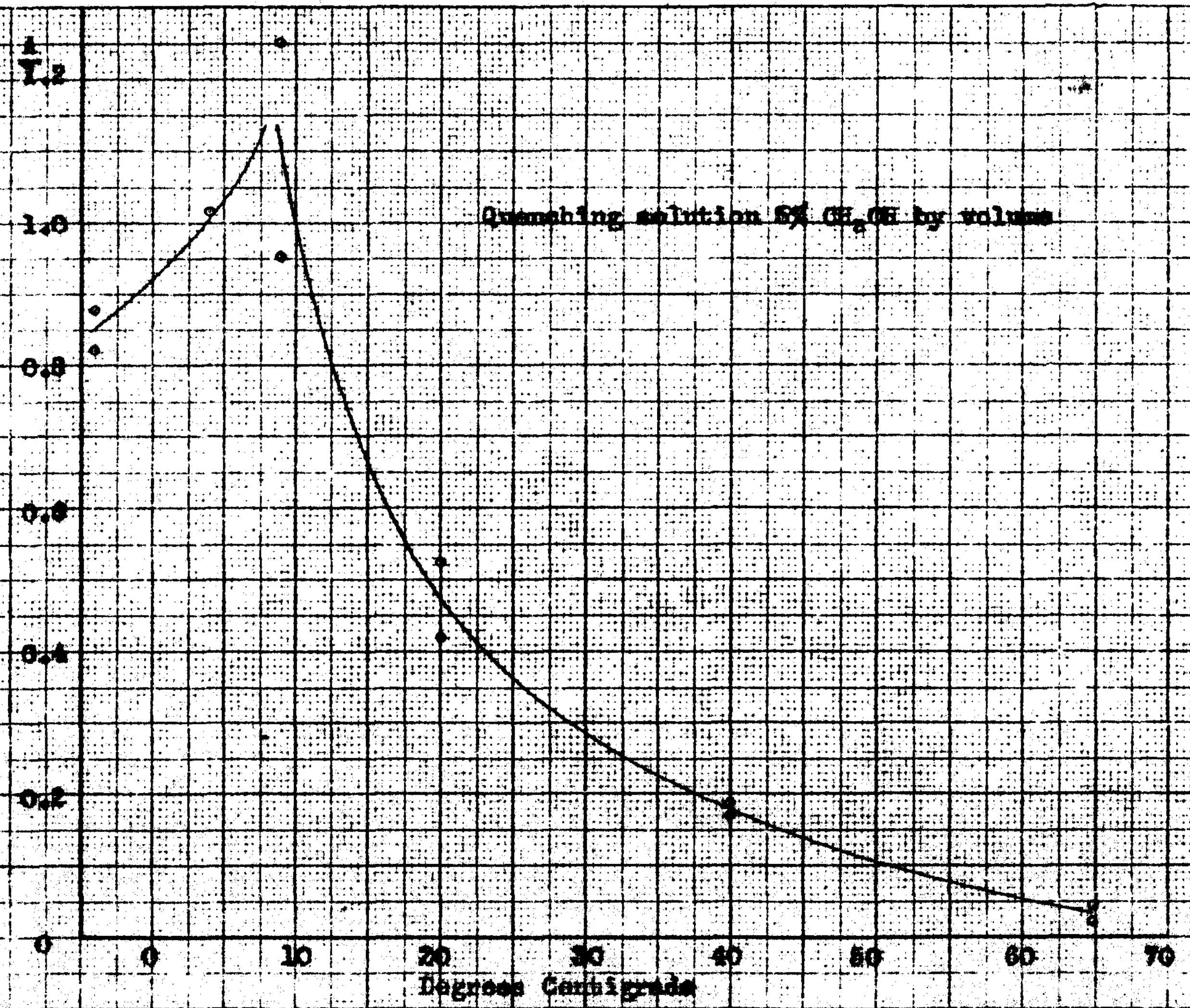


Figure 16. Variation of Constant A with Quenching Temperature

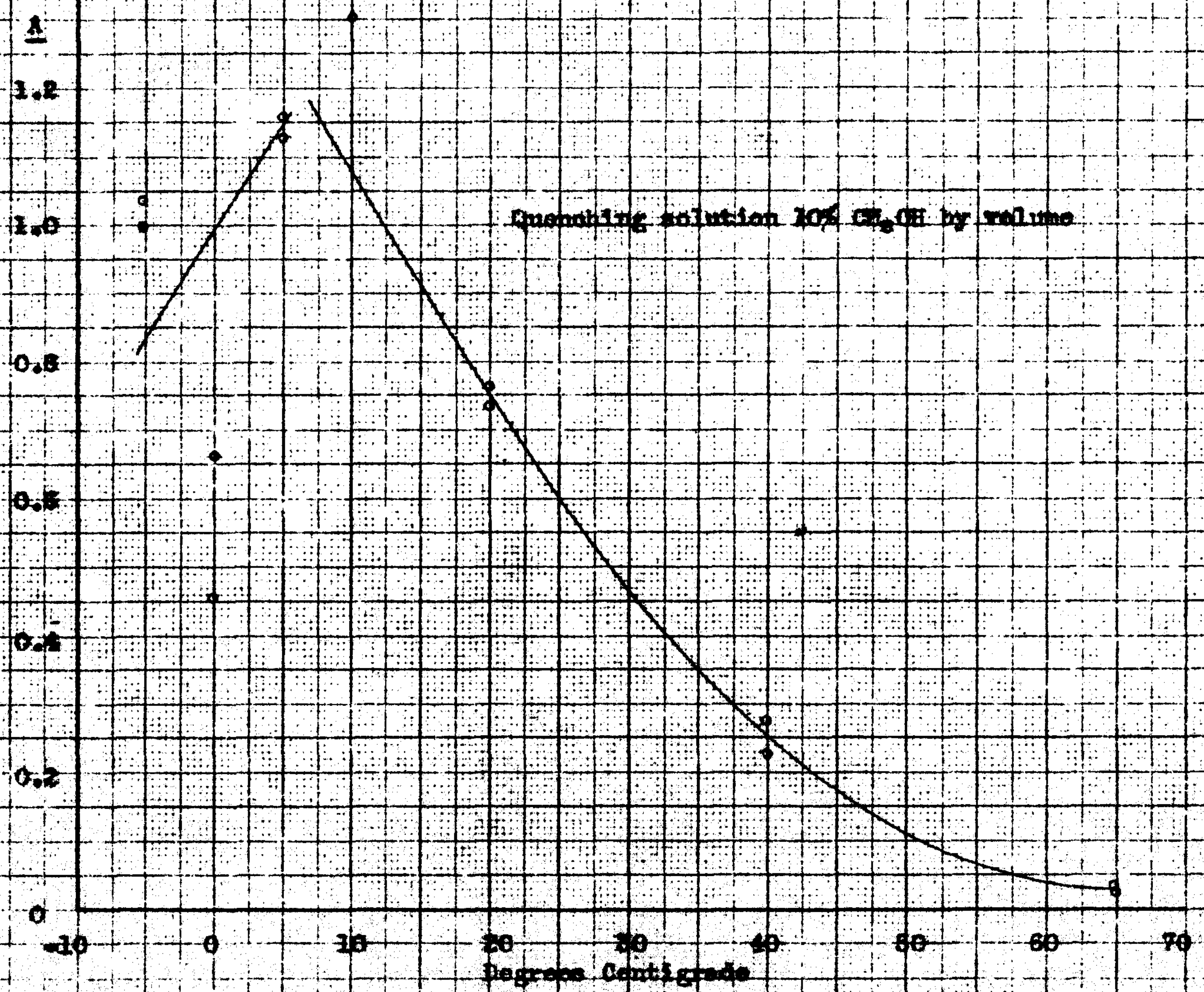


Figure 17. Variation of Constant A with Quenching Temperature

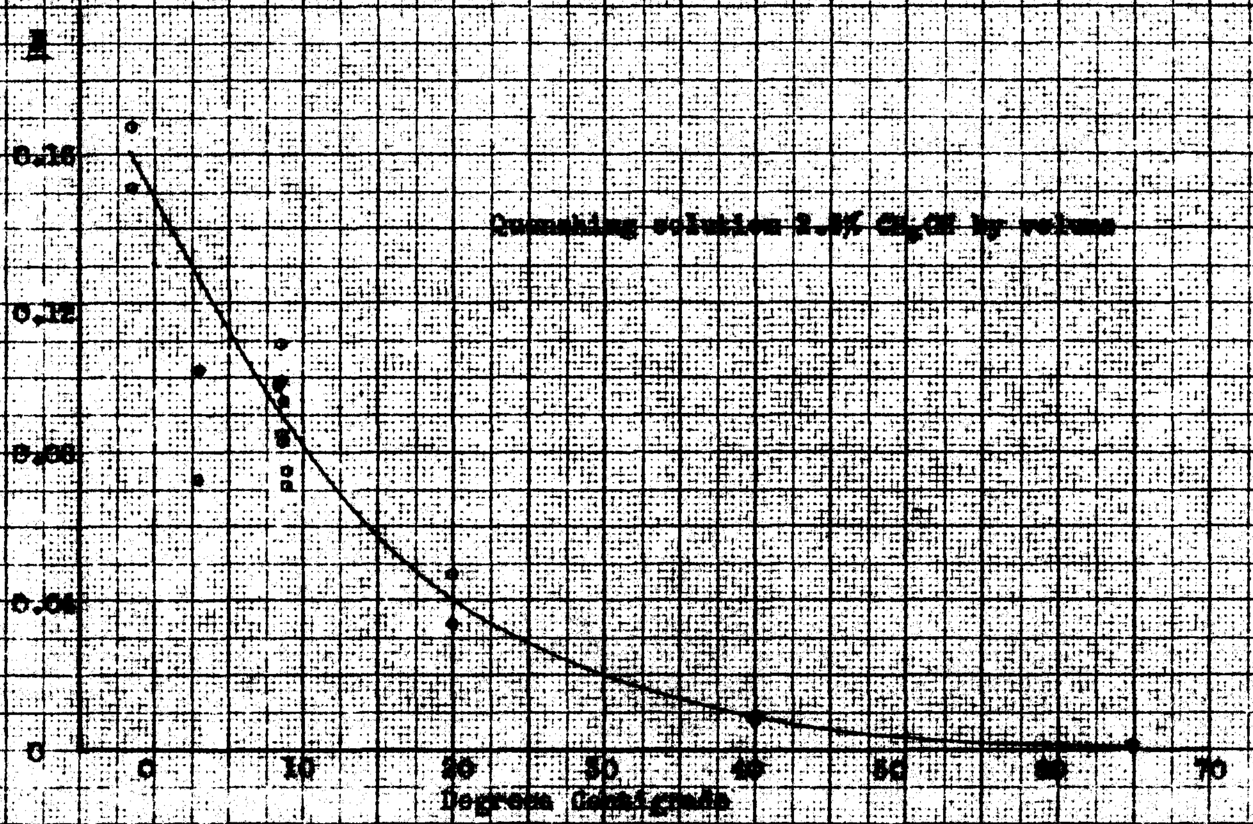


Figure 18. Variation of Constant k with Quenching Temperature

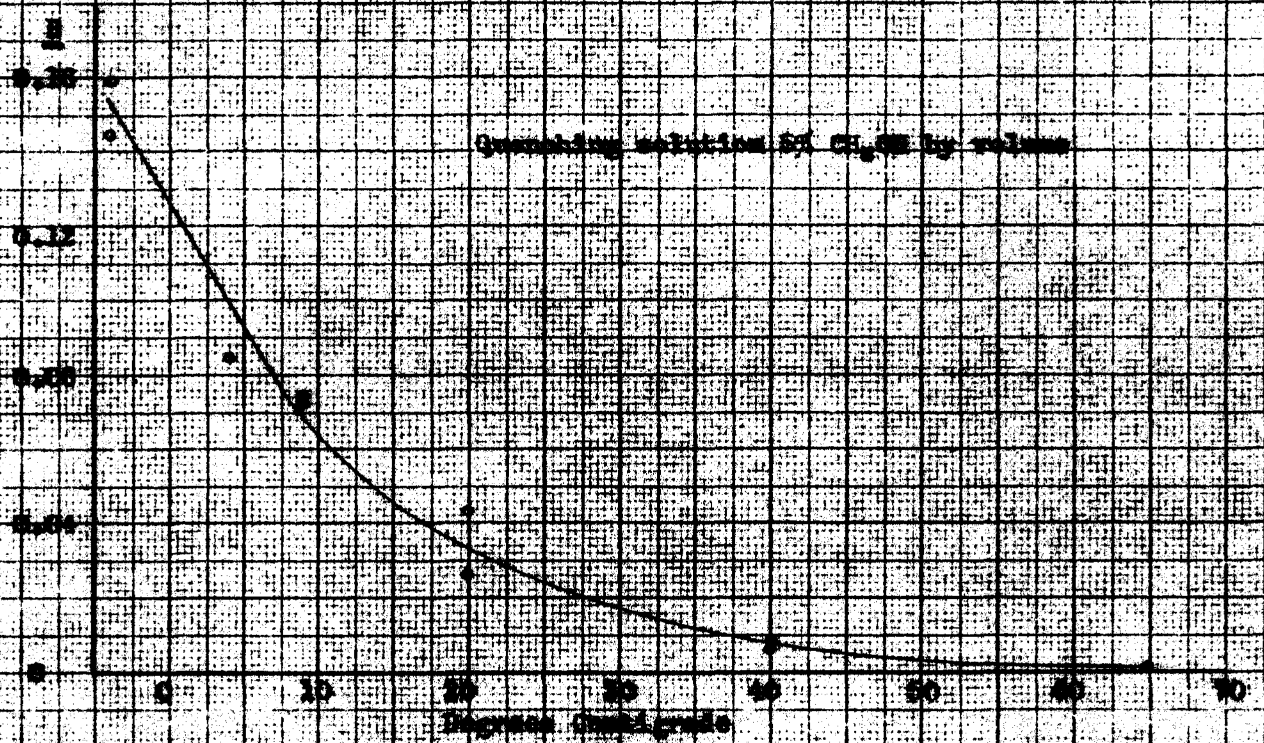


Figure 15. Variation of Constant K with Quenching Temperature

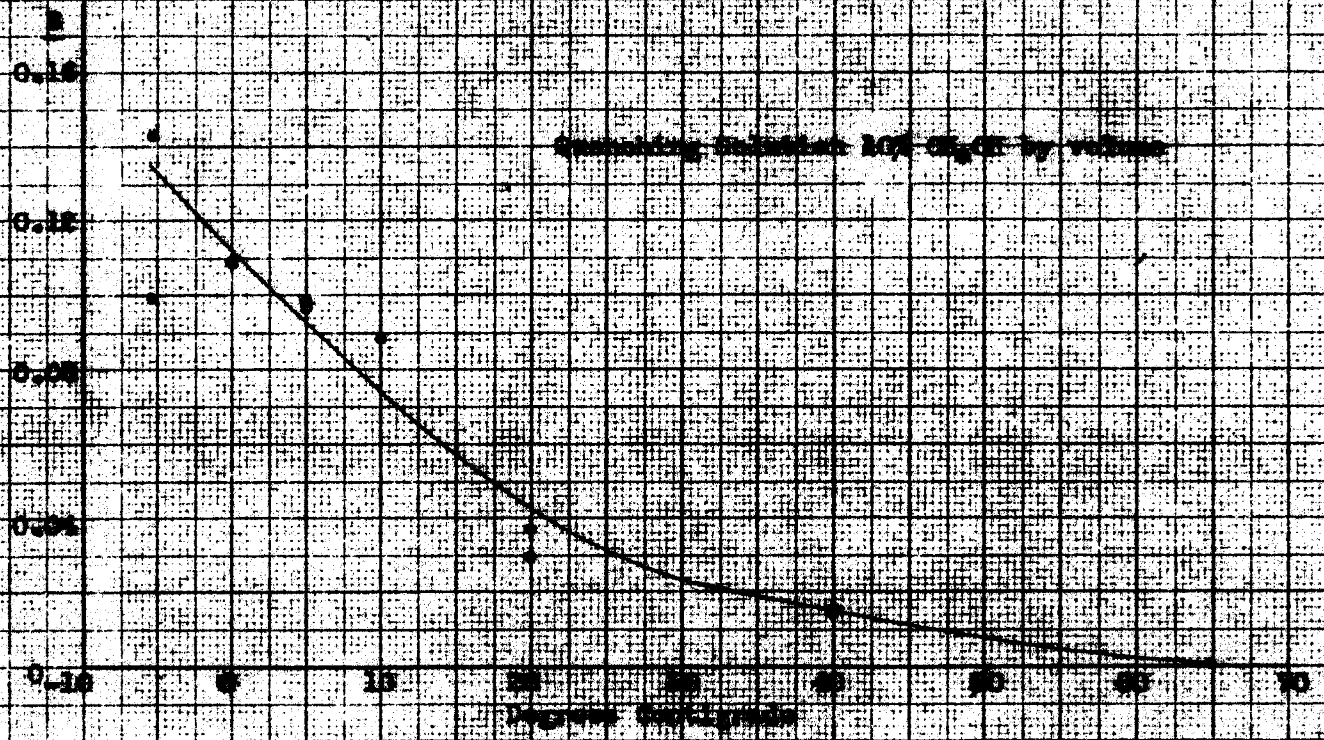


Figure 20. Variation of Constant B with Quenching Temperature

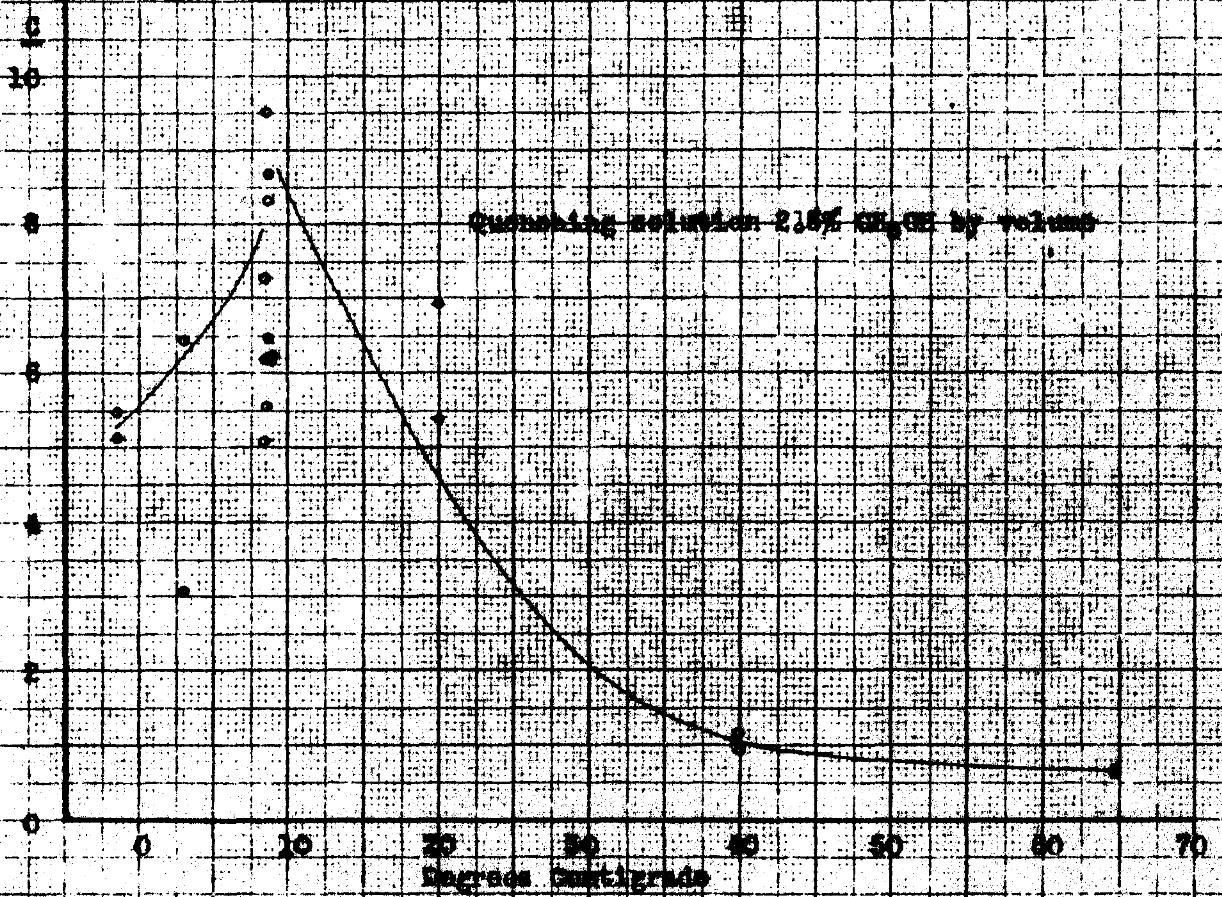


Figure 21. Variation of Constant C with Quenching Temperature

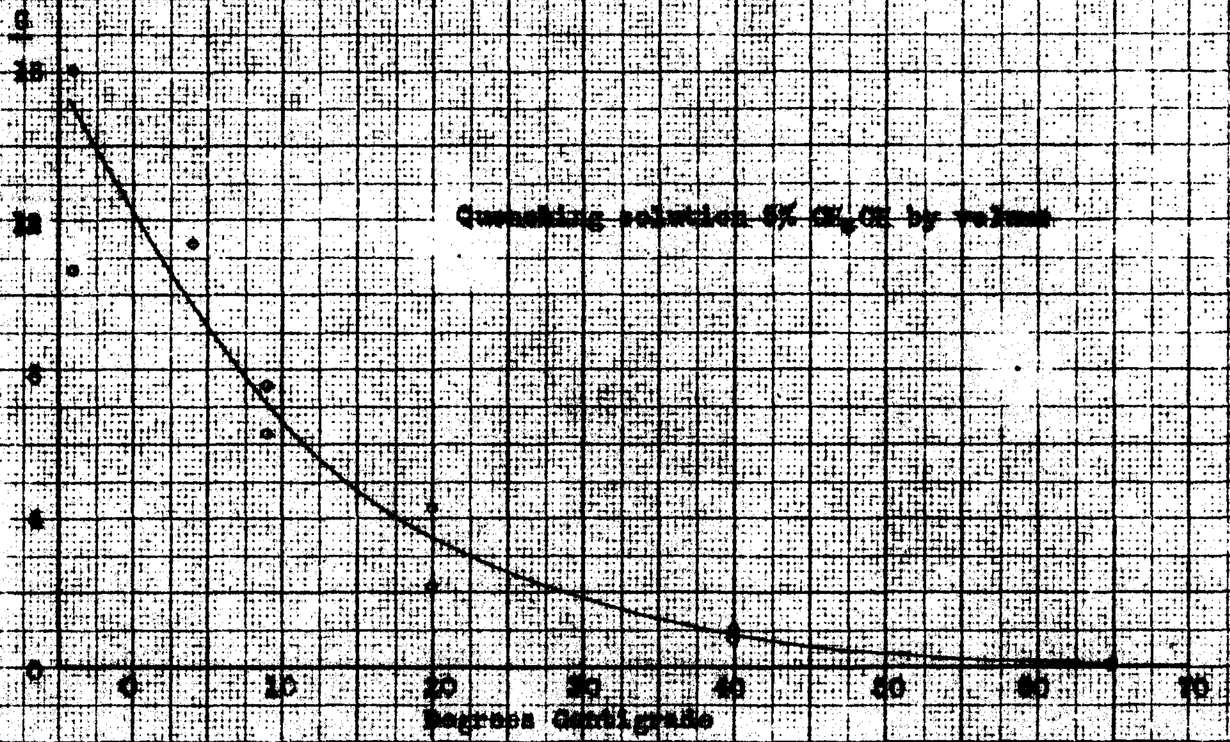
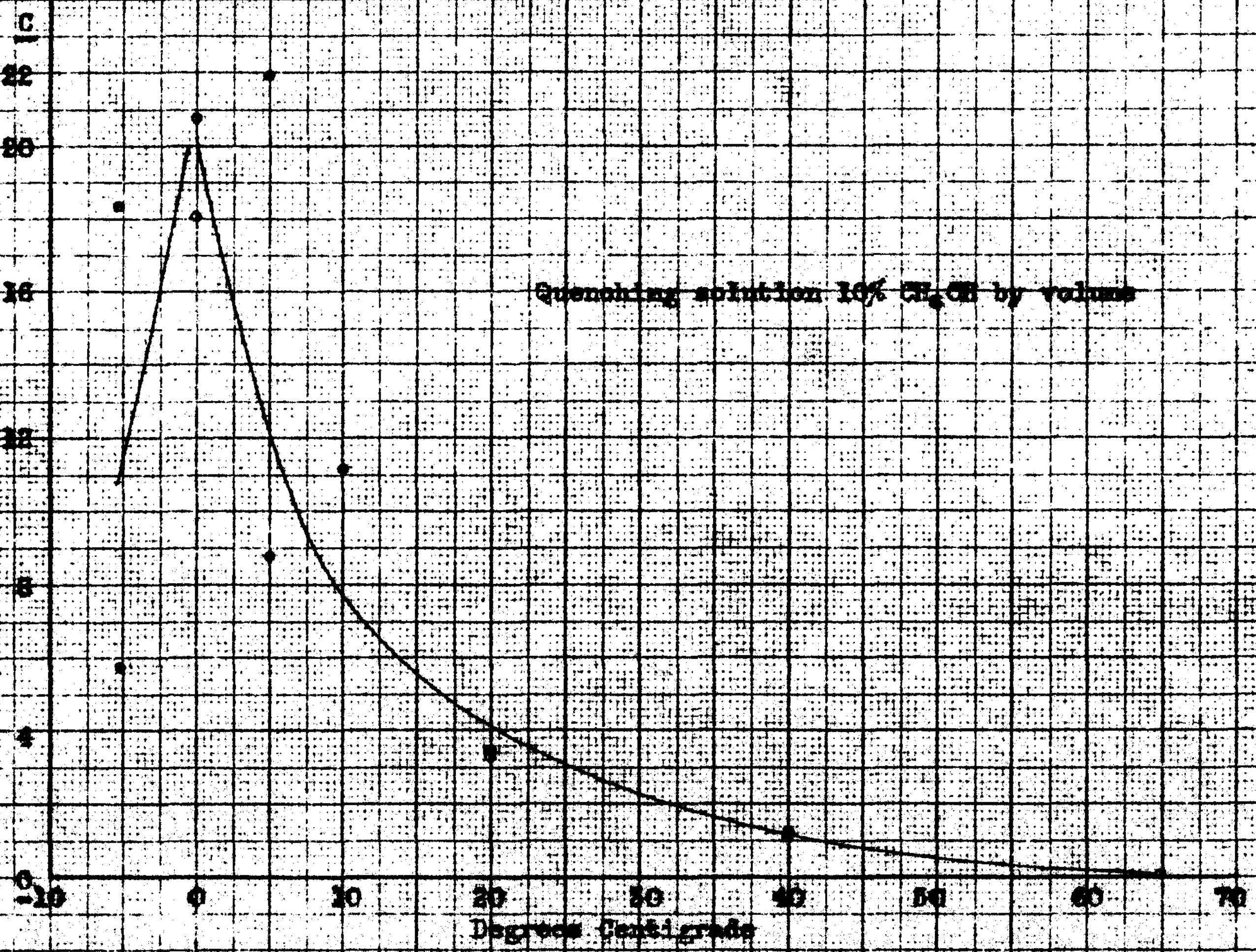


Figure 22. Variation of Constant C with Quenching Temperature



Quenching solution 10% CH_3OH by volume

Figure 25. Variation of Constant C with Quenching Temperature

B. Discussion of Results

1. Variation of preparation conditions

The values of the constants A, B, C, and D of the current-voltage equations for the several rectifiers are given in Appendix I. Figures 12 to 23 inclusive show the values of A, B, and C plotted against the variables of the time of heating and the temperature of the quenching bath. The constant D is nearly the same for all the rectifiers examined. Its value lies between 1.0283 for rectifier 121A and 1.354 for rectifier 82A. For a large portion of the rectifiers the value of D is between 1.150 and 1.250.

Figures 12, 13, and 14 show the variations of A, B, and C with the time of heating the rectifier. All the rectifiers used in this comparison were quenched in a solution of 2.5% by volume of methyl alcohol in water at approximately 9°C. It is to be seen that the values of A and C are a maximum in the neighborhood of 180 to 210 seconds of heating, but B becomes a maximum for the rectifiers heated as long as 360 to 390 seconds.

The thickness of the oxide layer and its chemical composition are the properties of the rectifier which can be varied by a variation of the length of the time of heating.

It has been noted in the section, Report of Previous Investigations that various writers differ as to the chemical nature of the cuprous oxide layer. No chemical analysis or photomicrographic study of the oxide layer was included in the present investigation.

Yet it might be suggested that the differences of chemical and physical structure found by Pélabon, Scharf and Weinbaum, Torres, Jacquelet, and Dubar might be due to differences in the methods of preparation of the rectifiers whose properties they investigated. The preceding statement can be given only as a suggestion since none of the above authors gave complete data of the method of preparation of the rectifiers used.

The measurements recorded in Table 5 show that on each specimen the thickness of the cuprous oxide layer may vary considerably, but that in general the thickness of the oxide increases with the length of the heating time. However, for longer heating times, the rate of growth of the cuprous oxide becomes increasingly slower.

Figures 15, 16, and 17 show the variation of the constant A with the temperature of the quenching bath for different quenching solutions. With increasing temperature of the quenching bath from a temperature near 10°C. the value of A falls steadily in all cases. For decreasing temperature below 10°C. the value of A falls but in an erratic manner.

Figures 18, 19, and 20 give the variation of the constant B with the temperature of the quenching bath for various quenching solutions. The variation of this quantity is consistent in all cases, and it decreases continually with rising temperature from a maximum value at the freezing temperature of the mixture used.

Figures 21, 22, and 23 illustrate the variation of the constant C with the temperature of the quenching mixture for different concentrations of the methyl alcohol solutions used. As the curves show, the variation is somewhat erratic. Yet it can be said that for increasing temperatures of the quenching bath above 10°C. the value of C falls rapidly, and that for temperatures below 10°C. the values of C are relatively high but vary over a considerable range.

For the rectifiers shown in Tables 3 and 4 the rectification ratios were calculated at 7.50 volts. Figures 24, 25, 26, and 27 show the rectification ratios plotted against quenching temperatures for different quenching solutions. The rectifiers represented in Figure 24 were quenched in water, and contact was made with the cuprous oxide by coating it with graphite and pressing a lead electrode against it.

The rectification ratios of two rectifiers prepared under apparently the same conditions sometimes differ greatly. From that fact it can only be concluded that some one or several of the preparation conditions which have an influence upon the characteristics of the rectifier were not controlled. What these preparation conditions may have been cannot be stated. However, in the present investigation, the variation of the rectifier characteristics with the controlled variable is quite definite enough that the following conclusions can be stated.

For each quenching solution there is an optimum temperature which gives the highest rectification ratio possible for that particular solution. When the quenching bath is water, the optimum temperature is between 65° and 93°C.

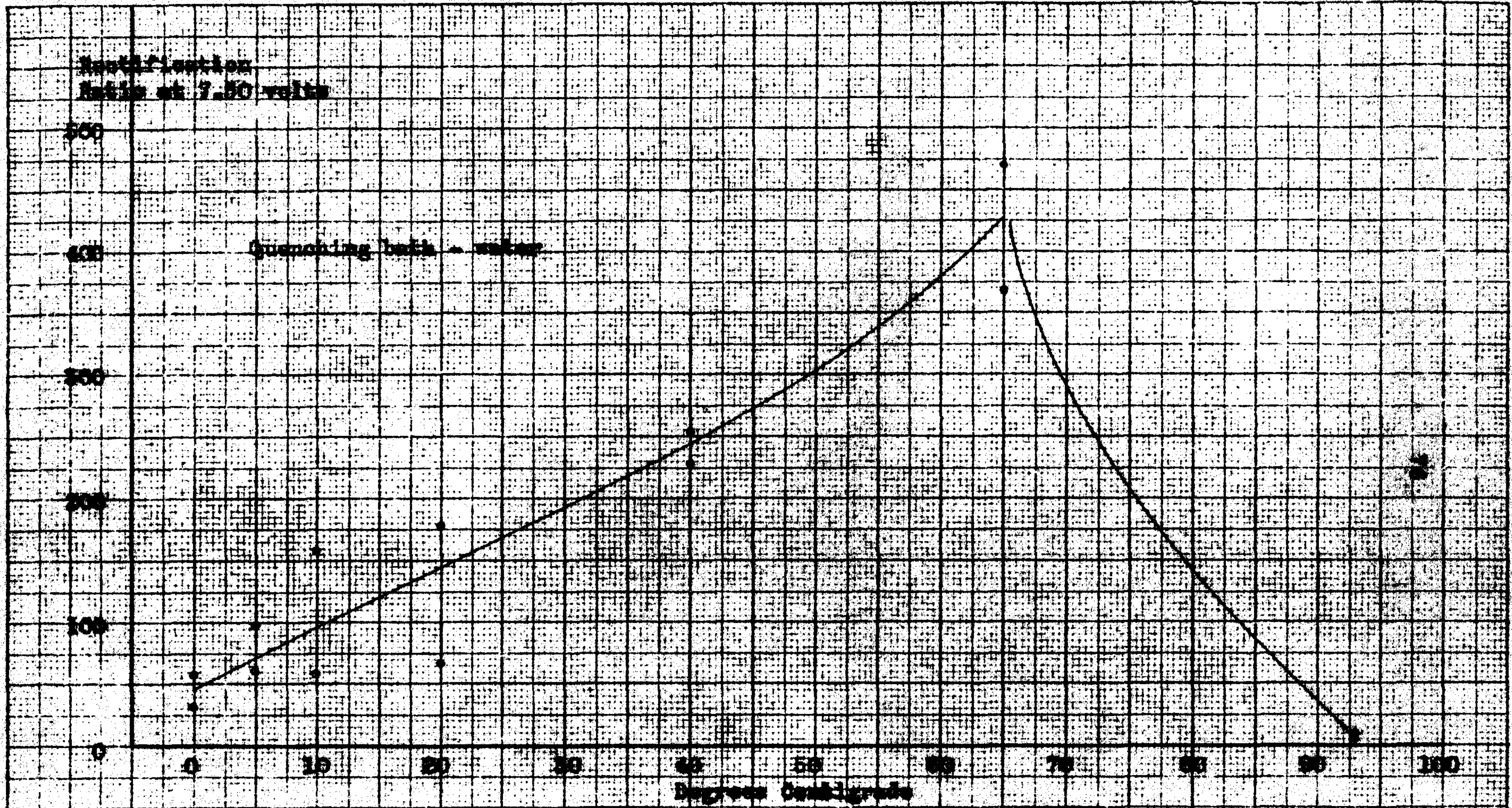


Figure 24. Variation of Rectification Ratio with Quenching Temperature

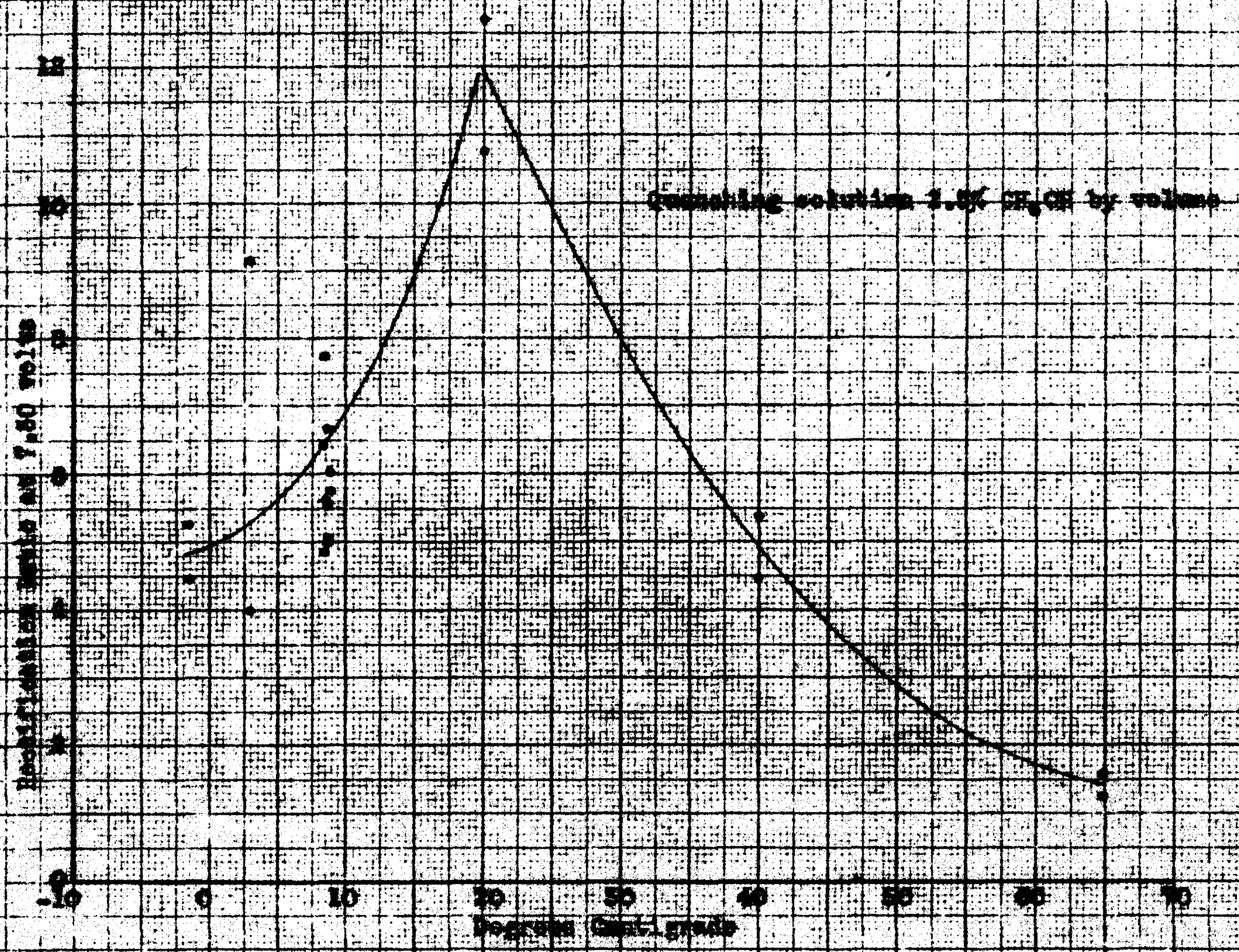


Figure 25. Variation of Rectification Ratio with Quenching Temperature

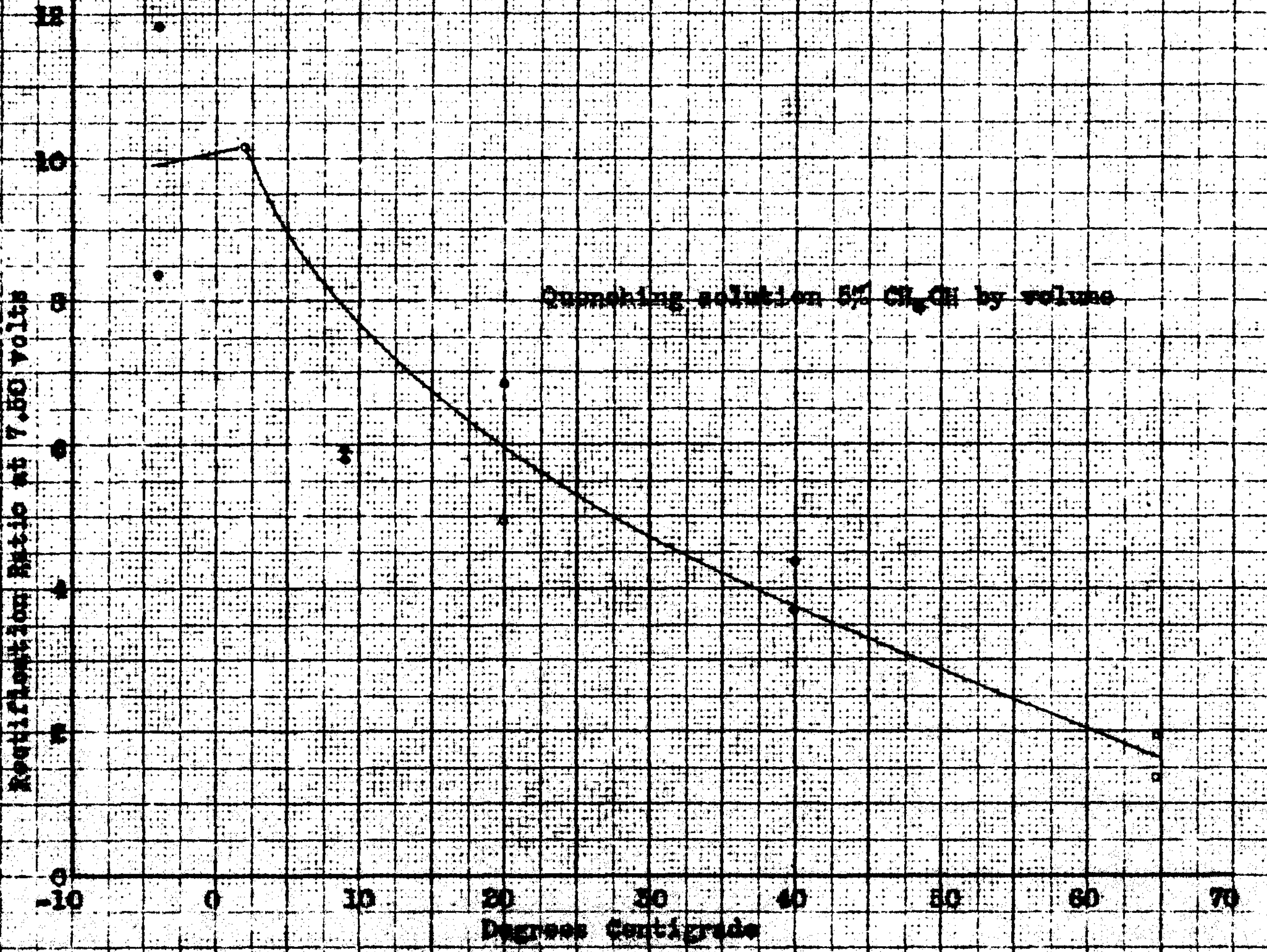


Figure 26. Variation of Rectification Ratio with Quenching Temperature

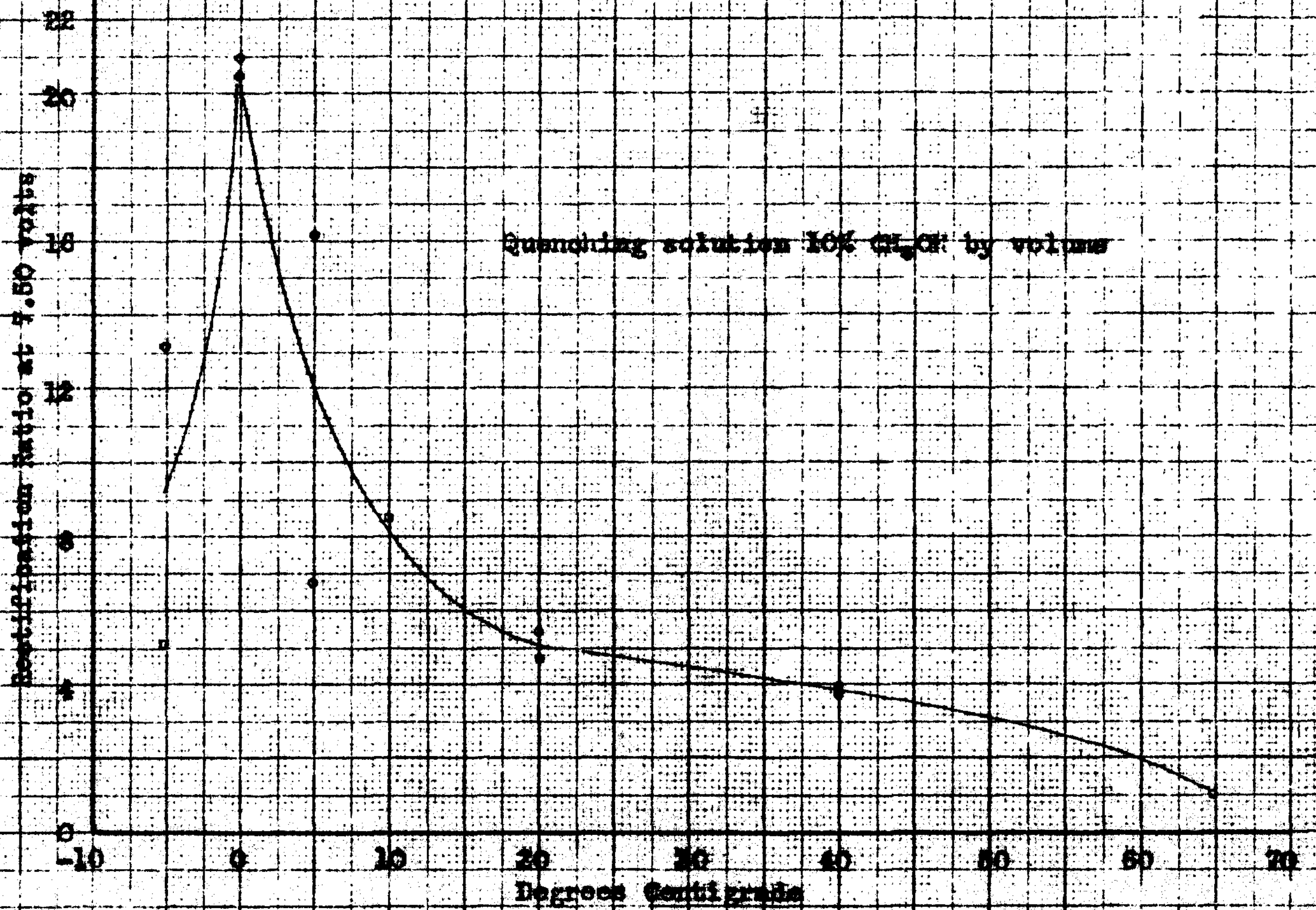


Figure 27. Variation of Rectification Ratio with Quenching Temperature

Figure 25 shows that the optimum quenching temperature is in the neighborhood of 20°C. when the quenching solution is 2.5% by volume of methyl alcohol in water. In Figure 26 it may be seen that the optimum quenching temperature occurs at about 5°C. for a 5% solution of methyl alcohol, while Figure 27 gives the optimum quenching temperature for a 10% methyl alcohol solution as 0°C.

From these data the conclusion is drawn that the optimum temperature for the cooling bath is lowered as the proportion of methyl alcohol it contains is increased. In view of Jacquelet's theory this phenomena can be explained by a consideration of the physical mechanism of quenching.

Since the copper upon being cooled contracts much more than does the cuprous oxide layer in contact with it, a strain of asymmetrical contraction is imposed upon the crystals of the cuprous oxide layer. Jacquelet finds this strain to be the mechanism by which rectification is caused. Then the degree of rectification will depend upon the magnitude of the strain.

There are two conditions in the quenching of a rectifier which can influence the magnitude of the strain imposed on the cuprous oxide. If the cooling of the rectifier is too slow, the cuprous oxide layer will find time to reduce the strain of contraction by flowing while it is still warm enough to be somewhat fluid. Should the temperature drop of the rectifier unit be too great or too sudden, the strain upon the cuprous oxide will exceed its adhesion force, and the strain of contraction will be reduced in the cuprous oxide by some of the individual crystals of it losing their contact with the copper. The latter effect is readily noticed in the preparation of copper oxide rectifiers using copper discs with sharp edges. The colder is the quenching bath, the more the chipping of the cuprous oxide at the edges of the copper occurs. Also, the hotter the copper is heated, the more the oxide will chip in the quenching. This is a manifestation of the same effect, since, with a given temperature of the cooling bath, the hotter the copper is heated, the more it expands, and the greater is the strain imposed on the oxide upon quenching. Thus, with the copper segment heated to a temperature of from 1017° to 1022°C., the optimum quenching temperature in water is found to be somewhere above 65°C. At this optimum quenching temperature the sum of the two effects described above are a minimum. At 93°C. the quenching bath is hot enough to allow the oxide to flow; the rectifiers made at this temperature have conductivities and rectification ratios much lower than those quenched at a lower temperature. Figure 24 shows that as the temperature of the quenching bath is lowered below 65°C. the rectification ratio is gradually reduced, probably due to the increase in the proportion of the oxide crystals that break loose from the copper.

When the quenching bath contains methyl alcohol, formaldehyde is produced in the solution when the hot copper comes into contact with it. At room temperature formaldehyde is a gas. The chemical reaction which takes place is given by Equation 7. When the gas is formed around the copper, its cooling is slower and more uneven than it would have been had the quenching taken place in water at the same temperature. Due to the uneven distribution of the gaseous formaldehyde formed about the cuprous oxide surface, the cooling is uneven, and consequently a poorer rectifier is produced than would have been had the cooling rate been uniform over the whole area of the oxide layer. In some spots on the layer of oxide where a bubble of formaldehyde is produced, the cooling may be slow enough to allow the oxide to flow slightly, while in an adjoining bit of oxide the quenching may have been so sudden as to cause a slight loosening of the crystals of the oxide from the copper. This unevenness of the cooling rate is sufficient to explain why rectifiers quenched in methyl alcohol solutions are much inferior to those quenched in water.

The advantage gained by the use of rectifiers quenched in alcoholic solutions is that the reduced copper oxide electrode formed on the outside of the cuprous oxide has a constant contact resistance regardless of pressure variations, while the contact resistance of the lead electrode required with the rectifiers quenched in water is so variable with pressure and with other conditions of application that small variations of the characteristics of the rectifier might be entirely masked by the changes of contact resistance.

In general, a rectifier quenched in a methyl alcohol solution at one temperature cools more slowly than does one quenched in water at the same temperature. Then it is to be expected that the optimum temperature of quenching bath, i.e., the temperature of the quenching bath which provides the most desirable rate of cooling, would be lower for the methyl alcohol solution than for water. The more methyl alcohol which is added to the solution, the more of the gaseous formaldehyde will be released in the solution, and the lower must be the solution temperature to give the optimum rate of cooling. The experimental results agree with the preceding deduction, as the following Table, taken from Figures 24, 25, 26, and 27, readily shows:

Table 8

Per cent by Volume of CH_3OH in Solution	Optimum Temperature of Quenching
0	65° to 90°C.
2.5	20°C.
5.0	5°C.
10.0	0°C.

Figure 28 shows the variation of the rectification ratio at 7.50 volts for rectifiers heated for different lengths of time. Apparently the maximum condition of strain which can be developed in the cuprous oxide depends to some extent upon the thickness of the oxide layer which is known to depend upon the time of heating. For rectifiers heated in the range of 1017° to 1022°C. and quenched in a 2.5% methyl alcohol solution at 9°C. the optimum time of heating is very near 210 seconds.

2. Variation of rectifier characteristics produced by bending

If Jacquelet's theory is correct, then any method of stretching the copper and reducing the contraction strain imposed on the oxide should lessen or destroy the rectification properties. Similarly, any further contraction of the copper should increase the rectification

Form E-2

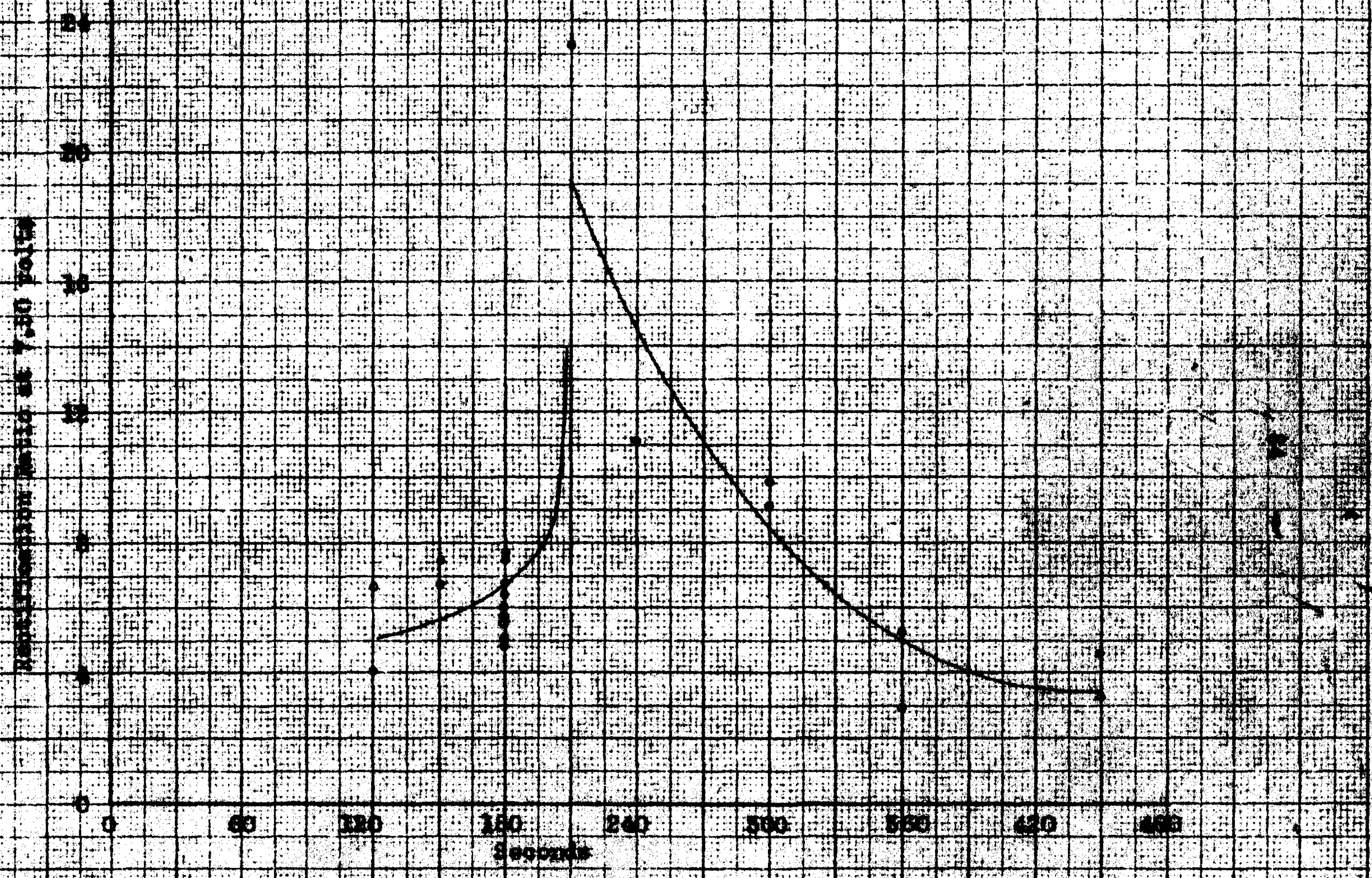


Figure 28. Variation of Rectification Ratio with Time of Heating

ratio, providing the cuprous oxide continues to adhere to the copper in order that the strain it experiences may be increased.

Tables 6 and 7 show the rectification ratios of rectifiers 81A and 81B at 3.50 and 7.50 volts for various radii of curvature. The data of these Tables are represented graphically in Figures 29 and 30. The solid dots are the rectification ratios of 81A which was on the inside of the copper arc, and the points shown by circles are for the rectification ratios of 81B which was on the outside of the mother copper piece as it was bent.

If there were no breaking loose of the cuprous oxide from the copper, according to Jacquelet's theory the rectification ratio of 81A should increase as the radius of curvature becomes smaller because the inside area of the mother copper is being reduced. Actually the rectification ratio of 81A decreases a little as the rectifier is bent more and more. However, at the radius of curvature of four inches, the rectification ratio for 3.50 volts of 81A becomes larger than that of the original rectifier. The failure of the rectification ratio to increase greatly is attributed to the fact that the cuprous oxide does not retain a complete contact with the copper.

For the outside rectifier, 81B, the rectification ratio decreases noticeably and finally drops abruptly to a very small value for a radius of curvature of two inches. This effect is to be explained by the provisions of Jacquelet's theory. As the strain on the cuprous oxide is released by the stretching of the outside copper surface, the rectification which is the result of that strain should, and does, decrease.

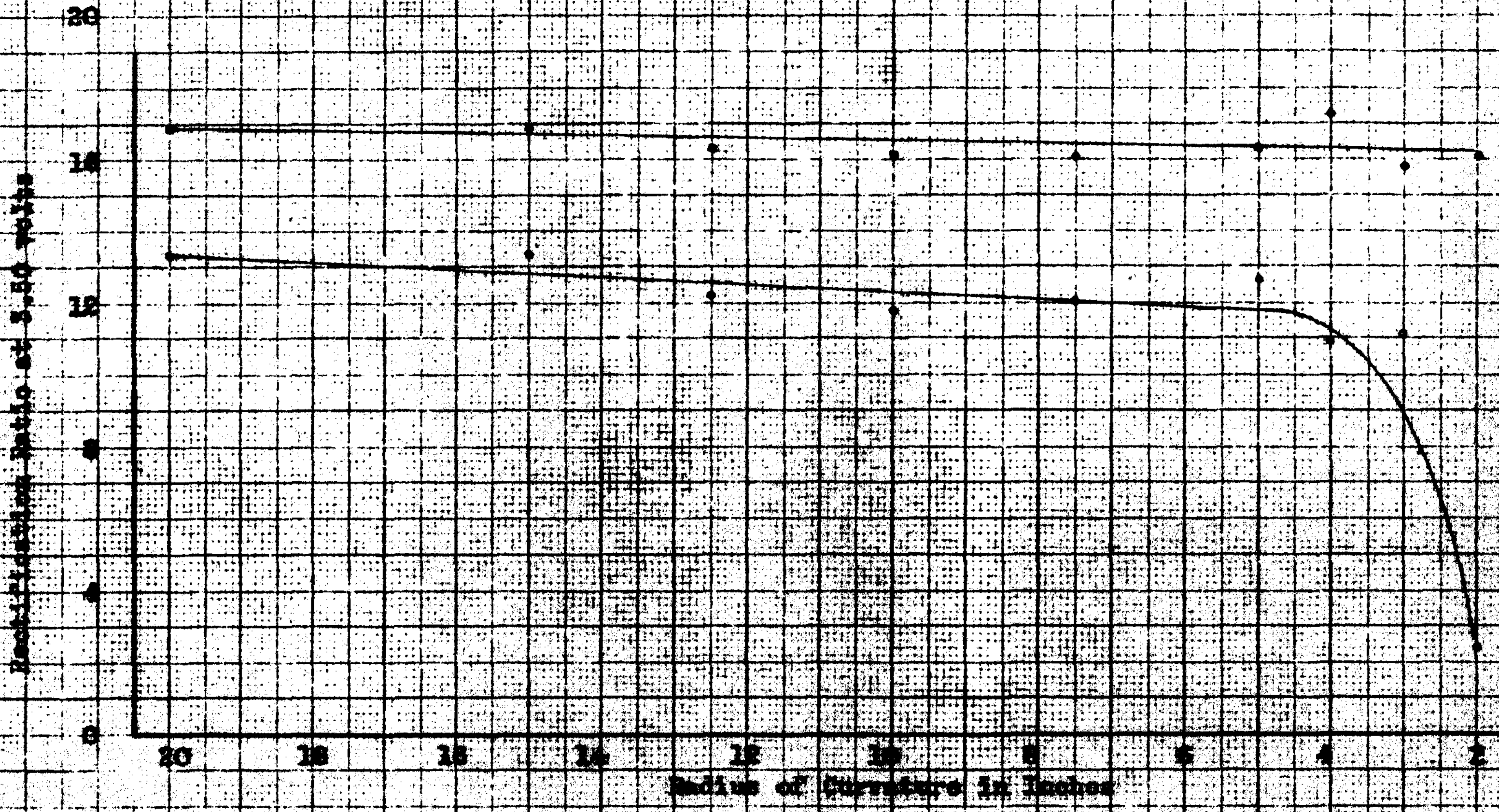


Figure 29. Variation of Rectification Ratio with Radius of Curvature, Rectifier 81

Form E-3

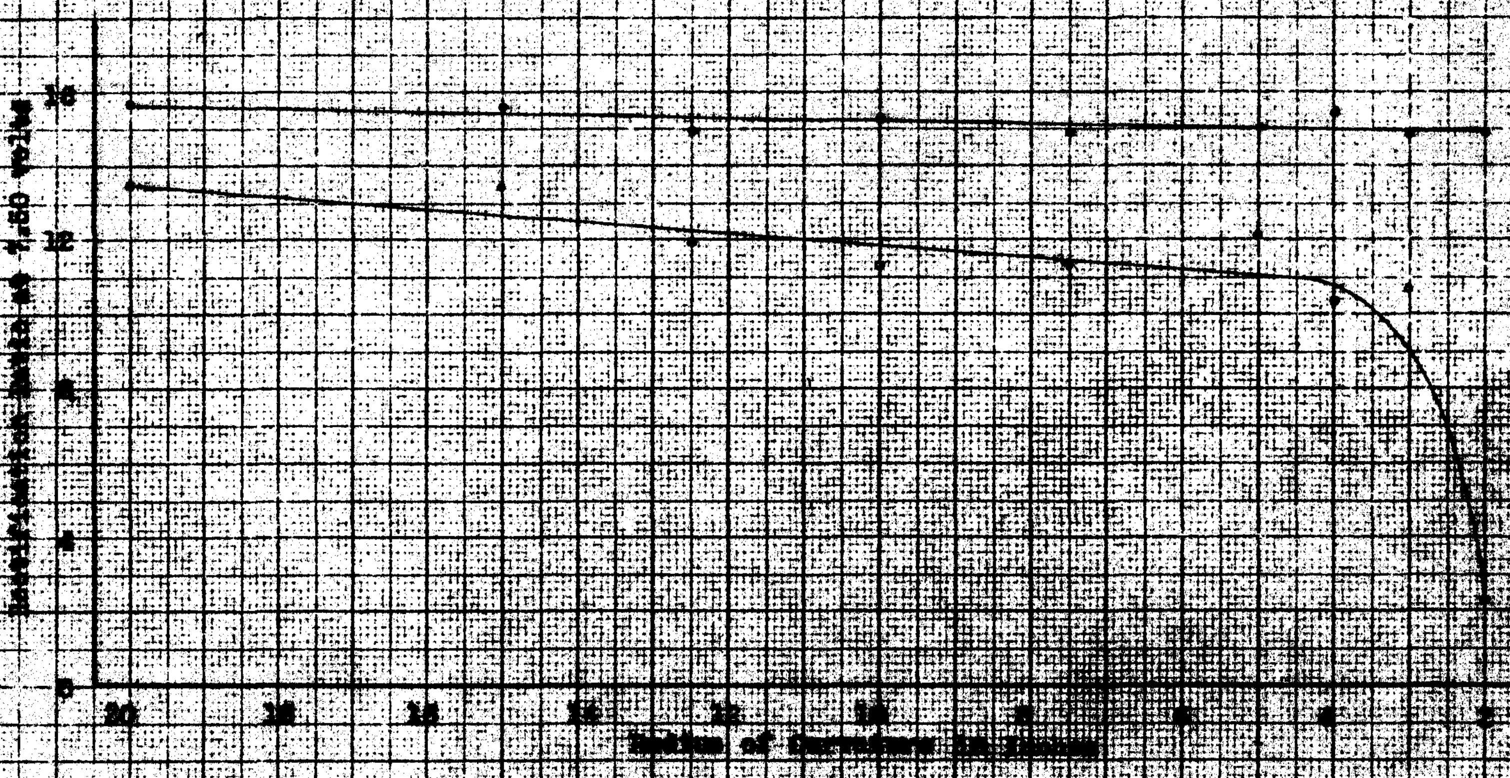


Figure 30. Variation of Rectification Ratio with Radius of Curvature, Detector 23

3. General Discussion

As Jacquelet has said (Jacquelet 12, pg. 371), his theory can apparently have no mathematical proof, but it explains all the physical properties of copper oxide rectifiers. The evidence of the present investigation is added to that supporting Jacquelet's theory.

The theory of copper oxide rectifiers cannot be complete until it can explain fully all the variations produced in the characteristics of rectifiers by variable preparation conditions. The preparation conditions which affect the nature of the rectifier are not all known as yet. The evidence of the present investigation is a start toward the definite singling out of variables which do influence the characteristics of rectifiers. Jacquelet (Jacquelet 12) states that the rectifier characteristics are affected by dimensions, form, and thickness of the cuprous oxide layer, and that these are influenced by the length of heating time, the temperature of heating, the temperature and time of cooling, the thickness and purity of the copper used, and the amount of rolling that has been given to the copper; but as yet there is no data published as to the kind and extent of the influence exerted by these preparation conditions.

From the fact that no derived equation gives the current-voltage characteristic of copper oxide rectifiers throughout the whole voltage range, it would seem that the rectifier current is probably composed of several components. Perhaps one of these components will predominate over one part of the voltage range, and another will produce the effective component of the current at some other part of the voltage range.

In Appendix II, Figures 31 to 50 inclusive, are given the logI-logE graphs for the forward currents of all the rectifiers with reduced cuprous electrodes which are listed in the Tables 3 and 4. The fact that, for sixty-six rectifiers made under a wide diversity of conditions, all points of the logI-log E curves deviate from straight lines only by amounts which are to be accounted for in the experimental error establishes the fact that for the rectifiers the current-voltage function in the range of two to twenty volts is given by the equation

$$I = CE^{D}. \tag{9}$$

The equation, Equation 2, derived by Wagner for the current-voltage function of the copper oxide rectifier is similar in form to Equation 3 which was formulated by Nordheim.

$$\frac{i}{q} = K_2 e(\epsilon^{\frac{eV}{KT}} -1) \tag{2}$$

$$I = DC\sigma(\epsilon^{\frac{\phi}{KT}} -1) \tag{3}$$

ϵ is the natural logarithm base, and V and ϕ represent the voltage drop applied to the rectifier. The general form of these equations is

$$I = M(\epsilon^{NE} -1) \tag{11}$$

where M and N are constants.

Substituting the value of current in Equation 9 into Equation 11 gives

$$\log\left(\frac{CE^{D} - M}{M}\right) = NE \tag{12}$$

Equation 12 is not an identity for all values of the voltage E. Therefore Equation 11 cannot be made identical with Equation 9, and from that it follows that the functions derived by Wagner and Nordheim do not hold for the forward current in the range of three to twenty volts for rectifiers which have been quenched in methyl alcohol solutions.

Similarly it is to be shown that the equations of van Geel and Wilson do not hold for the forward current of the given rectifiers in the stated voltage range. The equations of van Geel are

$$I = AE^{2}\epsilon^{-\frac{B}{E}}, \tag{4}$$

and $$I = CE^{3/2} \text{ for conditions of space charge.} \tag{5}$$

Substituting Equation 4 in Equation 9 gives

$$CE^{D} = AE^{2}\epsilon^{-\frac{B}{E}} \tag{13}$$

or $$\frac{CE^{D/2}}{A} = \epsilon^{-\frac{B}{E}} \tag{14}$$

which is not an identity for all values of voltage. Equations 5 and 9 are identical only if $D = 1.5$. The value of D, however, was found to be variable, but for the rectifiers examined it was never as large as 1.5. Most of the rectifiers investigated had values of D between 1.150 and 1.250. Consequently Equations 4 and 5 are not sufficient for the forward current of the rectifiers studied.

To test the validity of Wilson's equation, Equation 6, it was substituted into Equation 9:

$$CE^{D} = K_1 \left[\epsilon^{\alpha K_2 E} - \epsilon^{-(1-\alpha) K_2 E} \right] \qquad (15)$$

Equation 15 is not an identity for all values of voltage, and it must be rejected for the forward currents of the rectifiers which were investigated in the voltage range of two to twenty volts.

That the equations of Wagner and Nordheim do not hold for the reverse currents is apparent from an observation of the reverse current curves of copper oxide rectifiers. In all cases with increasing voltage both the current and the rate of current increase become continually larger. For negative values of the voltage E in Equation 11, which is the general form of Wagner's and Nordheim's equations, the current is seen to approach the constant value M as a limit.

The second equation derived by van Geel, Equation 5, may be seen to be incorrect for the rectifiers considered by reference to the curves *b* of Figures 6 and 8. Here are plotted the logI-logE curves of the reverse current of two rectifiers. Should Equation 5 be correct, these points would be required to fall along a straight line whose slope would have the value of three-halves. This was not the case for any of the rectifiers considered in the present investigation.

Except for the presence of a slight additional saturation current at the lower voltages, within the voltage range of two to thirty volts for copper oxide rectifiers having reduced cuprous oxide electrodes, the tabulated data of Appendix I shows that the reverse current is represented by Equation 10, where A and B are constants.

$$I = AE + BE^2 \tag{10}$$

Substituting van Geel's first equation, Equation 4, and Wilson's equation, Equation 6, into Equation 10 gives Equations 16 and 17 respectively:

$$AE + BE^2 = A_1 E^2 \epsilon^{\frac{-B_1}{E}} \tag{16}$$

$$AE + BE^2 = K_1 \left[\epsilon^{\alpha K_2 E} - \epsilon^{-(1-\alpha) K_2 E} \right] \tag{17}$$

Neither Equation 16 nor Equation 17 is an identity for all values of the voltage E, consequently it is concluded that Equations 4 and 6 do not apply to the rectifier conditions specified.

The fact that two rectifiers formed on the same piece of copper may have a wide difference in conduction and rectification ratio is apparent from some of the data given in Appendix I. (For example compare the rectifiers 103A and 103B.) This difference may be due to the slight bending of the copper of the rectifier segment as it was quenched, or it may be caused by a difference in the amount of etching the two sides experienced previous to the heating. Again some slight incident in its preparation, such as its falling with one side downward into the cooling bath could easily be sufficient to account for a large difference in the rectifying properties of the two sides. The experience of the present investigation leads to the conclusion that the physical conditions in the preparation of cuprous oxide rectifiers are numerous and varied, but they must all be accounted for in a quantitative manner before a quantitative theory of the rectifier can be proposed or justified. The investigation recorded herein is still in the qualitative field, but it is a definite step toward the quantitative treatment of the subject.

V. CONCLUSIONS

The data presented in this investigation prove the following:

1. For the voltage range of two to twenty volts with copper oxide rectifiers having reduced cuprous oxide electrodes, the forward current at 32°C. is given by the equation

$$I = CE^{D}, \qquad (9)$$

where C and D are constants whose values can be determined from the current-voltage characteristics of the individual rectifiers.

2. Within the voltage range of two to thirty volts with copper oxide rectifiers having reduced cuprous oxide electrodes, the reverse current at 32°C. is given by the equation

$$I = AE + BE^{2}, \qquad (10)$$

where A and B are constants whose values can be determined from the current-voltage characteristics of the individual rectifiers. The only deviation of the current from value indicated by Equation 10 is produced by the presence at lower voltages of a small saturation current which has also been noted by van Geel (van Geel 7).

3. Within the voltage range of two to twenty volts for copper oxide rectifiers having reduced cuprous oxide electrodes, the different equations derived respectively by Wagner, Nordheim, van Geel, and

Wilson all fail to express the true current-voltage characteristic of the forward current.

4. Within the voltage range of two to thirty volts for copper oxide rectifiers having reduced cuprous oxide electrodes, the different equations, derived respectively by Wagner, Nordheim, van Geel, and Wilson fail to express the true current-voltage characteristic for the reverse current.

5. For the rectifiers with reduced cuprous oxide electrodes, the constant $\underline{A}$ of Equation 10 has a definite qualitative variation, as shown by Figure 12, with the time used in the heating of the rectifier.

6. For the rectifiers with reduced cuprous oxide electrodes, the constant $\underline{B}$ of Equation 10 has a definite qualitative variation, as shown by Figure 13, with the time used in the heating of the rectifier.

7. For the rectifiers with reduced cuprous oxide electrodes, the constant $\underline{C}$ of Equation 9 has a definite qualitative variation, as shown by Figure 14, with the time used in the heating of the rectifier.

8. For the rectifiers with reduced cuprous oxide electrodes, the constant $\underline{A}$ of Equation 10 has a definite qualitative variation, as shown by Figures 15, 16, and 17, with the temperature of the quenching bath.

9. For the rectifiers with reduced cuprous oxide electrodes, the constant $\underline{B}$ of Equation 10 has a definite qualitative variation, as shown by Figures 18, 19, and 20, with the temperature of the quenching

bath.

10. For the rectifiers with reduced cuprous oxide electrodes, the constant C of Equation 9 has a definite qualitative variation, as shown by Figures 21, 22, and 23, with the temperature of the quenching bath when this temperature is above 10°C.

11. For copper oxide rectifiers quenched in water and in methyl alcohol, the rectification ratio at 7.50 volts has a definite qualitative variation, as shown by Figures 24, 25, 26, and 27, with the temperature of the quenching bath.

12. (a) For the conditions specified in part 11, immediately above, for each quenching solution there is an optimum temperature which gives the highest rectification ratio.

(b) The optimum temperature of the quenching solution varies inversely with the proportion of the methyl alcohol contained in it as shown by Table 8.

13. For rectifiers quenched in methyl alcohol solutions, the rectification ratio at 7.50 volts has a definite qualitative variation, as shown by Figure 28, with the time used in heating the rectifier.

14. Jacquelet's theory explains the phenomena of the variation of the optimum quenching temperature with the proportion of the methyl alcohol contained in the quenching bath.

15. Jacquelet's theory is supported by the change in rectification ratio with the bending of the rectifier unit.

16. Jacquelet's statement that rectifiers with reduced cuprous oxide electrodes have contact resistances invariant with pressure is corroborated.

VI. APPENDICES

Appendix I

In Appendix I are given the data of preparation of each of the sixty-six rectifiers whose characteristics are represented in Figures 12 to 23. For each observed voltage $\underline{E}$ there are recorded the corresponding observed current $\underline{I}$, in milliamperes, and the value $\underline{I_c}$, in milliamperes, which was calculated for that voltage by the use of the derived values of the constants $\underline{A}$, $\underline{B}$, $\underline{C}$, and $\underline{D}$ in the given empirical equations.

It is to be noticed that for both the forward and reverse characteristics the last one or two observed currents are higher than the calculated values due to the heating of the rectifier unit. Also the first two or three observed reverse currents are high. This effect is attributed to the predominance, at low voltages, of the saturation current which was noticed by van Geel.

Specimens 88 and 115 were spoiled in the preparation process and are not included in these tables. Specimens 90, 91, 92, 111, 112, 113, and 114 were quenched in water, and they also are omitted. Rectifiers 95B, 99B, 101A, and 106B developed short circuits while being tested; therefore their characteristics could not be determined.

SPECIMEN 82A

Time of heating	180 Seconds
Quenching temperature	-1.5° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 9

Reverse Direction $I_c = AE + BE^2$

$A = 0.8528$
$B = 0.1512$

E volts	I ma.	I_c ma.
1.22	1.8	1.26
3.76	6.4	5.36
6.15	12.1	10.97
9.88	23.2	23.49
14.35	42.9	43.38
20.45	80.7	80.69
26.45	128.4	128.36

Table 10

Forward Direction $I_c = CE^D$

$C = 5.1097$
$D = 1.354$

E volts	I ma.	I_c ma.
1.06	6.0	5.58
2.96	22.25	22.23
5.56	51.6	52.17
10.92	130.3	130.04
15.39	222.0	206.79
20.35	371.7	302.14

SPECIMEN 82B

Time of heating	180 Seconds
Quenching temperature	-1.5° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 11

Reverse Direction $I_c = AE + BE^2$

$A = 0.7827$
$B = 0.1675$

E volts	I ma.	I_c ma.
1.22	1.8	1.20
3.76	6.4	5.31
6.15	12.4	11.15
9.87	23.8	24.37
14.25	44.5	45.17
20.25	84.7	84.53
26.14	135.0	134.91

Table 12

Forward Direction $I_c = CE^D$

$C = 5.4830$
$D = 1.2509$

E volts	I ma.	I_c ma.
1.07	5.9	5.98
3.02	21.15	21.88
5.75	48.0	48.91
11.23	113.5	113.00
15.79	187.7	173.04
21.22	296.0	250.52

SPECIMEN 83A

Time of heating	180 Seconds
Quenching temperature	3.0° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 13

Reverse Direction $I_c = AE + BE^2$

$A = 0.6461$
$B = 0.0722$

E volts	I ma.	I_c ma.
1.25	1.17	0.92
3.89	4.16	3.61
6.43	7.85	7.10
11.54	17.32	17.07
16.47	29.46	30.23
22.30	49.93	50.31
29.08	80.23	79.84

Table 14

Forward Direction $I_c = CE^D$

$C = 3.0818$
$D = 1.2679$

E volts	I ma.	I_c ma.
1.17	3.92	3.76
3.38	14.49	14.42
6.55	32.85	33.41
11.68	69.8	69.56
16.63	115.3	108.88
22.67	184.5	161.27

SPECIMEN 83B

Time of heating	180 Seconds
Quenching temperature	3.0° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 15

Reverse Direction $I_c = AE + BE^2$

A = 0.4373
B = 0.1016

E volts	I ma.	I_c ma.
1.25	1.26	0.71
3.88	4.42	3.23
6.40	8.40	6.96
11.48	18.93	18.41
16.27	33.30	34.01
21.89	57.50	58.26
28.33	94.20	93.93

Table 16

Forward Direction $I_c = CE^D$

C = 6.4788
D = 1.263

E volts	I ma.	I_c ma.
1.04	6.75	6.80
2.88	24.65	24.62
5.47	54.92	53.90
11.00	134.7	133.92
15.57	218.0	207.65
20.98	343.7	302.62

SPECIMEN 84A

Time of heating	180 Seconds
Quenching temperature	8.4° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 17

Reverse Direction $I_c = AE + BE^2$

A = 1.1775
B = 0.0979

E volts	I ma.	I_c ma.
1.21	2.26	1.57
3.77	6.90	7.01
6.22	12.25	11.11
10.02	21.68	21.63
14.75	37.90	39.36
20.28	63.24	64.14
27.67	108.15	107.54

Table 18

Forward Direction $I_c = CE^D$

C = 7.2830
D = 1.2574

E volts	I ma.	I_c ma.
1.02	7.73	7.50
2.77	26.20	26.22
5.28	59.07	58.99
10.83	145.5	145.59
15.50	240.2	233.93
20.44	390.8	323.66

SPECIMEN 84B

Time of heating 180 Seconds

Quenching temperature 8.4° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 19

Reverse Direction $I_e = AE + BE^2$

$A = 1.1204$
$B = 0.0986$

E volts	I ma.	I_e ma.
1.21	2.26	1.50
3.77	6.80	5.63
6.24	11.95	10.84
10.02	21.28	21.14
14.78	37.19	38.12
20.30	62.60	63.41
27.71	107.4	106.80

Table 20

Forward Direction $I_e = CE^D$

$C = 9.5016$
$D = 1.2044$

E volts	I ma.	I_e ma.
0.93	8.71	8.74
2.60	30.16	30.03
4.96	65.68	65.37
10.72	165.5	165.42
15.18	265.0	251.51
20.20	415.5	354.79

SPECIMEN 85A

Time of heating 180 Seconds

Quenching temperature 8.5° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 21

Reverse Direction $I_e = AE + BE^2$

$A = 0.9915$
$B = 0.0850$

E volts	I ma.	I_e ma.
1.32	1.83	1.46
4.07	6.32	5.44
6.54	11.45	10.12
10.83	20.77	20.71
15.88	36.46	37.19
21.52	59.77	60.72
29.08	101.4	100.75

Table 22

Forward Direction $I = CE^D$

$C = 6.1962$
$D = 1.1928$

E volts	I ma.	I_e ma.
1.10	6.93	6.94
3.15	24.73	24.35
6.12	53.68	53.78
12.02	118.7	120.27
17.08	184.7	182.91
22.91	274.3	259.62

SPECIMEN 85B

Time of heating 180 Seconds

Quenching temperature 8.5° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 23

Reverse Direction $I_e = AE + BE^2$

$A = 1.0715$
$B = 0.0849$

E volts	I ma.	I_e ma.
1.32	1.63	1.56
4.07	6.49	5.77
6.53	11.90	10.62
10.80	21.72	21.48
15.84	37.48	38.28
21.47	61.22	62.15
29.08	103.6	102.97

Table 24

Forward Direction $I_e = CE^D$

$C = 5.0766$
$D = 1.2414$

E volts	I ma.	I_e ma.
1.14	6.31	5.99
3.29	22.23	22.29
6.24	49.50	49.29
12.06	111.5	111.69
17.12	180.3	172.50
22.82	281.7	246.47

SPECIMEN 86A

Time of heating 180 Seconds

Quenching temperature 8.5° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 25

Reverse Direction $I_e = AE + BE^2$

A = 1.2012
B = 0.0939

E volts	I ma.	I_e ma.
1.31	2.16	1.74
4.03	7.25	6.37
6.44	12.75	11.63
10.40	22.70	22.65
15.19	39.30	39.92
20.56	63.42	64.40
27.75	106.3	105.66

Table 26

Forward Direction $I = CE^D$

C = 5.5559
D = 1.2672

E volts	I ma.	I_e ma.
1.10	6.31	6.28
3.11	23.12	23.39
5.89	52.90	52.56
11.40	131.3	121.34
16.02	222.0	182.51
21.23	355.2	266.85

SPECIMEN 86B

Time of heating 180 Seconds

Quenching temperature 8.5° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 27

Reverse Direction $I_e = AE + BE^2$

A = 1.2445
B = 0.0825

E volts	I ma.	I_e ma.
1.31	2.16	1.77
4.05	7.10	6.38
6.44	12.25	11.46
10.43	21.88	21.96
15.22	37.65	38.06
20.71	60.55	61.17
28.09	100.6	100.08

Table 28

Forward Direction $I_e = CE^D$

C = 6.4733
D = 1.1865

E volts	I ma.	I_e ma.
1.07	6.90	6.99
3.04	24.47	24.21
5.98	53.14	54.05
11.53	117.2	117.75
16.47	181.7	179.76
22.10	270.6	254.85

SPECIMEN 87A

Time of heating 180 Seconds

Quenching temperature 8.9° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 29

Reverse Direction $I_e = AE + BE^2$

A = 1.0631
B = 0.0712

E volts	I ma.	I_e ma.
1.29	1.66	1.49
3.97	5.40	5.29
6.57	9.98	10.06
10.52	18.13	19.15
15.43	31.56	33.35
21.01	52.90	53.74
28.54	90.2	88.30

Table 30

Forward Direction $I_e = CE^D$

C = 6.2209
D = 1.1951

E volts	I ma.	I_e ma.
1.07	6.70	6.72
3.07	23.75	23.76
5.92	51.82	52.13
11.53	114.8	115.58
16.46	179.7	176.86
22.10	268.3	251.51

SPECIMEN 87B

Time of heating	180 Seconds
Quenching temperature	8.9° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 31

Reverse Direction $I_o = AE + BE^2$

$A = 0.9466$
$B = 0.0750$

E volts	I ma.	I_o ma.
1.29	1.66	1.35
3.97	5.49	4.88
6.57	10.00	9.45
10.48	18.30	18.15
15.43	31.93	32.45
21.05	52.53	53.14
28.58	88.7	88.28

Table 32

Forward Direction $I_o = CE^D$

$C = 6.1685$
$D = 1.1906$

E volts	I ma.	I_o ma.
1.07	6.70	6.66
3.07	23.75	23.44
5.94	51.55	51.51
11.60	111.3	114.18
16.50	171.3	173.64
22.24	252.6	241.62

SPECIMEN 89A

Time of heating 180 Seconds

Quenching temperature 8.7° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 33

Reverse Direction $I_c = AE + BE^2$

A = 1.2805
B = 0.0993

E volts	I ma.	I_c ma.
1.29	2.12	1.82
3.87	7.20	6.44
6.37	13.11	12.19
10.13	23.23	23.16
14.80	40.40	40.70
20.28	66.70	66.80
27.47	110.7	110.09

Table 34

Forward Direction $I_c = CE^D$

C = 8.3139
D = 1.1472

E volts	I ma.	I_c ma.	E volts	I ma.	I_c ma.
0.97	7.5	8.06	12.07	141.0	144.83
2.73	26.3	26.27	14.77	182.	182.49
4.48	46.3	46.47	17.40	220.	220.24
6.15	67.0	66.84	19.97	269.	257.98
7.85	88.6	88.38	22.47	318.	295.39
9.46	110.3	109.49			

SPECIMEN 89B

Time of heating 180 Seconds

Quenching temperature 8.7° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 36

Reverse Direction $I_e = AE + BE^2$

$A = 0.9892$
$B = 0.1089$

E volts	I ma.	I_e ma.
1.30	1.89	1.47
3.90	6.65	5.53
6.42	11.42	11.98
10.21	21.76	21.65
14.21	38.80	39.17
20.34	64.49	65.67
27.47	110.7	110.08

Table 36

Forward Direction $I_c = CE^D$

$C = 8.6824$
$D = 1.1656$

E volts	I ma.	I_c ma.	E volts	I ma.	I_c ma.
0.96	7.6	8.25	12.07	155.	158.28
2.69	27.2	27.52	14.77	198.	195.70
4.38	48.2	48.53	17.37	246.	241.98
6.05	70.1	70.76	19.94	296.	284.17
7.70	92.7	93.77	22.47	345.	326.63
9.23	116.3	115.62			

SPECIMEN 93A

Time of heating **150 Seconds**

Quenching temperature **9.0° Centigrade**

Quenching solution **12.5 cc. Methyl alcohol in 487.5 cc. water**

Table 37

Reverse Direction $I_e = AE + BE^2$

$A = 0.6100$
$B = 0.0188$

E volts	I ma.	I_e ma.
1.35	0.83	0.86
4.07	2.59	2.80
6.78	4.82	4.98
10.79	8.54	8.77
16.06	14.65	14.65
22.28	23.38	22.91
33.85	42.03	42.19

Table 38

Forward Direction $I_e = CE^D$

$C = 4.1660$
$D = 1.1532$

E volts	I ma.	I_e ma.
1.16	4.82	4.95
3.36	18.73	16.83
6.59	37.15	36.57
10.61	62.8	63.34
17.03	109.0	109.26
23.19	159.6	156.02
30.42	244.3	213.33

SPECIMEN 93B

Time of heating	150 Seconds
Quenching temperature	9.0° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 39

Reverse Direction $I_c = AE + BE^2$

$A = 0.6942$
$B = 0.0393$

E volts	I ma.	I_c ma.
1.34	1.16	1.00
4.02	3.68	3.43
6.65	6.82	6.35
10.66	11.92	11.86
15.75	20.18	20.67
21.42	32.85	32.88
30.07	56.49	56.37

Table 40

Forward Direction $I_c = CE^D$

$C = 5.2533$
$D = 1.1216$

E volts	I ma.	I_c ma.
1.12	5.38	5.99
3.24	19.70	19.65
6.34	41.88	41.71
10.51	72.7	73.49
16.85	125.2	124.77
22.88	183.0	175.88

SPECIMEN 94A

Time of heating 120 Seconds

Quenching temperature 9.0° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 41

Reverse Direction $I_c = AE + BE^2$

$A = 0.5018$
$B = 0.0412$

E volts	I ma.	I_c ma.
1.35	0.93	0.75
4.06	3.16	2.72
6.71	5.82	5.22
10.71	10.48	10.10
15.91	18.25	18.40
22.06	30.25	31.10
30.36	53.53	53.17

Table 42

Forward Direction $I_c = CE^D$

$C = 4.4036$
$D = 1.1027$

E volts	I ma.	I_c ma.
1.16	4.92	5.20
3.38	16.88	16.87
6.63	35.65	35.45
11.00	61.50	61.96
16.12	94.5	94.41
23.30	145.5	137.35
30.78	207.5	192.44

SPECIMEN 94B

Time of heating 120 Seconds

Quenching temperature 9.0° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 43

Reverse Direction $I_c = AE + BE^2$ $A = 0.4177$

$B = 0.0221$

E volts	I ma.	I_c ma.
1.37	0.66	0.61
4.11	2.16	2.09
6.79	3.93	3.86
10.89	7.24	7.17
16.21	12.48	12.59
22.46	20.49	20.55
31.24	34.69	34.65

Table 44

Forward Direction $I_c = CE^D$ $C = 1.9500$

$D = 1.0951$

E volts	I ma.	I_c ma.
1.29	2.49	2.57
3.80	8.48	8.42
7.63	17.83	18.06
12.48	30.40	30.95
18.46	47.27	47.50
25.80	68.22	67.61
32.02	87.8	86.81
39.90	114.	110.47

SPECIMEN 95A

Time of heating 210 Seconds

Quenching temperature 9.0° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 45

Reverse Direction $I_c = AE + BE^2$

A = 0.7904
B = 0.1069

E volts	I ma.	I_c ma.
1.32	1.83	1.23
3.91	6.15	4.76
6.42	11.13	9.57
10.29	20.19	19.67
15.07	35.67	36.65
20.56	60.43	62.29
27.67	106.4	105.27

Table 46

Forward Direction $I_c = CE^D$

C = 26.8105
D = 1.1658

E volts	I ma.	I_c ma.
0.70	14.18	17.69
1.73	50.13	50.94
3.20	105.1	104.02
9.02	346.0	348.27
12.59	518.7	513.69
21.24	998.	945.07

SPECIMEN 96A

Time of heating	300 Seconds
Quenching temperature	9.0° Centigrade
Quenching solution	12.5 cc.Methyl alcohol in 487.5 cc. water

Table 47

Reverse Direction $I_e = AE + BE^2$

$A = 0.5207$
$B = 0.2808$

E volts	I ma.	I_e ma.
1.28	2.26	1.13
3.81	7.65	6.58
6.21	14.97	14.06
9.72	30.10	31.60
13.76	59.44	69.29
18.25	103.8	101.48

Table 48

Forward Direction $I_e = CE^D$

$C = 18.9683$
$D = 1.1529$

E volts	I ma.	I_e ma.
0.79	12.23	14.61
2.06	43.40	43.44
3.89	90.8	90.86
9.81	262.3	263.85
12.90	361.8	361.73
18.61	565.8	551.98

SPECIMEN 96B

Time of heating	300 Seconds
Quenching temperature	9.0° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 49

Reverse Direction $I_c = AE + BE^2$

$A = 0.6015$
$B = 0.3169$

E volts	I ma.	I_c ma.
1.27	2.39	1.15
3.79	7.98	6.45
6.15	16.15	15.07
9.59	32.52	33.95
13.52	63.48	64.70
17.89	111.3	110.39

Table 50

Forward Direction $I_c = CE^D$

$C = 17.8477$
$D = 1.1889$

E volts	I ma.	I_c ma.
0.84	11.40	14.46
2.08	42.75	42.66
3.90	90.7	89.95
9.81	266.0	269.50
13.80	405.5	404.43
18.40	587.8	569.34

SPECIMEN 97A

Time of heating	450 Seconds
Quenching temperature	9.0^{0} Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 51

Reverse Direction $I_c = AE + BE^2$

$A = 0.1493$
$B = 0.3743$

E volts	I ma.	I_c ma.
1.28	2.09	0.81
3.81	7.73	6.00
6.16	16.07	15.12
9.50	34.48	35.20
13.35	68.10	68.69
17.56	117.5	118.03
27.16	280.5	280.14

Table 52

Forward Direction $I_c = CE^D$

$C = 8.8213$
$D = 1.2194$

E volts	I ma.	I_c ma.
0.98	8.53	8.56
2.69	29.77	29.46
5.20	65.42	65.90
10.88	160.0	162.05
15.43	250.5	248.14
20.76	373.7	356.29

SPECIMEN 97B

Time of heating 450 Seconds

Quenching temperature 9.0° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 53

Reverse Direction $I_c = AE + BE^2$ $A = 0.7726$
$B = 0.2571$

E volts	I ma.	I_c ma.
1.31	1.66	1.45
3.88	6.48	6.87
6.27	14.12	14.95
9.66	30.25	31.46
13.76	59.83	59.31
18.35	102.2	100.75
27.78	219.3	219.87

Table 54

Forward Direction $I_c = CE^D$ $C = 6.0575$
$D = 1.1787$

E volts	I ma.	I_c ma.
1.09	6.42	6.71
3.05	22.56	22.53
5.93	49.33	49.37
11.41	106.0	106.79
16.37	163.5	163.43
22.19	242.0	233.88

SPECIMEN 98A

Time of heating	360 Seconds
Quenching temperature	9.0° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 55

Reverse Direction $I_c = AE + BE^2$

$A = 0.1512$
$B = 0.4209$

E volts	I ma.	I_c ma.
1.29	1.99	0.89
3.79	7.65	6.62
6.10	16.71	16.58
9.36	37.13	38.29
13.08	73.78	73.99
17.11	126.3	125.80
26.84	307.2	307.26

Table 56

Forward Direction $I_c = CE^D$

$C = 11.1971$
$D = 1.2183$

E volts	I ma.	I_c ma.
0.87	9.4	9.41
2.41	32.6	32.70
3.92	58.0	59.12
5.23	84.2	84.09
6.80	115.0	115.67
11.97	235.0	230.44
14.73	300.	296.72
17.30	359.	360.88
19.85	441.	426.72
22.47	509.	496.37
25.00	603.	565.23

SPECIMEN 98B

Time of heating 360 Seconds

Quenching temperature 9.0° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 57

Reverse Direction $I_c = AE + BE^2$

$A = 0.6384$
$B = 0.4302$

E Volts	I ma.	I_c ma.
1.25	2.59	1.47
3.70	9.58	8.25
5.95	19.68	19.03
9.15	41.18	41.86
12.90	78.7	79.82
16.80	132.6	132.14
26.72	324.3	324.20

Table 58

Forward Direction $I_c = CE^D$

$C = 7.2795$
$D = 1.2188$

E volts	I ma.	I_c ma.
0.95	7.2	6.84
2.78	25.4	25.33
4.51	45.6	45.64
6.10	65.4	65.95
7.75	88.8	88.30
12.05	149.1	151.20
14.76	190.	193.63
17.42	231.	236.95
19.97	291.	279.90
22.52	344.	324.08
25.10	408.	369.87

SPECIMEN 99A

Time of heating 250 Seconds

Quenching temperature 8.7° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 59

Reverse Direction $I_c = AE + BE^2$ $A = 1.0396$
$B = 0.1764$

E volts	I ma.	I_c ma.
1.27	2.43	1.60
3.81	7.90	6.52
6.25	14.45	13.39
9.92	26.30	27.67
14.28	49.98	50.81
19.26	86.1	85.45
28.28	189.0	170.46

Table 60

Forward Direction $I_c = CE^D$ $C = 19.3040$
$D = 1.1525$

E volts	I ma.	I_c ma.
0.79	12.42	14.67
2.04	43.83	43.82
3.84	92.1	91.11
9.86	267.5	269.87
13.93	401.2	401.91
18.60	577.2	560.78

SPECIMEN 100A

Time of heating 180 Seconds

Quenching temperature -4° Centigrade

Quenching solution 25 cc. Methyl alcohol in 475 cc. water

Table 61

Reverse Direction $I_c = AE + BE^2$

$A = 0.8239$
$B = 0.1592$

E volts	I ma.	I_c ma.
1.29	1.99	1.33
3.84	7.31	5.51
6.30	13.54	11.51
10.01	24.85	24.20
14.56	44.60	45.74
19.67	75.70	77.79
28.72	156.0	154.94

Table 62

Forward Direction $I_c = CE^D$

$C = 16.0277$
$D = 1.1988$

E volts	I ma.	I_c ma.
0.84	11.63	13.30
2.18	41.03	40.87
4.10	87.0	87.03
10.01	250.7	253.72
14.08	384.0	381.78
18.82	562.3	540.61

SPECIMEN 100B

Time of heating	180 Seconds
Quenching temperature	-4° Centigrade
Quenching solution	25 cc. Methyl alcohol in 475 cc. water

Table 63

Reverse Direction $I_c = AE + BE^2$

$A = 0.8803$
$B = 0.1445$

E volts	I ma.	I_c ma.
1.29	1.99	1.38
3.85	7.03	5.53
6.32	13.03	11.33
10.05	24.05	23.44
14.63	43.10	43.80
19.97	73.03	75.19
28.80	146.2	145.17

Table 64

Forward Direction $I_c = CE^D$

$C = 10.6768$
$D = 1.2159$

E volts	I ma.	I_c ma.
0.96	8.86	10.14
2.54	33.47	33.20
4.81	72.53	72.07
10.67	185.3	189.94
15.05	291.2	288.59
20.19	434.5	412.44

SPECIMEN 101B

Time of heating 180 Seconds

Quenching temperature 4° Centigrade

Quenching solution 25 cc. Methyl alcohol in 475 cc. water

Table 65

Reverse Direction $I_o = AE + BE^2$

$A = 1.0176$
$B = 0.0849$

E volts	I ma.	I_o ma.
1.29	1.73	1.45
3.89	6.15	5.24
6.41	11.13	10.01
10.32	20.00	19.54
15.23	34.47	35.18
20.91	57.13	58.38
28.47	98.5	97.76

Table 66

Forward Direction $I_o = CE^D$

$C = 11.3995$
$D = 1.1910$

E volts	I ma.	I_o ma.
0.92	9.75	10.26
2.50	34.37	33.97
4.75	73.82	72.96
10.79	189.0	193.79
15.23	292.0	292.06
20.40	434.5	413.69

SPECIMEN 102A

Time of heating	180 Seconds
Quenching temperature	9.0° Centigrade
Quenching solution	25 cc. Methyl alcohol in 475 cc. water

Table 67

Reverse Direction $I_c = AE + BE^2$

$A = 0.9537$
$B = 0.0743$

E volts	I ma.	I_c ma.
1.32	1.59	1.39
3.93	5.49	4.90
6.49	9.93	9.32
10.39	18.10	17.93
15.27	31.85	31.88
21.23	52.60	53.72
28.93	90.3	89.75

Table 68

Forward Direction $I_c = CE^D$

$C = 6.3015$
$D = 1.1741$

E volts	I ma.	I_c ma.
1.08	6.70	6.87
3.05	23.33	23.32
5.88	50.48	50.41
11.50	109.7	110.84
16.43	168.5	168.57
22.26	249.3	240.78

SPECIMEN 102B

Time of heating	180 Seconds
Quenching temperature	9.0° Centigrade
Quenching solution	25 cc. Methyl alcohol in 475 cc. water

Table 69

Reverse Direction $I_c = AE + BE^2$ $A = 1.2521$ $B = 0.0725$

E volts	I ma.	I_c ma.
1.30	1.83	1.75
3.90	6.32	5.99
6.41	11.55	11.00
10.26	20.60	20.48
15.12	35.02	35.50
20.86	57.40	57.65
28.60	95.3	95.08

Table 70

Forward Direction $I_c = CE^D$ $C = 7.5960$ $D = 1.1558$

E volts	I ma.	I_c ma.
1.02	8.53	7.75
2.90	26.00	25.98
5.58	56.97	55.37
11.36	125.0	126.02
16.23	190.3	190.36
22.10	277.3	271.94

SPECIMEN 103A

Time of heating 180 Seconds

Quenching temperature -5.2° Centigrade

Quenching solution 50 cc. Methyl alcohol in 450 cc. water

Table 71

Reverse Direction $I_c = AE + BE^2$

$A = 1.0372$
$B = 0.0994$

E volts	I ma.	I_c ma.
1.31	1.83	1.53
3.89	6.45	5.54
6.39	11.90	10.69
11.40	25.25	24.74
16.18	42.47	42.80
21.64	68.14	68.99
29.38	116.8	116.28

Table 72

Forward Direction $I_c = CE^D$

$C = 5.7410$
$D = 1.2278$

E volts	I ma.	I_c ma.
1.08	6.31	6.32
3.07	22.88	22.73
5.89	50.32	50.64
11.44	112.5	114.42
16.32	177.0	177.00
22.17	267.0	257.83
29.02	396.0	358.87

SPECIMEN 103B

Time of heating 180 Seconds

Quenching temperature -5.2° Centigrade

Quenching solution 50 cc. Methyl alcohol in 450 cc. water

Table 73

Reverse Direction $I_c = AE + BE^2$

$A = 0.9982$
$B = 0.1428$

E volts	I ma.	I_c ma.
1.29	2.26	1.48
3.82	7.65	5.90
6.27	14.10	11.87
11.30	29.53	29.51
15.75	50.48	51.14
20.99	81.6	83.86
28.97	150.0	148.76

Table 74

Forward Direction $I_c = CE^D$

$C = 18.3829$
$D = 1.1951$

E volts	I ma.	I_c ma.
0.80	12.40	14.15
2.06	43.52	43.57
3.85	92.4	92.10
9.76	279.3	279.79
13.66	428.5	418.21
18.31	629.0	605.72

SPECIMEN 104A

Time of heating	180 Seconds
Quenching temperature	0.0° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 75

Reverse Direction $I_c = AE + BE^2$

$A = 0.6617$
$B = 0.1091$

E volts	I ma.	I_c ma.
1.31	1.66	1.06
3.93	5.63	4.22
6.47	10.93	8.85
11.53	22.32	22.14
16.30	38.82	39.78
21.79	64.45	66.24
29.44	115.2	114.08

Table 76

Forward Direction $I_c = CE^D$

$C = 20.7755$
$D = 1.2004$

E volts	I ma.	I_c ma.
0.76	13.03	14.96
1.94	46.03	46.12
3.61	97.8	97.02
9.49	309.5	309.56
13.15	477.0	457.89
17.54	698.0	646.95

SPECIMEN 104B

Time of heating 180 Seconds

Quenching temperature 0.0° Centigrade

Quenching solution 50 cc. Methyl alcohol in 450 cc. water

Table 77

Reverse Direction $I_c = AE + BE^2$ $A = 0.4556$ $B = 0.1091$

E volts	I ma.	I_c ma.
1.31	1.39	0.79
3.96	4.98	3.51
6.52	9.45	7.61
11.60	20.60	19.96
16.42	35.95	36.85
22.08	60.92	63.24
29.54	110.0	108.64

Table 78

Forward Direction $I_c = CE^D$ $C = 18.0252$ $D = 1.1825$

E volts	I ma.	I_c ma.
0.81	12.12	14.06
2.09	43.10	43.08
3.91	92.2	90.49
9.92	271.8	271.82
13.91	410.7	405.39
18.62	596.3	572.30

SPECIMEN 105A

Time of heating 180 Seconds

Quenching temperature 5.0° Centigrade

Quenching solution 50 cc. Methyl alcohol in 450 cc. water

Table 79

Reverse Direction $I_e = AE + BE^2$

$A = 1.1568$
$B = 0.0965$

E volts	I ma.	I_e ma.
1.30	2.06	1.67
3.87	7.00	5.92
6.36	12.58	11.26
11.23	25.45	25.16
16.14	43.30	43.82
21.68	68.88	70.45
29.38	118.2	117.31

Table 80

Forward Direction $I_e = CE^D$

$C = 21.9305$
$D = 1.1622$

E volts	I ma.	I_e ma.
0.63	12.82	12.94
1.96	45.88	48.03
3.63	97.0	98.03
9.55	302.0	301.98
13.32	462.0	444.53
17.70	680.	618.66

SPECIMEN 105B

Time of heating	180 Seconds
Quenching temperature	5.0° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 81

Reverse Direction $I_c = AE + BE^2$

$A = 1.1266$
$B = 0.0985$

E volts	I ma.	I_c ma.
1.30	1.89	1.63
3.87	6.88	5.84
6.37	12.48	11.17
11.33	25.20	25.41
16.12	43.44	43.76
21.65	69.40	70.56
29.38	118.8	118.12

Table 82

Forward Direction $I_c = CE^D$

$C = 8.7712$
$D = 1.1745$

E volts	I ma.	I_c ma.
0.99	8.42	8.68
2.76	28.90	28.94
5.30	63.08	62.19
11.14	146.3	148.76
15.84	225.0	224.98
21.47	333.	321.55

SPECIMEN 106A

Time of heating 180 Seconds

Quenching temperature 10.0° Centigrade

Quenching solution 50 cc. Methyl alcohol in 450 cc. water

Table 83

Reverse Direction $I_c = AE + BE^2$

$A = 1.3013$
$B = 0.0886$

E volts	I ma.	I_c ma.
1.28	2.09	1.81
3.84	7.20	6.30
6.30	12.98	11.71
11.33	25.80	26.11
16.10	43.58	43.91
21.65	68.63	69.69
29.36	115.2	114.55

Table 84

Forward Direction $I_c = CE^D$

$C = 11.1159$
$D = 1.1829$

E volts	I ma.	I_c ma.
0.92	9.50	10.12
2.54	33.48	33.46
4.83	71.87	71.59
10.79	180.0	185.30
15.24	278.8	278.79
20.62	414.3	398.73

SPECIMEN 107 A

Time of heating	180 Seconds
Quenching temperature	-12.0° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 85

Reverse Direction $I_c = AE + BE^2$

$A = 1.0627$
$B = 0.1449$

E volts	I ma.	I_c ma.
1.31	1.93	1.64
3.84	7.20	6.22
6.29	13.48	12.42
11.21	29.23	30.12
15.70	51.50	52.40
20.84	85.7	85.07
28.86	169.0	151.34

Table 86

Forward Direction $I_c = CE^D$

$C = 26.8819$
$D = 1.1931$

E volts	I ma.	I_c ma.
0.70	14.15	17.47
1.70	50.63	50.81
3.13	106.7	104.84
8.95	362.8	367.48
12.48	546.2	546.24
21.34	1050.	1036.03

SPECIMEN 107B

Time of heating	180 Seconds
Quenching temperature	-12.0° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 87

Reverse Direction $I_c = AE + BE^2$

$A = 1.1478$
$B = 0.1375$

E volts	I ma.	I_c ma.
1.29	1.93	1.71
3.84	7.20	6.44
6.29	13.54	12.66
11.21	29.35	30.15
15.73	51.47	52.09
20.88	84.4	83.93
28.93	159.8	148.31

Table 88

Forward Direction $I_c = CE^D$

$C = 21.5965$
$D = 1.2041$

E volts	I ma.	I_c ma.
0.75	13.35	15.33
1.90	46.78	46.86
3.48	99.9	96.97
9.39	320.0	320.28
13.03	475.2	475.12
21.47	903.	867.10

SPECIMEN 108A

Time of heating	180 Seconds
Quenching temperature	0.0° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 89

Reverse Direction $I_c = AE + BE^2$ $A = 0.7998$ $B = 0.0671$

E volts	I ma.	I_c ma.
1.33	1.43	1.18
3.96	4.92	4.22
6.53	8.95	8.09
11.75	18.85	18.66
16.74	31.45	32.20
22.52	51.47	52.07
29.31	81.6	81.10

Table 90

Forward Direction $I_c = CE^D$ $C = 9.2106$ $D = 1.1767$

E volts	I ma.	I_c ma.
0.99	8.42	9.12
2.72	29.90	29.93
5.20	64.63	64.11
11.03	154.0	155.29
15.63	234.0	233.95
21.38	345.3	329.28

SPECIMEN 108B

Time of heating 180 Seconds

Quenching temperature 0.0° Centigrade

Quenching solution 100 cc. Methyl alcohol in 400 cc. water

Table 91

Reverse Direction $I_c = AE + BE^2$

$A = 0.7188$
$B = 0.0630$

E volts	I ma.	I_c ma.
1.33	1.26	1.09
3.97	4.59	3.85
6.56	8.45	7.43
11.80	17.84	17.26
16.81	29.41	29.89
22.65	47.00	48.62
29.59	77.4	76.48

Table 92

Forward Direction $I_c = CE^D$

$C = 6.4139$
$D = 1.1706$

E volts	I ma.	I_c ma.
1.07	6.65	6.93
3.03	23.48	23.47
5.86	51.32	50.80
11.49	110.3	111.79
16.44	170.0	170.03
22.34	256.0	243.40

SPECIMEN 109A

Time of heating 180 Seconds

Quenching temperature 4.5° Centigrade

Quenching solution 100 cc. Methyl alcohol in 400 cc. water

Table 93

Reverse Direction $I_o = AE + BE^2$

$A = 0.6195$
$B = 0.0416$

E volts	I ma.	I_o ma.
1.34	1.00	0.91
4.02	3.56	3.17
6.66	6.49	5.97
12.03	13.52	13.48
17.21	22.70	23.00
23.31	36.67	37.07
30.56	58.18	57.89

Table 94

Forward Direction $I_o = CE^D$

$C = 8.1758$
$D = 1.1775$

E volts	I ma.	I_o ma.
1.01	7.90	8.26
2.81	27.60	27.63
5.39	60.77	59.44
11.24	139.5	141.20
16.02	214.3	214.29
21.51	327.7	303.16

SPECIMEN 109B

Time of heating	180 Seconds
Quenching temperature	4.5° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 95

Reverse Direction $I_o = AE + BE^2$

$A = 0.6646$
$B = 0.0506$

E volts	I ma.	I_o ma.
1.33	1.23	0.97
4.00	4.09	3.47
6.57	7.40	6.55
11.96	15.45	15.19
17.07	24.95	26.10
22.96	41.88	41.94
30.16	66.38	66.08

Table 96

Forward Direction $I_o = CE^D$

$C = 7.7687$
$D = 1.1742$

E volts	I ma.	I_o ma.
1.02	7.74	7.92
2.85	26.57	26.57
5.50	58.58	57.49
11.28	132.0	133.62
16.17	204.0	204.01
21.88	301.	290.94

SPECIMEN 110A

Time of heating	180 Seconds
Quenching temperature	10.0° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 97

Reverse Direction $I_c = AE + BE^2$

$A = 0.6795$
$B = 0.0655$

E volts	I ma.	I_c ma.
1.33	1.33	1.02
3.98	4.49	3.74
6.57	8.22	7.29
11.83	17.48	17.20
16.79	29.00	29.87
22.67	48.43	49.06
29.59	78.0	77.46

Table 98

Forward Direction $I_c = CE^D$

$C = 9.0718$
$D = 1.2682$

E volts	I ma.	I_c ma.
0.97	8.86	8.71
2.65	31.22	31.21
4.98	69.02	69.49
10.76	184.6	184.61
15.05	299.6	282.50
20.09	468.8	407.50

SPECIMEN 110B

Time of heating	180 Seconds
Quenching temperature	10.0° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 99

Reverse Direction $I_c = AE + BE^2$

$A = 0.6412$
$B = 0.0686$

E volts	I ma.	I_c ma.
1.33	1.33	0.97
3.98	4.49	3.64
6.57	8.22	7.17
11.83	17.62	17.19
16.79	29.00	30.11
22.67	49.08	49.80
29.55	79.5	78.86

Table 100

Forward Direction $I_c = CE^D$

$C = 8.0692$
$D = 1.1961$

E volts	I ma.	I_c ma.
1.00	8.06	8.06
2.79	28.00	27.48
5.38	61.18	60.28
11.21	141.8	145.06
15.91	220.6	220.58
21.53	346.0	316.80

SPECIMEN 116A

Time of heating 180 Seconds

Quenching temperature 64.8° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc.water

Table 101

Reverse Direction $I_c = AE + BE^2$

$A = 0.05821$
$B = 0.00031$

E volts	I ma.	I_c ma.
16.47	0.97	1.04
24.52	1.67	1.61
32.85	2.26	2.25
41.20	2.92	2.92
49.70	3.65	3.66

Table 102

Forward Direction $I = CE^D$

$C = 0.07749$
$D = 1.0912$

E volts	I ma.	I_c ma.
16.46	1.81	1.65
24.50	2.54	2.54
32.75	3.51	3.49
41.12	4.45	4.47
49.65	5.49	5.49

SPECIMEN 116B

Time of heating	180 Seconds
Quenching temperature	64.8° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 103

Reverse Direction $I_c = AE + BE^2$

$A = 0.07059$
$B = 0.00015$

E volts	I ma.	I_c ma.
16.47	1.15	1.20
24.52	1.85	1.82
32.85	2.44	2.48
41.20	3.27	3.17
49.70	3.83	3.88

Table 104

Forward Direction $I_c = CE^D$

$C = 0.07399$
$D = 1.0888$

E volts	I ma.	I_c ma.
16.47	1.57	1.56
24.50	2.44	2.41
32.75	3.27	3.30
41.12	4.18	4.23
49.65	5.22	5.20

SPECIMEN 117A

Time of heating	180 Seconds
Quenching temperature	64.8° Centigrade
Quenching solution	25 cc. Methyl alcohol in 475 cc. water

Table 105

Reverse Direction $I_c = AE + BE^2$

$A = 0.02181$
$B = 0.00034$

E volts	I ma.	I_c ma.
16.47	0.45	0.46
24.45	0.70	0.74
32.73	1.11	1.06
41.21	1.50	1.48
49.69	1.91	1.92

Table 106

Forward Direction $I_c = CE^D$

$C = 0.01676$
$D = 1.3351$

E volts	I ma.	I_c ma.
16.47	0.70	0.71
24.45	1.15	1.20
32.73	1.81	1.77
41.12	2.44	2.38
49.72	3.06	3.08

SPECIMEN 117B

Time of heating	180 Seconds
Quenching temperature	64.8° Centigrade
Quenching solution	25 cc. Methyl alcohol in 475 cc. water

Table 107

Reverse Direction $I_c = AE + BE^2$

$A = 0.04320$
$B = 0.00057$

E volts	I ma.	I_c ma.
16.46	0.87	0.87
24.45	1.39	1.40
32.73	2.02	2.03
41.21	2.78	2.75
49.69	3.55	3.56

Table 108

Forward Direction $I_c = CE^D$

$C = 0.06926$
$D = 1.1401$

E volts	I ma.	I_c ma.
16.37	1.67	1.68
24.40	2.61	2.64
32.65	3.76	3.69
41.12	4.80	4.79
49.60	5.91	5.94

SPECIMEN 118A

Time of heating	180 Seconds
Quenching temperature	20° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 109

Reverse Direction $I_o = AE + BE^2$ $A = 0.4633$, $B = 0.0479$

E volts	I ma.	I_o ma.
1.30	0.87	0.68
3.97	1.64	2.59
6.57	5.84	5.11
11.70	12.45	11.98
16.80	21.18	21.30
22.77	34.80	35.38
29.87	56.85	56.57

Table 110

Forward Direction $I_o = CE^D$ $C = 6.9166$, $D = 1.2047$

E volts	I ma.	I_o ma.
1.01	7.00	6.99
2.86	25.23	24.55
5.56	54.10	54.64
11.15	123.1	126.37
15.87	193.3	193.32
21.32	293.8	275.83

SPECIMEN 118B

Time of heating	180 Seconds
Quenching temperature	20.0° Centigrade
Quenching solution	12.5 cc. Methyl alcohol in 487.5 cc. water

Table 111

Reverse Direction $I_c = AE + BE^2$

$A = 0.3953$

$B = 0.0336$

E volts	I ma.	I_c ma.
1.33	0.63	0.59
4.01	2.26	2.12
6.66	4.25	4.12
11.90	9.55	9.46
16.93	16.30	15.64
23.20	26.90	27.23
30.58	43.63	43.46

Table 112

Forward Direction $I_c = CE^D$

$C = 5.3784$

$D = 1.1288$

E volts	I ma.	I_c ma.
1.09	5.30	5.92
3.13	19.50	19.52
6.18	41.80	42.00
11.47	83.4	84.49
16.45	126.9	126.88
22.50	187.7	180.71

SPECIMEN 119A

Time of heating	180 Seconds
Quenching temperature	64.8° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 113

Reverse Direction $I_c = AE + BE^2$

A = 0.02925
B = 0.00014

E volts	I ma.	I_c ma.
24.52	0.87	0.80
33.00	1.08	1.12
41.30	1.39	1.45
49.87	1.85	1.81

Table 114

Forward Direction $I_c = CE^D$

C = 0.01719
D = 1.2591

E volts	I ma.	I_c ma.
24.53	0.97	0.97
33.00	1.39	1.40
41.30	1.91	1.91
49.87	2.37	2.36

SPECIMEN 119B

Time of heating	180 Seconds
Quenching temperature	64.8° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 115

Reverse Direction $I_c = AE + BE^2$

$A = 0.03306$
$B = -0.000084$

E volts	I ma.	I_c ma.
24.52	0.77	0.76
33.00	0.97	1.00
41.30	1.25	1.22
49.87	1.43	1.44

Table 116

Forward Direction $I_c = CE^D$

$C = 0.02430$
$D = 1.1271$

E volts	I ma.	I_c ma.
24.53	0.91	0.90
33.00	1.22	1.26
41.30	1.60	1.61
49.87	2.02	1.99

SPECIMEN 120A

Time of heating	180 Seconds
Quenching temperature	40.0° Centigrade
Quenching solution	12.5 cc. Methyl Alcohol in 487.5 cc. Water

Table 117

Reverse Direction $I_c = AE + BE^2$

$A = 0.1888$
$B = 0.0097$

E volts	I ma.	I_c ma.
1.35	0.28	0.27
2.71	0.63	0.58
6.83	1.74	1.74
10.87	3.24	3.20
16.43	5.74	5.72
22.77	9.23	9.33
30.83	15.08	15.04

Table 118

Forward Direction $I_c = CE^D$

$C = 1.1543$
$D = 1.0981$

E volts	I ma.	I_c ma.
1.29	1.53	1.52
2.59	3.38	3.29
6.44	8.90	8.92
10.35	14.90	15.03
15.40	22.95	23.25
21.60	33.40	33.71
29.17	46.75	46.88
38.05	63.00	62.76

SPECIMEN 120B

Time of heating 180 Seconds

Quenching temperature 40.0° Centigrade

Quenching solution 12.5 cc. Methyl alcohol in 487.5 cc. water

Table 119

Reverse Direction $I_c = AE + BE^2$

$A = 0.1680$
$B = 0.00804$

E volts	I ma.	I_c ma.
1.35	0.28	0.24
2.71	0.63	0.51
6.83	1.57	1.52
10.95	2.78	2.80
16.32	4.94	4.88
22.80	8.15	8.01
30.93	12.80	12.89

Table 120

Forward Direction $I_c = CE^D$

$C = 0.9113$
$D = 1.0551$

E volts	I ma.	I_c ma.
1.31	1.22	1.24
2.65	2.80	2.52
6.57	6.78	6.64
10.55	11.00	10.95
15.75	16.80	16.71
22.10	24.05	23.89
29.90	32.53	32.86
39.15	42.90	43.67

SPECIMEN 121A

Time of heating 180 Seconds

Quenching temperature 40.0° Centigrade

Quenching solution 25 cc. Methyl alcohol in 475 cc. water

Table 121

Reverse Direction $I_e = AE + BE^2$

$A = 0.17025$
$B = 0.00623$

E volts	I ma.	I_e ma.
1.35	0.17	0.24
4.09	0.70	0.80
6.81	1.32	1.45
10.87	2.61	2.59
16.38	4.52	4.46
22.96	7.30	7.19
29.72	10.50	10.56

Table 122

Forward Direction $I_e = CE^D$

$C = 0.7539$
$D = 1.0283$

E volts	I ma.	I_e ma.
1.32	0.87	1.00
3.98	2.96	3.12
6.63	5.22	5.27
10.65	8.55	8.59
15.93	13.00	12.99
22.40	18.50	18.44
29.05	24.10	24.10
39.80	32.97	33.30

SPECIMEN 121B

Time of heating 180 Seconds

Quenching temperature 40.0° Centigrade

Quenching solution 25 cc. Methyl alcohol in 475 cc. water

Table 123

Reverse Direction $I_c = AE + BE^2$

$A = 0.1888$
$B = 0.0083$

E volts	I ma.	I_c ma.
1.35	0.24	0.27
4.09	0.77	0.91
6.80	1.60	1.67
10.95	3.03	3.06
16.30	5.36	5.28
22.85	8.75	8.65
29.62	12.80	12.88

Table 124

Forward Direction $I_c = CE^D$

$C = 1.0332$
$D = 1.0297$

E volts	I ma.	I_c ma.
1.29	1.15	1.34
3.93	4.17	4.23
6.52	7.15	7.12
10.50	11.70	11.63
15.75	17.65	17.66
22.10	25.05	25.03
28.67	32.40	32.73
39.15	44.48	45.11

SPECIMEN 122A

Time of heating	180 Seconds
Quenching temperature	20.0° Centigrade
Quenching solution	25 cc. Methyl alcohol in 475 cc. water

Table 125

Reverse Direction $I_e = AE + BE^2$

$A = 0.4208$
$B = 0.0262$

E volts	I ma.	I_e ma.
1.33	0.63	0.61
4.02	2.16	2.12
6.68	4.11	3.98
10.70	7.50	7.50
15.95	13.27	13.38
22.17	22.22	22.22
29.80	35.85	35.83

Table 126

Forward Direction $I_e = CE^D$

$C = 2.1652$
$D = 1.1687$

E volts	I ma.	I_e ma.
1.22	2.78	2.73
3.64	9.80	9.81
6.02	17.60	17.65
9.57	29.60	30.33
14.23	48.22	48.22
21.80	84.40	79.40
30.00	138.5	115.30

SPECIMEN 122B

Time of heating 180 Seconds

Quenching temperature 20.0° Centigrade

Quenching solution 25 cc. Methyl alcohol in 475 cc. water

Table 127

Reverse Direction $I_c = AE + BE^2$ $A = 0.5233$
$B = 0.0437$

E volts	I ma.	I_c ma.
1.32	0.84	0.77
3.98	3.06	2.74
6.60	5.74	5.36
10.62	10.52	10.49
15.70	18.80	18.99
21.75	31.60	32.06
28.90	51.90	51.62

Table 128

Forward Direction $I_c = CE^D$ $C = 4.3395$
$D = 1.1441$

E volts	I ma.	I_c ma.
1.12	4.94	4.95
3.28	17.10	16.88
5.40	29.95	29.86
8.62	50.25	51.03
12.66	79.20	79.20
19.45	131.35	129.45
29.07	221.0	205.00

SPECIMEN 123A

Time of heating	180 Seconds
Quenching temperature	20.0° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 129

Reverse Direction $I_c = AE + BE^2$

$A = 0.7625$
$B = 0.0303$

E volts	I ma.	I_c ma.
1.32	1.04	1.06
3.97	3.59	3.48
6.58	6.44	6.33
10.55	11.35	11.42
15.68	19.28	19.41
21.75	30.90	30.92
29.20	48.16	48.11

Table 130

Forward Direction $I_c = CE^D$

$C = 3.4847$
$D = 1.1457$

E volts	I ma.	I_c ma.
1.17	4.17	4.18
3.42	14.60	14.25
6.74	27.65	31.01
10.12	48.60	55.06
15.37	79.75	79.73
21.42	119.47	116.63
29.50	184.5	168.31

SPECIMEN 123B

Time of heating	180 Seconds
Quenching temperature	20.0° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 131

Reverse Direction $I_c = AE + BE^2$

$A = 0.7336$
$B = 0.0368$

E volts	I ma.	I_c ma.
1.32	1.04	1.03
3.97	3.59	3.46
6.58	6.79	6.42
10.56	11.80	11.84
15.68	20.35	20.56
21.67	32.97	33.19
28.90	52.12	51.95

Table 132

Forward Direction $I_c = CE^D$

$C = 3.3239$
$D = 1.2465$

E volts	I ma.	I_c ma.
1.12	5.15	3.82
3.25	14.45	14.46
6.39	37.90	33.54
9.57	58.93	56.51
14.25	95.45	91.17
22.90	164.7	164.70
28.95	229.0	220.61

SPECIMEN 124A

Time of heating 180 Seconds

Quenching temperature 20.0° Centigrade

Quenching solution 100 cc. Methyl alcohol in 400 cc. water

Table 133

Reverse Direction $I_c = AE + BE^2$

$A = 0.5023$
$B = 0.0740$

E volts	I ma.	I_c ma.
1.30	1.22	0.78
3.94	4.11	3.13
6.53	7.50	6.44
10.45	13.80	13.33
15.40	24.63	25.29
22.40	46.90	48.38
29.15	78.45	77.52

Table 134

Forward Direction $I_c = CE^D$

$C = 14.5968$
$D = 1.1749$

E volts	I ma.	I_c ma.
0.84	10.75	11.90
2.26	38.05	38.10
4.28	81.80	80.58
10.23	219.7	224.38
14.43	336.0	336.06
20.28	564.5	501.17

SPECIMEN 124B

Time of heating	180 Seconds
Quenching temperature	20.0° Centigrade
Quenching solution	100 cc. Methyl alcohol in 400 cc. water

Table 135

Reverse Direction $I_c = AE + BE^2$

$A = 0.4740$
$B = 0.0712$

E volts	I ma.	I_c ma.
1.31	1.11	0.74
3.95	3.83	2.98
6.54	7.17	6.15
10.50	13.10	12.83
15.47	23.75	24.37
22.45	45.40	46.52
29.27	75.60	74.87

Table 136

Forward Direction $I_c = CE^D$

$C = 9.0632$
$D = 1.1885$

E volts	I ma.	I_c ma.
0.97	8.20	8.74
2.68	29.25	29.27
5.14	63.22	63.44
10.90	150.1	154.98
15.50	235.5	235.46
21.90	388.5	355.19

SPECIMEN 125A

Time of heating	180 Seconds
Quenching temperature	40.0° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 137

Reverse Direction $I_c = AE + BE^2$

$A = 0.2754$
$B = 0.0159$

E volts	I ma.	I_c ma.
1.34	0.35	0.40
4.06	1.32	1.38
6.76	2.58	2.59
10.87	4.87	4.86
16.20	8.60	8.63
22.62	14.43	14.35
30.48	23.10	23.14

Table 138

Forward Direction $I_c = CE^D$

$C = 1.2854$
$D = 1.097$

E volts	I ma.	I_c ma.
1.27	1.67	1.67
3.85	5.85	5.64
6.39	10.05	9.83
10.30	16.65	16.60
16.57	28.00	27.97
22.75	39.50	39.59
30.25	54.10	54.13

SPECIMEN 125B

Time of heating	180 Seconds
Quenching temperature	40.0° Centigrade
Quenching solution	50 cc. Methyl alcohol in 450 cc. water

Table 139

Reverse Direction $I_c = AE + BE^2$

$A = 0.2271$
$B = 0.0145$

E volts	I ma.	I_c ma.
1.35	0.28	0.33
4.07	1.11	1.16
6.78	2.19	2.21
10.87	4.18	4.18
16.25	7.55	7.52
22.74	12.70	12.67
30.67	20.60	20.62

Table 140

Forward Direction $I_c = CE^D$

$C = 1.5168$
$D = 1.0362$

E volts	I ma.	I_c ma.
1.27	1.67	1.94
3.84	5.99	6.10
6.37	10.40	10.33
10.25	16.90	16.91
16.60	27.90	27.90
22.77	38.70	38.68
30.28	51.98	51.97
39.45	68.30	68.35

Appendix II

Appendix II is composed of the logI-logE graphs for the forward current of all rectifiers given in Appendix I. In these graphs the straight line character of the logI-logE function is well illustrated. The rise of the last one or two points above the straight line is attributed to the heating of the rectifier by the large currents. Constant terms are added to the logarithm of the current in order that there would be no confusion of the points of the several functions given on the same page.

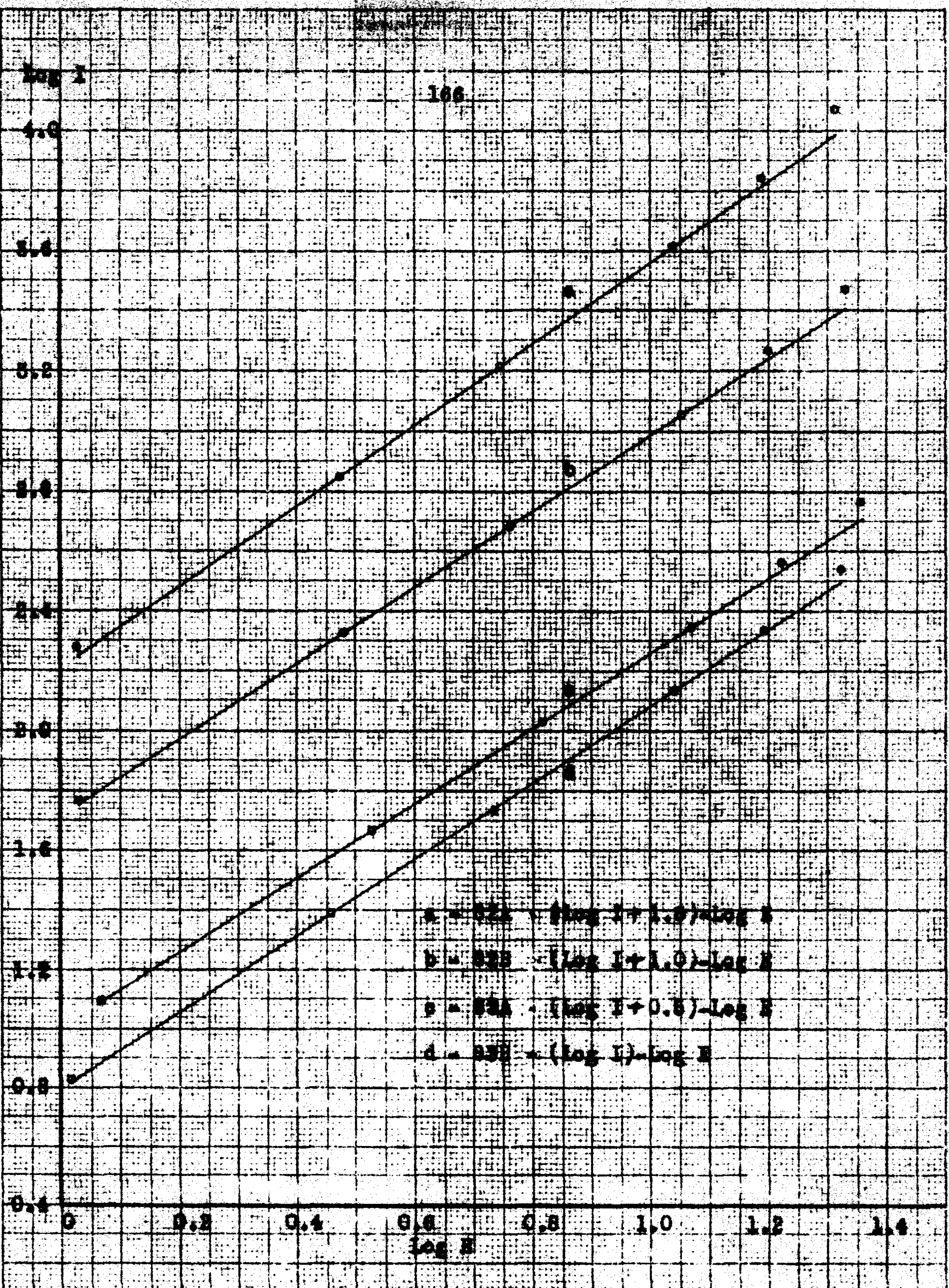


Figure 31. Current-Voltage Logarithm Curves for Forward Current

Form E-3

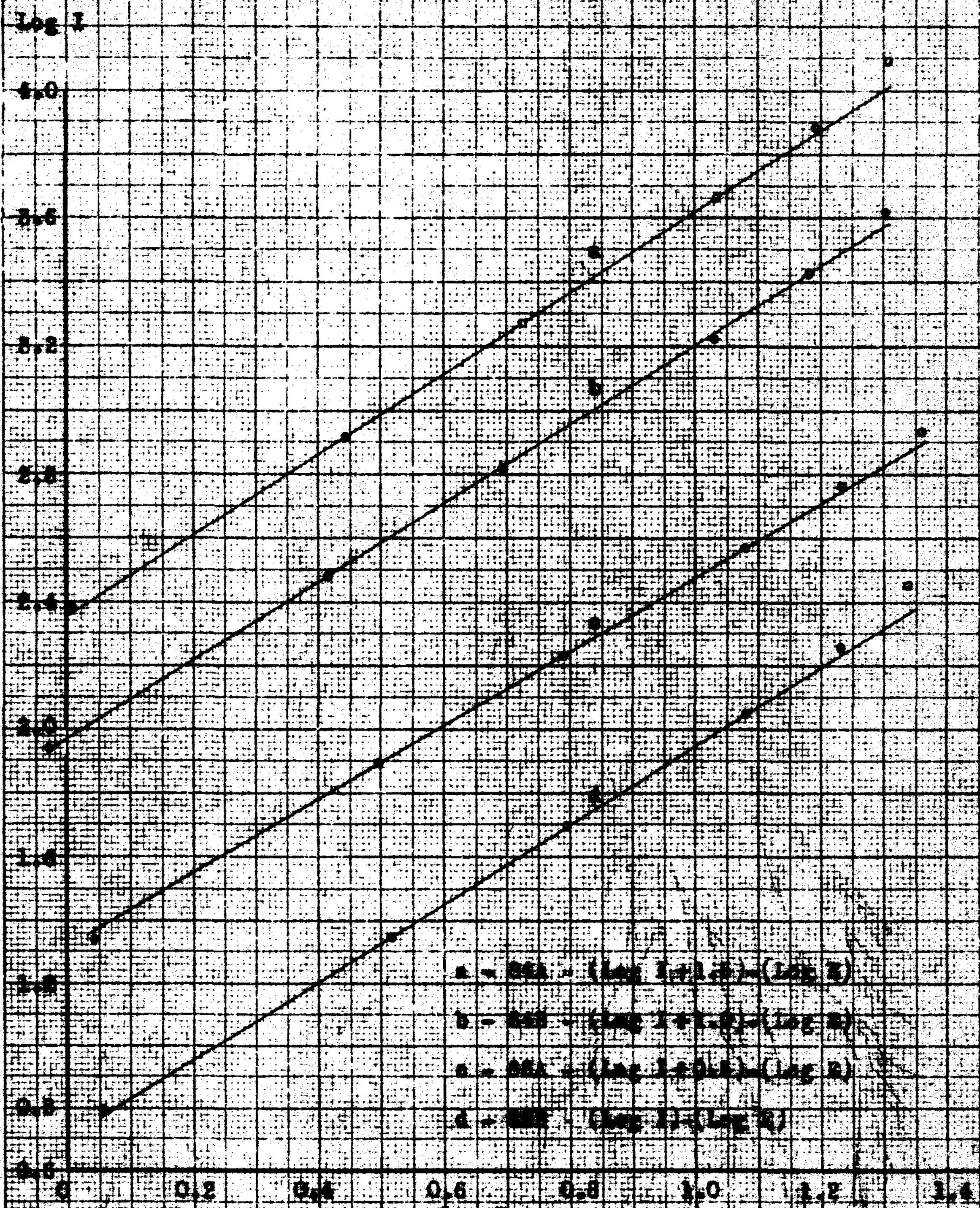


Figure 52. Current-Voltage Logarithm Curves for Forward Current

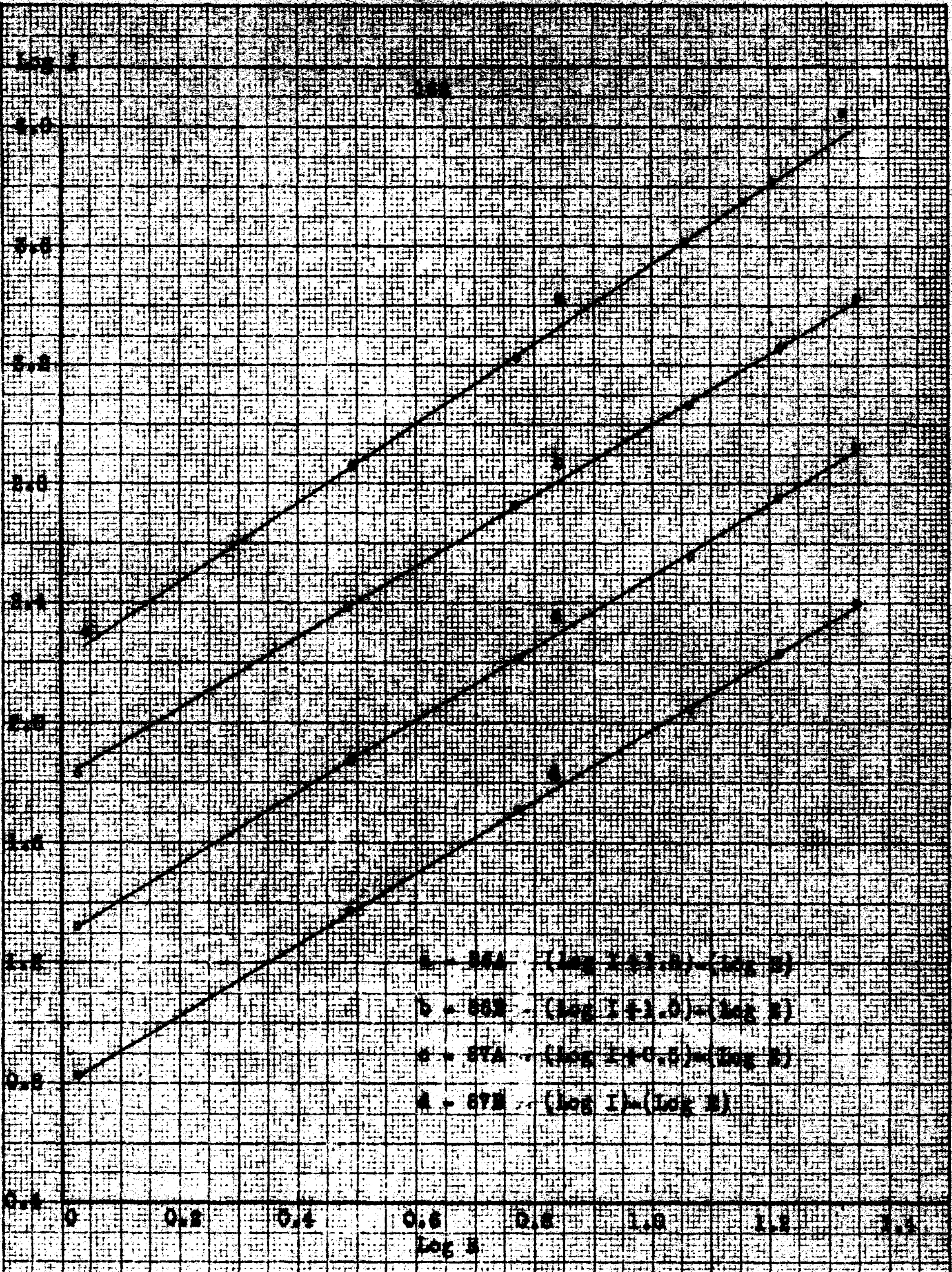


Figure 35. Current-Voltage Logarithm Curves for Forward Current

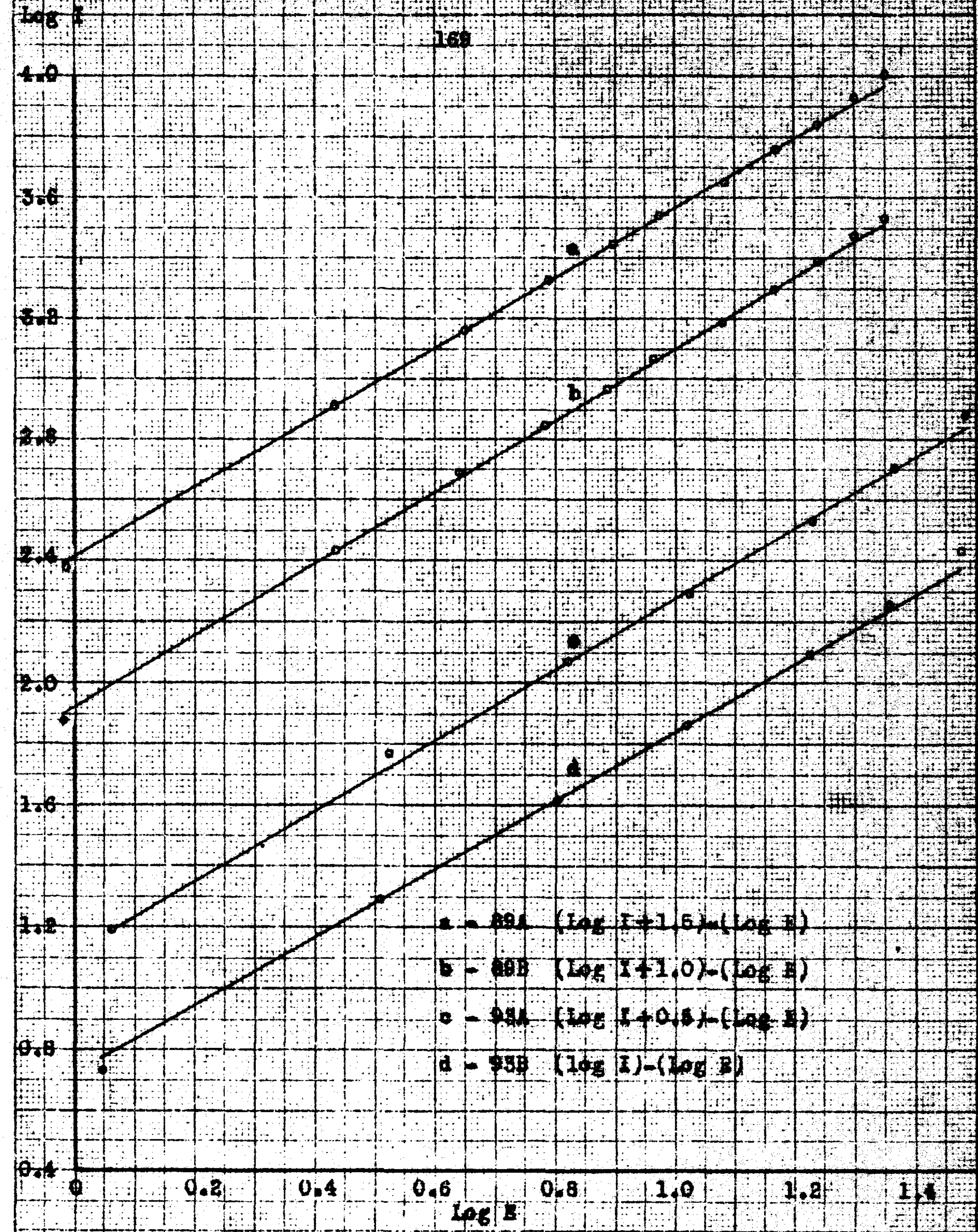


Figure 34. Current-Voltage Logarithm Curves for Forward Current

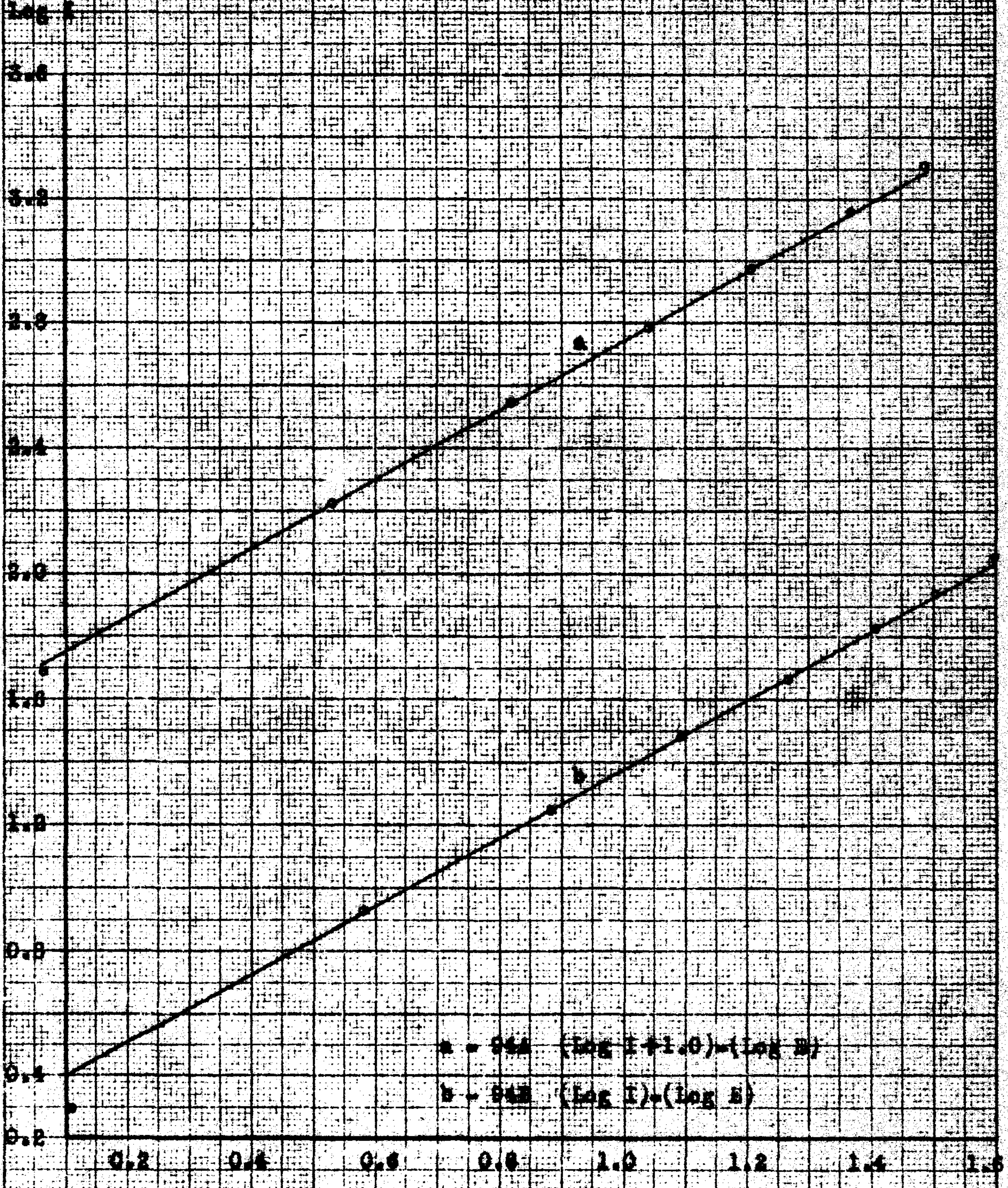


Figure 55. Current-Voltage Logarithm Curves for Forward Current

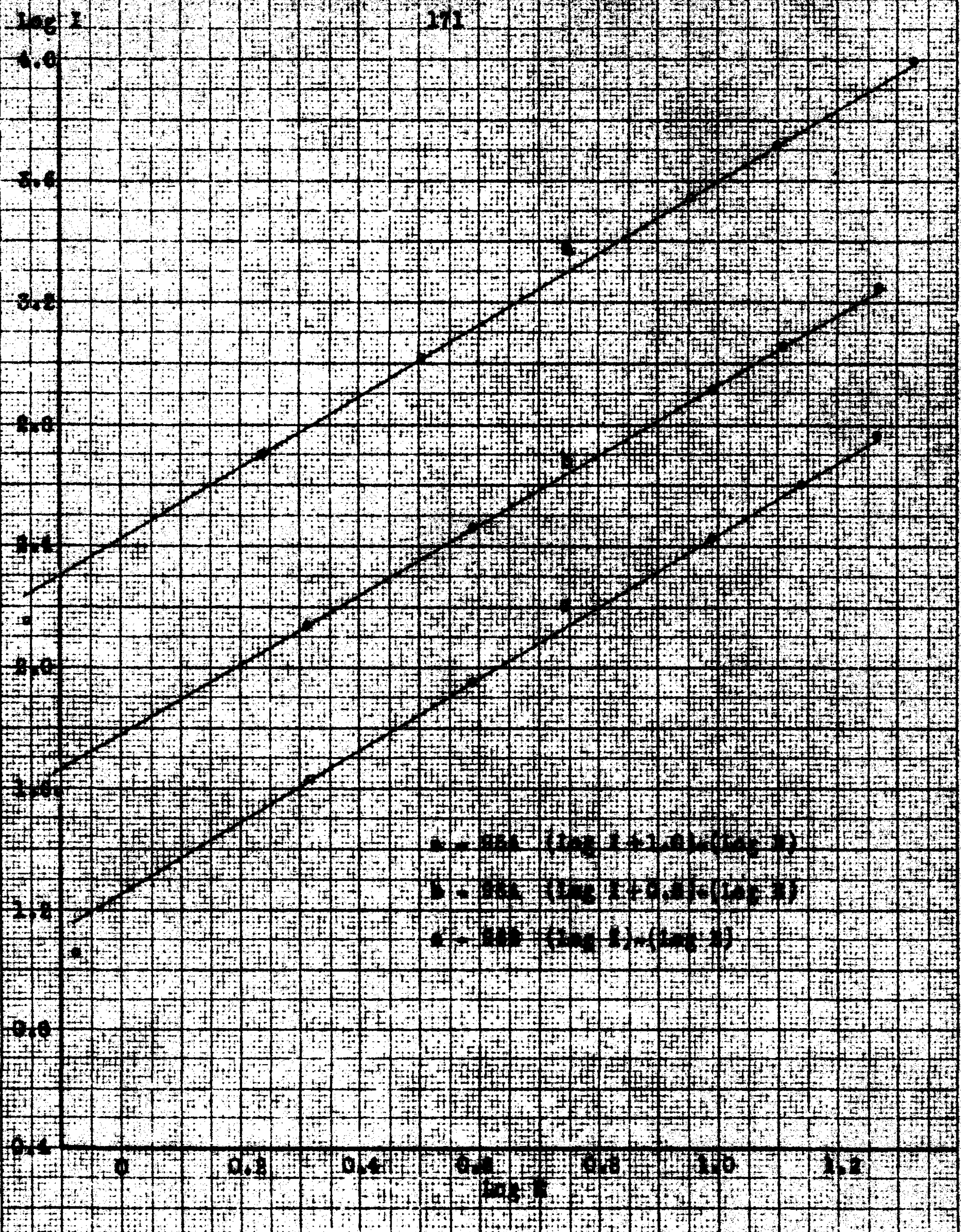


Figure 34. Current-Voltage Logarithm Curves For Forward Current

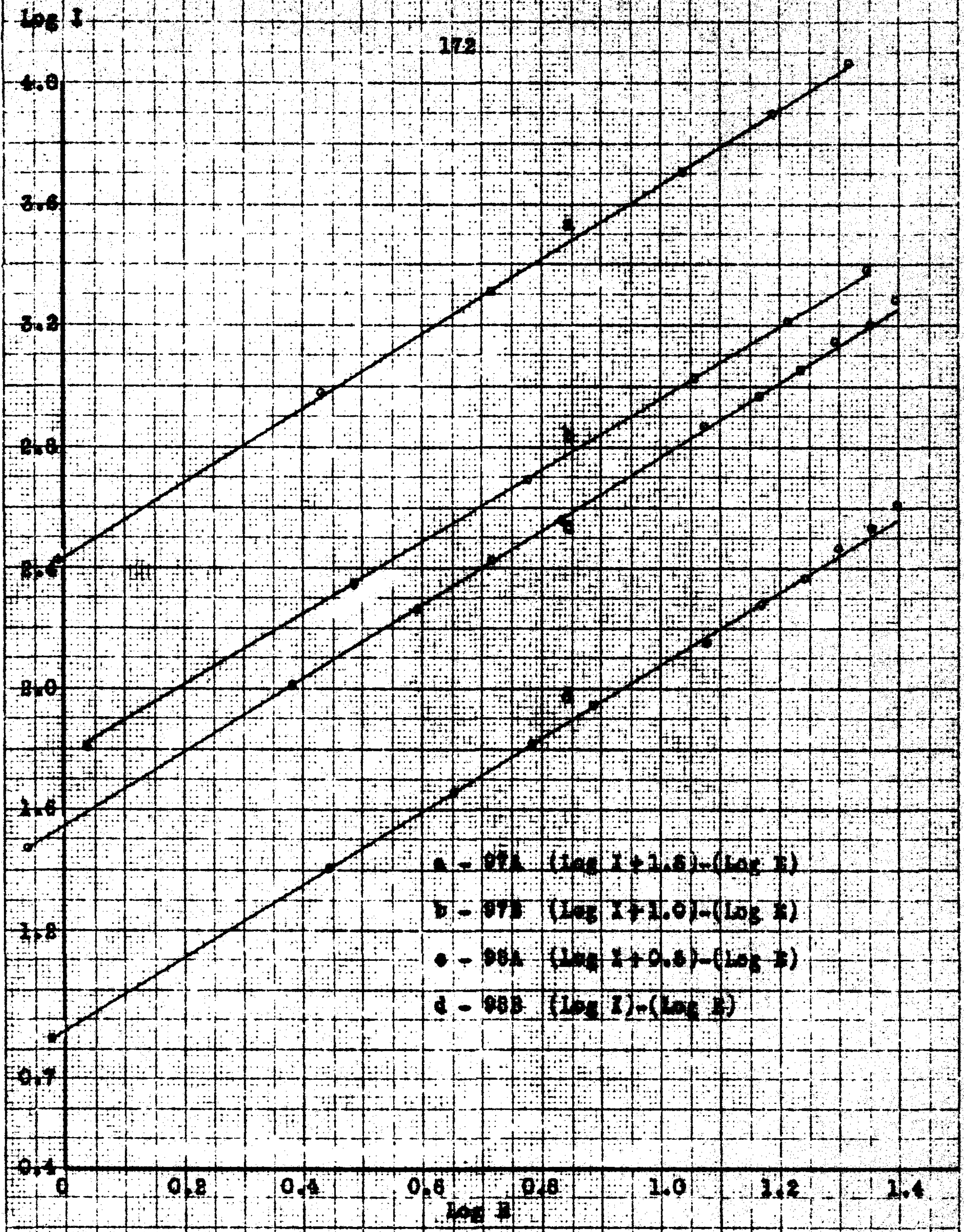


Figure 37. Current-Voltage Logarithm Curves for Forward Current

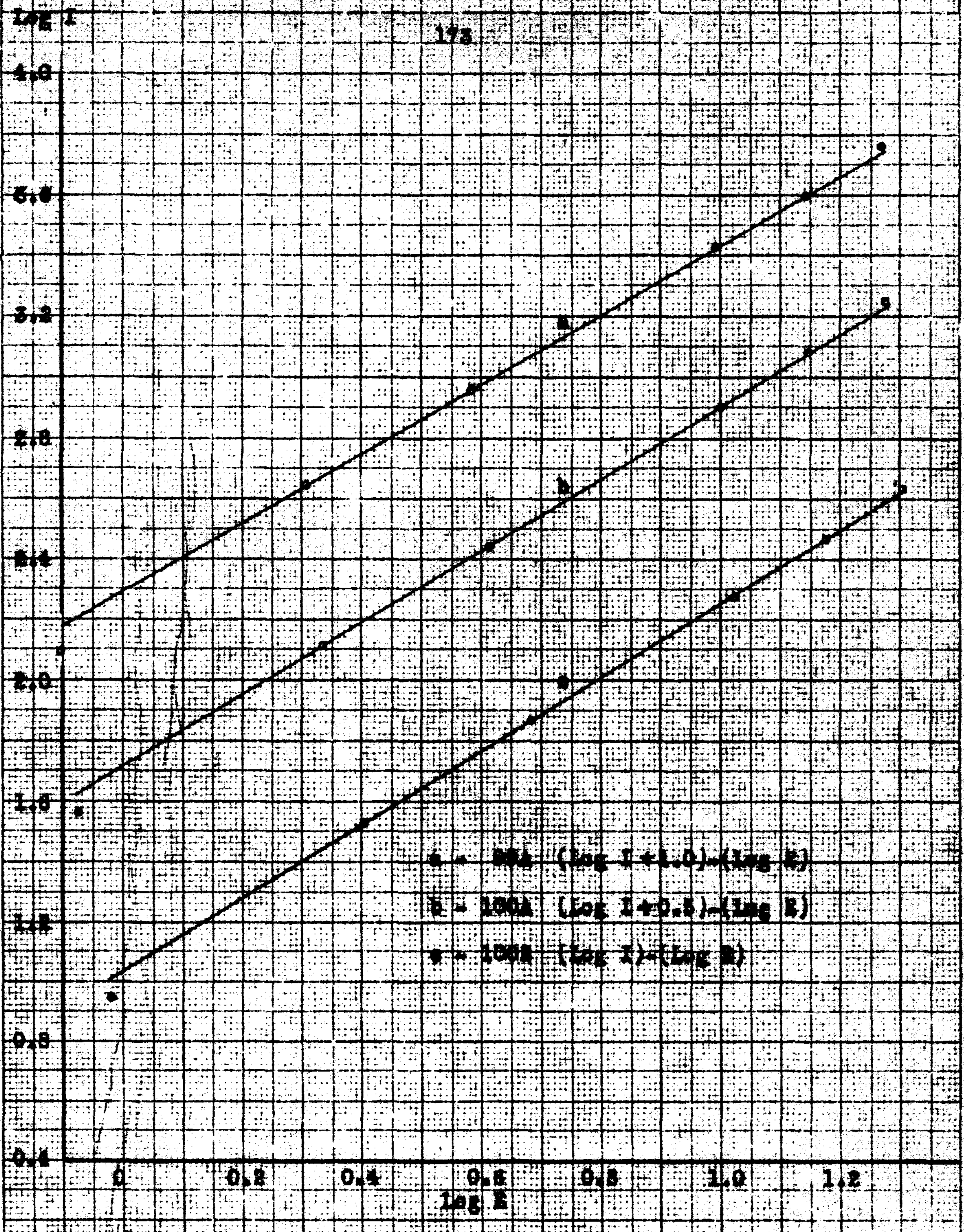


Figure [illegible]. Current-Voltage Logarithm Curves for Forward Current

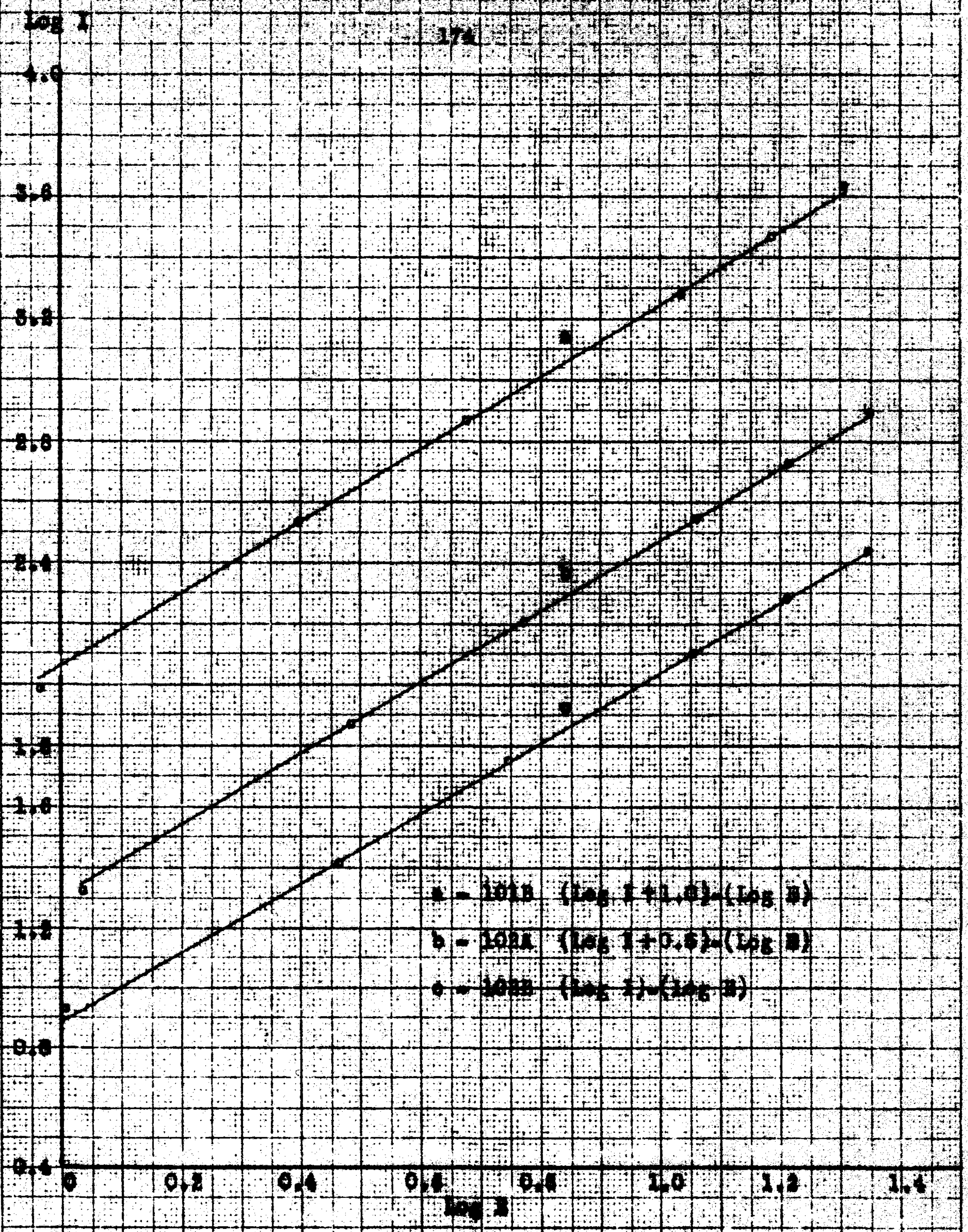


Figure 39. Current-Voltage Logarithm Curves for Forward Current

Form E-3

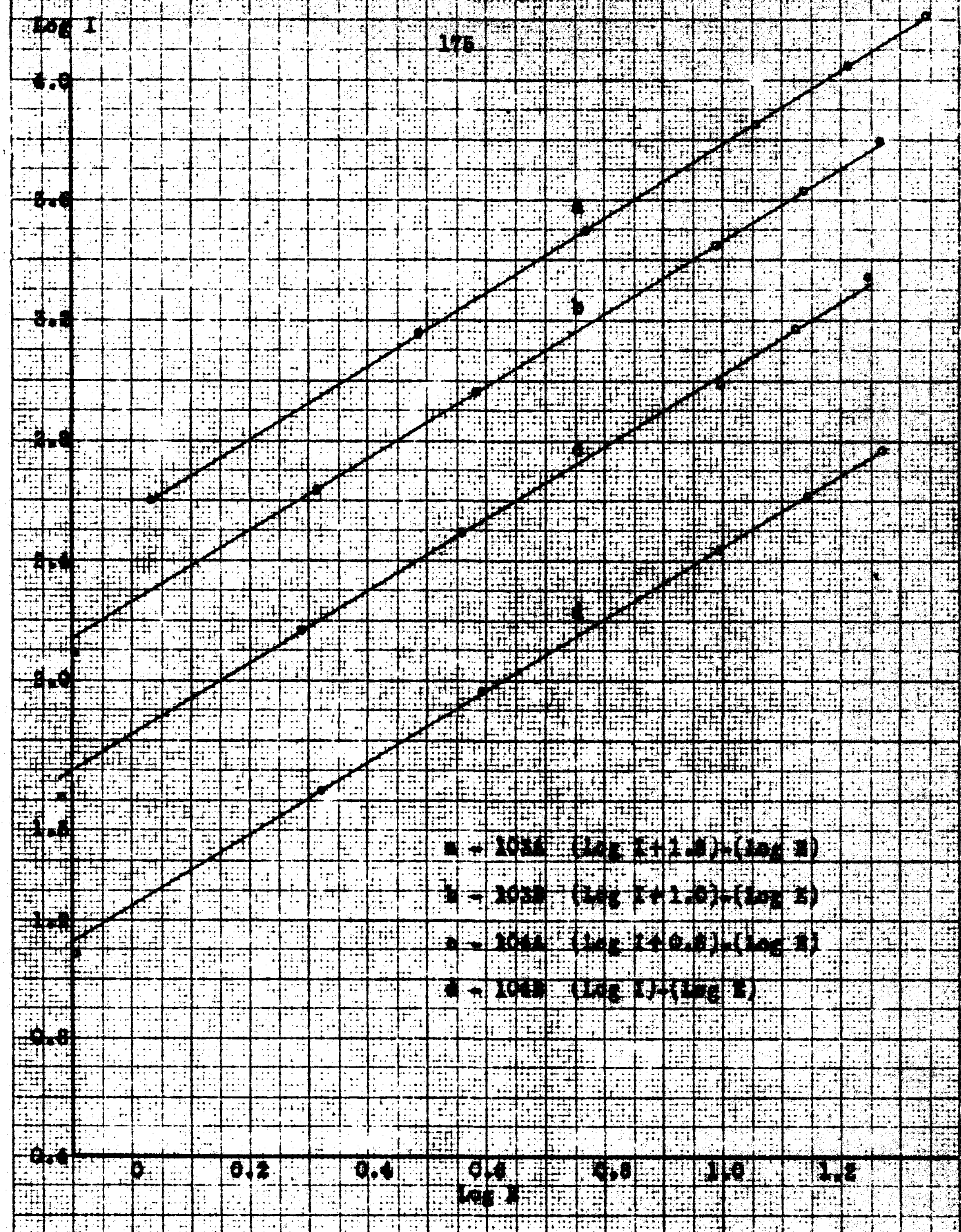


Figure 40. Current-Voltage Logarithm Curves for Forward Current

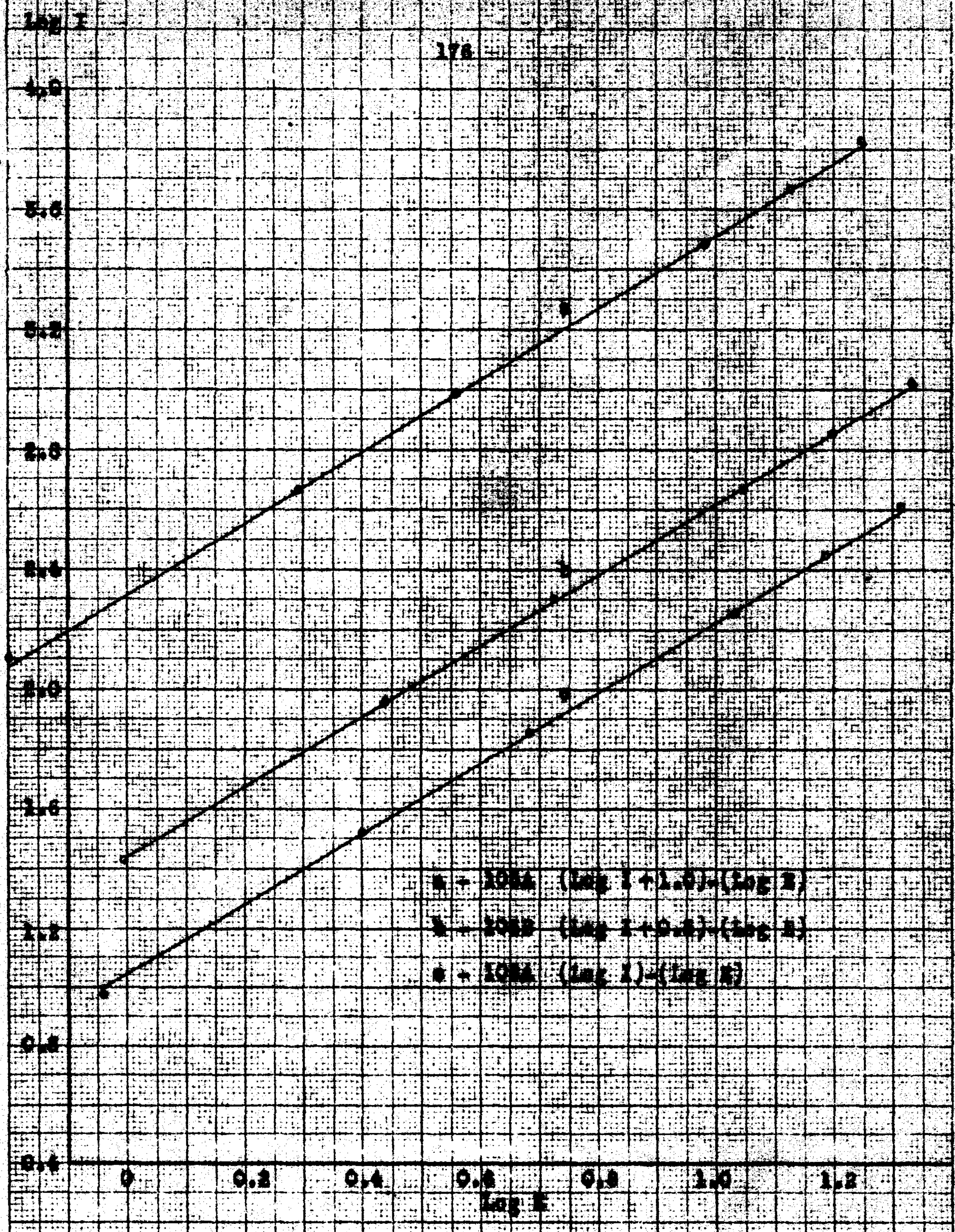


Figure 41. Current-Voltage Logarithm Curves for Forward Current

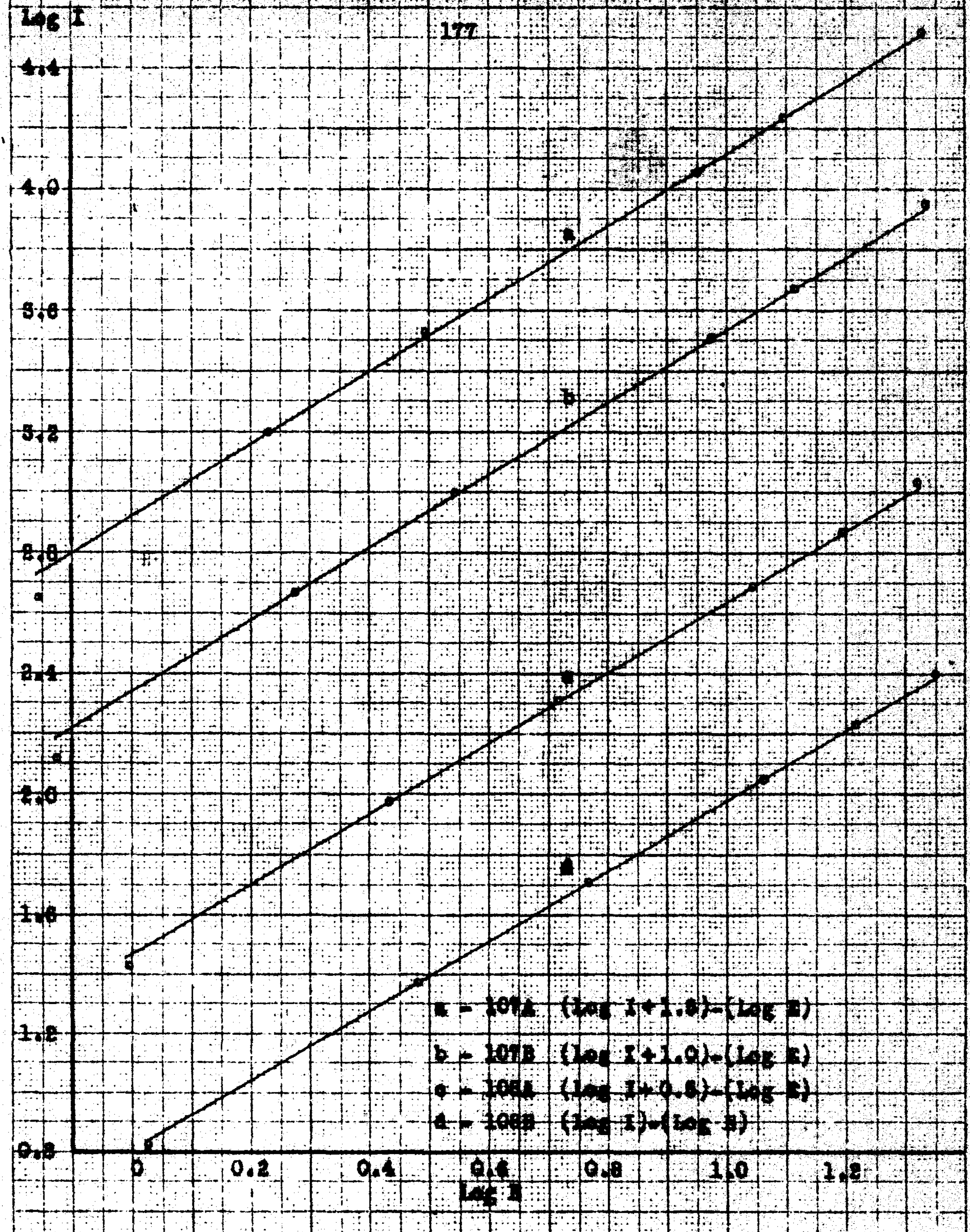


Figure 42. Current-Voltage Logarithm Curves for Forward Current

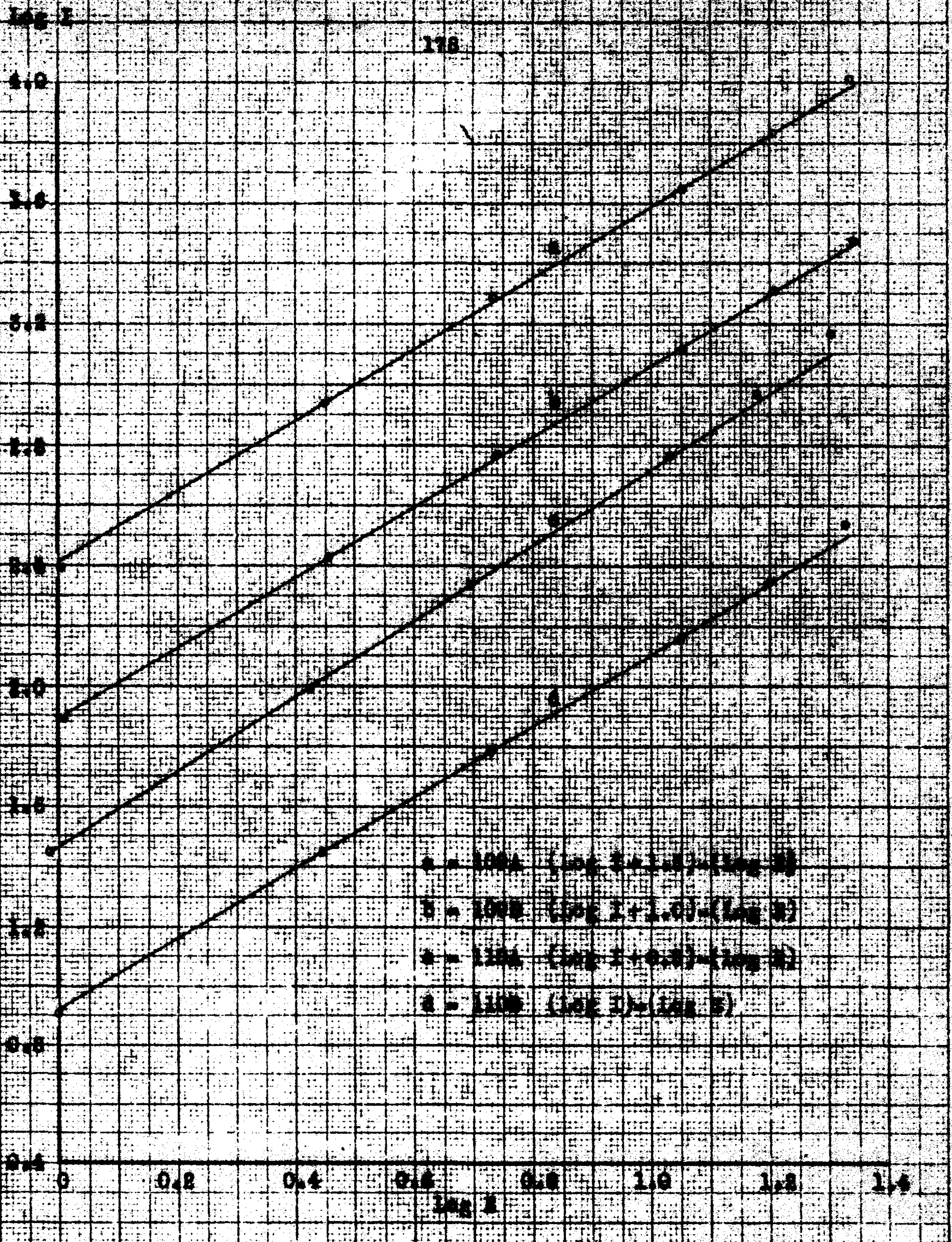


Figure 45. Current-Voltage Logarithm Curves for Forward Current

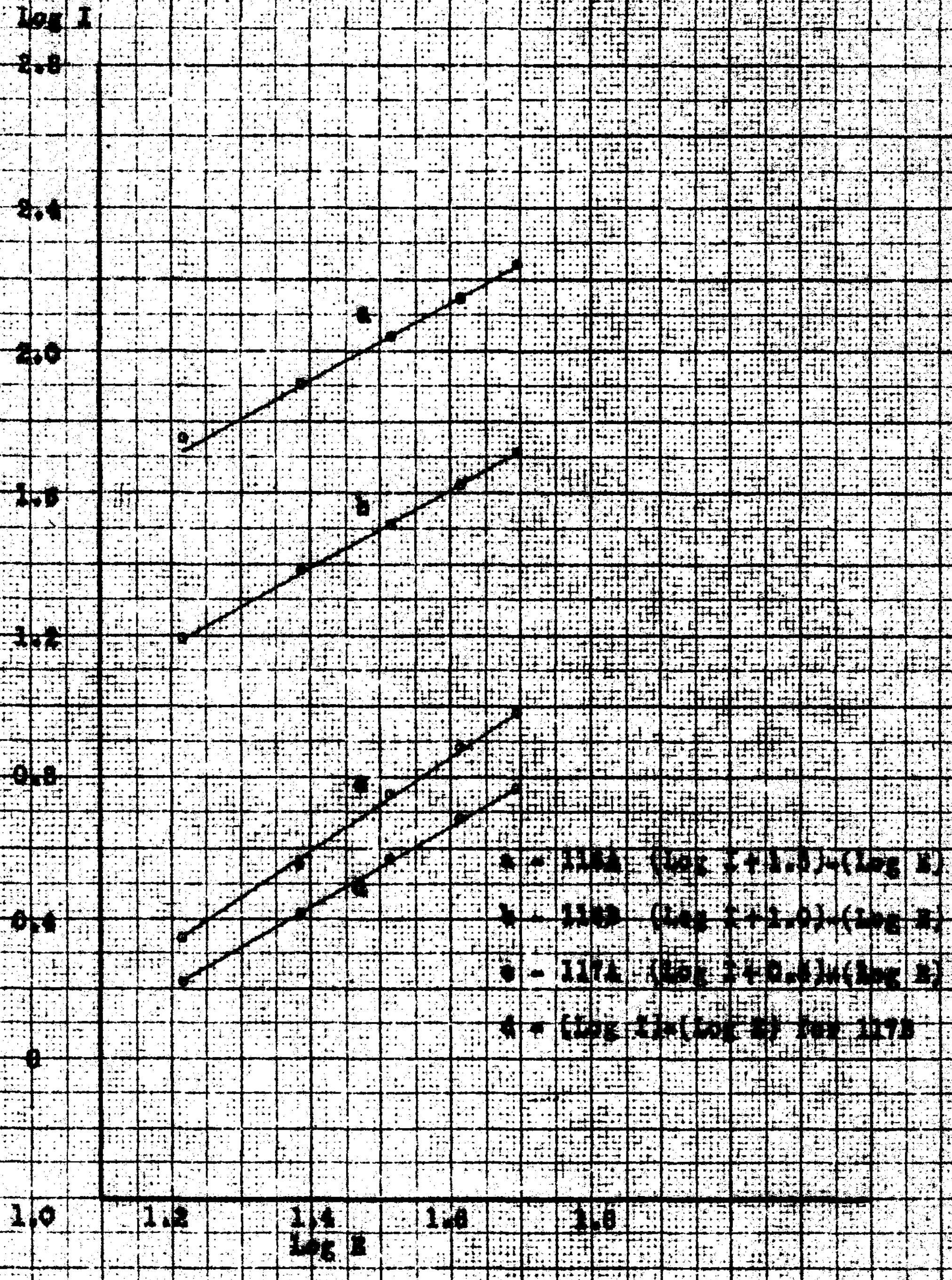


Figure 44. Current-Voltage Logarithm Curves for Forward Current

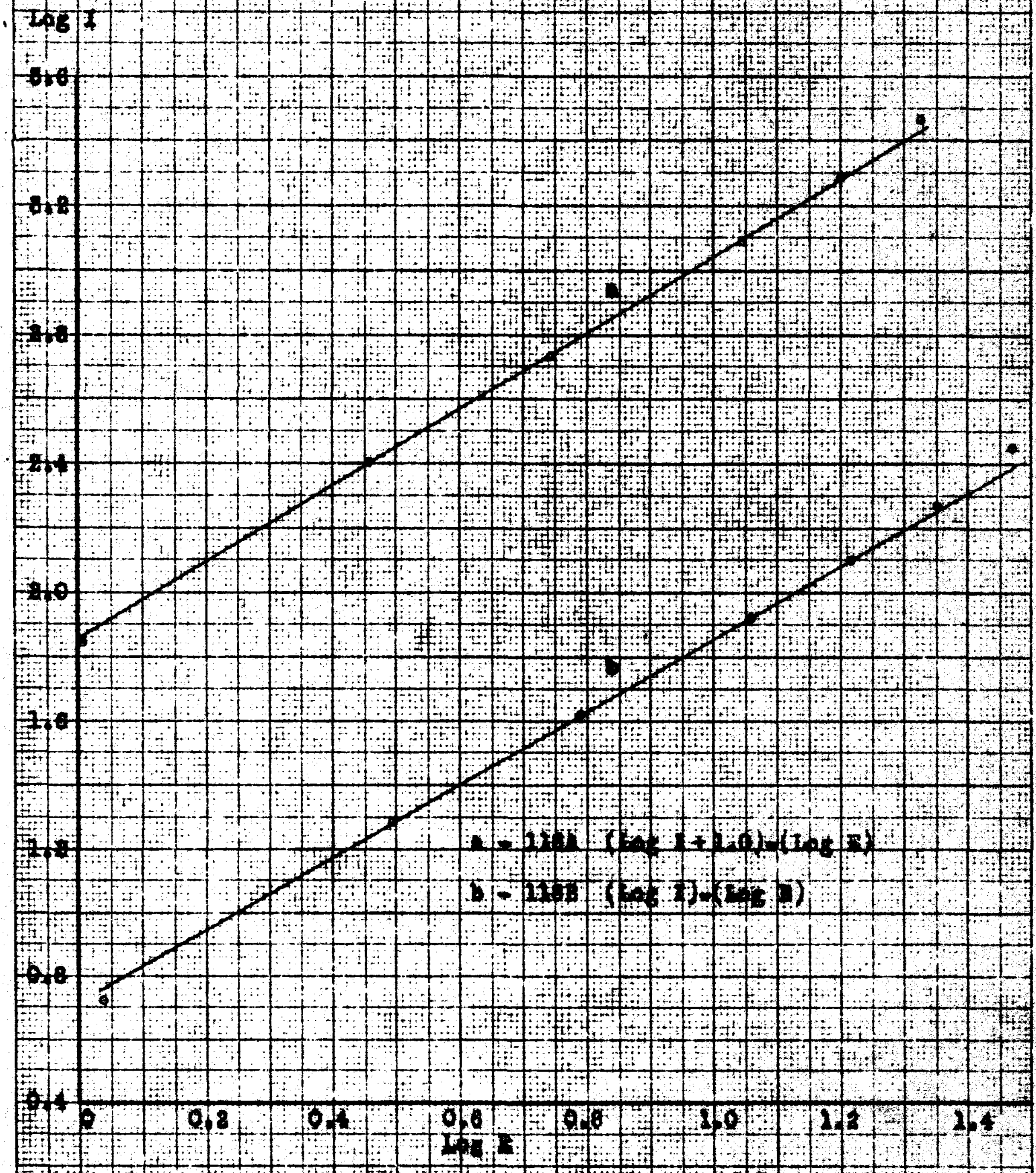


Figure 45. Current-Voltage Logarithm Curves for Forward Current

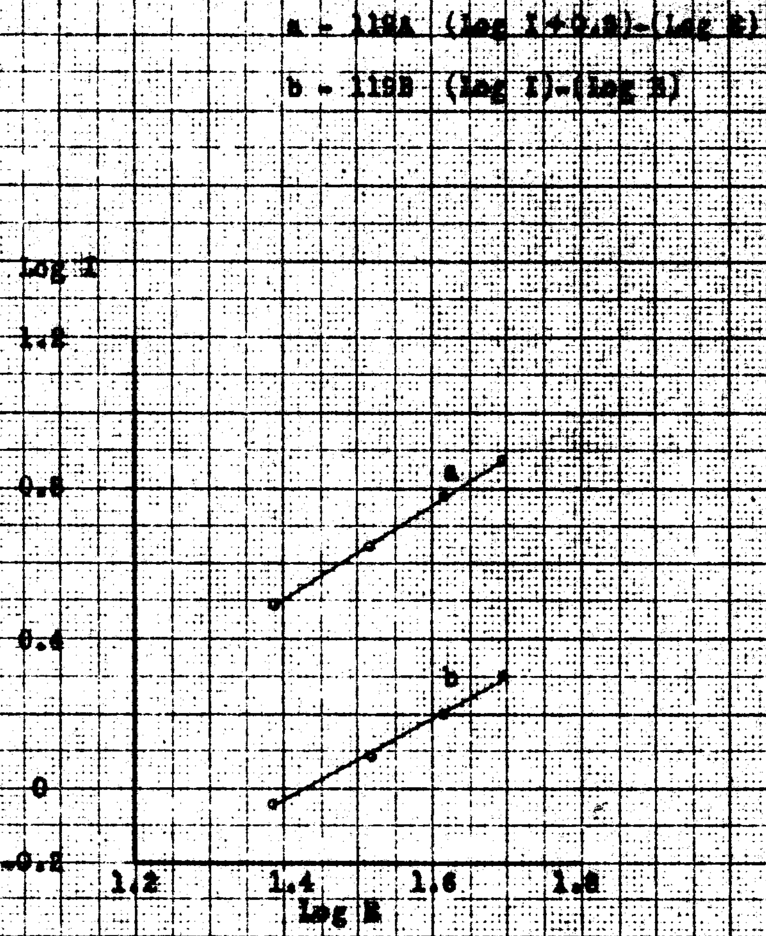


Figure 46. Current-Voltage Logarithm Curves for Forward Current

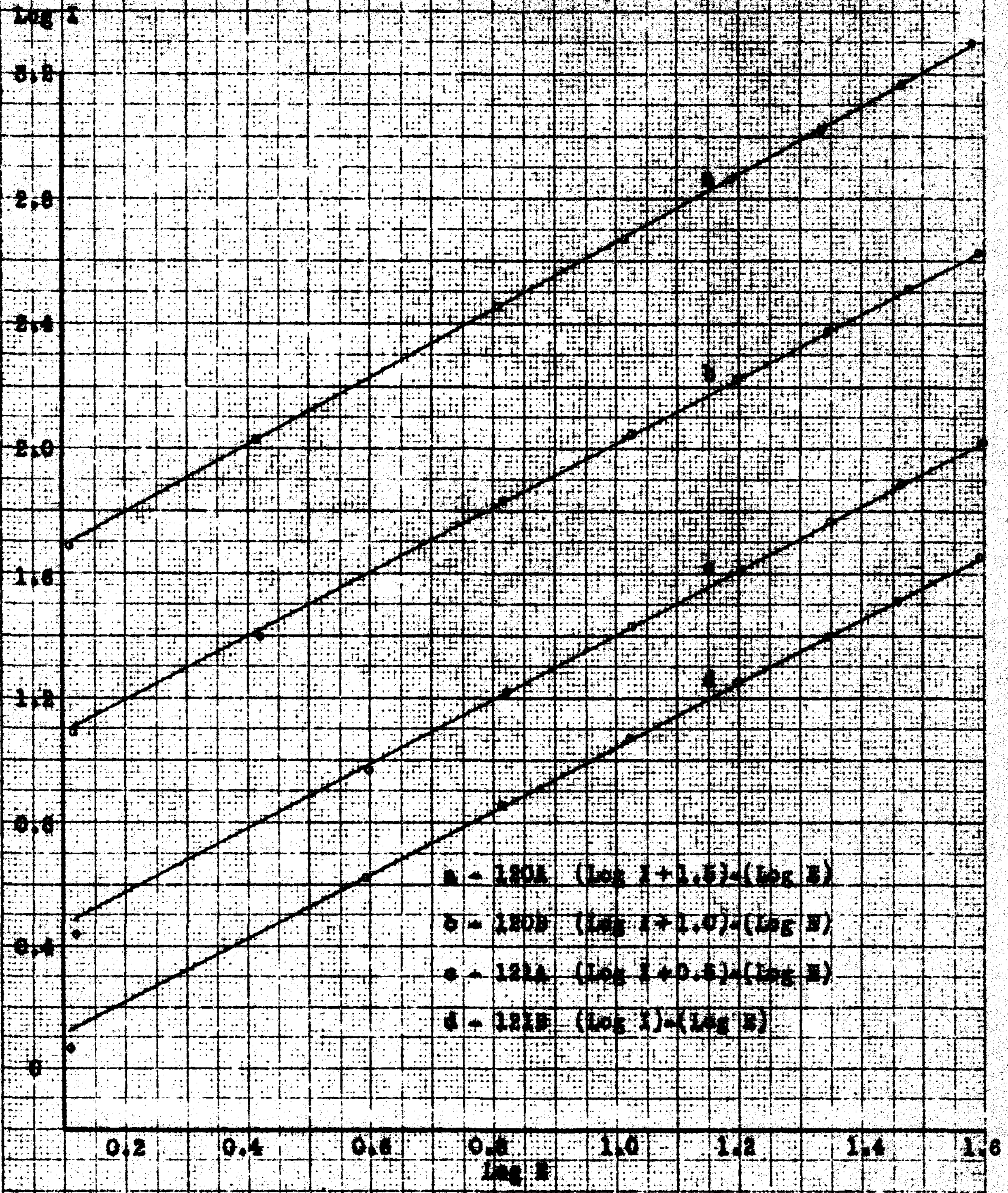


Figure 47. Current-Voltage Logarithm Curves for Forward Current

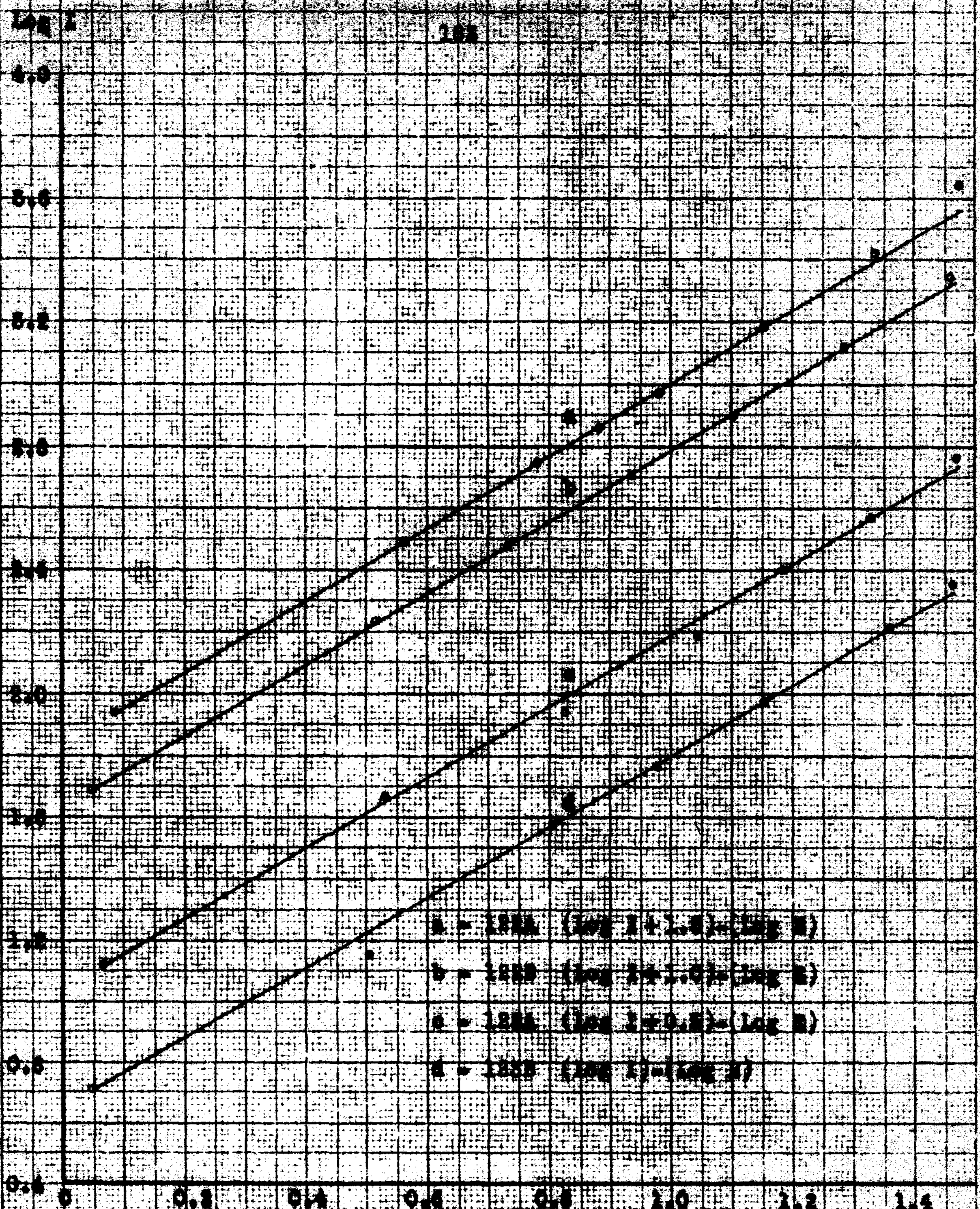


Figure 48. Current-Voltage Logarithm Curves for Forward Current

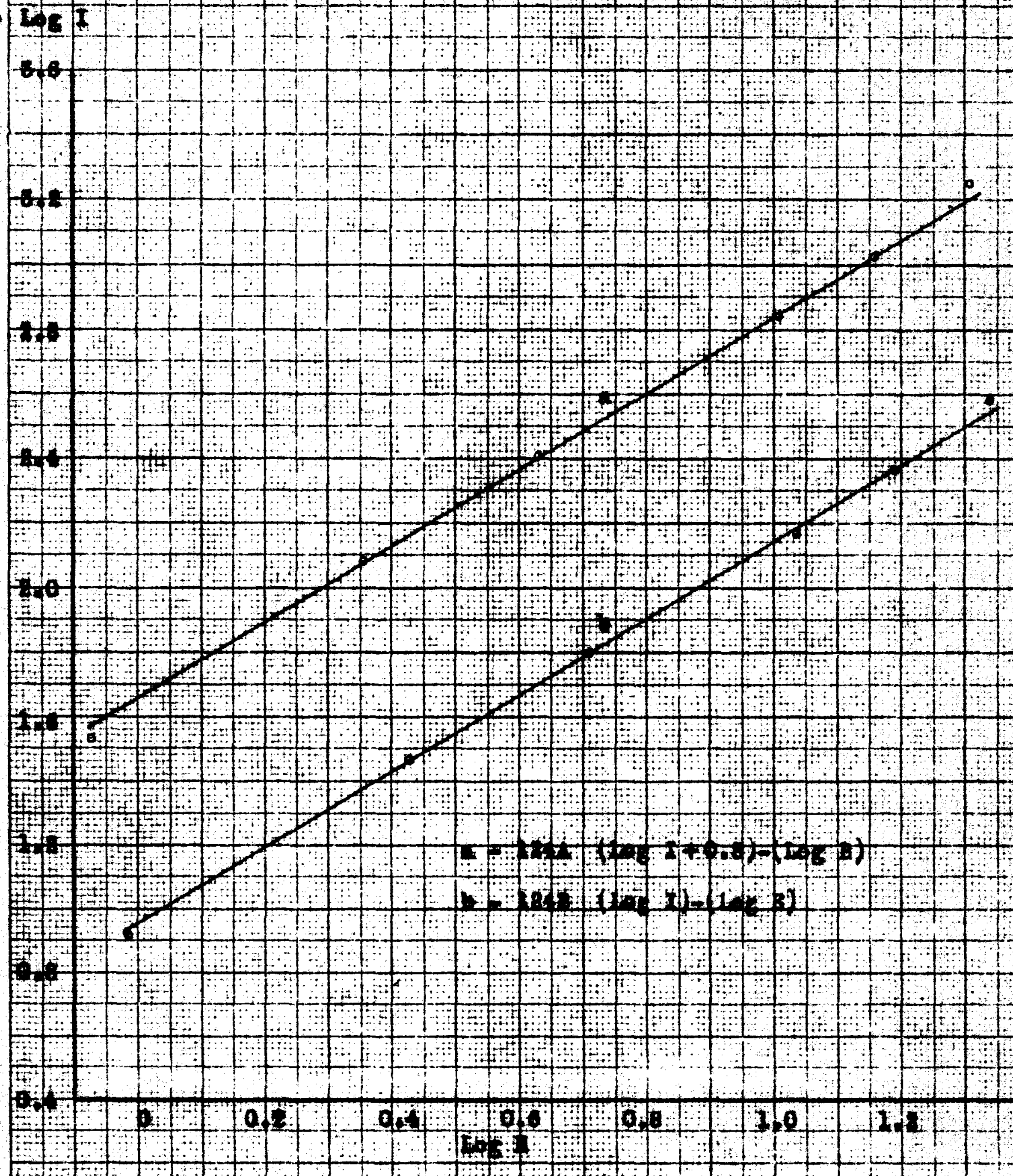


Figure 40. Current-Voltage Logarithm Curves for Forward Current

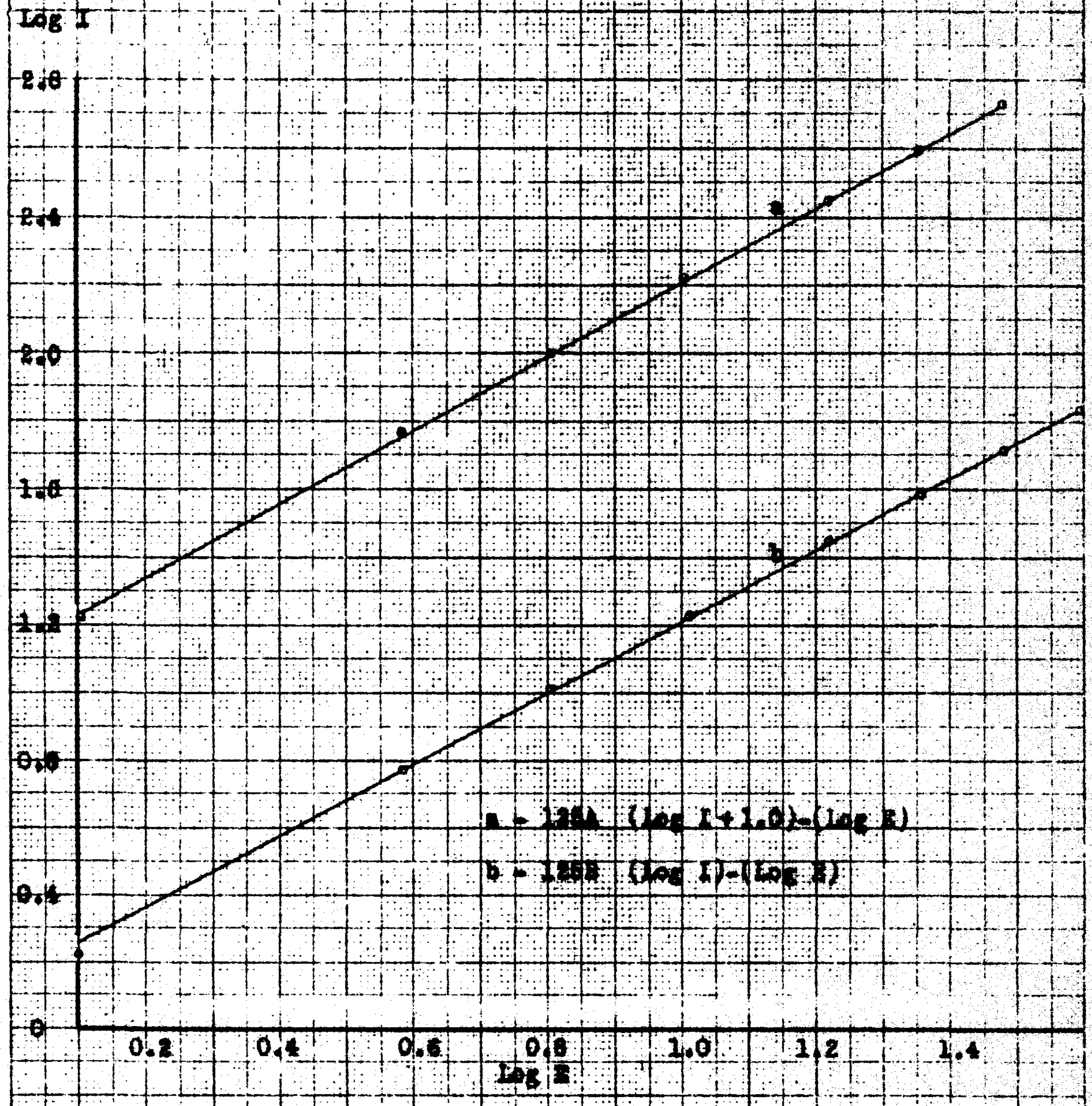


Figure 50. Current-Voltage Logarithm Curves for Forward Current

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