1934

The effect of various operating conditions upon electrical brush wear

Victor Peter Hessler
Iowa State College

Recommended Citation

Hessler, Victor Peter, "The effect of various operating conditions upon electrical brush wear " (1934). *Retrospective Theses and Dissertations*. 13844.
https://lib.dr.iastate.edu/rtd/13844

THE EFFECT OF VARIOUS OPERATING CONDITIONS UPON ELECTRICAL BRUSH WEAR

BY

VICTOR PETER HESSLER

A Thesis Submitted to the Graduate Faculty
for the Degree of

DOCTOR OF PHILOSOPHY

124/44-26

Major Subject Electrical Engineering

Approved:

Signature was redacted for privacy.

In charge of Major work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State College
1934

TABLE OF CONTENTS

I. INTRODUCTION

Faraday built the first simple dynamo in 1832. Ever since that time the problem of current collection from rotating rings and commutators has confronted the electrical experimenter and electrical engineer. The operation of every other part of the machine has been reduced to a mathematical science, but many of the phenomena of the sliding contact are still unexplained. New brush materials have been developed which are a vast improvement over the early copper leaf and copper gauze brushes, but it is still impossible to predict the performance of these materials with any degree of accuracy.

The commutator, slip rings and brushes are the most sensitive parts of a rotating electrical machine. A very large percentage of the maintenance cost of rotating machinery is chargeable to these items. One large power company spends $25,000 per year for brushes. Obviously any addition which can be made to the present operating data and theories of the sliding contact will be of value to the electrical industries.

A careful survey of the literature reveals practically no quantitative data upon electrical brush wear. Only one set of curves of electrical brush wear is found (10) and these are based upon four experimental points. All of the theories of the sliding contact are based upon contact drop phenomena. This situation suggests two reasons for conducting an experimental investigation of electrical brush wear.

First the data should have considerable value in checking or extending the present theories of the sliding contact. Second, such data should have real value for the brush manufacturer and operating engineer in improving electrical brush operation.

It is the purpose of this investigation to develop apparatus and a method of procedure for investigating electrical brush wear, to obtain quantitative data of the effect of various operating conditions upon electrical brush wear, and to check the present theories of the sliding contact in the light of a rather extensive experimentation upon the rate of wear and contact drop of electrical brushes.

II. REVIEW OF THEORIES AND PREVIOUS INVESTIGATION

A. Presentation of Theories

1. The arc theory

According to this theory all of the current is carried across the contact in the form of minute arcs.

Hunter-Brown (10) states, "The voltage drop at the contact does not vary proportionally with the current but remains remarkably constant over a wide range, and there is for each quality of brush a critical value below which no current will flow. In this respect the behavior somewhat resembles that of an electric arc, where there is a certain minimum voltage below which the arc cannot be maintained." "With the ring at rest some current passes at very low voltage, but not with the collector running. Even at the so-called points of contact between brush and collector I think the contact is not sufficiently intimate and continuous to prevent minute arcing, and that even when collection appears to be sparkless the current passes in the form of minute arcs."

Dr. M. Kahn in a discussion of Hunter-Brown's (10) article upholds the arc theory for the following reasons:

(1) There is a great similarity between the brush contact drop curve and that of the electric arc. (2) There is a phenomenon commonly called "copper picking" whereby particles of copper are transfered to the brush in a manner which suggests electrolytic action. A similar action is found in the electric arc. (3) There is a difference in the positive and negative contact drops.

Binder (4) assumes that at very low current densities all of the current is carried across the contact through the loose particles of carbon which are abraided from the brush and roll between it and the ring. As the current density is increased these particles are heated and finally burn. As the particle is burned a very short arc is formed. He arranged a carbon cylinder to roll upon a slip-ring and obtained its voltage-current characteristics for both current directions. The characteristics were the same up to about .016 amperes per square centimeter and above that point the characteristic for the current direction ring to brush was considerably higher. A slight spark or arc appeared at the line of contact simultaneously with the separation of the voltage-current characteristics.

Czepeck (7) obtained oscillograms of both sliding contacts and arcs with alternating current under various operating conditions. This investigation is described more fully under the heading of previous investigations. As a result of this work he concluded that the carbon brush behaves somewhat as a combination of an electric arc and a solid conductor.

2. The thermal ionization theory

The observation of the bright spark or arc which appears when a low voltage circuit is opened led Slepian (18) to develop the formula given below for the temperature of the last contact.

$$T = \frac{E^2}{33.5\,k\,\rho}$$

T= Temperature of last point of contact in deg. cent.
E = volts applied to the electrodes.
k = thermal conductivity in cal. per sq. cm. per deg. cent. per cm.
ρ = electrical resistivity in ohms per cu. cm.

The above formula applied to various conducting materials indicates that, even for small voltages, temperatures are obtained which would bring about both thermal emission and thermal ionization. Accordingly Slepian concludes that current is carried across a sliding contact by means of a relatively few points which reach such high temperature that conductivity is given to the space about them. He has collected data for the contact drop of carbon brushes and high resistivity autovalve arrester disks which indicate a proportionality between the square of the contact drop and the brush resistivity.

3. The multiple point conductance theory

Ludwig and Baker (15) as well as Slepian (18) find that there is a proportionality between the square of the contact drop and the brush resistivity. Also it has been shown experimentally by Little (14) that even with a well fitted brush the current at any instant is carried by a comparatively few minute contact points. The experiment consisted of discharging a condenser across the sliding contact and observing the surface of the brush afterward. From these facts Ludwig and Baker (15) concluded that the voltage drop does not occur at the contact itself, but in a very thin layer of the brush next to the contact. As the current is increased the temperature of the contact points rise. They consider that somehow this will bring about a more intimate contact between the brush and the ring and result in a lower contact resistance.

B. Report of Previous Investigations

1. Introduction

Throughout the text all references to polarity will be given in the motor sense. The positive brush is the one at which the current flows from the brush to the ring (conventional current direction). The positive brush will also be referred to as the anode in the discussion of thermal ionization.

2. Electrical brush wear

Hunter-Brown (10) states, "The wear of a collector ring is due to three causes: mechanical abrasion, a kind of electrolytic action, and burning away of the metal. The rate of wear is dependent upon brush material, brush quality, current density and intimacy of contact." A set of curves are given showing the rate of wear of carbon brushes and of the ring in relation to the current density. The negative brush and ring both wear at a greater rate than the positive, and are approximately proportional to the current density. These are the only curves of brush wear revealed by a thorough search of the literature.

J. S. Dean (8) made an extensive survey of the life of carbon brushes in d-c railway service. In this type of service the actual end wear between the brush and commutator is small compared to all of the other factors which bring about deterioration of brushes. Brushes subjected to end wear alone would give a probable life of 200,000 car miles, whereas the addition of side wear, hammer wear, chipping and breakage reduce the average life to 40,000 car miles. These figures are based upon modern high grade graphitized brushes on a commutating pole motor with undercut mica. With modern medium grade carbon brushes on non-commutating pole motors with flush mica the probable life due to end wear is 20,000 car miles with an average life of 12,000 car miles. It is noted that end wear is a much higher percentage of the total in the second case. These results are explained by the fact that, to a large extent, burning action is responsible for most of the end wear. He gives two very extensive tables of the factors which cause brush wear in railway service. These tables indicate that if good contact is maintained between the brush and commutator at all times brush wear will be low.

Under very low humidity conditions the rate of wear of metallic brushes on high speed converter rings often becomes excessive. Bracken (5) states that whole sets of brushes are sometimes worn out in from 30 minutes to one and one half hours. This effect has never appeared on the lower speed 25 cycle machines. He finds that rapid wear is likely to start whenever the absolute humidity drops below 1.25 grains per cubic foot. His company has equipped each of their substations with humidifying equipment, hair hygrometers and simplified humidity charts. With the aid of this equipment the operator always maintains an absolute humidity above 1.5 grains per cubic foot. He is also making a study of the effect of humidity upon carbon brush wear. This study is not complete, but the results so far indicate an increased wear at extremely low humidity. However, there is no tendency toward rapid disintegration.

A series of tests were conducted by Baker (3) to determine the effect of a hydrogen atmosphere upon electrical brush wear and commutation. A d-c machine was operated both in air and in an atmosphere of hydrogen with varying qualities of commutation. Two runs were made to determine the effect of humidity in a hydrogen atmosphere with poor commutation. The following conclusions were drawn from this series of tests: (1) A well designed commutator machine will operate satisfactorily and give good brush life in hydrogen. (2) If a brush must spark in hydrogen the brush life may be increased many times by keeping the relative humidity below 10 percent. This effect was not checked in air. (3) Carbon and graphite brushes cannot be operated upon a tool steel ring in hydrogen. Particles of cementite (Fe_3C) are formed in the brush face which immediately begin to score the ring and the brush face.

Perrier (16) finds that the rate of wear is increased with the oxidation, sulfuration or chlorination of the ring surface.

3. Contact drop

a. Current density The investigations upon this factor have been so numerous that no attempt will be made to give a complete review. Practically every investigator of sliding contact phenomena obtains curves of contact drop versus current density at some time during the investigation, and everyone interested in brush operation is familiar with them. In general these curves do not extend very much above the commercial working range of the brush material. At very low densities the results of various investigators differ quite widely. Hunter-Brown (11, page 69) states, "The voltage drop at the contact does not vary proportionally with the current, but remains remarkably constant over a wide range, and there is for each quality of brush a value below which no appreciable current will flow." Considerable exception was taken to this same statement in the discussion of his paper before the Institution of Electrical Engineers (3). As a result of this controversy Taylor (22) obtained curves of contact drop versus current density at both positive and negative brushes for very low values of current. He does not give the experimental points, but he shows both curves passing through the origin. The negative and positive brush contact drop curves rise as straight lines to .7 and .2 volts respectively at .03 ampere. Thus in terms of commercial operation there is a certain magnitude of voltage below which no appreciable current will flow, but for theoretical purposes the curves must be considered to pass through the origin.

b. Effect of atmospheric pressure Baker (2), while investigating the effect of various atmospheres upon the operation of electrical brushes, placed a ring and brush under a bell jar and exausted it to 50 microns. No observable change occurred in the contact drop throughout this range of pressure.

c. Brush dimensions Stine (21) and Baily and Cleghorne (1) both found that for a given total current and total brush pressure the contact drop is independent of the brush size. Baily and Cleghorne found that with only 20% of the brush face bearing on the ring the contact drop was increased only 5% over that for complete bedding. Stine obtained a group of curves of contact drop against brush pressure at fixed nominal current densities for various brush sizes. The contact drop increased for each increase in brush size, indicating that the actual current densities are higher in the larger brushes.

d. Effect of mercury vapor While studying the effect of a hydrogen atmosphere upon brush wear, Baker (3) discovered that carbon brushes on a brass ring in a non-oxidizing atmosphere would sometimes give a very low contact drop. Also the contact behaved as a constant ohmic resistance. Later he found (2) that the low contact drop was caused by a mercury amalgam on the brass ring. A mercury vapor pressure of .006 in a non-oxidizing atmosphere will amalgamate a brass ring (40 per cent zinc) sufficiently to reduce the contact drop approximately 95 per cent. If air is admitted to the contact 50 per cent of the contact drop is recovered in about one minute. A ring amalgamated with solid mercury requires more time for recovery and if the amalgamated ring is allowed to stand overnight several hours are required for recovery. A copper ring does not give quite as pronounced an effect as the brass ring, and the effect was not even observable upon a steel ring. In conjunction with the above experiment Baker also found that, if no mercury vapor is present, the contact drop is independent of the pressure or material of the surrounding atmosphere. Atmospheres of hydrogen and nitrogen gave the same contact drop as air.

e. Transient current changes It has been shown by several investigators that there is a definite time lag between the change in current across a sliding contact and the resulting change in resistance. Kahn, (13) showed this to be true by means of a rather complicated rotary switch arrangement. Little (14) observed the same effect by taking oscillograms of the contact drop with alternating current. At 25 cycles the current and voltage waves were similar, whereas at 3 cycles the contact drop wave was badly distorted indicating the usual change in resistance with current. Ludwig and Baker (15) obtained a "transient brush drop curve," which is almost a straight line, but no information is given concerning the method of obtaining it.

A very extensive investigation of this phenomenon was performed by Czepek (7). He obtained a large number of oscillograms of current and voltage across a sliding contact, for different values of frequency, current, polarity and brush materials. From these oscillograms he obtained the data for voltage-current and resistance-current characteristics for both polarities. The voltage current characteristics appear quite similar to the ordinary magnetic hysteresis loop except that the curves pass through the origin. For the current direction of ring to brush the voltage-current characteristic for rising currents always lies above that for decreasing current. For the other current direction the converse is generally true, but in some cases the descending curve crosses the ascending curve. The ascending and descending curves for the current direction of brush to ring are in general closer together than for the opposite current direction. These experiments were repeated with a copper-carbon arc and somewhat similar results obtained. The results with a copper brush were entirely different. The copper brush contact acted as a conductor with a negative temperature coefficient of resistance. Also the results were identical for both directions of current flow.

f. Ring speed Taylor conducted a series of tests upon the effect of high ring speeds upon contact drop. He found that for every value of brush pressure and current there was a critical ring speed above which the contact drop increased very rapidly. For higher values of either current density or brush pressure the critical speed was increased. The increased contact drop at instability was always accompanied by increased sparking. It was also found that an unstable voltage at a particular brush pressure could be made stable by an increase of current.

Baily and Cleghorne (1) found that for ring speeds below 3300 feet per minute the contact drop was independent of speed, unless the pressure was reduced below 18 ounces per square inch. Below 18 ounces per square inch the contact drop increased decidedly with increase of speed.

g. Ring material Edgecomb and Dick (9) found that the voltage drop is less for a ring material which does not form a non-conducting oxide on its surface. It was noted that brass collector rings containing zinc became coated with an oxide which increased the contact drop. The voltage drop was reduced by cleaning the ring surface with acid. On the basis of the above results they state that the voltage drop is probably increased also by the glaze or polish which results from operating a machine. Experimental investigations by Perrier (16 and 17) have shown this supposition to be correct. He found that the contact drop is decreased considerably by roughening the brush surface and cleaning the ring surface. He also found that oxidation, sulfuration and chlorination of the ring surface all bring about an increase in the contact drop.

Hunter-Brown (11, page 132) states that the contact drop with iron or steel rings even when clean is about 30 per cent greater than with bronz rings.

h. Brush holder Hunter-Brown and Hews (12) made a very extensive investigation of the effect of brush holder design upon the contact drop. The experiments were performed upon a commutator with one high bar and two flats. They studied each type of brush holder from the standpoint of stability as affected by sudden irregularities, constancy of arc as affected by gradual irregularities, and suitability for reversible running.

For sudden irregularities the ordinary radial was very sensitive, the cantilever radial good, the trailing very good and the reaction 32 degrees centigrade excellent. For gradual irregularities the ordinary radial and cantilever radial were excellent, the trailing very good and the reaction easily upset. For reversible running the ordinary radial was bad, the cantilever radial excellent and the trailing and reaction types bad. The effect of inertia of the brush and pressure arm were investigated by weighting them alternately with lead. Any increase in the inertia of the brush itself seriously affects the stability of the contact drop upon an imperfect commutator. However, an increase in the inertia of the pressure arm produces decided improvement in the stability of the contact drop.

C. Discussion of Theories

The various theories of the sliding contact stated in more detail above may be restated briefly as follows:

1. All of the current is carried across the contact by means of electrical conduction through the actual points of contact.

2. All of the current is carried across the contact in the form of an arc.

3. The current is carried across the contact by means of solid particles and electric arcs in parallel.

4. The current is carried across the contact as a result of thermal ionization and thermal emission resulting from the high temperature of the last point of contact.

The resistance of a solid conductor is given by

$$r = \frac{\rho l}{a} .$$

If all of the current is carried across the contact by means of electrical conduction through the actual points of contact, all contact resistance phenomena must be explained on the basis of changes in the resistivity, length, or cross-section of the materials at the contact. The resistivities of carbon and graphite are reduced to approximately 66 and 69 per cent respectively of their value at 25 deg. Cent. when heated to 2500 deg. Cent. Above this temperature carbon begins to give thermal emission, so the phenomena could no longer be considered as simple conduction. This reduction in resistivity is not sufficient to account for the change in resistance with current of the carbon contact. The length of the contact might be considered as a function of the particle size of the brush material. There is no apparent reason why this should change with current. A reduction in area could be obtained by increasing the size or number of points of contact between the brush and ring. An increased current would heat the contact points and bring about thermal expansion. This expansion would tend to raise the brush and decrease the area of contact rather than increase it. In the case of a metallic brush the thermal coefficient of resistivity is positive so this factor cannot account for decreased resistance. The area of contact could be increased by melting of the copper, but it does not seem possible that this could account for the uniform change in resistance which occurs with current change. There is no factor in the electrical conduction theory to account for the difference in the positive and negative contact drops of both carbon and metallic brushes. The above evidence indicates that the phenomena of the sliding contact cannot be explained upon the basis of electrical conduction alone.

If all of the current was carried across the sliding contact as an arc a certain minimum potential would be required to start the current flowing. In fact, that is the salient point presented in support of the arc theory. Some investigators report that there is a definite minimum below which no current will flow, but the most conclusive data are presented by Taylor (22) and Binder (4) who show that the current-voltage characteristics do pass through the origin. Stark and Cassuto (20) have shown that a metal disk kept cool by being rotated can be used as the anode of an electric arc but not as the cathode. Thus it is indicated that the phenomena of the sliding contact cannot be explained upon the basis of the electric arc alone.

Theories three and four are fundamentally the same since they differ only in the manner in which the thermal ionization is produced. Binder (4) suggests that as the current is increased the I^2r loss at the points of contact will finally volatilize the conducting material and form an arc. This process may take place either through a salient point of the brush or across a bridge formed by an abraided carbon particle rolling between the surfaces. Slepian (18) suggests that the points of contact are continually changing due to the motion of the ring. This continual breaking of the points of contact results in thermal ionization, according to his theory of the temperature of the last contact. It must be shown that it is possible to produce ionization thermionically with the voltage and materials involved in the sliding contact.

First let us consider the heat generated in a cube of conducting material with current flowing from one face to the opposite face.

According to Joule's law

$$P = \frac{E^2}{r}$$

The resistance of a solid conductor is given by

$$r = \frac{\rho l}{a}$$

Where ρ = resistivity
l = length of conductor
a = cross sectional area of conductor

From the above

$$P = \frac{E^2 a}{4.186 \rho l} \text{ calories per second.}$$

If the conductor is in the form of a cube

$$P = \frac{E^2 l}{4.186 \rho} \text{ calories per second.}$$

The time required to raise the temperature of a body through a given difference in temperature is equal to the total heat required divided by the rate at which heat is delivered to it if no heat is conducted or radiated from the body during the process. If C is the specific heat in calories per deg. Cent. per cubic centimeter, the time required to raise the temperature of a cube of conducting material $(T_2 - T_1)$ is given by

$$t = \frac{W}{P} = \frac{l^3 \ C \ (T_s - T_1)}{\frac{E^2 \ l}{4.186 \ \rho}}$$

$$t = \frac{4.186 \ \rho \ C \ l^2 \ (T_s - T_1)}{E^2}$$

Substituting, $\rho = .003$; $C = .4$; $l = .001$; $(T_s - T_1) = 3000$, and $E = 1$ in the above equation, t is found to be $1.5 \ 10^{-5}$ seconds. It must be understood that this calculation is roughly approximate since radiation, conduction and change in the physical constants with temperature have been neglected. However it indicates that it would be possible to attain a thermal ionization temperature with the materials of ordinary carbon brushes. For metallic brushes the time is much shorter than for carbon brushes since the resistivity decreases much more than the thermal capacity increases. Also the metallic brush would give thermal emission at a lower temperature than the carbon brush.

According to Slepian's theory (18) a potential difference of 1 volt across copper electrodes would produce a temperature of 3000 deg. Cent. at the last point of contact. The corresponding value for carbon brush materials is 60 degrees. These values do not account for thermal ionization since metallic brush drop is ordinarily a fraction of one volt and the temperature is too low in the case of carbon.

However the average drop across the sliding contact is always small compared to the total voltage available in the circuit, so the instantaneous voltage could rise to a sufficient value to attain the thermal ionization temperature.

From the above it is seen that temperatures corresponding to those of the electric arc can be attained in the sliding contact, but the voltage is only a fraction of that required in the arc. The question immediately arises whether the thermal ionization required to carry the sliding contact currents could be obtained by temperature alone without the intense electrical field which exists at the electrodes of an electric arc.

Thomson (23, page 595) states, "The theory that the arc is maintained by thermionic emission from the cathode is generally accepted for arcs where the boiling point of the cathode is so high that thermionic emission at that temperature is sufficient to account for the current carried by the arc. Objections have been raised to its application to such metals as mercury and copper, which boil at temperatures lower than those at which thermionic emission is appreciable." He suggests that the thermionic emission of a mercury arc could be produced by a layer only a few molecules thick and that the positive ions dropping into this surface would prevent a very rapid evaporation. The energy available at the cathode is shown to be sufficient to heat the surface mercury to 3000 degrees Cent. even with the cathode rotating at a high velocity. A theory has been advanced that the extraction of electrons at the cathode of the arc is due to "auto-electronic emission." A check of the theories and experimental results of "auto-electronic emission" shows that only a very small percentage of the cathode emission could be accounted for by this phenomenon.

The time lag in the resistance change is consistent with the arc theory since an appreciable time is required to heat the contact materials. The same phenomenon was observed in the electric arc by Czepek (7).

A larger contact drop with higher resistivity materials should be expected since more voltage is required to heat them to emission temperatures. The increased contact drop with the oxidation, chlorination, or sulfuration of the ring follows for the same reason.

The contact drop of metallic brushes is smaller than that for carbon brushes. This is consistent with the above theory and also corresponds to the contact drop of the ordinary arc.

III. EXPERIMENTAL

A. Description of Apparatus

1. The mechanical arrangement

The mechanical details of the apparatus are shown clearly by Figures 1 and 2. The rings were carried on a 1 3/16 inch shaft, rotating in self-aligning ball bearings. The bearing brackets were bolted to a heavy cast iron base, making a very rigid support for the entire ring and brush holder structure. The rings were carefully balanced before assembling on the shaft, so there was very little vibration at any of the speeds used in the tests. For practically all of the tests the brushes were arranged side by side, so that the positive and negative brushes rode on separate paths. This arrangement will be designated as "brushes not tracking."

2. The brush electrical circuit

In practically all of the tests the various pairs of brushes were connected in series and the entire group connected to a 90 volt d-c generator through a series resistor. A low voltage plating generator was first used

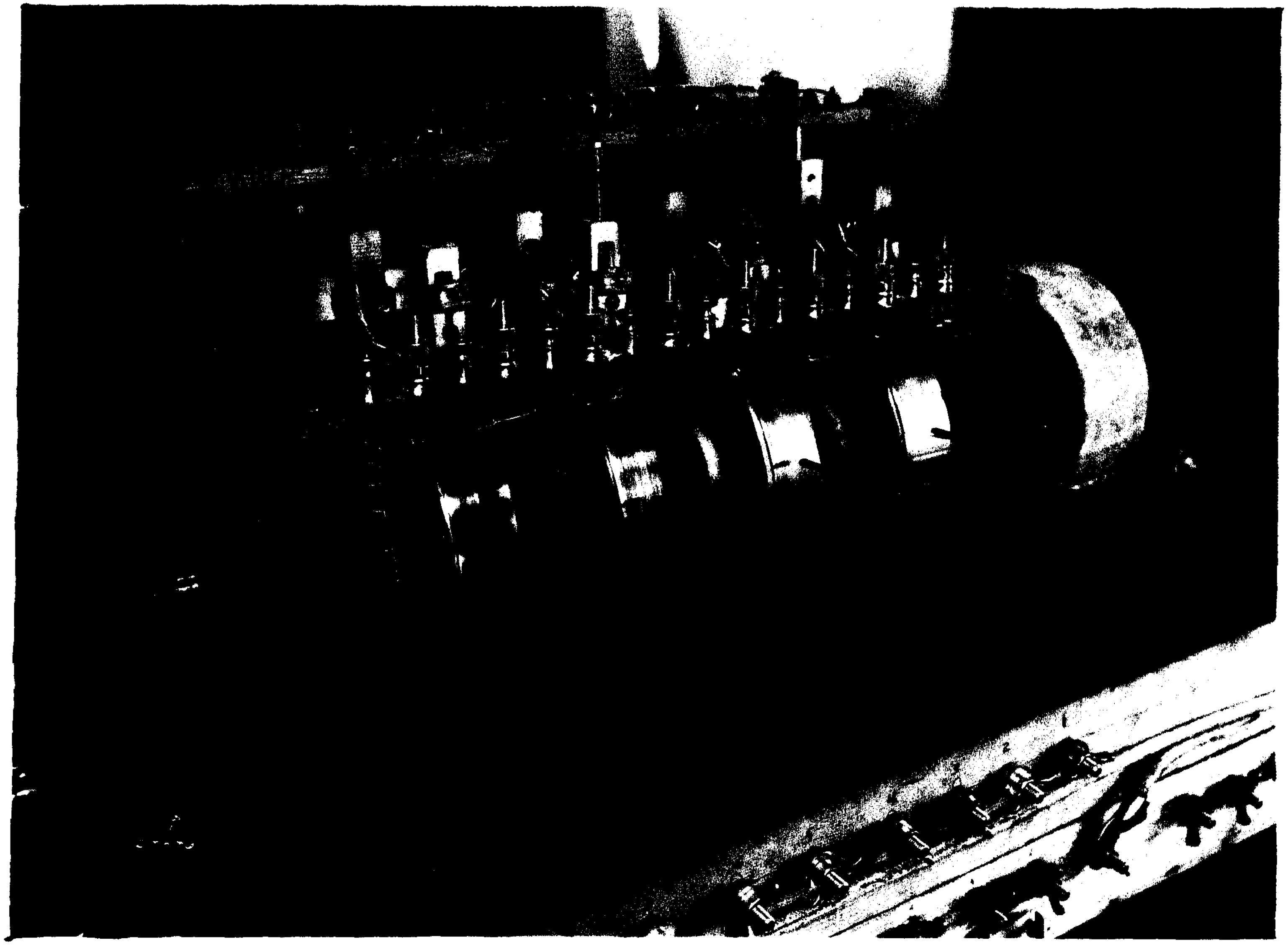


Figure 1. General vies of brush holder and ring mechanism.

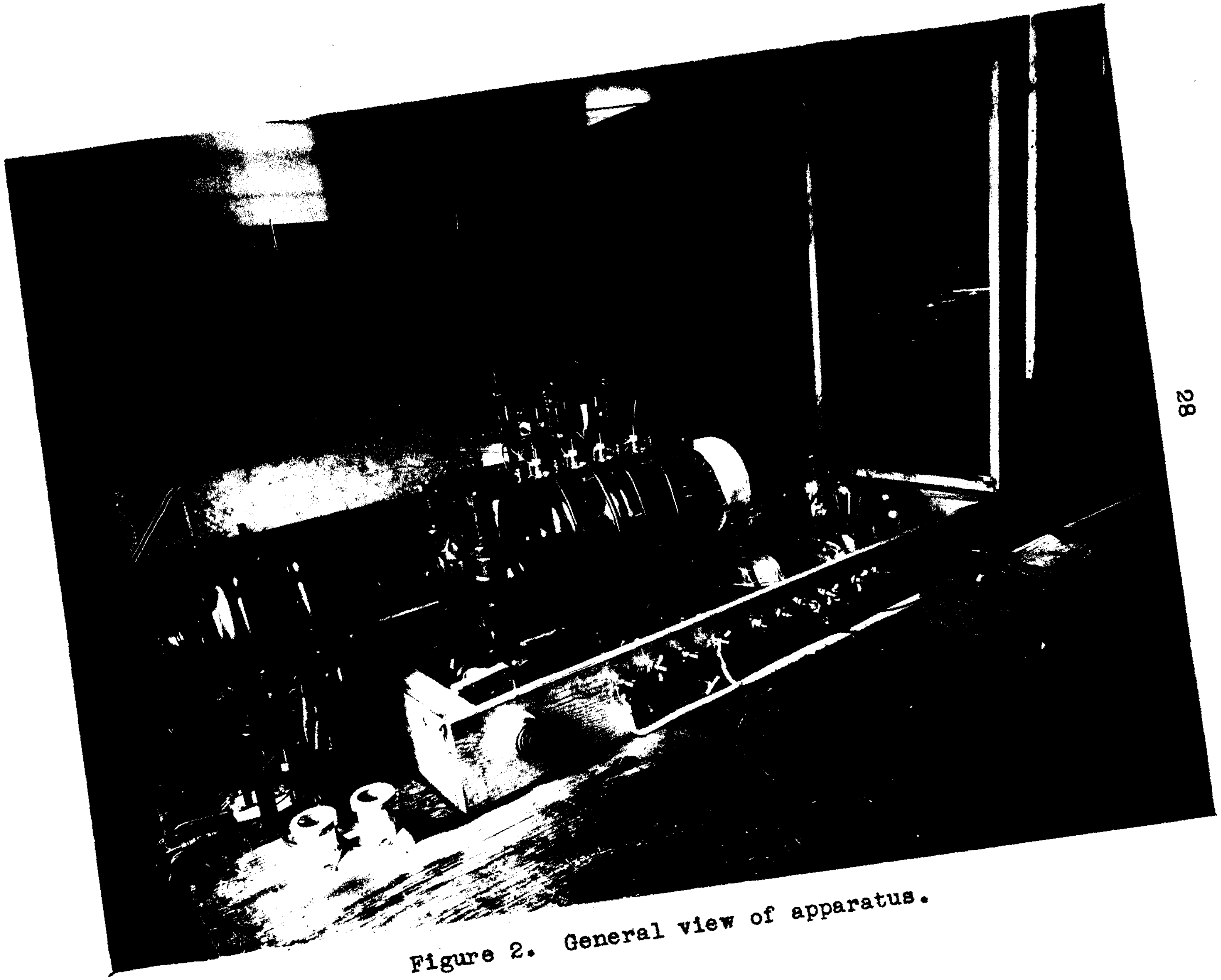


Figure 2. General view of apparatus.

to supply the circulating current, but it was impossible to maintain a constant current due to the change in contact drops. With the higher voltage machine the contact drops were such a small percentage of the total that no trouble was experienced in maintaining constant current.

The positive and negative contact drops were determined with the aid of auxiliary copper leaf brushes (Figures 1 and 3). These brushes were made sufficiently narrow that they did not touch the paths of the test brushes. They were equipped with a brush lifting mechanism to prevent their wearing away too rapidly. The total positive and negative contact drop was always read to check the sum of the individual values.

3. Rings

The first ring obtained was of cast copper. The ring, being very dense and free from blow holes, gave satisfactory results. The other five rings consisted of aluminum disks with rolled and brazed rings of hard drawn electrolytic copper pressed upon them. The former will be called the cast ring and the latter the drawn rings.

The rings were insulated from each other by means of wood spacers and from the shaft by means of .005 inch vulcanized fiber.

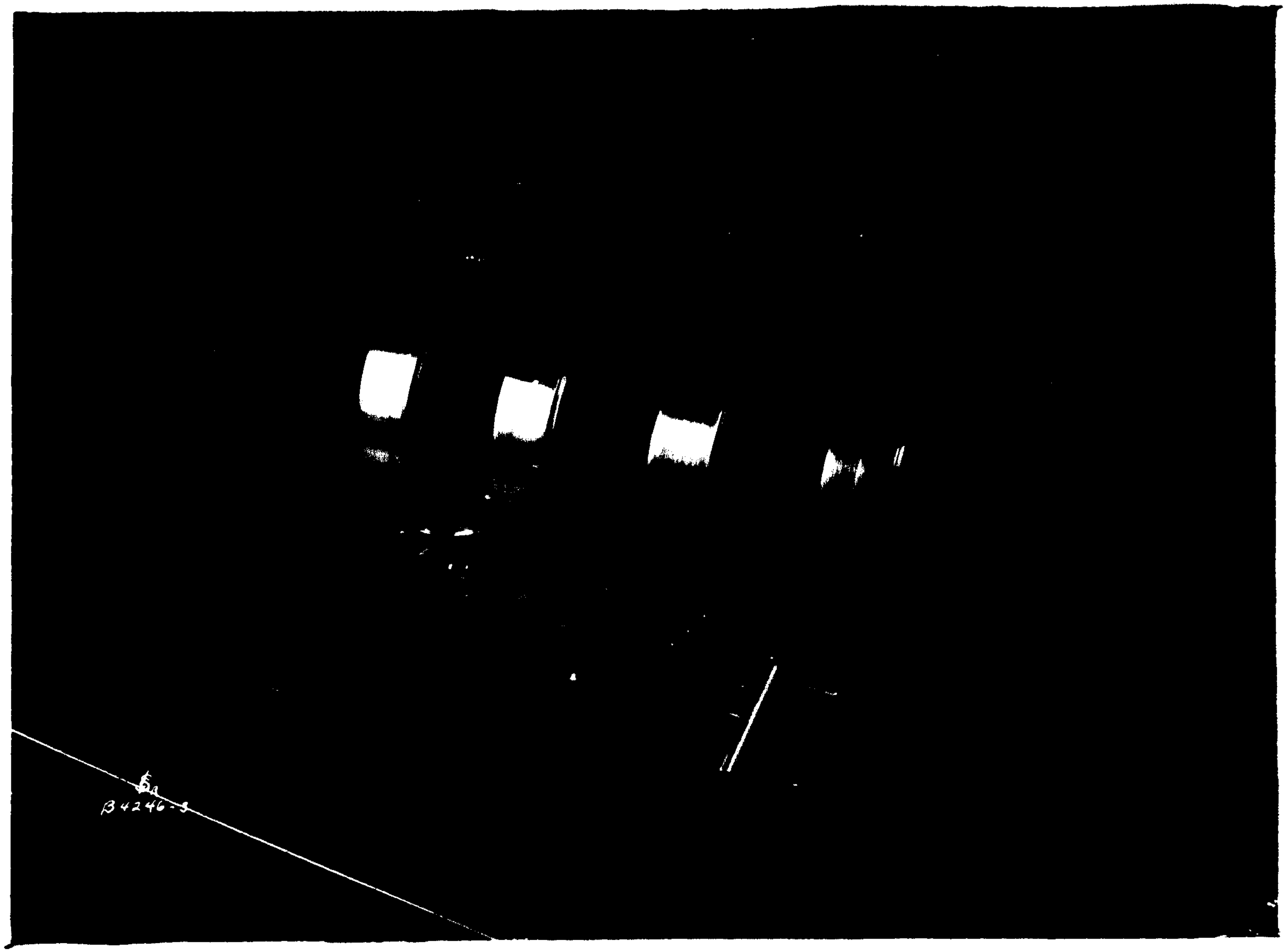


Figure 3. Ring grinding mechanism.

The rings were ground by means of the grinding mechanism shown in Figure 3. The abrasive was a commercial commutator dressing stone. After grinding the ring true with the stone it was polished with a fine alundum cloth and finally burnished with a piece of beech wood. The burnishing was not continued to the extent of visibly oxidizing the surface. Next the eccentricity of the ring was checked and if it exceeded .002 inches the ring was reground. Some of the earlier data was taken without checking the eccentricity.

4. The brush holders

The brush boxes were made by soldering together four pieces of 1/8 inch brass. They were made very accurately; so there was just enough clearance to allow the brushes to move freely up and down in the holder with very little side play. The boxes were one inch long. Several improvements in the holders were made as the work progressed. However, the changes were made mostly for the purpose of operating convenience. Figure 4 shows the details of the final design. By changing the springs it was possible to obtain a very wide range of pressures and to adjust the pressure accurately to any value desired. The fulcrum was adjustable so that the pressure arm could always be kept perpendicular to the brush.

The pressure was checked by means of a sensitive spring

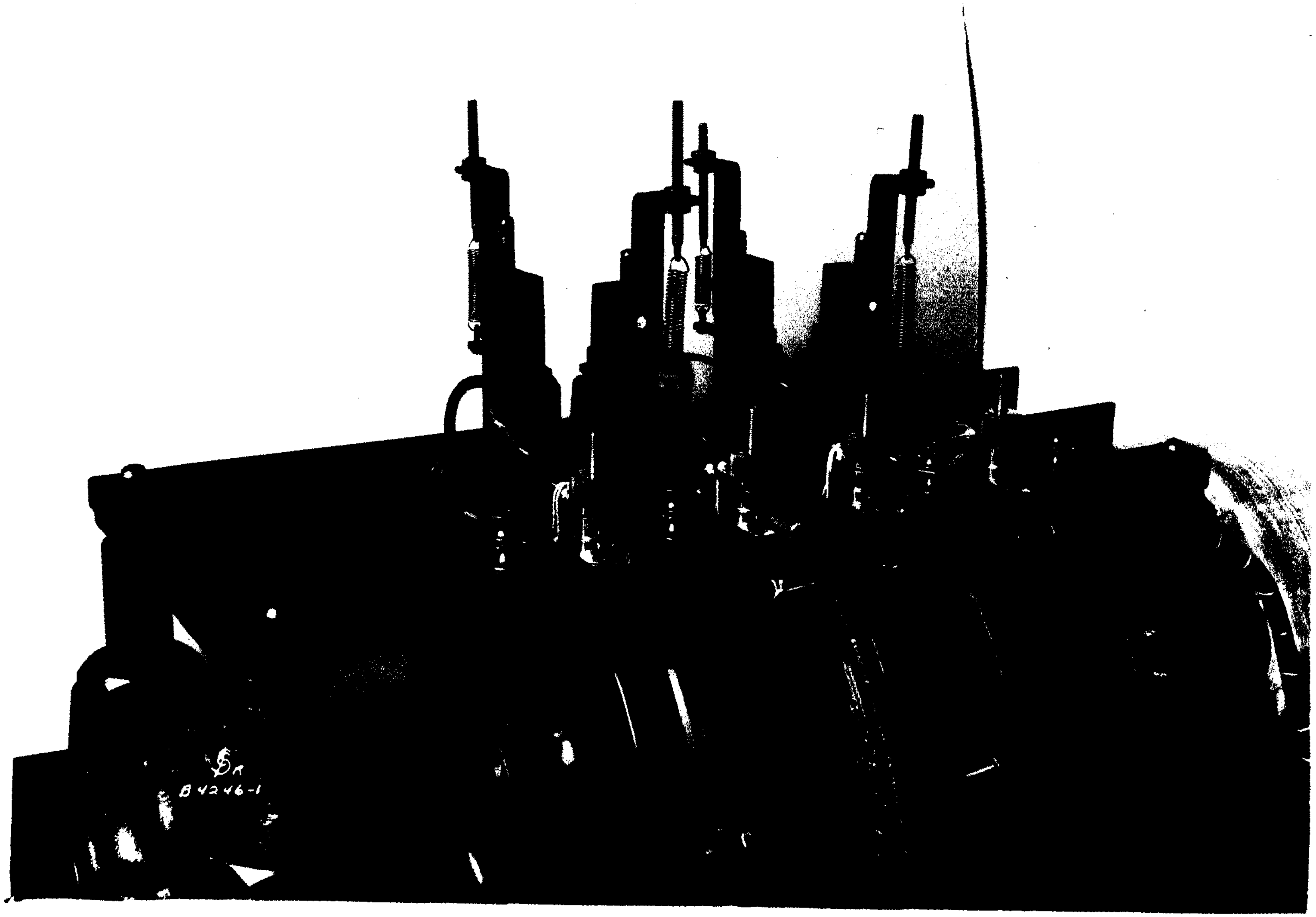


Figure 4. Detail of brush holders.

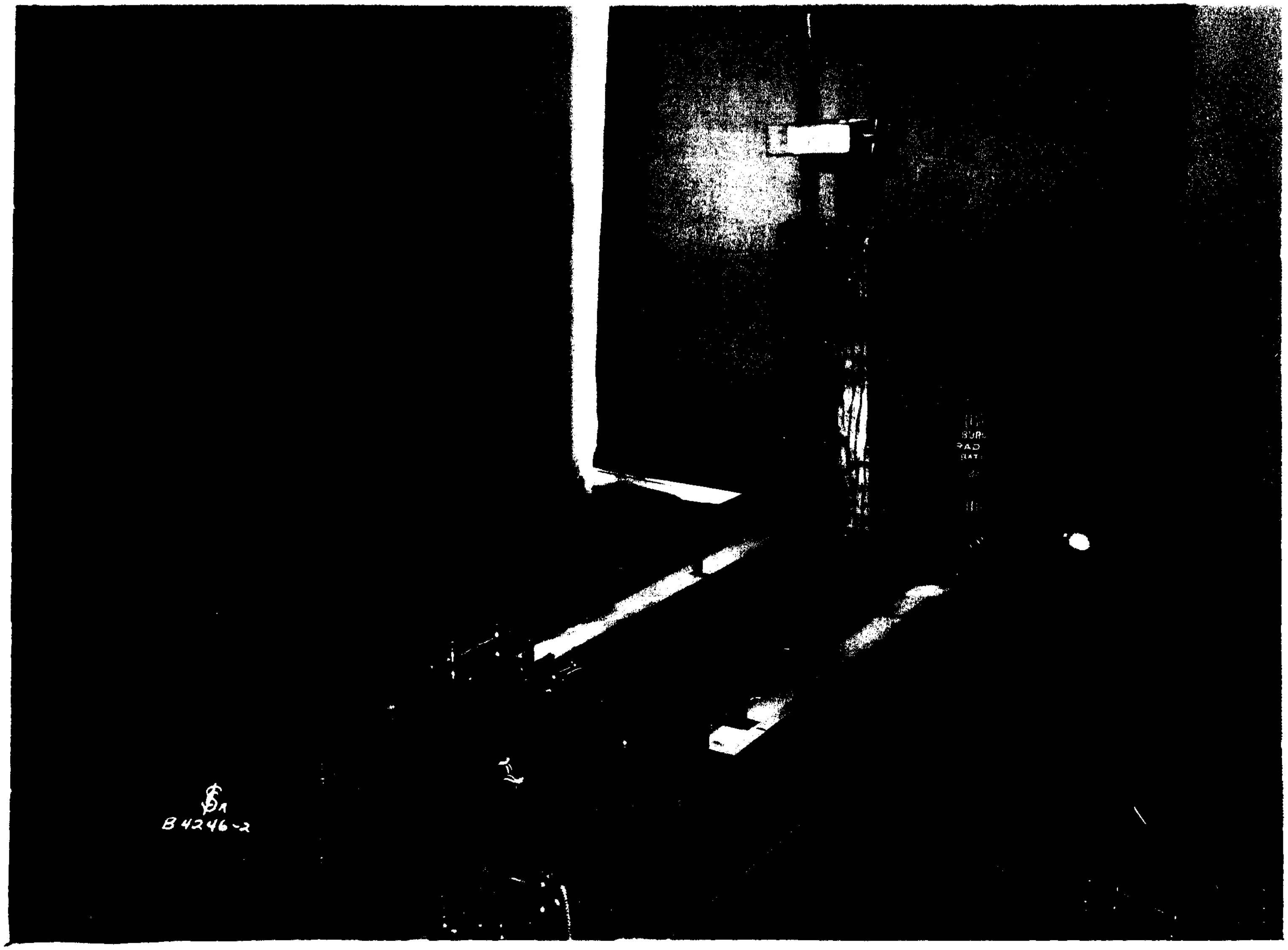


Figure 5. Method of adjusting brush pressure.

balance, a dry cell and a pair of ear phones. The pressure arm was pulled up by the balance until a click in the ear phones indicated separation from the brush. The pressure, indicated by the balance, was corrected for the weight of the brush. The apparatus is shown ready for use in Figure 5.

5. The dust collector

When the apparatus was first enclosed in a box considerable increase in wear occurred. This was assumed to be due at least partially to the increased dust content of the air. To remove some of this dust from the air a radial blade fan was attached to the end of the shaft and covered with several layers of cloth. The air was drawn in through the central opening and forced out through the cloth, leaving most of the dust particles in the cloth. The clothes became blackened with carbon and copper dust in a few days, indicating the effectiveness of the device. It also served as a fan to keep the air in circulation to maintain a uniform temperature throughout the box.

6. Temperature and humidity control

The apparatus was enclosed in boxes as shown in Figures 2 and 6, and temperature and humidity maintained constant at all times.

The dry bulb temperature was maintained constant by

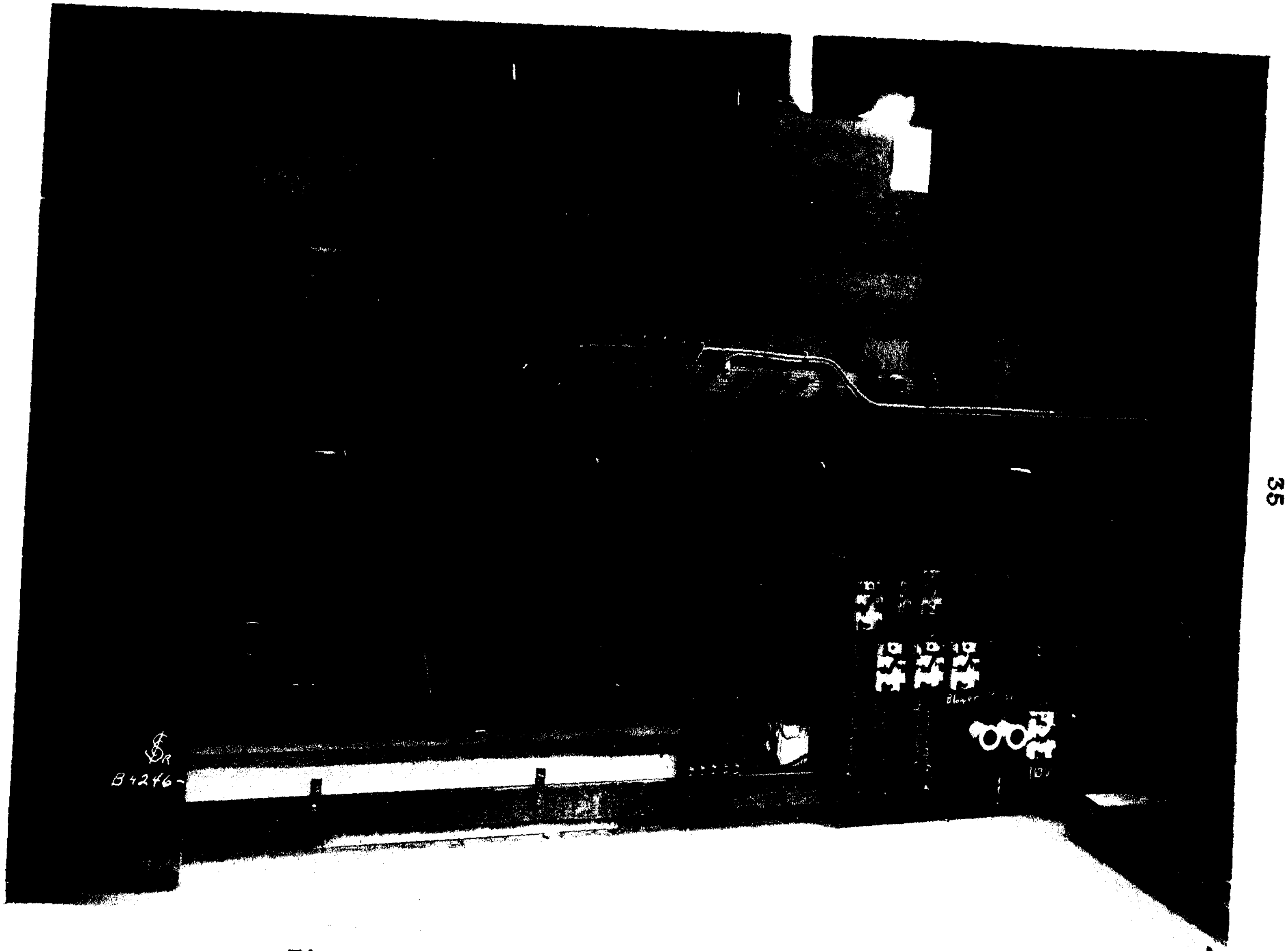


Figure 6. Humidity control equipment.

means of a sensitive thermostat controlling a number of light bulbs through an auxiliary relay. The temperature was held constant at 45±.2 deg. Cent. except for occasional variations due to contact troubles.

In the early part of the work the relative humidity was maintained constant by means of a calcium chloride solution of constant saturation. This method gave satisfactory control of humidity, but for the higher current densities the brush contact loss was so large that the temperature rose above 45 deg. Cent. To overcome this difficulty the humidity control equipment shown in Figure 6 was constructed. The air from the room was blown through a series of four water spray nozzles, then through a series of baffle plates to remove entrained moisture, next past a heater where the temperature was raised sufficiently to prevent condensation in the tunnel, and finally through a series of air nozzles into the box. The water was forced through the spray nozzles by a centrifugal pump and flowed back to the supply tank. Humidity control with this apparatus consisted simply of holding the spray water temperature at the dewpoint corresponding to the relative humidity and air temperature desired. The water temperature in the supply tank was held constant with a thermostat. The relative humidity was determined by means of wet and dry bulb thermometers placed in the air stream from the dust collector. This is a standard method of air conditioning.

The method of humidity control in the box with two rings was somewhat different. A pan of water was placed below the dust collector, from which more water evaporated than was needed to maintain the desired humidity. A container into which a thermostat and two copper tubes were sealed was mounted above the pan. One tube was connected to the water supply through an electrically operated needle valve and the other connected to the drain. The thermostat was set to hold a constant water temperature in the can corresponding to the dewpoint for the desired relative humidity and temperature. With a slight increase in temperature the thermostat caused the needle valve to open and cold water flowed into the can. The excess moisture evaporated was condensed upon the surface of the can and drained back into the pan below. This apparatus gave very accurate control, but it was impossible to obtain humidities below 20% at 45 deg. Cent., because the tap water temperature was never below the dewpoint corresponding to the above humidity conditions. All tests below this humidity were made by removing the moisture supply and drying with calcium chloride. The above method of holding constant humidity was original with the author, since no reference to it was found in the literature.

7. The brushes

All of the brushes tested were one half inch square and two inches long. The physical constants given in table 14 are actual measured values on the individual brushes used and not average values for the particular grade.

8. Method of measuring wear

An attempt was first made to determine the wear by weighing the brushes. It was impossible to determine the wear by this method because the water content of the carbon brushes varied more than the weight of the brush material worn away. A micrometer arrangement for measuring the change in length of the brush was finally developed which gave excellent results. The final design is shown in Figure 7. The bed plate is of invar steel and has an effective expansion of less than .00002 inch for the greatest change in room temperature. To measure the length of a brush it was placed in the V-groove and weighted with the V-block as shown. The micrometer head was screwed in until the hammer plate of the brush made contact with an insulated point as indicated by a click in the ear phones. The smallest division on the dial represented .0001 inch. This division was about .1 inch long; so the readings were

Figure 7. Brush measuring device.

easily estimated to .00001 inch. It was easy for the author or another experienced operator to check readings within .00002. In many cases 0.00000 inch wear was indicated on the positive carbon brush, but a negative wear was rarely ever indicated. This justifies reading the instrument to .00001 inch. It must be understood that these readings did not give any indication of the absolute length of the brush, but simply indicated the difference in length from the beginning to the end of a run.

B. Method of Procedure

The brushes were always carefully worn in before any measurements were taken. They were first sanded as nearly as possible to the curvature of the ring and then run at approximately normal current until the entire brush face made contact with the ring. Much less time was required and a better surface was obtained when "running in" with current than without current.

In some cases the rings were resurfaced at the close of each run, while in other cases they were not resurfaced for several runs. Information concerning the ring preparation and ring condition during the tests will be given in the presentation of data. The condition of the ring surface is one of the most difficult factors of brush wear to control in a quantitative study. It has a decided effect upon brush wear and therefore should be held constant while studying the effect of other variables.

The procedure throughout the experimental work consisted of holding all of the factors constant except one and noting the effect of it upon brush wear.

Several values of contact drop were taken for each wear test. These readings were corrected for I R drop through the brush material and shunts. In the later part of the work auxiliary potential leads were soldered to the hammer plate to eliminate the correction for the shunt.

The duration of the individual tests was varied from one and one half hours to ninety-six hours, depending upon the type of brush material and conditions of the test.

C. Presentation of Data

1. Introduction

The curves and the complete tabulation of the experimental data are given in Appendix I. In this section a more detailed description of the test conditions will be given, than was possible in the space limitations of the data sheets.

It should be remembered that all reference to the polarity of the contact drops are given in the motor sense.

The positive brush is the one at which the current flows from the brush to the ring (conventional current direction).

Throughout the experimental work a careful record was kept of the physical appearance of ring and brush surfaces. This material is too voluminous to present in detail, but reference will be made to it in this section and in the discussion of results.

The brushes are referred to by their letter notation. The nature of the brush materials and their physical constants are given in Table 14, Appendix 2. A chart for obtaining life in hours per inch from wear in inches per 100,000 hours, and another for obtaining absolute humidity in grains per cubic foot from relative humidity at 45 deg. Cent. are also given in Appendix 2.

2. Carbon brush wear versus current density

In Table 1 are given the data for the first wear tests. Some of the test conditions were not held very constant since the apparatus was being perfected during this period. The extent of the variation is indicated on the data sheets. The rings were ground in carefully before the first data were taken. However, the rings were not ground or polished again in the entire two and one-half month period during which these data were taken. The data are recorded in the chronological order in which they were taken. This series of tests was stopped at 70 amperes per square inch because the contact losses became so large that the temperature could not be maintained at 45 deg. Cent.

The contact drop points represent the average of all of the readings taken at a particular current density. Every point represents the average of 12 to 15 readings taken at intervals throughout the period of the tests.

The order in which the points were taken probably accounts for the lack of correlation of the 35 and 45 ampere per square inch points.

The data given in Table 2 were obtained after the air conditioning apparatus illustrated in Figure 6 was constructed. In this and all following series of tests no difficulty was experienced in holding constant air conditions in the box. In this series of tests the rings were reground and repolished at each change in current density. Several readings were obtained at each current density with the hope of obtaining the normal ring surface for that particular current density. Every point has been plotted and numbered on Figures 12 to 15. The numbers indicate the order in which the points were obtained, number 1 always being the first point obtained after the ring was repolished.

3. Carbon brush wear versus ring speed

The data for this test are given in Table 3. The rings were reground and repolished at each change in speed. It should be noted that the same brush material was used in all four brush holders, but one pair was riding on the cast ring with separate paths and the other on a drawn ring with the positive and negative brushes on the same paths.

4. Carbon brush wear versus brush pressure.

The data for this test are given in Table 4. The rings were repolished at each change of pressure. The data show a decided increase in wear of the brushes on the drawn ring at 120 ounces per square inch. This increase is not due to increased pressure alone. As hereinbefore described the drawn ring consists of a 1/8 inch thick band of copper pressed upon a cast aluminum ring. The oxide film between the aluminum and the copper presented sufficient heat insulation to cause a decided increase in temperature of the ring, brushes, and brush holder. The run was interrupted after 21.75 hours, when the solder in one of the brush boxes melted. In the cast copper ring the heat was conducted away from the ring surface so that it was possible to go to 144 ounces per square inch without encountering operating difficulties.

5. Carbon brush wear versus relative humidity

The data for these tests are given in Tables 5 and 6. The data of Table 5 were taken just after the current density tests of Table 1. The rings were not repolished until after these data were taken. The data of Table 6 were taken several months later on different rings and in the apparatus of Figure 2. The rings were polished before the tests were started and then repolished at each change of humidity. The two points in Figure 24 marked "photo" are high because of a "photograph" which developed on the ring. A photograph is a blackened spot on the ring starting with a very sharp line showing the exact outline of the brush face and gradually diminishing in intensity against the direction of rotation. A gage reading almost always shows a flat spot on the ring surface where these photographs appear. They also have a tendency to reappear on the same section of the ring even after the ring has been carefully repolished. They always increase in length with operation and cause an increased rate of wear as indicated in this case.

6. Metallic brush wear versus current density

The data for metallic brush wear versus current density for various operating conditions are given in Tables 7 to 10. The rate of wear of metallic brushes is so much larger than for carbon brushes that it was possible to decrease the length of the runs to a small fraction of that required for carbon brushes. The rings were ground and polished carefully at the beginning of each series and then not polished again until the test conditions were changed. That is, all the data given in Table 7 were obtained without repolishing the rings. Then the rings were polished and the data of Table 8 obtained. The changes in the test conditions other than current density are indicated clearly on the data sheets.

Brush F is a very heavy metal brush material which contains some lead. In all of the runs a grayish-white coating (assumed to be lead) was deposited upon the ring surfaces under the positive brush. This coating always resulted in a decided increase in wear. In Figure 26 the coating began to form at 40 amperes per square inch and continued to increase in density throughout the run. The negative path remained smooth and bright throughout the test. In fact, the negative path always remained in excellent condition except for a very slight trace of lead during part of the relative humidity run.

Brush F was not included in the low voltage run because of operating difficulties. The lead coating caused such an erratic voltage drop that the current could not be maintained constant.

The increased wear above 100 amperes per square inch in Figure 37 was caused by this lead coating. The coating began to form at this value on the one path and at 140 amperes per square inch on the other. The conditions became so bad at 160 amperes per square inch that one of the brush boxes was melted apart in an hour. The excessive increase in wear at 280 amperes per square inch in Figure 35 was also caused by the formation of this lead coating.

The increased wear at the higher current densities in Figure 27 was accompanied by blackening of the ring and the formation of indistinct photographs. In Figure 34 the blackening of the ring and increased wear occurred even at low current densities. The ring was repolished after the 60 ampere per square inch run. The large increase in wear at 280 amperes per square inch was accompanied by extreme blackening of the ring.

Brush I caused photographs to form in every test made upon it. The intensity and length of these photographs increased both with current density and time of operation. It should be noted that this is a copper impregnated brush with a normal capacity considerably lower than the other three brushes. The correlation between the positive and negative contact drops and the positive and negative wears is very close in the case of this brush. There was almost as close a qualitative relation between the ring surface and the above factors, but unfortunately it is impossible to present this relation quantitatively. It will be mentioned again under the effect of relative humidity.

7. Metallic brush wear versus ring speed

The data in Table 11 are listed in the chronological order in which they were taken. The rings were ground and polished carefully at the beginning of the run and then not touched throughout the run. Thus it is evident that the increased wear at higher speeds is due to the change in speed and not to a change in the ring surface conditions with time. Brush F developed a heavy lead-coating on the positive ring at 1750 R.P.M., which did not change very much throughout the run .

8. Metallic brush wear versus brush pressure

The data are listed in Table 12 in the chronological order in which they were taken. The rings were ground and polished, the brushes worn in and the rings polished again before starting the run. The rings remained in good condition throughout the test.

9. Metallic brush wear versus relative humidity

The data are listed in Table 13 in the chronological order in which they were taken. The rings were ground and polished at the beginning of the run and not repolished during the run. The rings upon which brushes G and H were riding remained in good condition throughout the run. The data for brush I does not represent the relation between brush wear and relative humidity. The ring started to blacken at the beginning of the run and continued throughout the run. At the close of the run the negative path was in much worse condition than the positive path. There is a very close correlation between the ring condition and both the contact drops and brush wear.

10. Metallic brush contact drop versus current density

The data for the contact drop curves of Figures 50 to 52 were not taken in conjunction with wear tests. The rings were cleaned at the beginning of the test. A complete set of readings had to be taken in a few minutes to prevent overheating the apparatus at the high current densities. The two high points on the negative curve in Figure 50 were obtained after the circuit had been opened for a few minutes. The usual lead coating formed under the positive brush F.

IV. DISCUSSION OF RESULTS

Electrical current may be conducted across a contact by ordinary conduction or by some ionization phenomenon. It is well known that ionization may be produced by electrochemical action, by electric fields or by thermionic effects. Part of these phenomena have been discussed hereinbefore. They will now be discussed in the light of the experimental results of this investigation.

Electrical brush wear must be explained largely upon the basis of electrical phenomena rather than mechanical phenomena. When brushes are run on a smooth copper ring with no current flowing the rate of wear is very low. When direct current is caused to flow through the brushes the wear at one or in some cases both brushes begins to increase. This increase in wear cannot be explained upon the basis of a change of surface conditions set up by the flow of current since a reduction of the current to zero always returns the rate of wear to its original low value, And furthermore operation of the positive and negative brushes on the same path does not give materially different results than when they are operated on separate paths. The positive carbon brush wear and the negative metallic brush wear are not affected by the flow of current in the range of normal operating current densities. Throughout this range their wear remains at the same value which it has at zero current. If the current was carried across the sliding contact by electrical conduction the heat generated at the contact might account for an increase in wear at both brushes, but this does not account for the large difference in positive and negative brush wear. There seems to be no possibility of explaining, on the basis of electrical conductance, the hundredfold decrease in resistance which occurs at the negative brush contact as shown in Figures 50 to 52. Thus it is apparant that a complete explanation of the phenomena of the sliding contact cannot be made upon the basis of electrical conduction alone.

Referring to Figure 51 it is noted that the current was increased to 380 amperes per square inch with a negative contact drop of only .15 volt. Thus if the current is conducted across the contact by ionization, the ionization must be produced by some means other than by an electrical field, since .15 volt is less than the ionization potential of any of the materials involved.

An explanation on the basis of electrochemical action would require that a definite amount of material be deposited in the direction of the current flow. If the current were carried in this manner, calculations show that the entire copper surface of the slip ring under the negative brush would be removed in a few days. Actually the rings were used for a time equivalent to 8 or 10 months of continuous operation without removing an appreciable amount of copper. The electrochemical action also indicates a direct relation between the rate of wear and current density of the positive brush. Figures 8 to 15 show that carbon brushes do not wear even approximately in this manner. The wear of positive metallic brushes increases with current density, but electrochemical action indicates that much more material should be removed from the brush. However there are two phenomena which indicate a limited positive ion flow. In the case of carbon brushes the positive ring path acquires a darkened appearance as if carbon had been transferred to the ring, whereas the negative path retains a more or less bright copper appearance. Also the negative brush has a tendency to pick copper. That is, small particles of copper are transferred to the brush in some manner and remain imbedded in the brush face. The heavy metal graphite brush F contains several per cent of lead. In every test which was made upon this brush a grayish white coating of lead was deposited on the positive ring path sometime during the run. Thus the positive metallic brush presents metal to the ring leaving the brush face somewhat enriched in graphite and the negative brush receives metal from the ring maintaining a high metal content at its surface. From the above it is seen that although there is evidence that a portion of the current is due to the flow of positive ions this cannot account for more than a small fraction of the total current flow. However this small amount of ion flow is sufficient to have a rather decided effect upon the operation of some brushes.

It has been shown hereinbefore that, according to the present theories of thermal ionization, it is possible to produce ionization thermionically under the conditions of the sliding contact. Also many of the sliding contact phenomena observed by previous investigators can be explained on the basis of thermal ionization acting in conjunction with electrical conduction, while none of the observed phenomena precludes the possibility of thermal ionization.

The number of electrons available for carrying current across the sliding contact depends upon the temperature and material of the cathode. The negative carbon brush contact drop is found to be higher than the positive contact drop under many operating conditions. If the brush is cathode the carbon must be raised to a thermal ionization temperature, whereas if the brush is anode only the copper needs to be raised to a thermal ionization temperature. Thus a lower contact drop at the positive brush is indicated since the copper does not need to be raised to as high a temperature as the carbon to produce thermal ionization. This might indicate a greater difference in contact drop than actually exists, if the rotation of the ring is not considered. If the brush is the cathode the same surface is involved continuously, so there is sufficient time available for its temperature to rise to a thermal ionization value. However, if the ring is the cathode a given spot must be raised to a thermal ionization temperature while it is passing under the brush. The fact that an ordinary arc cannot be maintained with a revolving cathode (20) is not a valid objection to this theory because new arcs are being formed continuously under the brush.

The positive metallic brush contact drop is found to be higher than the negative contact drop under most operating conditions. Ion flow is in such a direction that the negative metallic brush receives copper from the ring and thereby maintains a copper to copper contact. Ion flow at the positive metallic brush carries copper toward the ring, weakening the brush structure and causing it to present a surface more or less enriched in graphite to the ring. Since the voltage required to produce thermal ionization increases with the resistivity of the materials at the contact a higher contact drop is indicated at the positive metallic brush. With metallic brushes operating on a copper ring the cathode material is copper under both the positive and negative brushes. Since the cathode materials are the same a higher contact drop is indicated at the contact which has the moving cathode. Thus a higher contact drop is indicated at the positive metallic brush.

The theoretical results discussed above may be restated briefly as follows:

1. Electrical conduction does not explain the contact drop and wear phenomena of electrical brushes.

2. Ionization at the brush contact by an electrochemical action or by an electrical field is shown to be impossible.

3. Thermal ionization at the brush contact does explain contact drop phenomena and is not inconsistent with brush wear phenomena.

4. There are no experimental results which preclude the explanation of the sliding contact on the basis of thermal ionization acting in conjunction with electrical conduction.

Thus the conduction of electricity across a sliding contact is shown to be a thermal ionization phenomenon in which electrical conduction is a necessary factor but actually carries a very small percentage of the current. There is also a small positive ion flow which carries very little of the current but has a decided effect upon the rate of wear and contact drop of metallic brushes.

V. CONCLUSIONS

1. Positive carbon brush wear is very low and independent of current density below a critical value. The critical value varies with different brush materials.

2. Negative carbon brush wear is much larger than the positive and is proportional to current density below a critical value. Above this value there is a decrease in the wear with increasing current density.

3. As the current densities are increased to abnormal values the ring temperature is increased and both positive and negative brush wear become excessive.

4. An oxidized or blackened ring increases the negative carbon brush wear decidedly.

5. The negative contact drop of carbon brushes is higher than the positive contact drop.

6. The contact drop of all brushes tested is increased with the oxidizing of the ring surface.

7. The static voltage-current characteristics of some carbon brushes decrease with increasing current.

8. There is no consistent relation between the wear and contact drop of carbon brushes.

9. The wear of both positive and negative carbon

brushes is practically independent of ring speed from 400 to 3700 feet per minute.

10. Carbon brush wear is increased by a deviation in either direction from a certain optimum brush pressure. The optimum pressure is not critical. The effect is much more pronounced upon the negative brush.

11. Negative brush wear is decidedly increased by an increase in relative humidity from 20 to 75 per cent (45 deg. Cent.) if the rings are oxidized.

12. Negative carbon brush wear increases at very low humidities.

13. Positive metallic brush contact drop is higher than the negative.

14. Metallic brushes wear more rapidly than carbon brushes.

15. The positive metallic brush wear increases with increasing current density.

16. The negative metallic brush wear is low and independent of current density.

17. The rate of wear of metallic brushes is reduced by lowering the brush circuit potential.

18. Positive metallic brush wear increases decidedly with increased ring speed.

19. Wear of both the positive and negative metallic

brushes is increased by a deviation in either direction from a certain optimum brush pressure.

20. Positive metallic brush wear is increased by an increase in relative humidity from 20 to 75 per cent (45 deg.Cent)

21. Metallic brush wear becomes more excessive at lower values of current density with alternating current than with direct current.

22. A very definite correlation exists between the contact drop and wear of copper impregnated brushes under certain operating conditions.

23. The negative contact drop of some metallic brushes remains practically constant over a hundred fold increase of current density.

24. The phenomena of the sliding contact can be explained upon the basis of thermal ionization, operating in conjunction with electrical conduction. Most of the current is carried by the thermionically emitted electrons, but this effect could not be continous without the aid of electrical conduction. Only a very small percentage of the current is carried by positive ions, but this has a decided effect upon contact drop and brush wear under certain operating conditions.

VI. APPENDICES

Appendix 1

In appendix 1 are given the tabulations and curves of all the brush wear and contact drop tests. It should be noted that the tabulations give complete data, concerning test conditions. The corresponding curves follow immediately after the tabulations. The duration of the run is considered an important item of the tabulations since it should aid the reader materially in interpreting the data.

The symbol ● ordinarily represents the positive brush (motor sense), the symbol ⊖ the negative brush and the symbol ○ indicates that the positive and negative points coincide. The one exception to the above is the run with alternating current in which all points are indicated with the symbol ○ (Figures 37-40).

A complete table of symbols is given on page 122.

Table 1

Rate of Wear versus Current Density

Test Conditions

Ambient Temperature - 45-55°C
Relative Humidity - 45-55%
Brush Circuit Potential - 80 volts d-c
Drawn Copper Rings

Ring Speed - 3400-3700 feet per min.
Current Density - varied
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

		Brush A		Brush B		Brush C		Brush D	
t	I_d	W-	W+	W-	W+	W-	W+	W-	W+
34.40	50	11.4	1.89	12.2	1.98	7.44	1.16	4.13	.03
23.00	50	11.3	1.30	8.98	.91	6.31	.09	4.47	.69
23.33	50	10.5	1.71	9.43	.21	7.38		2.45	.03
40.75	40	9.82	1.22	8.08	.87	3.93		2.49	.37
22.50	40	5.78	.44	7.56	.27	4.09		3.91	.36
19.42	40	8.24	2.21	5.56	1.13	3.45	.36	2.21	.16
48.50	40	5.30	.75	8.75	.63	6.65	.26	3.87	.28
46.50	30	3.93	.00	6.40		3.83	.28	3.34	.34
42.70	30	5.50	.68	7.75		4.50	.07	3.68	.05
22.25	30	5.03	.22	7.32	.00	4.67	.18	4.50	.45
25.00	30	5.16	.24	5.44	.00	3.88	.36	3.56	.28
42.50	20	2.56	.47	5.90	.35	3.53	.12	5.04	.56
46.50	20	3.16	.52	5.44	.52	3.16	.11	3.44	.00
50.38	20	3.71	.50	4.92	.18	3.06	.04	3.33	.32

Table 1 (cont.)

t	I_d	W-	W+	W-	W+	W-	W+	$W\underline{-}$	W+
42.25	10	2.13	.52	3.55	.38	3.17	.31	3.31	.00
46.52	10	2.00	.77	3.59	.21	3.07	.09	1.59	.34
38.33	10	2.61	.68	4.41	.42	2.06	.26	2.01	.23
47.47	10	2.50	.57	4.36	.38	1.92	.19	1.10	.19
72.42	0	.40	.28	1.13	.36	1.42	.04	.75	.23
40.67	0	.05	.20	.61	.29	.88		.29	.12
31.17	0	.32	.19	.42	.29	.70	.15	.54	.00
40.08	0	.32	.12	.60	.05	.67	.20	.32	.17
40.00	45	4.67	.98	8.84	.15	7.78	.23	11.3	.12
27.75	45	4.36	.50	7.92	.79	8.32	.50	14.1	.32
44.17	45	5.46	.66	8.44	.32	8.31	.34	10.2	.34
36.00	35	3.64	.42	1.61	.47	5.75	.25	6.47	.17
27.75	35	4.61	.29	7.68	.43	7.74	.48	8.36	.00
40.00	35	4.60	1.40	6.40	.43	4.23	.17	6.55	.15
41.33	60	13.1	1.26	7.54	.70	6.60	.36	10.5	.44
45.00	60	14.7	.49	7.40	.51	7.98	.28	9.33	.13
29.00	60	15.0	.93	8.82	.55	8.00	.24	8.93	.10
47.33	70	34.1	1.20	8.36	.00	8.34	.30	9.02	.40
43.75	70	34.0	.98	8.05	.10	11.4	.41	12.7	.07

Figure [illegible]

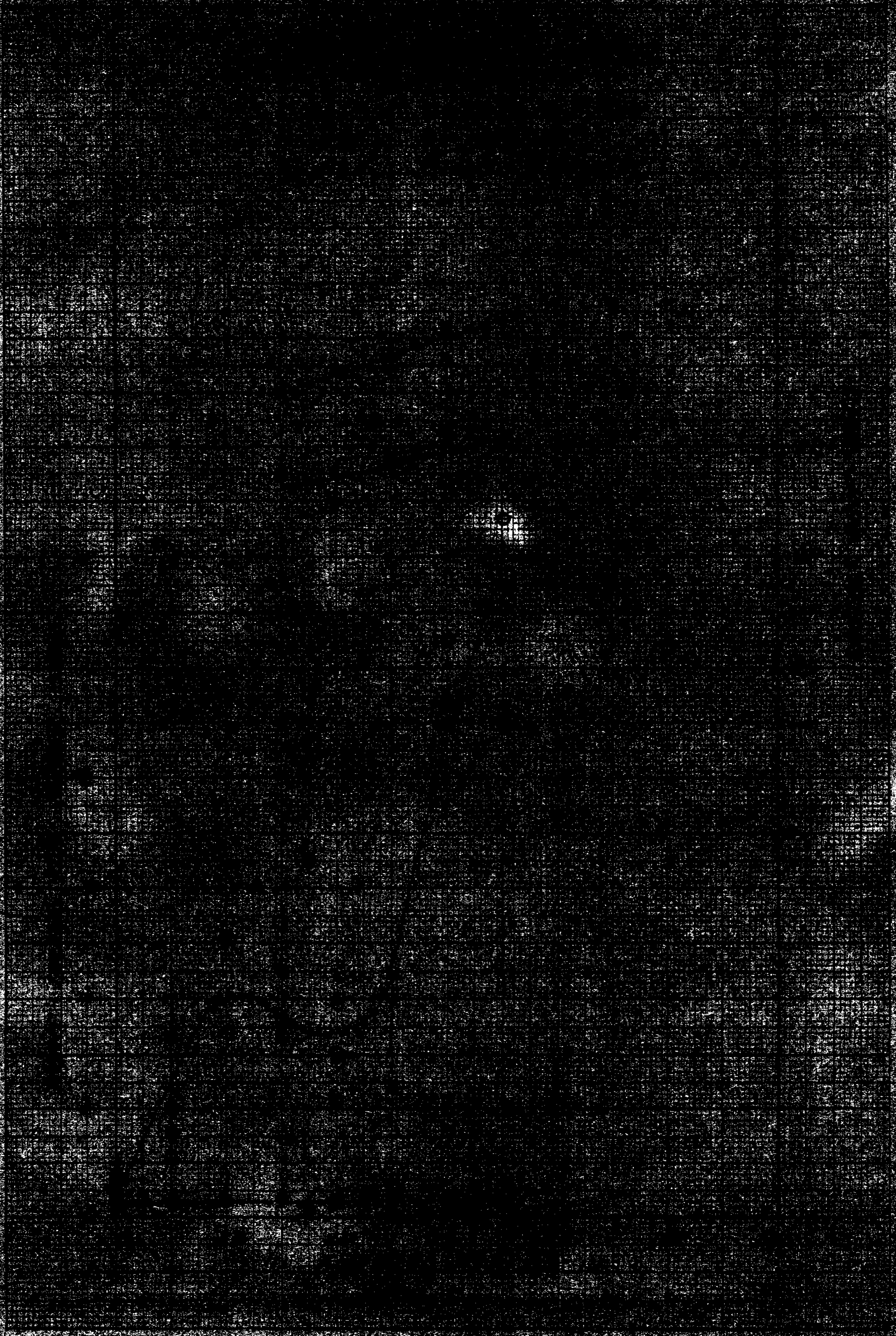


Table 2

Rate of Wear versus Current Density

Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 80 volts d-c
Drawn Copper Rings

Ring Speed - 3500 feet per min.
Current Density - varied
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

		Brush A		Brush B		Brush C		Brush D	
t	I_d	W-	W+	W-	W+	W-	W+	W-	W+
25.00	0	.00	.00	.00	.40	.00	.00	.48	.56
92.66	0	.49	.23	.00	.13	.22	.11	.93	1.01
45.75	30	1.46	.44	3.89	.35	1.95	.66	3.48	.39
47.50	30	1.54	.29	2.76	.36	3.62	.13	2.76	.36
43.00	30	1.51	1.14	2.63	.26	4.40	.33	2.38	.23
47.41	50	4.01	.70	6.83	.59	3.88	.00	2.70	.00
48.66	50	2.24	.47	3.49	.43	4.81	.20	2.32	.64
44.50	50	2.76	.07	2.72	.61	2.85	.09	1.68	.27
21.25	50	3.29	1.08	3.76	.38	3.76	.75	1.41	.38
21.50	70	4.46	1.86	7.22	.23	1.77	.84	7.72	
20.00	70	5.05	1.90	6.80	1.45	3.60	.65	5.40	2.90
26.83	70	5.15	1.34	6.36	.71	2.54	.11	5.04	.82
40.00	70	8.45	.65	6.00	.56	1.98	.30	2.85	.45
29.25	70	6.50	.58	4.41	.92	2.46	.44	3.62	3.21

Table 2 (cont.)

t	I_d	W-	W+	W-	W+	W-	W+	W-	W+
44.50	80	9.30	2.04	6.74	.38	3.53	.29	5.12	2.18
71.75	80	8.95	1.04	5.88	.85	2.18	.39	3.16	.52
48.00	80	10.8	.94	3.42	.54	1.96	.25	5.32	1.94
62.75	80	11.5	.94	3.76	.75	1.96	.32	3.86	.80
50.75	90	4.97	2.50	6.38	.45	4.99	.45	5.70	4.16
46.42	90	5.64	.84	6.06	1.14	4.14	.49	3.90	1.79
23.25	90	4.65	1.89	5.76	.21	4.56	.00	4.69	3.83
44.00	90	4.82	.25	5.07	.84	4.25	.09	4.66	3.34
47.83	100	5.88	4.18	6.21	1.25	6.54	2.64	7.76	3.97
45.25	100	7.49	3.76	5.77	.75	4.55	.44	5.30	3.32
23.83	100	5.50	3.61	4.87	.76	3.90	.42	4.20	2.47
46.25	110	4.04	2.12	5.19	.89	4.89	4.34	6.66	4.87
20.42	110	8.32	3.33	8.03	.64	5.68	4.95	9.06	6.66
50.16	110	14.8	.90	5.00	.50	4.85	4.25	6.76	5.90
40.00	120	3.20	1.70	5.52	.25	5.60	.87		
44.00	120	5.05	4.18	5.43	.73	4.78	3.25		
54.00	120	19.1	6.98	4.02	.37	9.08	3.94		
56.33	140	28.2	30.7		38.6	16.5	5.82		

Table 3

Rate of Wear versus Ring Speed

Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 80 volts d-c

Ring Speed - varied
Current Density - 50 amp. per sq. in.
Brush Pressure - 48 oz. per sq. in.

		Brush C Drawn Ring Brushes tracking		Brush C Cast Ring Brushes not tracking	
t	S	W-	W+	W-	W+
18.00	2550	1.33	1.56	2.44	1.39
50.16	2550	1.81	.42	2.43	.08
22.33	2550	2.46	1.16	1.03	.09
44.00	1275	1.54	.36	2.71	.36
54.00	1275	1.13	.91	2.50	
44.33	425	.77	.65	1.31	.29
25.42	425	.91	.28	1.10	.20
47.75	3828	3.06	2.18	2.77	.31

Table 4

Rate of Wear versus Brush Pressure

Test Conditions

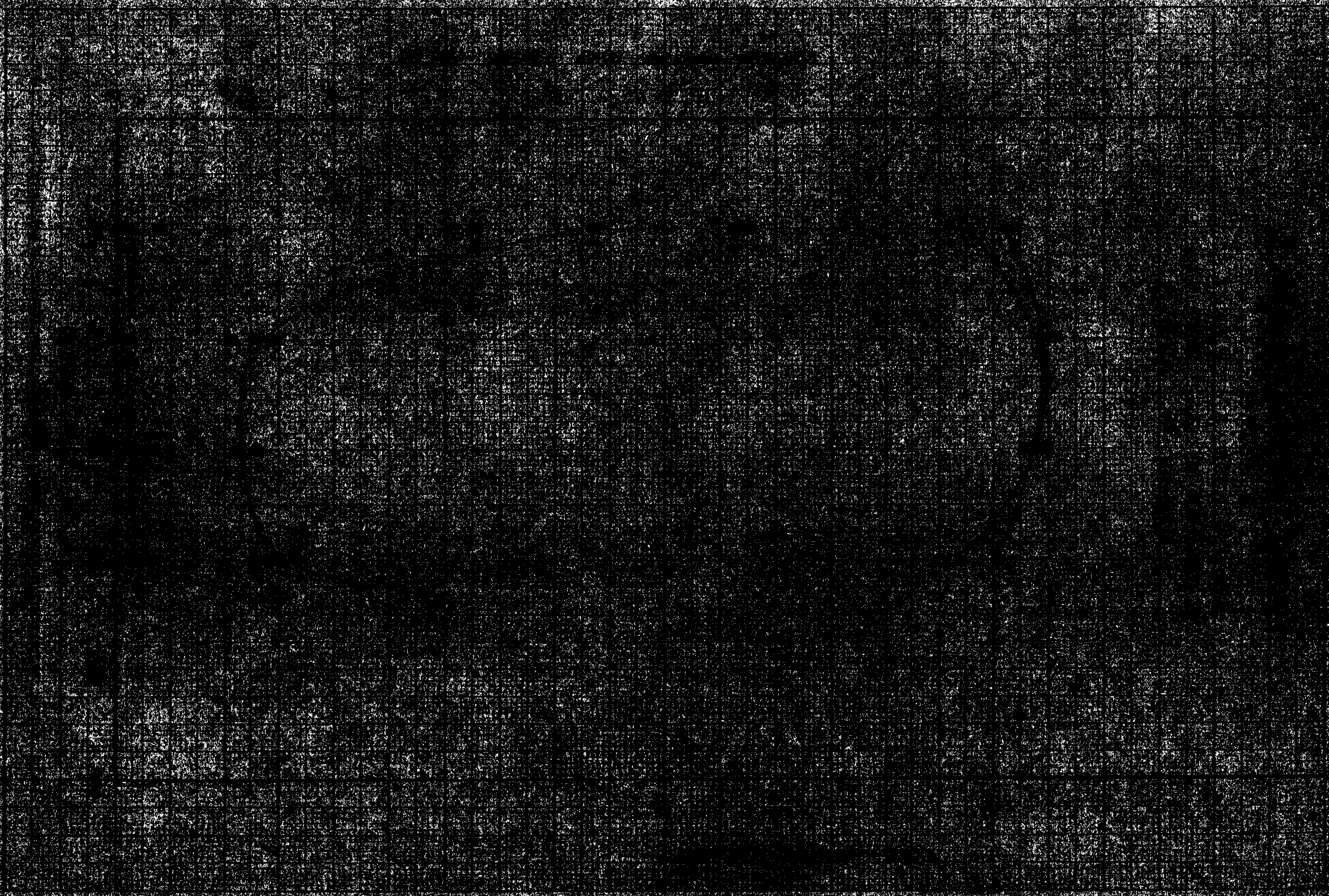
Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 80 volts d-c

Ring Speed - 3760 feet per min.
Current Density - 50 amp. per sq. in.
Brush Pressure - varied
Brushes not tracking

		Brush C Drawn Ring		Brush C Cast Ring	
t	P	W-	W+	W-	W+
31.00	24	6.13	.74	4.00	3.29
38.33	24	6.52	.00	2.77	.96
52.50	24	8.74	.82	4.12	1.00
40.50	24	11.3	.296	2.80	.42
45.00	24	11.6	.18	3.98	.66
47.50	48	2.88	.06	3.68	.27
44.75	48	2.55	.00	2.59	.45
22.75	48	2.11	.44	2.24	.22
45.00	72	2.27	.64	3.31	.11
23.00	72	2.61	.39	3.52	.22
41.00	72	2.68	.46	2.90	.27

Table 4 (cont.)

t	P	W-	W+	W-	W+
51.25	96	2.87	.27	3.43	.41
44.00	96		.55	6.18	.39
25.50	96	2.82	.35	4.12	.12
23.00	96	2.61	.65	4.74	.35
23.50	96	3.36	.21	4.21	.38
22.00	96	2.86	.50	3.82	.18
21.75	120	16.9	30.3	2.53	.00
48.00	120			4.23	.00
22.50	120			5.11	.13
21.00	120			6.96	.76
25.75	120			7.85	.70
45.5	144			10.44	.77
45.75	144			11.60	.37
48.00	144			14.45	.63



[illegible]

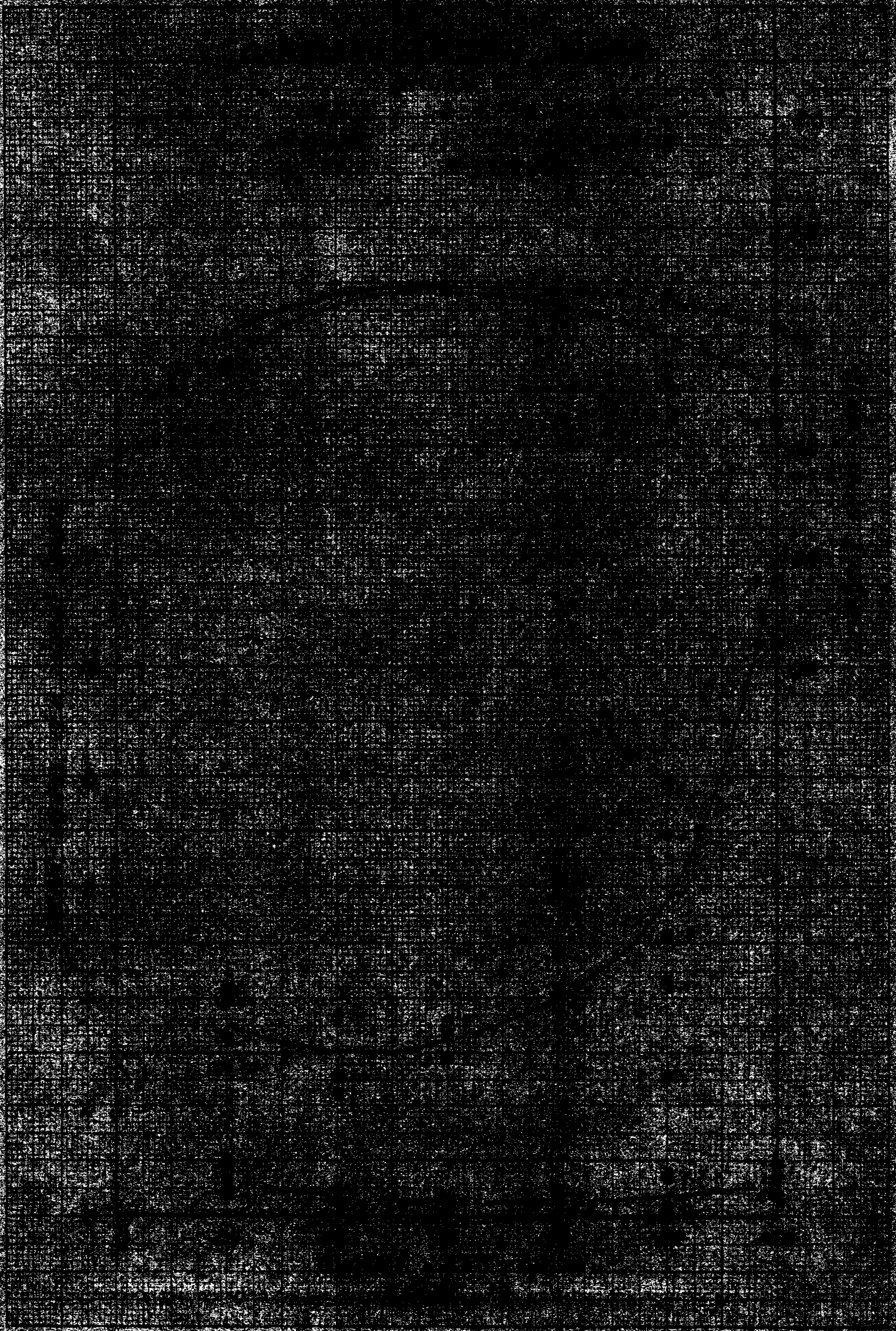


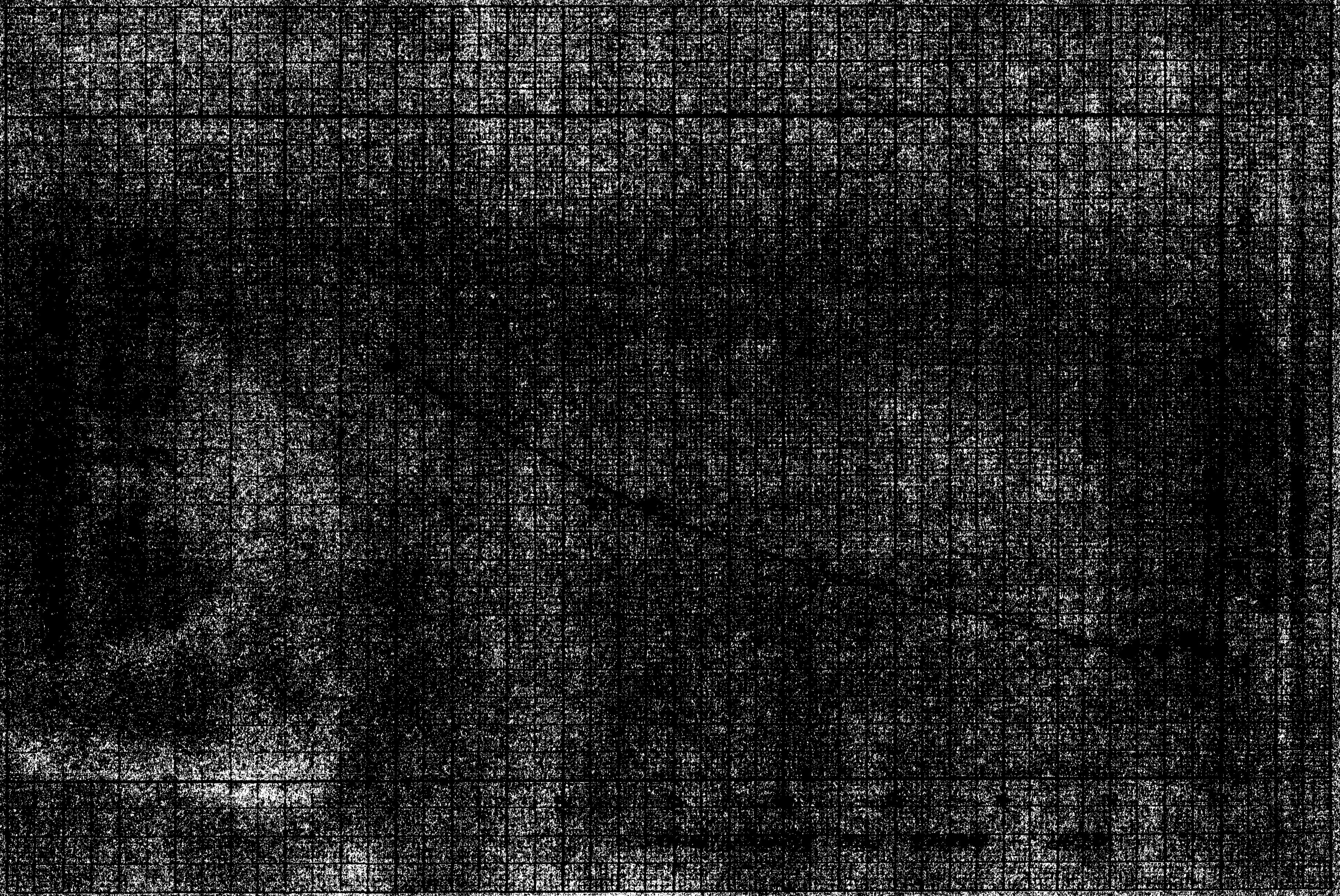
Table 5

Rate of Wear versus Relative Humidity

Test Conditions

Ambient Temperature 45°C	Ring Speed - 3400 feet per min.
Relative Humidity - varied	Current Density - 50 amp. per sq. in.
Brush Circuit Potential - 90 volts d-c	Brush Pressure - 48 oz. per sq. in.
Drawn Copper Rings	Brushes not tracking

		Brush A		Brush B		Brush C		Brush D	
t	H	W-	W+	W-	W+	W-	W+	W-	W+
24.50	23	4.24	1.76	2.33	.86	1.05	.37	1.63	.45
39.17	23	4.95	.43	3.14	.67	1.63	.00	1.25	.00
26.75	25	5.04	2.54	4.11	1.83	2.62	.52	3.40	.34
69.00	50	9.68	.36	10.9	.26	10.3	.09	14.00	.28
42.00	50	10.8	.36	11.5	.36	11.3	.12	13.3	.26
27.25	75	10.8	.40	12.0	.11	15.1	.22	12.5	.00



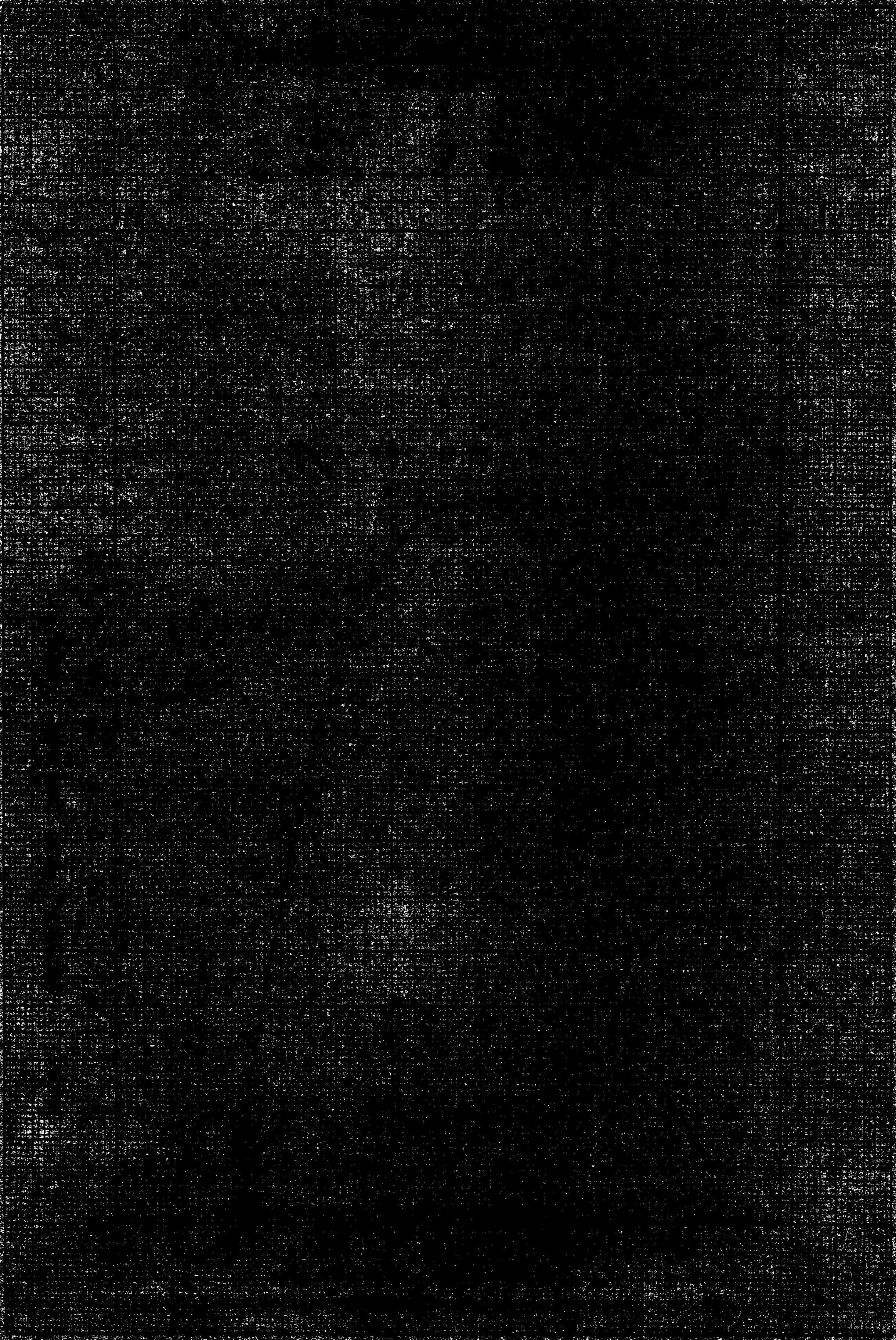


Table 6

Rate of Wear versus Relative Humidity

Test Conditions

Ambient Temperature - 45°C	Ring Speed - 3760 feet per min.
Brush Circuit Potential - 80 volts d-c	Current Density - 50 amp. per sq. in.
Relative Humidity - varied	Brush Pressure - 48 oz. per sq. in.

		Brush C Drawn Ring Brushes tracking		Brush C Cast Ring Brushes not tracking	
t	H	W-	W+	W-	W+
45.75	69	2.10	1.40	3.58	.00
25.09	69	2.15	1.12	4.47	.00
44.58	69	3.50	1.77	.92	.00
24.00	69	2.92	.92	.46	.00
41.50	35	2.10	1.45	2.34	.10
48.00	35	2.38	1.04	1.06	.54
50.66	35	2.78	1.22	1.78	.34
44.00	35	10.0	.68	1.80	.34
22.00	35	5.64	2.18	1.82	.55
16.33	4.5	15.4	4.41	4.71	.00
7.17	4.5	18.3	10.8	4.61	.14
7.50	4.5	15.7	9.74	2.53	.00
15.00	4.5	10.4	4.40	1.40	.00

Table 7

Rate of Wear versus Current Density

Test Conditions

Ambient Temperature - 45°C	Ring Speed - 3760 feet per min.
Relative Humidity - 50%	Current Density - varied
Brush Circuit Potential - 90 volts d-c	Brush Pressure - 48 oz. per sq. in.
Drawn Copper Rings	Brushes not tracking

		Brush F		Brush G		Brush H		Brush I	
t	I_c	W-	W+	W-	W+	W-	W+	W-	W+
3.50	0	17.7	27.1	6.28	6.57	14.6	14.3	1.14	1.71
5.33	20	6.19	26.3	.75	11.6	11.3	13.1	97.2	48.8
3.00	40	14.7	120.	13.7	18.3	45.3	31.3	235.	76.3
3.00	60	10.0	304.	1.00	23.7	4.66	35.3	321.	100.
3.00	80	13.3	482.	10.7	33.7	13.7	66.3	484.	116.
2.50	100	16.0	932.	8.00	41.2	9.8	132.	432.	134.
2.33	120	27.5	1199.	14.6	73.8	15.5	146.	437.	151.
2.00	140	2.00	1295.	4.00	132.	15.0	307.	402.	198.
2.00	160	16.0	2000.	14.0	165.	10.5	463.	495.	183.
1.33	180	27.8	2230.	20.3	120.	24.8	493.	1030.	283.

Form F-3

Table 8

Rate of Wear versus Current Density

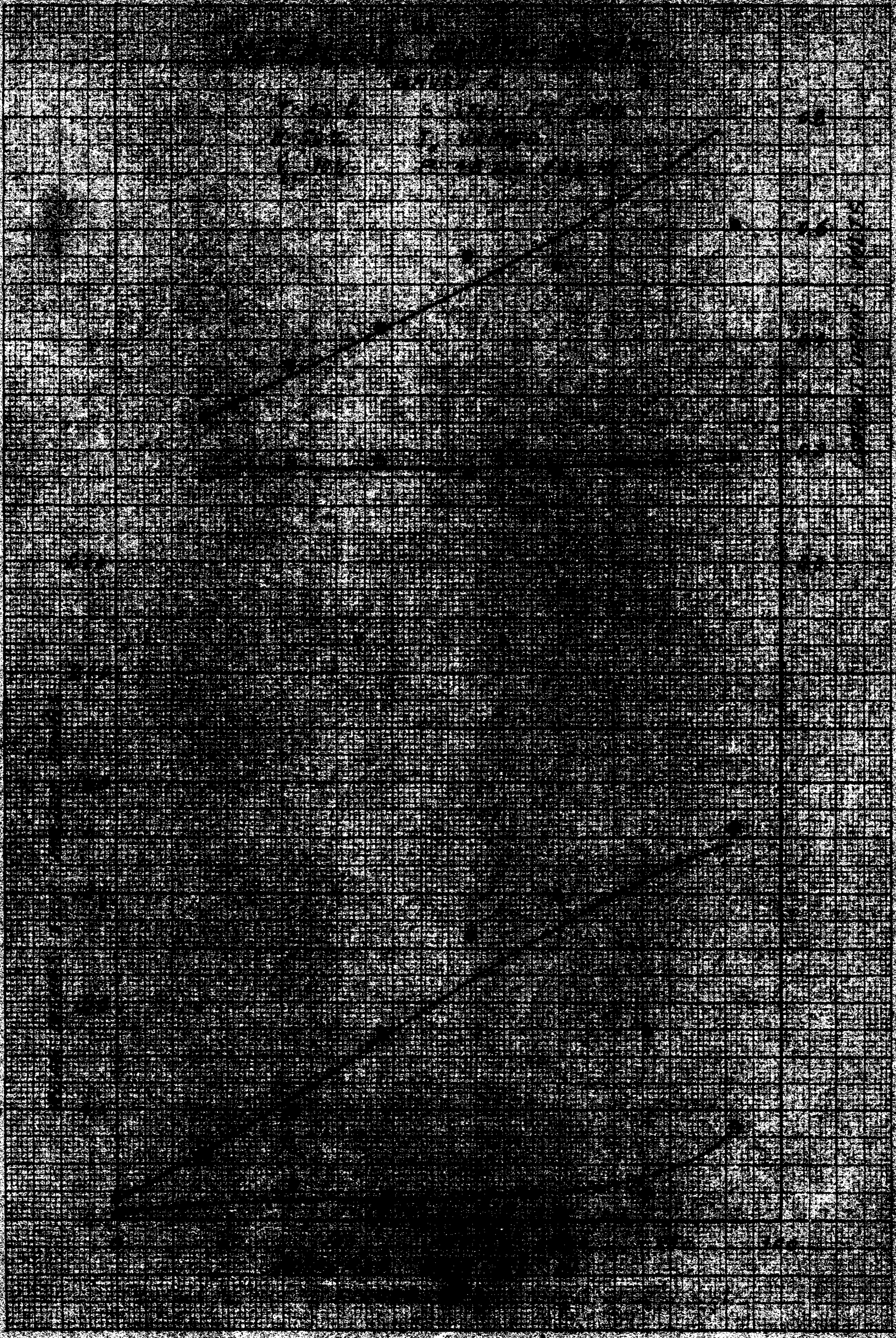
Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 10 volts d-c
Drawn Copper Rings

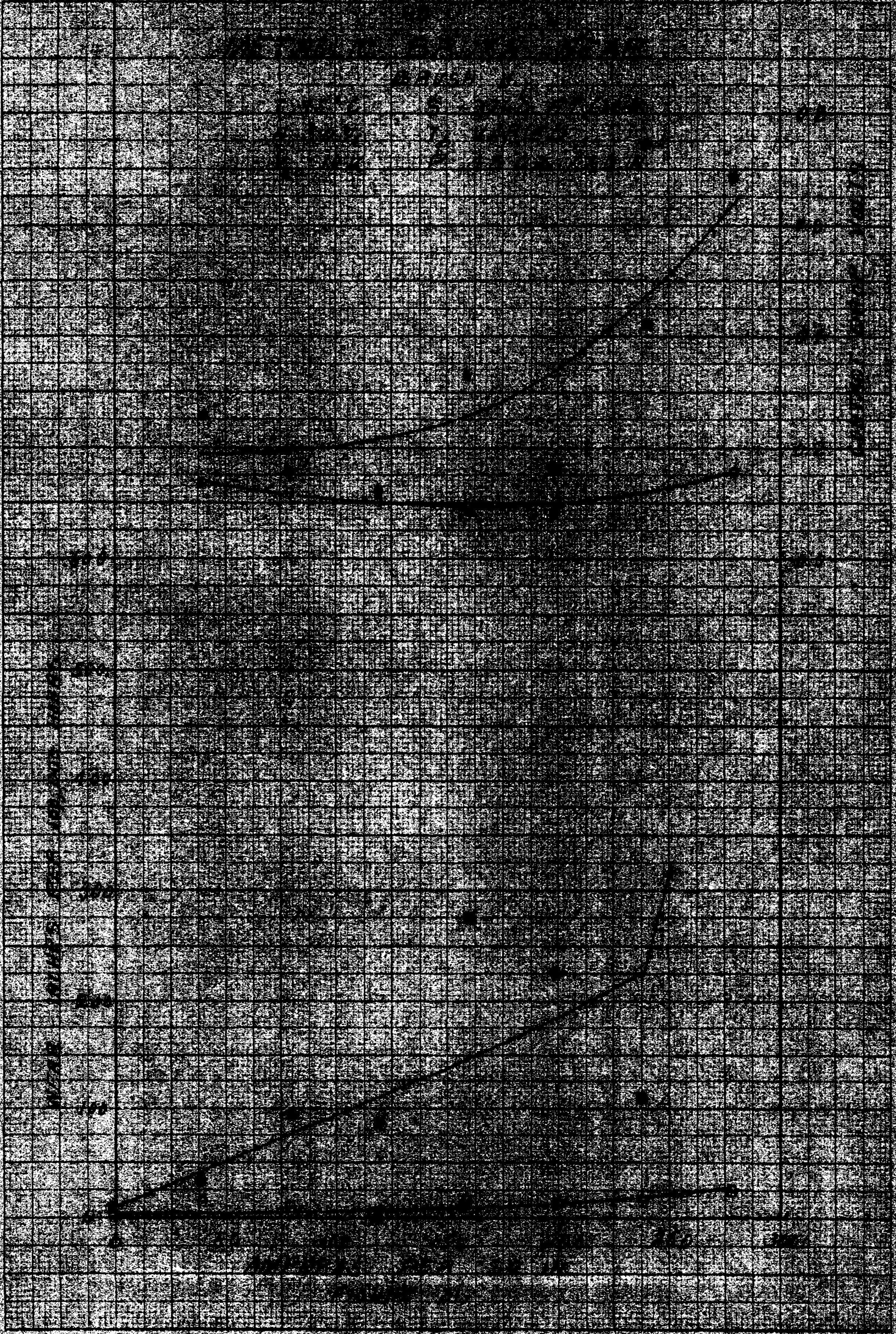
Ring Speed - 3760 feet per min.
Current Density - varied
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

		Brush G		Brush H		Brush I	
t	I_c	W-	W+	W-	W+	W-	W+
2.00	40	22.0	23.0	12.5	31.0	19.5	114.
1.66	80	12.1	39.7	9.04	94.0	42.8	64.5
1.50	120	4.00	68.0	.00	86.2	61.4	113.
1.50	160	8.00	105.	14.0	273.	101.	135.
1.50	200	1.33	120.	11.3	226.	159.	127.
1.83	240	9.84	69.4	16.4	110.	229.	142.
1.75	280	34.3	144.	24.6	1400.	296.	267.

[illegible] E-3



Form M 2



Form E-3

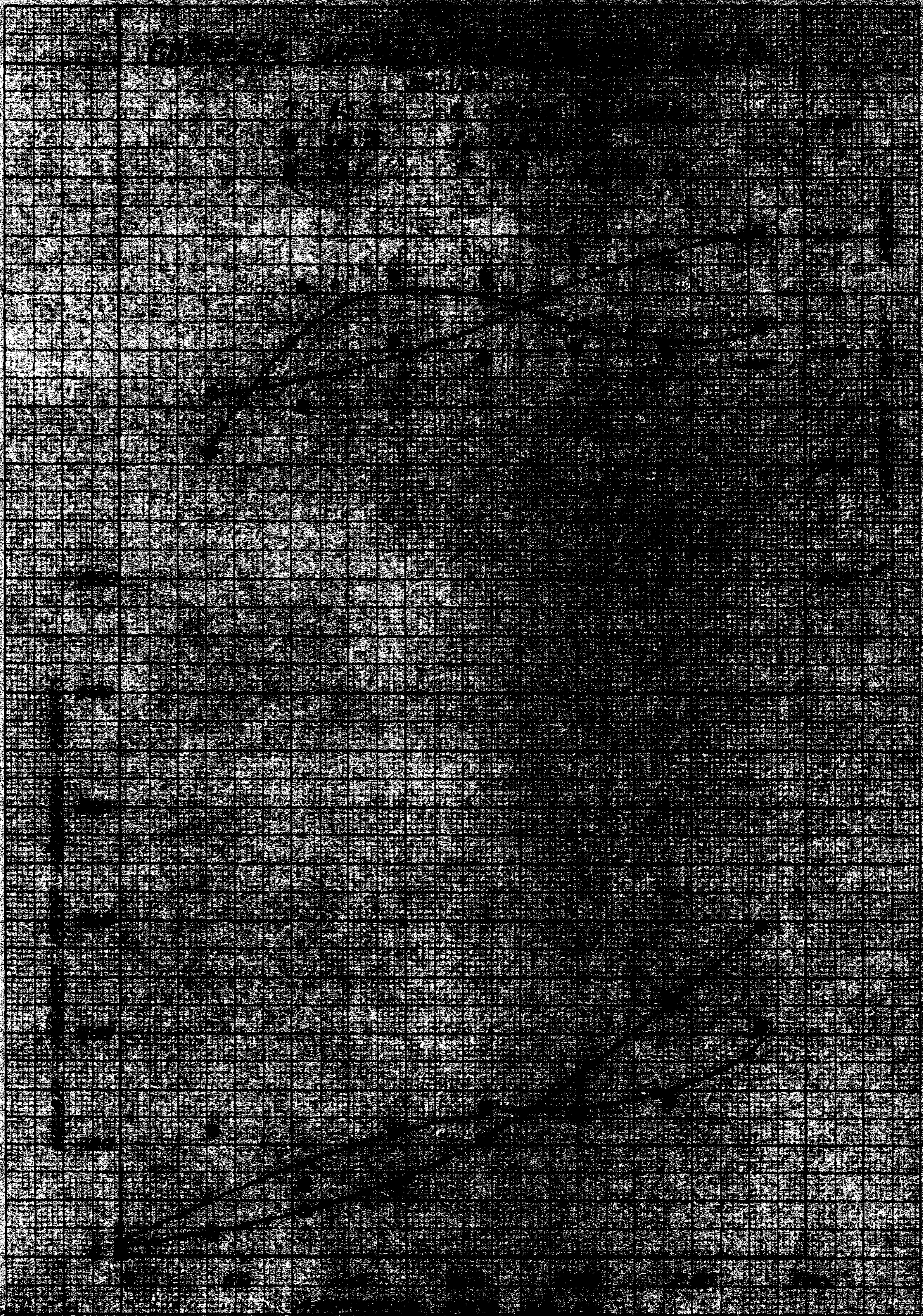


Table 9

Rate of Wear versus Current Density

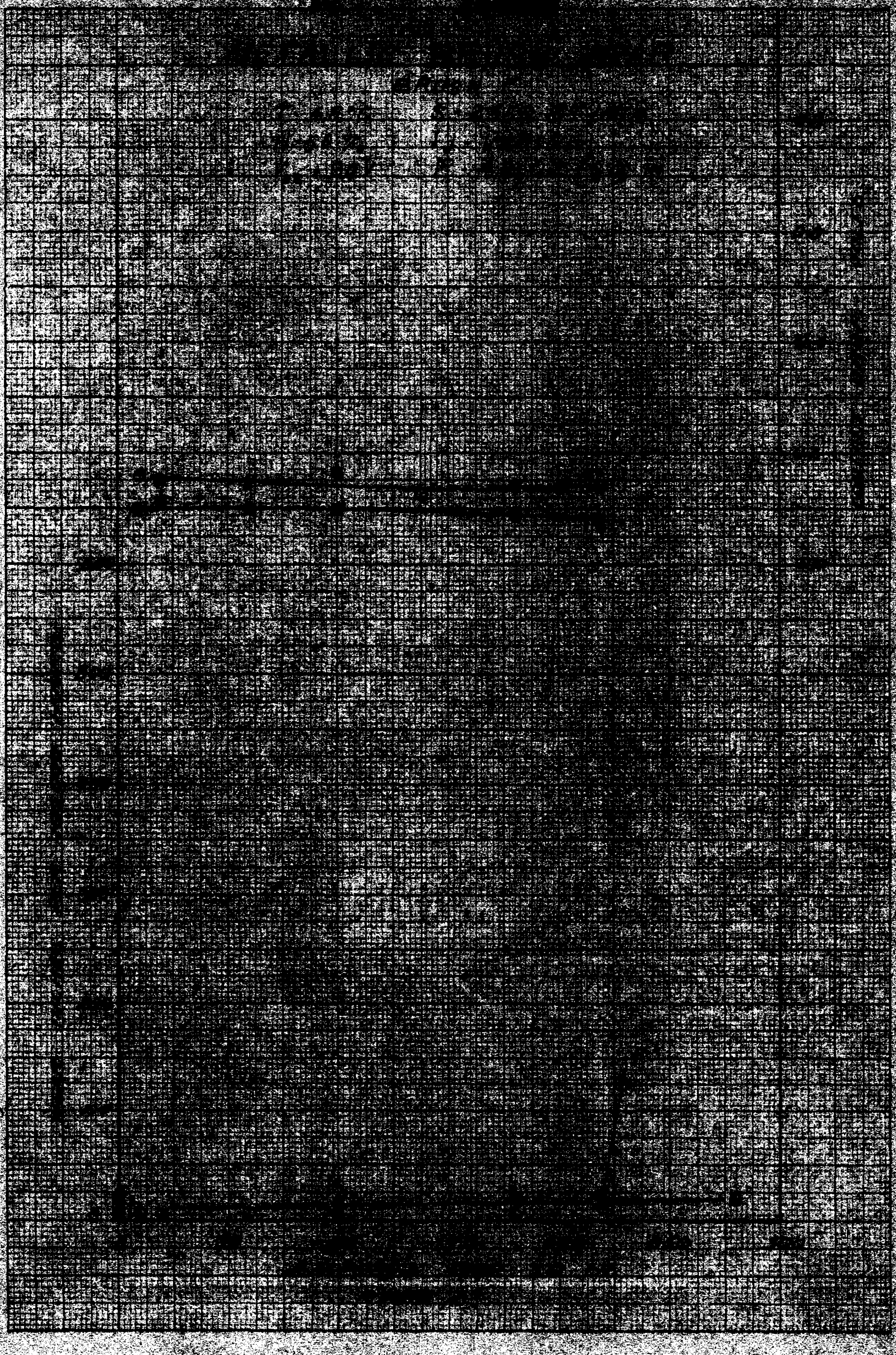
Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 90 volts d-c
Drawn Copper Rings

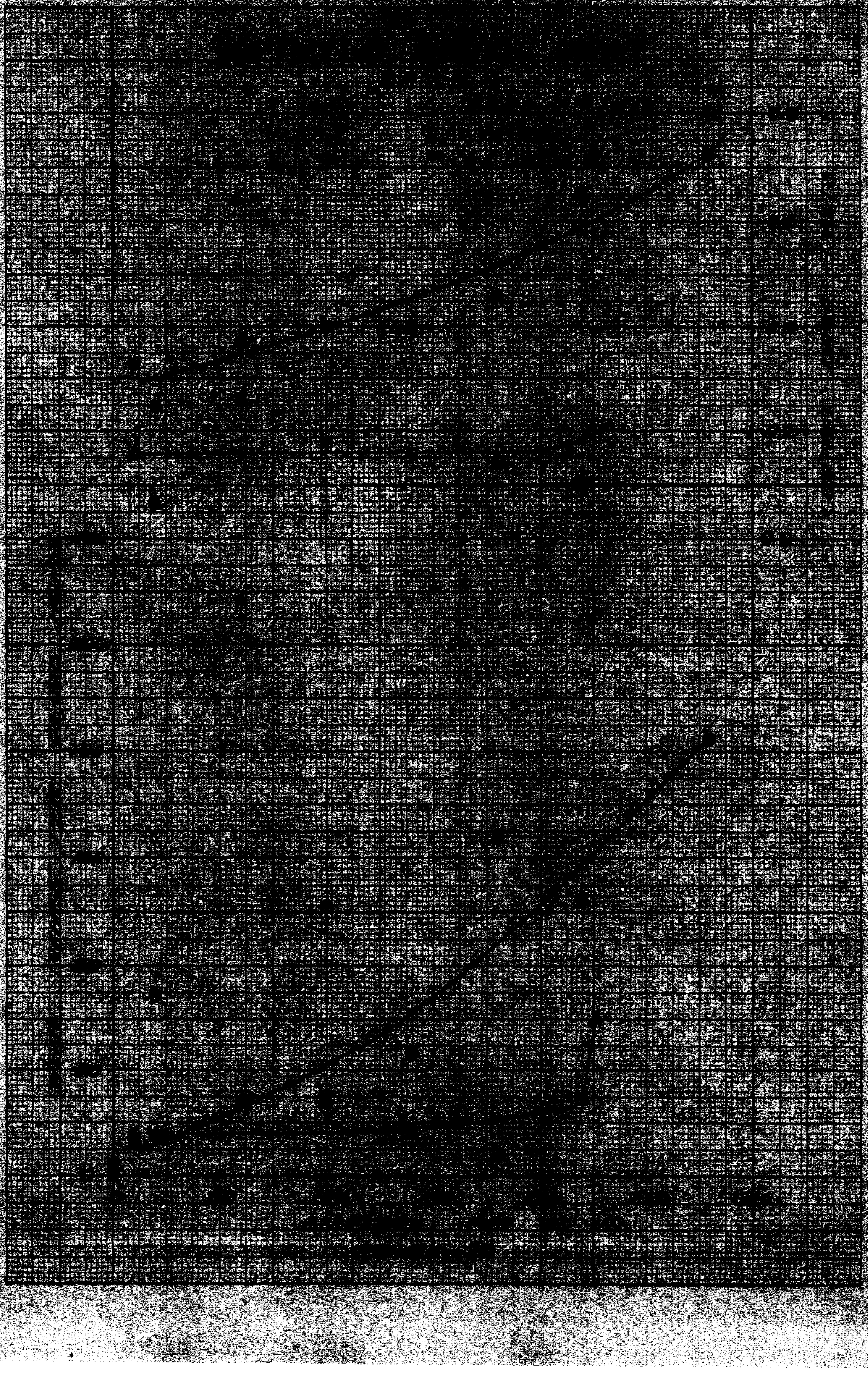
Ring Speed - 2550 feet per min.
Current Density - varied
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

t	I_c	Brush F		Brush G		Brush H		Brush I	
		W-	W+	W-	W+	W-	W+	W-	W+
4.25	0	20.5	9.41	.00	2.82	14.6	11.3	3.06	1.18
2.66	10.0	11.7	5.26	15.0	13.9	9.4	10.9	3.39	.38
3.75	20.0	4.26	8.80	69.3	15.2	3.2	9.06	17.1	1.07
2.50	60.0	6.80	9.20	216.	29.6	12.4	15.2	73.6	18.8
2.00	100.	7.00	15.0	101.	30.0	.00	39.5	117.	21.0
2.00	140.	20.5	20.0	17.0	47.0	19.5	106.	118.	74.0
2.00	180.	4.50	21.5	8.00	128.	3.00	151.	81.5	90.0
2.00	220.	13.0	20.5	28.5	105.	10.0	213.	144.	64.5
1.00	280.	19.0	2812.	1781.	165.	5.0	250.	472.	62.0

Form E-[illegible]



Form E-1



[illegible]

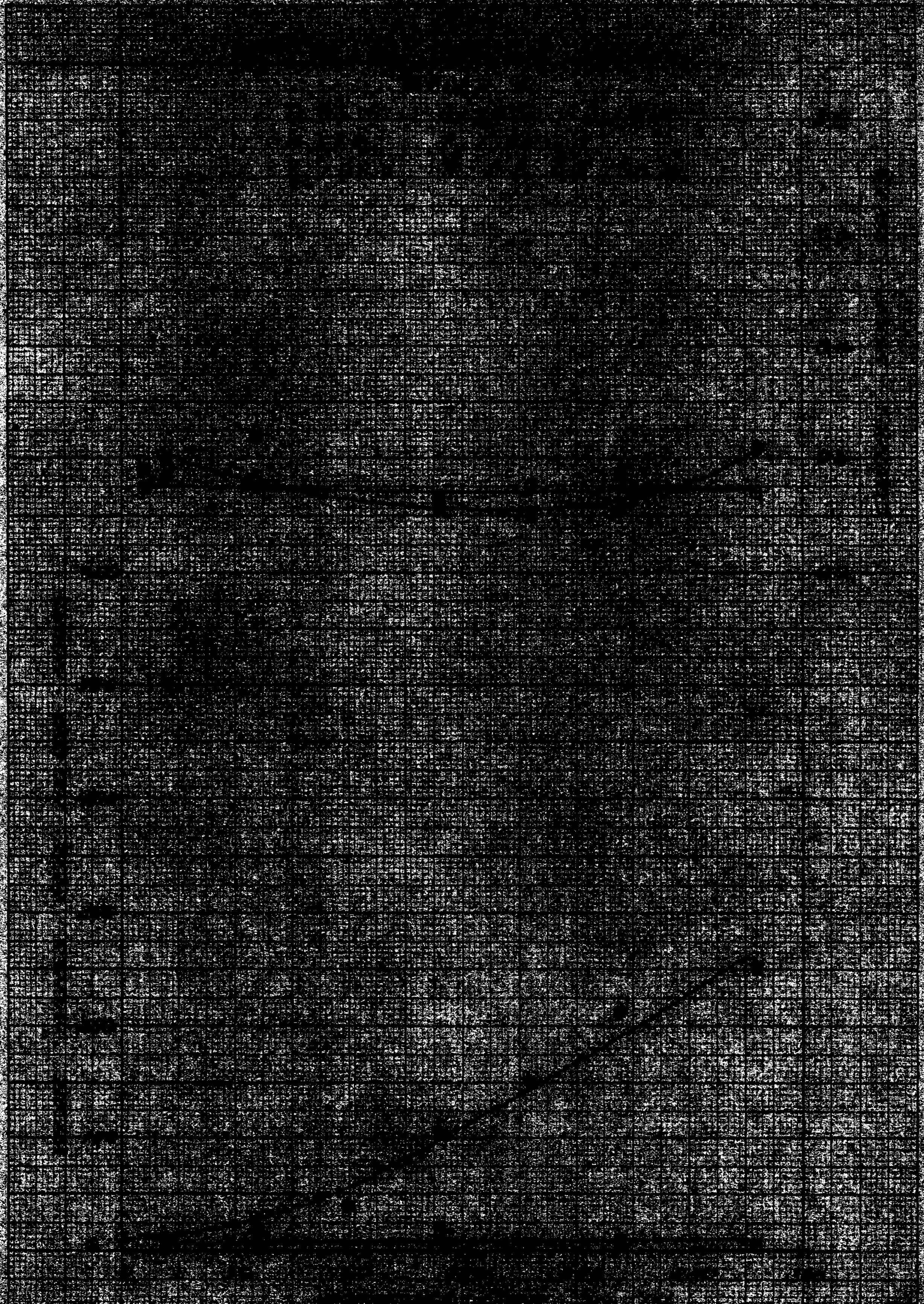


Table 10

Rate of Wear versus Current Density

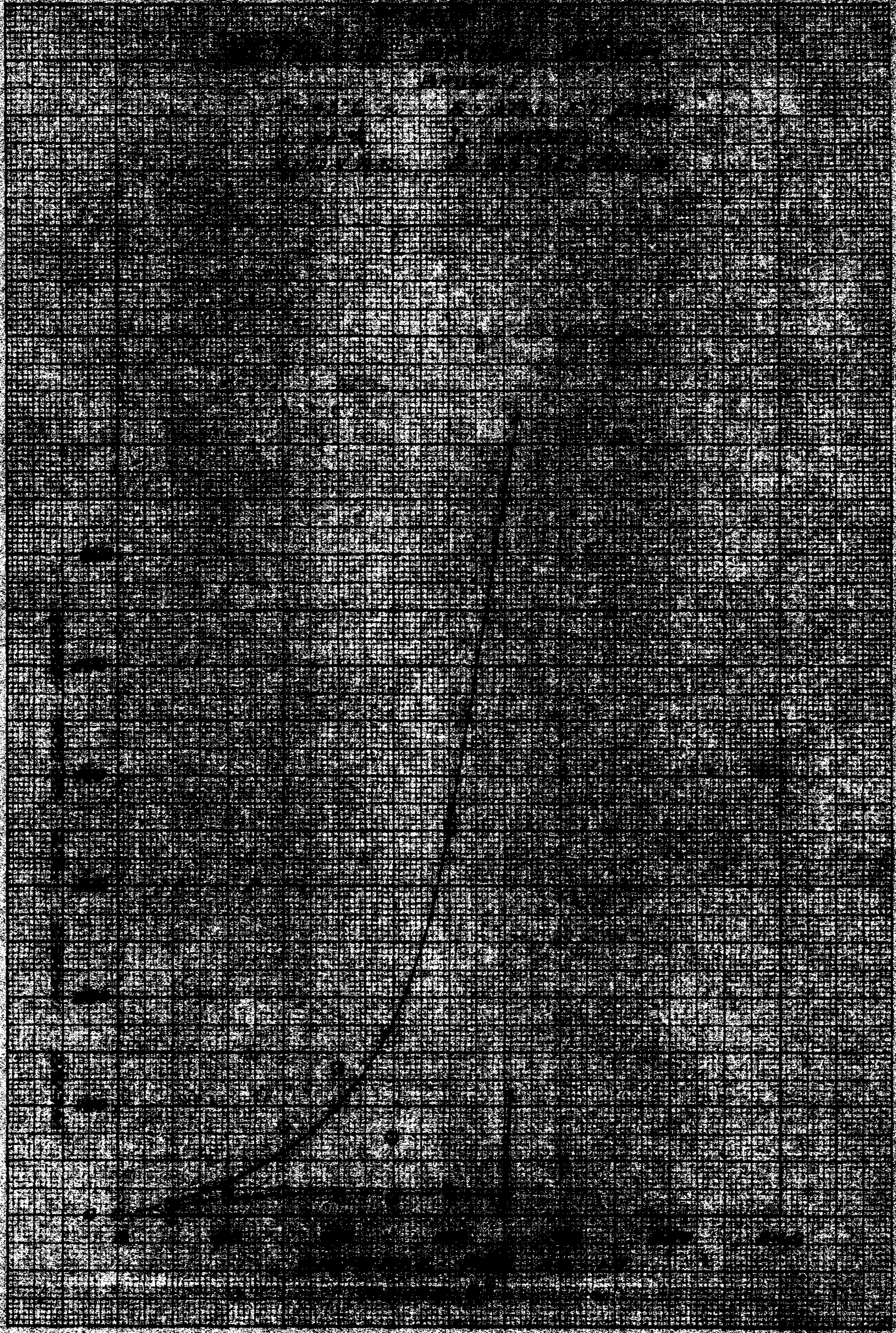
Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 110 volts a-c
Drawn Copper Rings

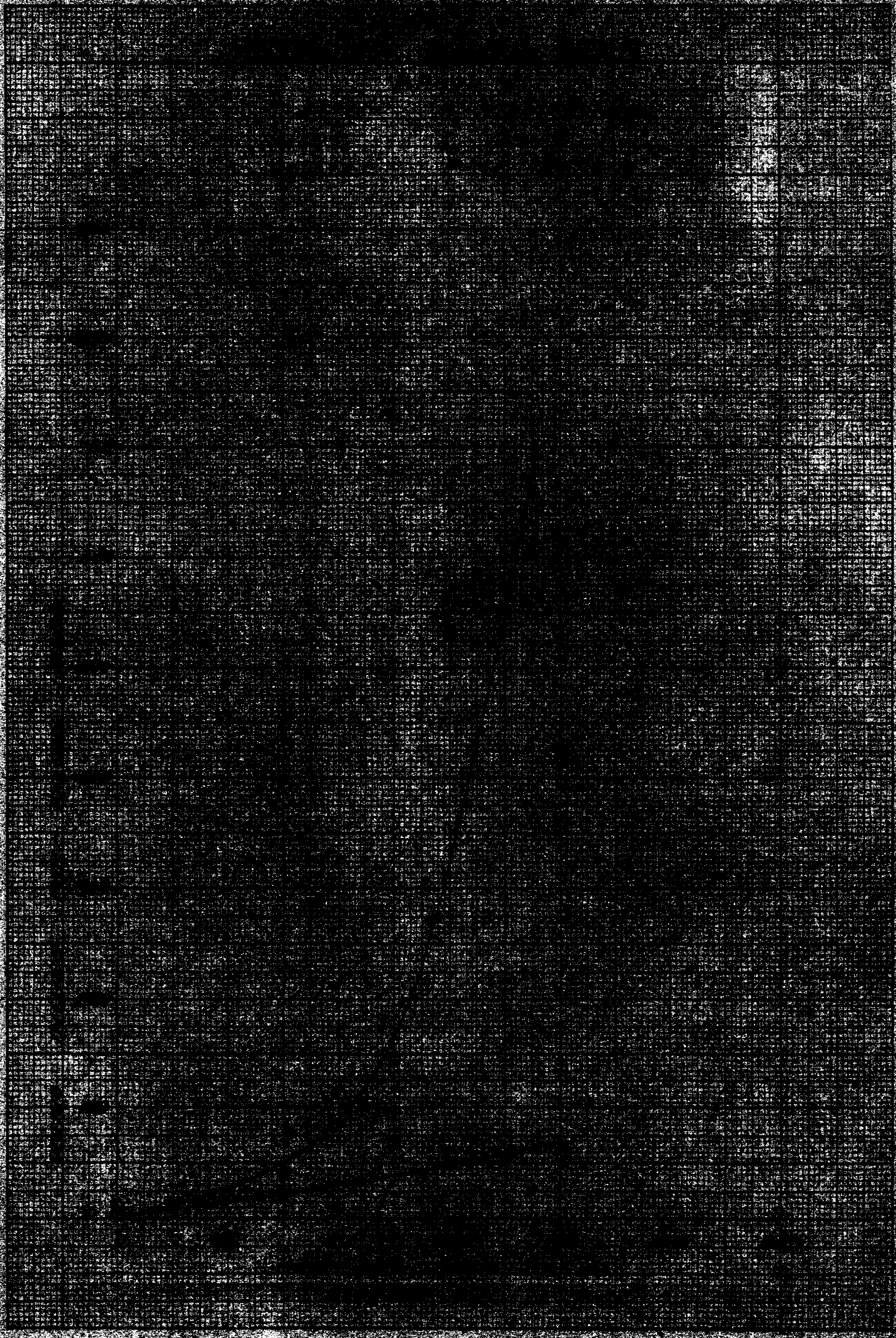
Ring Speed - 3760 feet per min.
Current Density - varied
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

		Brush F		Brush G		Brush H		Brush I	
t	I_d	W	W	W	W	W	W	W	W
4.00	0	0.0	.25	.75	0.0	3.0	11.7	2.75	4.25
2.00	20	0.0	7.50	13.5	19.0	8.0	11.0	56.0	44.5
2.00	40	21.5	16.5	22.0	11.0	23.0	21.0	78.5	85.1
2.00	60	24.0	82.0	25.0	16.5	23.0	41.5	160.	150.
2.00	80	19.5	136.	38.5	6.5	10.	115.	228.	160.
2.75	100	17.1	73.5	29.4	16.7	69.8	145.	305.	188.
2.00	120	25.0	350.	30.5	59.0	59.0	533.	372.	211.
1.50	140	14.7	654.	105.	333.	55.3	945.	566.	279.
1.42	160	1581.	2366.	874.	1014.	60.6	396.	641.	353.

Form E-9



Form B-3



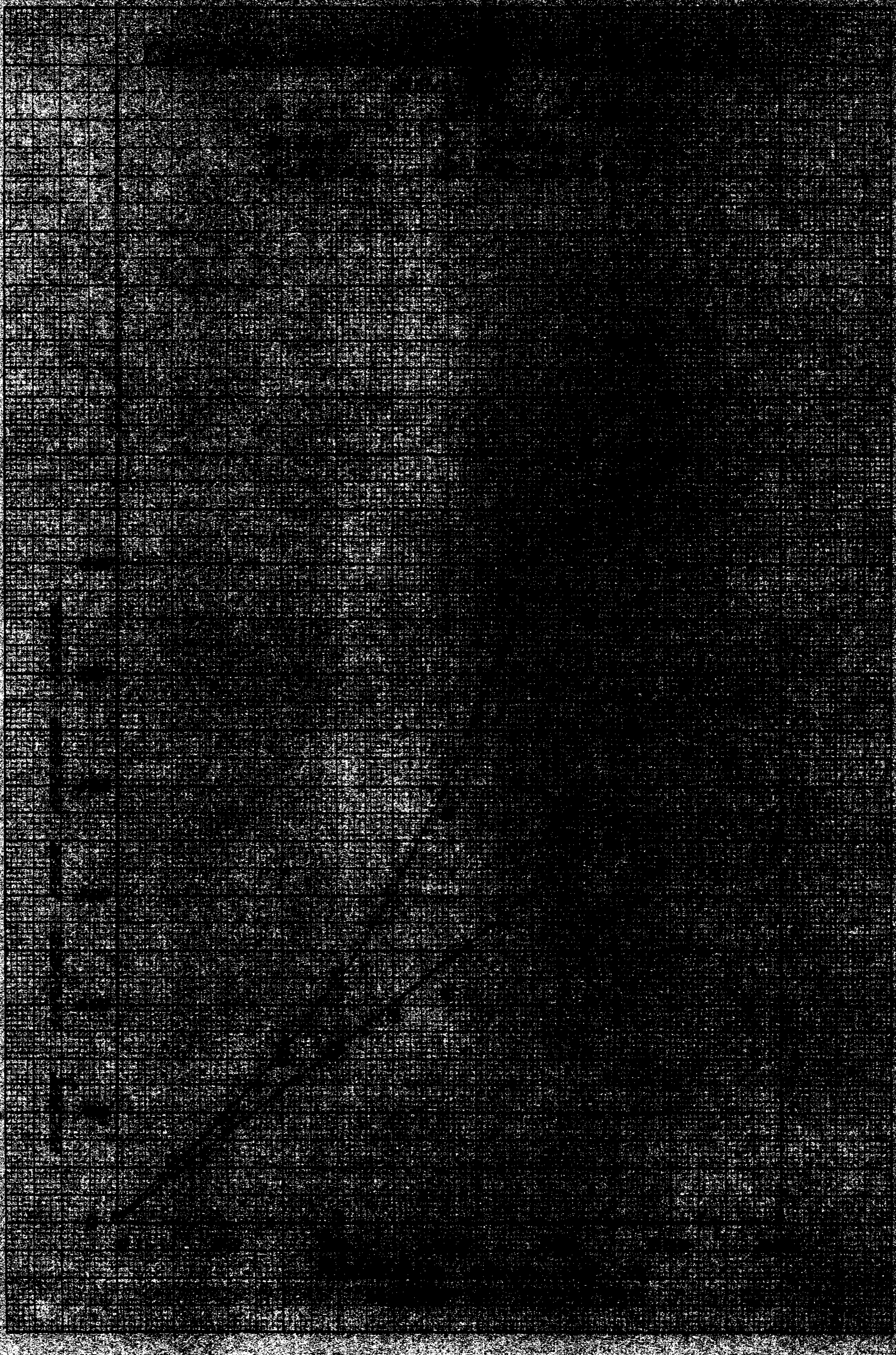


Table 11

Rate of Wear versus Ring Speed

Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 90 volts d-c
Drawn Copper Rings

Ring Speed - varied
Current Density - 120 amp. per sq. in.
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

		Brush F		Brush G		Brush H		Brush I	
t	S	W-	W+	W-	W+	W-	W+	W-	W+
3.00	3700	30.0	1378.	7.0	43.3	17.0	134.	441.	162.
2.00	3188	6.50	647.	6.50	101.	5.50	162.	255.	185.
2.00	2550	14.5	299.	4.50	36.0	8.00	80.5	179.	155.
1.50	1913	30.0	81.4	16.9	31.3	15.2	44.0	77.4	120.
1.55	1275	3.87	4.51	.00	22.6	.00	14.2	41.9	68.4
1.50	638	20.0	18.0	8.67	31.3	13.3	22.0	8.67	36.7
2.00	4463	10.5	1708.	7.0	188.	.00	222.	329.	237.

Form N-3

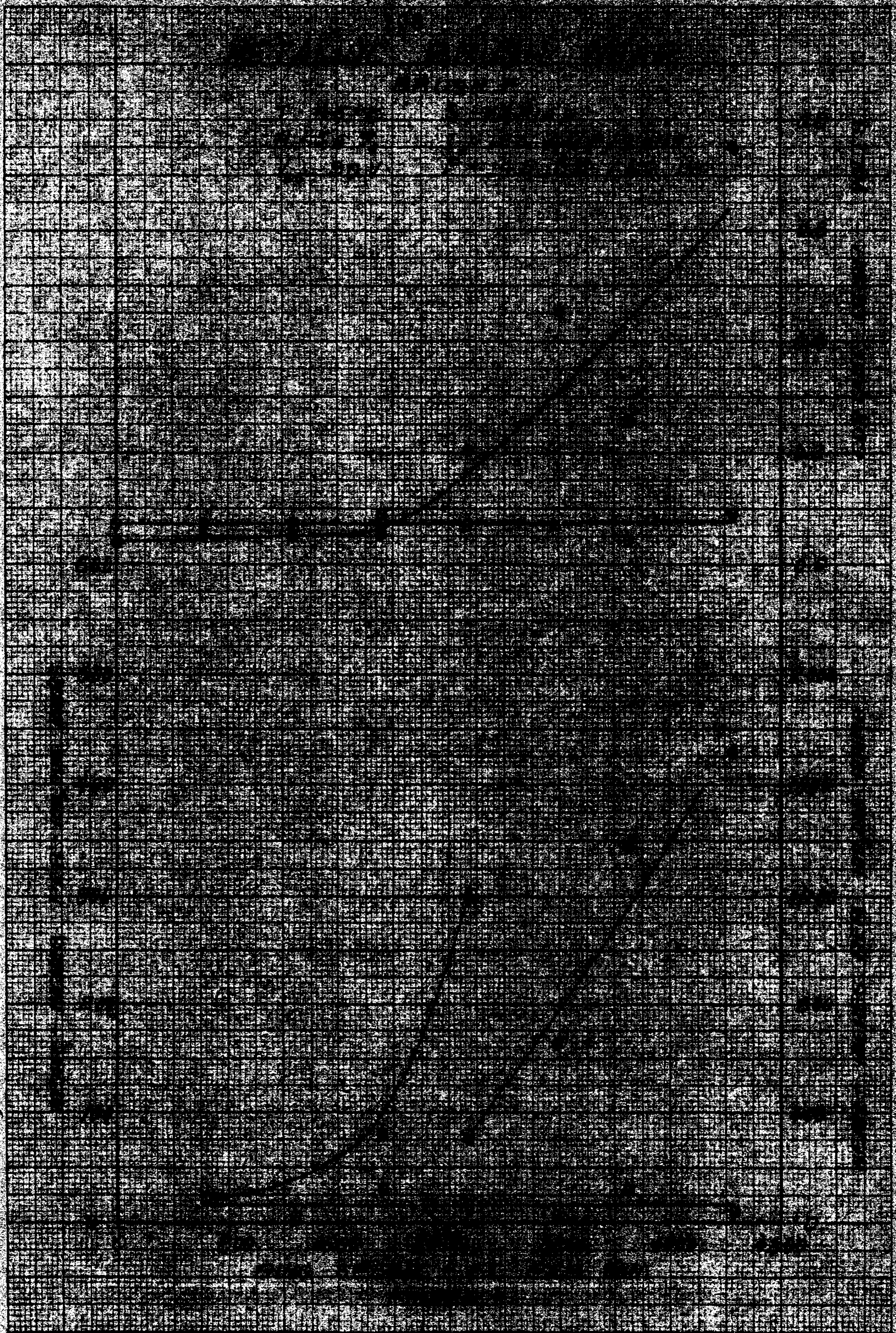
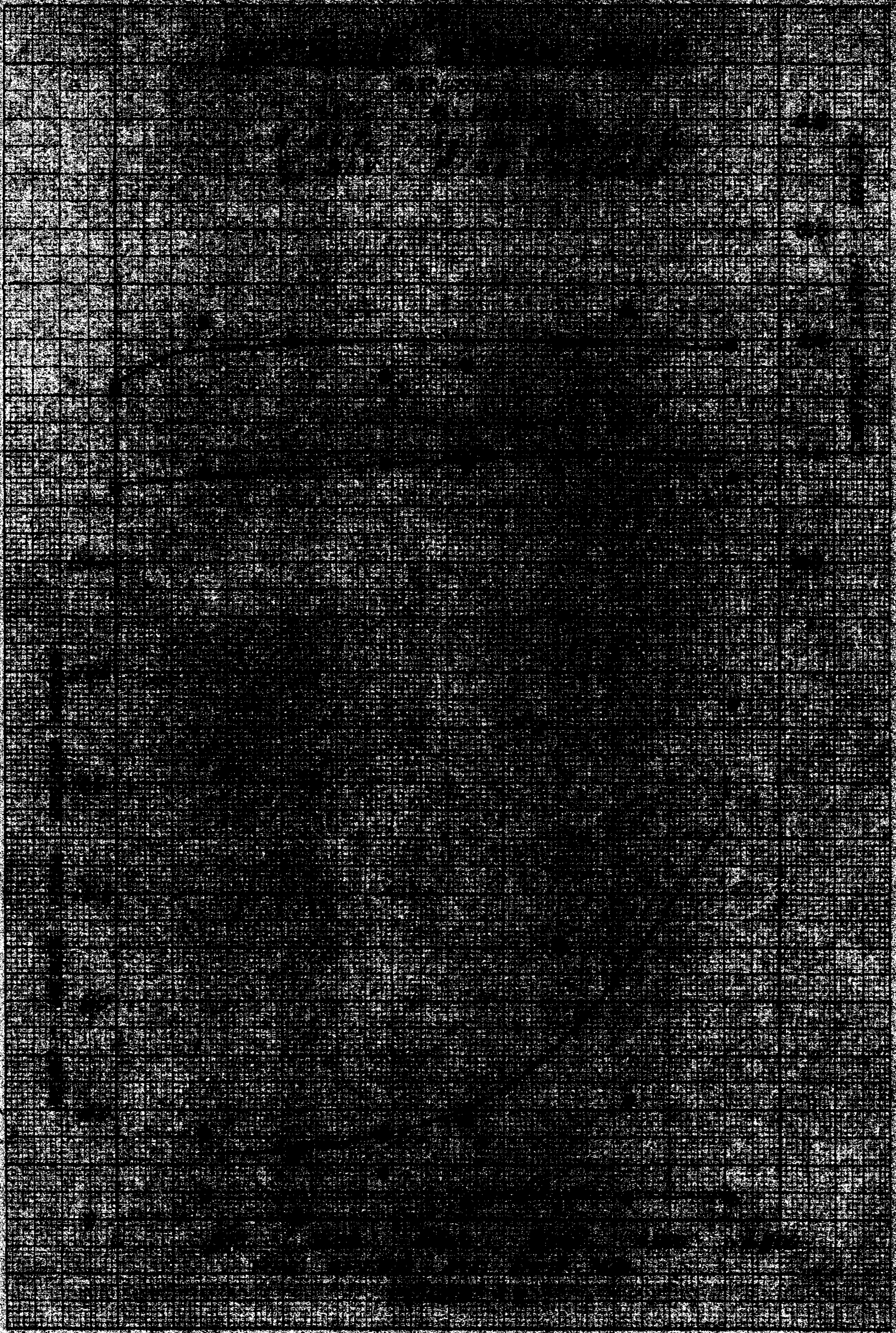


Figure E-1



Form B-b

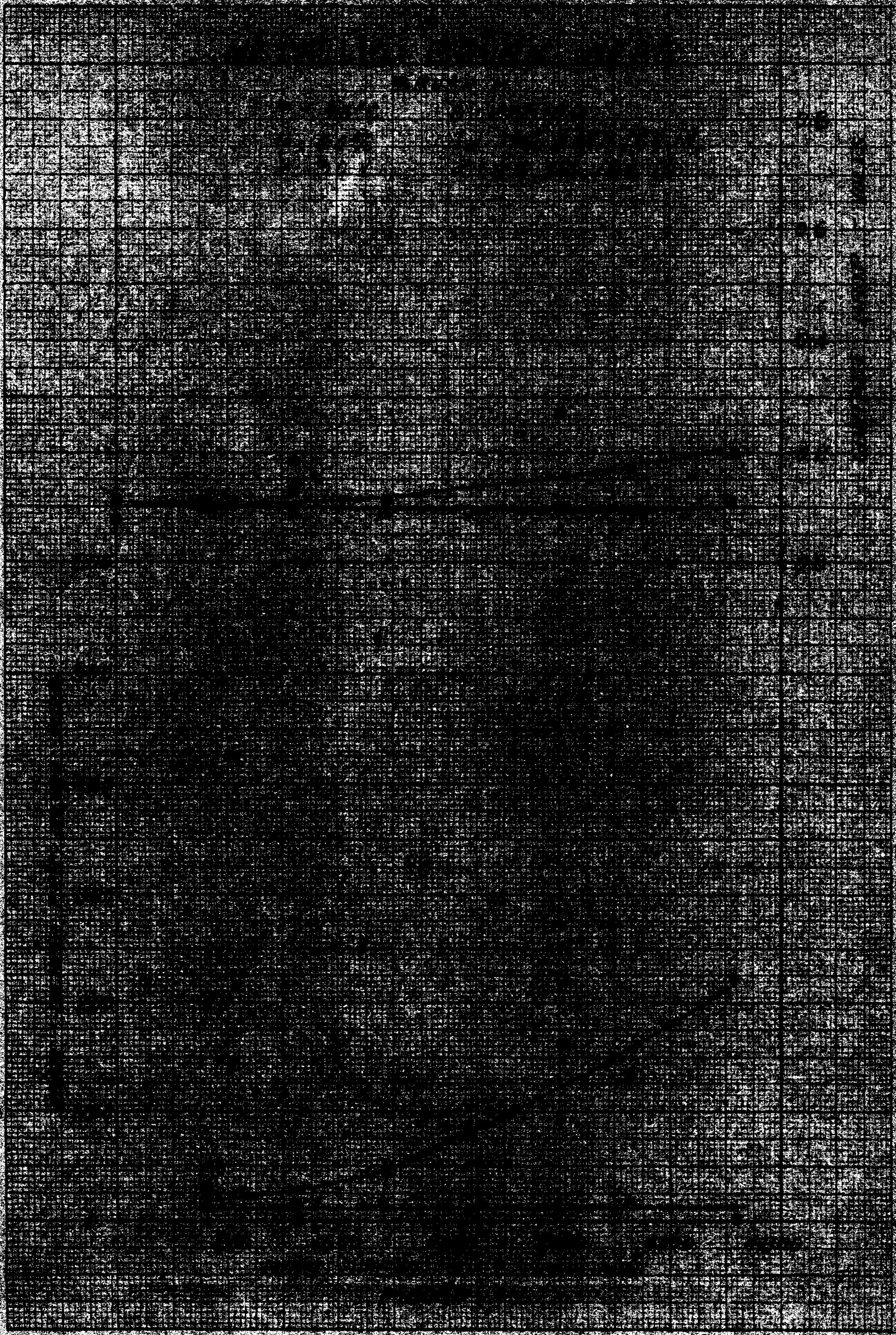


Table 12

Rate of Wear versus Brush Pressure

Test Conditions

Ambient Temperature - 45°C
Relative Humidity - 50%
Brush Circuit Potential - 80 volts d-c

Ring Speed - 3760 feet per min.
Current Density - 120 amp. per sq. in.
Brush Pressure -
Brushes not tracking

		Brush H Drawn Ring		Brush G Cast Ring	
t	P	W-	W+	W-	W+
2.00	48	44.5	60.5	19.5	7.5
2.33	72	13.7	50.2	27.9	48.1
1.50	96	32.0	34.7	38.0	64.6
2.00	120	33.5	71.0	75.0	140.
2.17	144	85.8	145.	230.	323.
2.00	168	243.	262.	430.	434.
2.00	24	1765.	131.	.0	458.

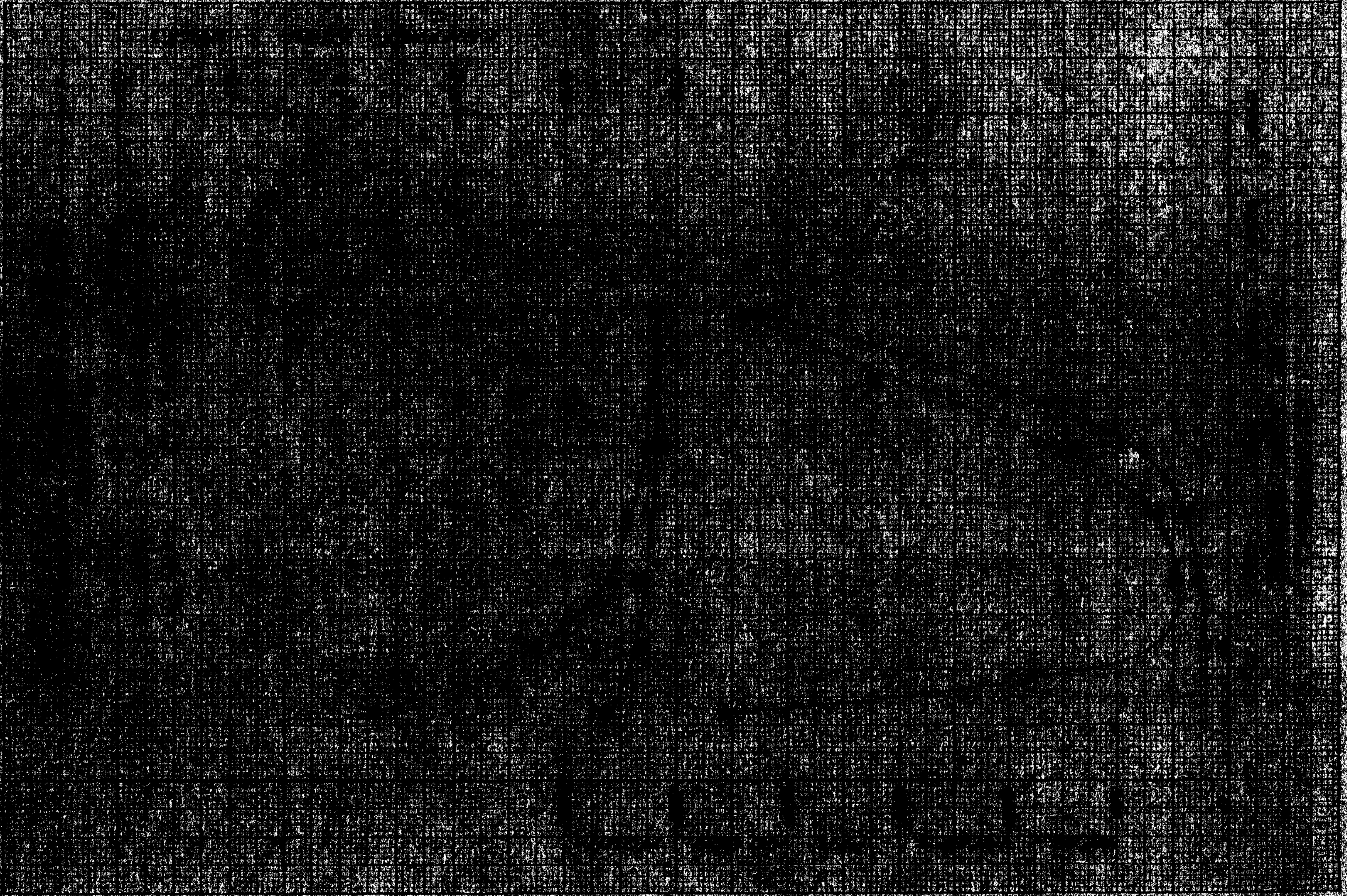


Table 13

Rate of Wear versus Relative Humidity

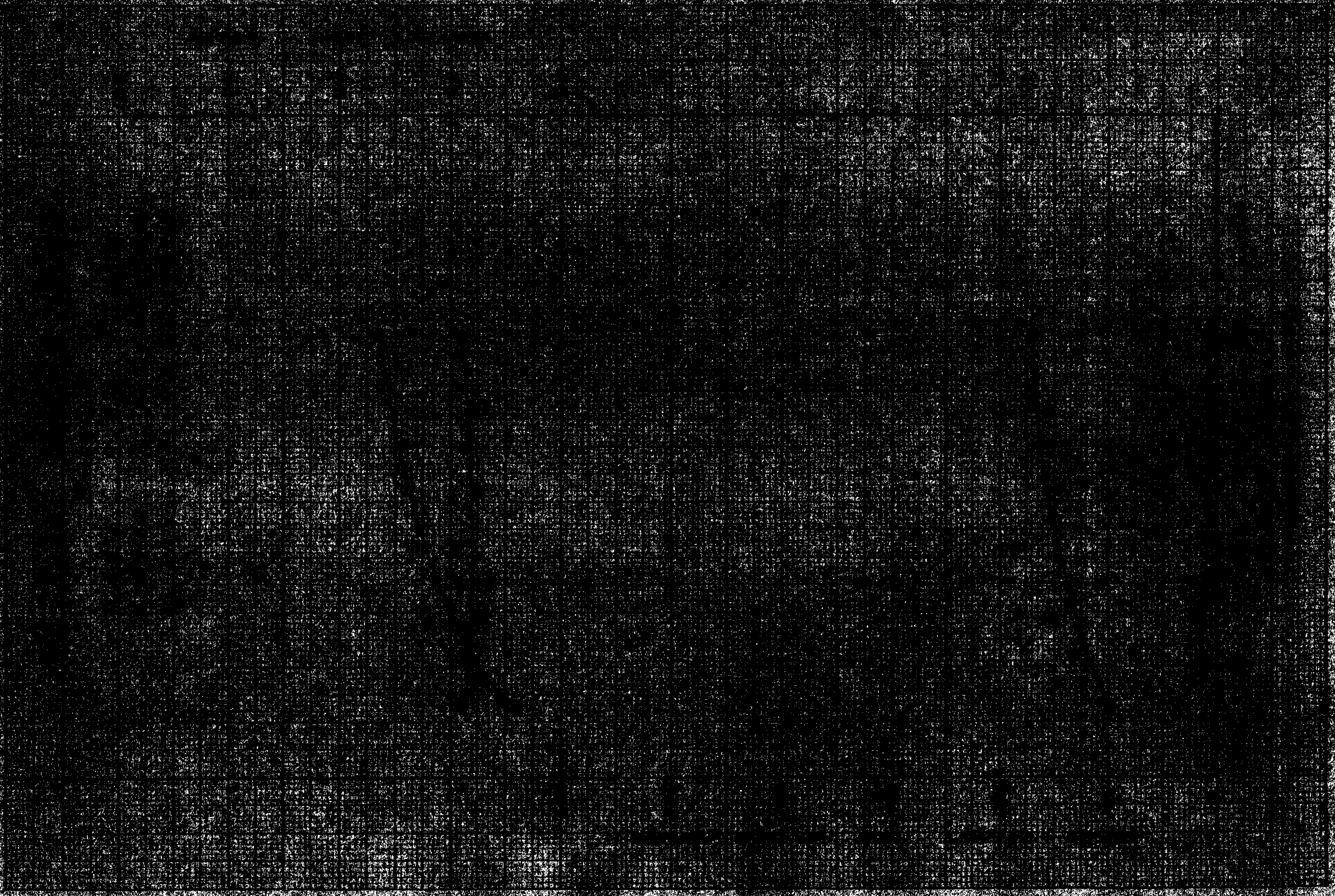
Test Conditions

Ambient Temperature - 45°C
Relative Humidity - varied
Brush Circuit Potential - 90 volts d-c
Drawn Copper Rings

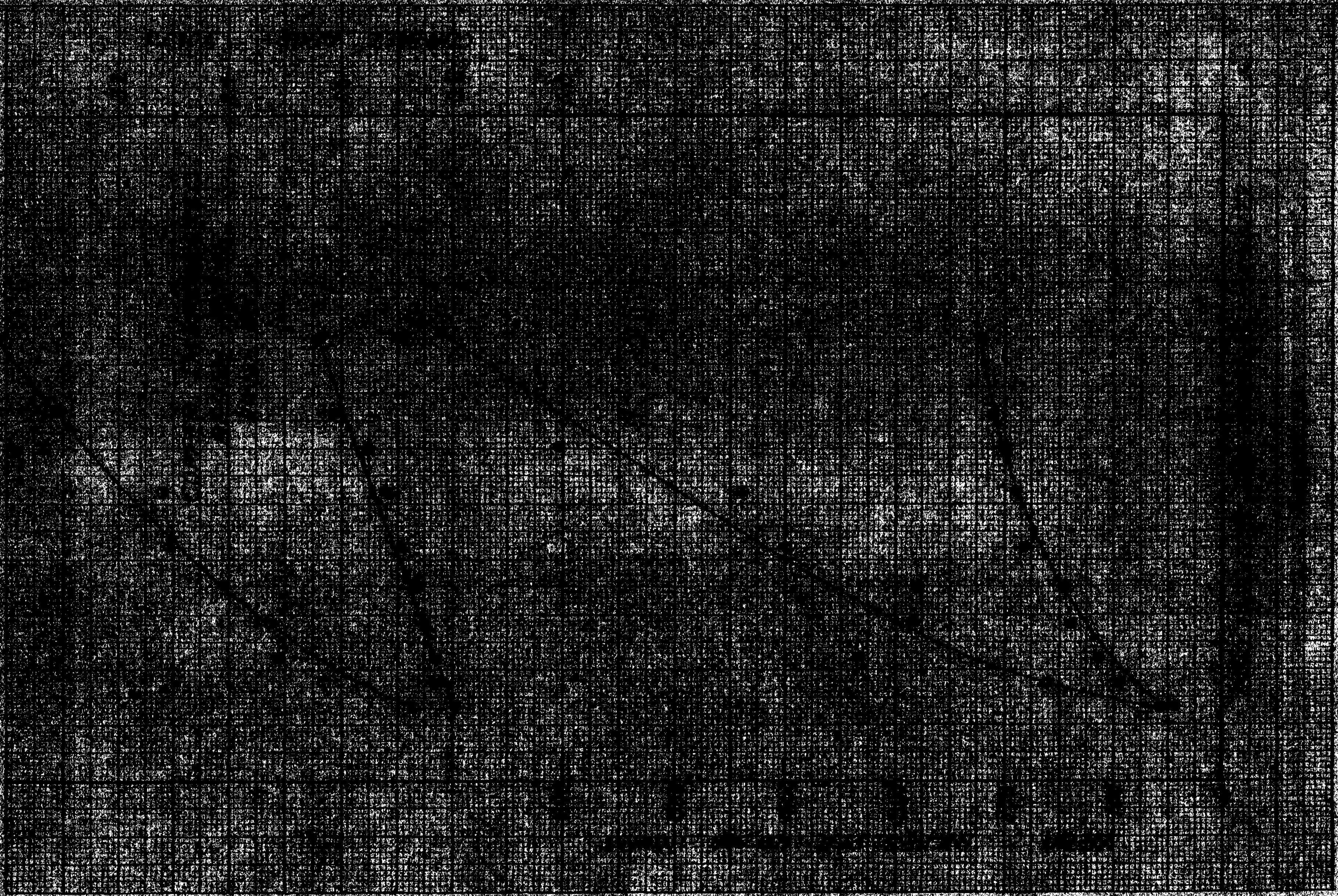
Ring Speed - 3760 feet per min.
Current Density - 120 amp. per sq. in.
Brush Pressure - 48 oz. per sq. in.
Brushes not tracking

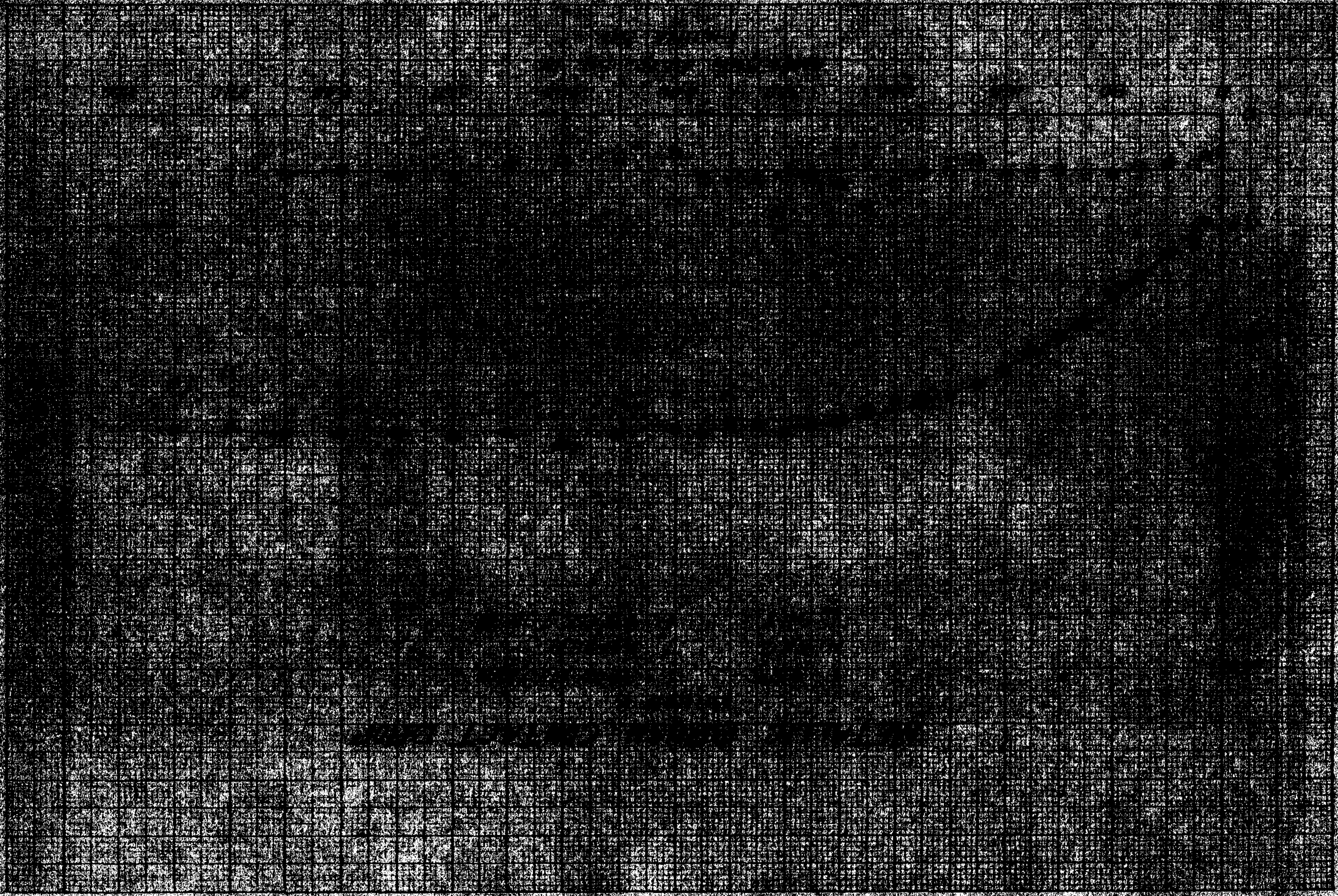
		Brush G		Brush H		Brush I*	
t	H	W-	W+	W-	W+	W-	W+
2.00	13	24.0	.00	35.0	100.	43.0	56.5
2.00	17.5	8.50	28.0	16.0	124.	160.	94.0
1.50	22	17.3	27.3	12.0	129.	333.	114.
1.50	28.5	15.3	29.3	20.0	153.	283.	140.
2.00	35	8.00	37.5	5.00	108.	278.	147.
2.00	42	.50	45.0	11.0	187.	400.	182.
2.00	52	0.00	100.	8.50	148.	439.	185.
2.00	60	5.00	121.	10.5	164.	601.	200.
2.00	66	10.0	198.	10.0	155.	545.	210.
2.00	80	.00	165.	9.00	168.	765.	245.

* The increase in wear is largely due to change in the ring condition.

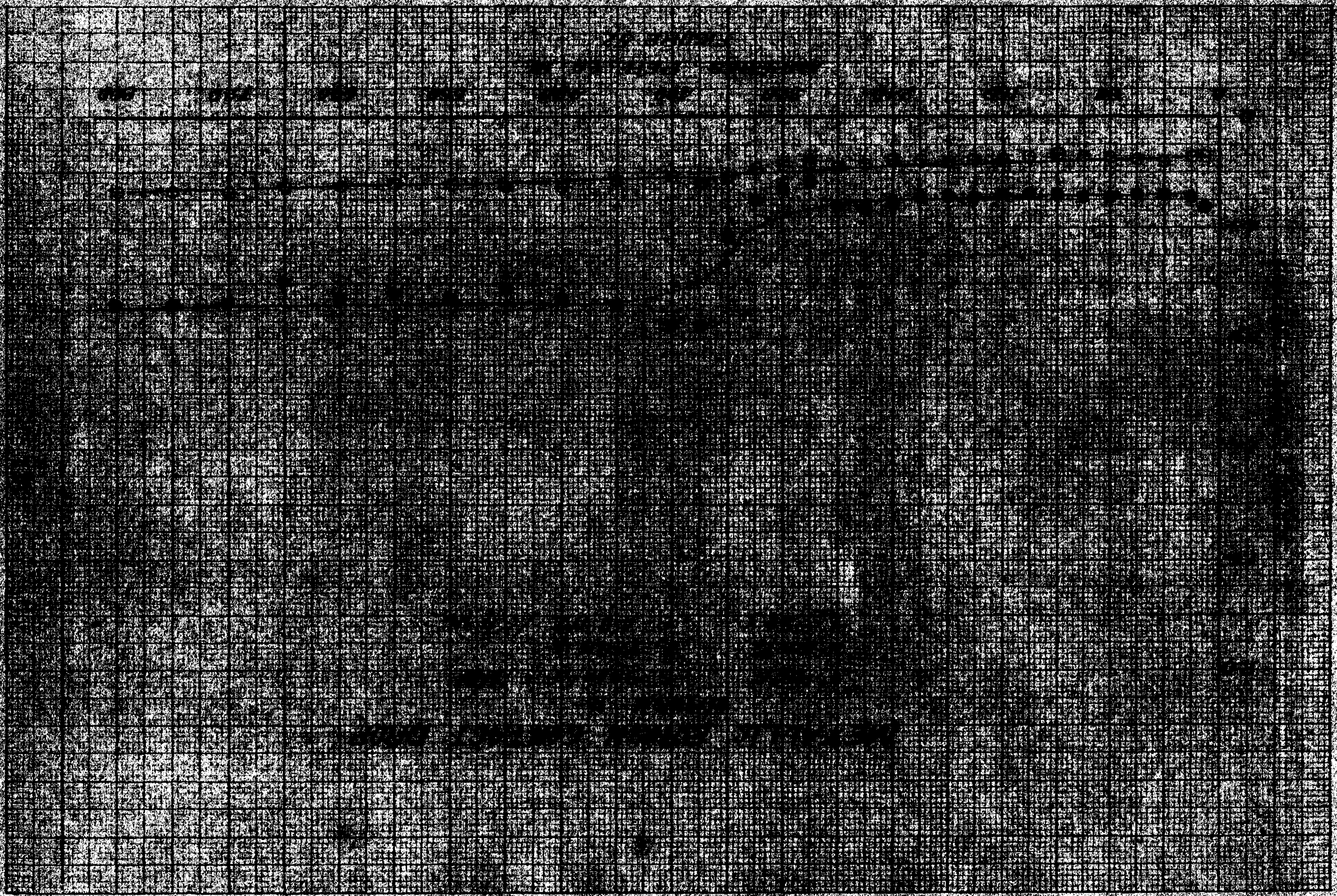


Form F2





Form E



Appendix 2

In Appendix 2 are given a table of symbols which are used consistently throughout the text and several charts to aid in interpreting the data.

Symbols

H - Relative humidity in per cent.

H_a - Absolute humidity in grains per cu. ft.

I_d - Current density in amperes per sq. in.

P - Brush pressure in ounces per sq. in.

S - Ring speed in feet per min.

t - Time in hours.

T_d - Dry bulb or air temperature in deg. Cent.

T_w - Wet bulb temperature in deg. Cent. (forced circulation).

V_{tc}- Total brush circuit potential.

V_t - Total brush contact drop.

V_+ - Positive brush contact drop (motor sense).

V_- - Negative brush contact drop (motor sense).

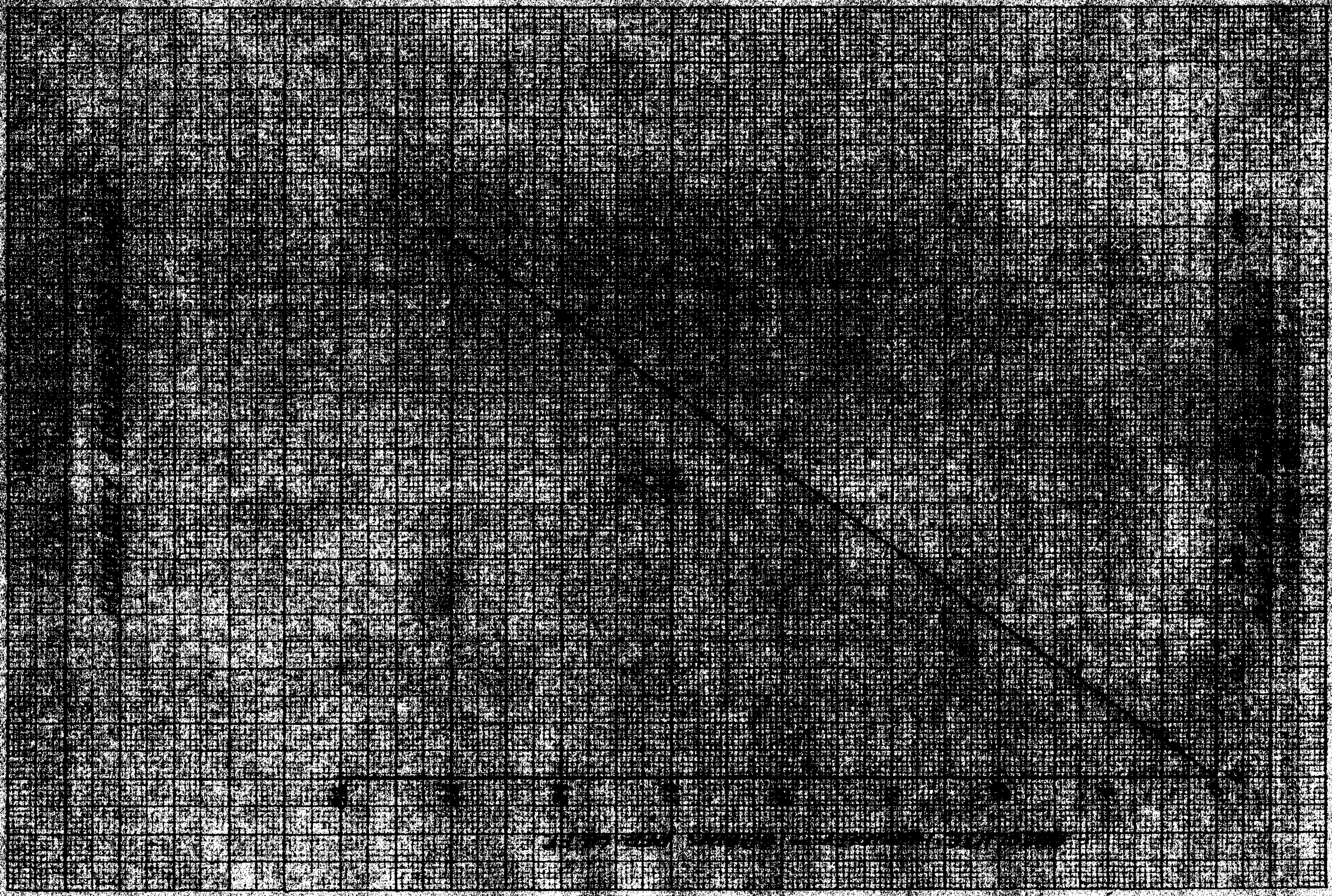
W_+ - Positive brush wear in in. per 100,000 hrs.

W_- - Negative brush wear in in. per 100,000 hrs.

Table 14

Physical Constants of the Brush Materials

Brush	ρ ohms/cu.in.	Normal Current Density	Coefficient of Friction	Type of Material
A	.0020	55	.21	Electrographitic lampblack
B	.00225	60	.15	Electrographitic lampblack
C	.00106	45	.35	Carbon graphite
D	.00142	45	.29	Carbon graphite
E	.00030	70	.18	Electrographitic coke base
F	.00000242	150	.02	Heavy metal graphite
G	.000010	100	.20	Metal graphite
H	.0000064	115	.02	Metal graphite
I	.000214	85	.23	Copper impregnated carbon


Form E-1

VII. LITERATURE CITED

1. Baily, F. G. and Cleghorne, W. S. H. Some Phenomena of Commutation. Jour. Inst. of Elec. Engrs. (London) 38:150-190. 1906.
2. Baker, Robert M. The Effect of Mercury Vapor on Sliding Contacts. Elec. Jour. 29:64-65. 1923.
3. Baker, Robert M. Commutation and Current Collection in Hydrogen. Trans. Amer. Inst. of Elec. Engr. 50:714-717. 1931.
4. Binder, Ludwig. Über die Vorgänge an den Bürsten von Schleifringen und Stromwendern. Wissenschaftliche Veröffentlichungen aus dem Siemens-Konzern. 2:158-165. 1922.
5. Bracken, Ellis F. Humidity Control Prevents A-C Brush Disintegration. Elec. World 102:410-411. 1933.
6. Child, C. D. Electric Arcs. D. Van Nostrand Company, New York. 1913.
7. Czepek, Rudolf. Der Übergangswiderstand von Kohlenbürsten am Kollektor. Archiv für Elektrotechnik. 6:161-174. 1917.
8. Dean, J. S. Carbon Brush Life on Direct-current Railway Motors. Elec. Jour. 14:416-419. 1917.

9. Edgecomb, H. R. and Dick, W. A. Methods of Determining Brush Losses Due to Contact and Friction. Trans. Amer. Inst. of Elec. Engr. 32:565-575. 193$\overset{13}{1}$.

10. Hunter-Brown, P. Carbon Brushes: Considered in Relation to the Design and Operation of Electrical Machinery. Jour. Inst. of Elec. Engr. (London) 57:193-224, 257-266. 1919.

11. Hunter-Brown, P. Carbon Brushes and Electrical Machines. The Morgan Crucible Company Ltd. London. 1923. Published for private circulation only.

12. Hunter-Brown, P. and Hews, C. J. A Practical Investigation into the Design of Brushes and Brush Holders. Jour. Inst. of Elec. Engr. (London) 71:799-818. 1932.

13. Kahn, Max. Der Übergangswiderstand von Kohlenbürsten. Sammlung Elektrotechnischer Vorträge 3:437-491. 1902.

14. Little, G. M. The Application of the Helical Groove to Slip Rings and Commutators. Trans. Amer. Inst. of Elec. Engr. 50:718-723. 1931.

15. Ludwig, L. R. and Baker, R. M. Influence on Commutation of Brush Contact Drop. Trans. Amer. Inst. of Elec. Engr. 51:959-963. 1932.

16. Perrier, M. La chute de tension au contact des balais sur les bagues collectrices. Bulletin de la Société Française des Électriciens. 10:903-917. 1930.

17. Perrier, M. Traces de balais sur les bagues de machines synchrones. Revue Générale de L'Électricité. 28:413-416. 1930.

18. Slepian, J. Temperature of a Contact and Related Current Interruption Problems. Jour. Amer. Inst. of Elec. Engr. 45:930-933. 1926.

19. Smithsonian Inst. Misc Collection 86:176. 1931.

20. Stark, J. and Cassuto, L. Der Lichtbogen zwischen gekuhlten Elektroden. Physikalische Zeitschrift 5:264-269. 1904.

21. Stine, W. E. Brushes for Electric Motors and Generators. Jour. Amer. Soc. of Naval Engrs. 37:312-331. 1925.

22. Taylor, H. G. Phenomena Connected with the Collection of Current from Commutators and Slip-Rings. Jour. Inst. of Elec. Engr. (London) 68:1356-1363. 1930

23. Thomson, G. P. Conduction of Electricity through Gases. Third edition, Volume II Cambridge at the University Press. 1933.

VIII. ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to the following men and organizations for their co-operation during the investigation:

To Professor F. Ellis Johnson who sponsored the experimental work and offered many helpful suggestions.

To the Iowa Engineering Experiment Station, whose co-operation made it possible for the author to conduct the investigation.

To Mr. J. A. Robinson of the National Carbon Company who suggested the investigation and who has made many helpful suggestions and criticisms throughout the work.

To the National Carbon Company for furnishing the brushes used in the tests.

To Dr. O. A. Brown for friendly interest and suggestions.