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# A Study of Current Noise in Cokes, Carbons, and Graphites

Robert J. Lanter

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**A STUDY OF CURRENT NOISE IN COKES,  
CARBONS, AND GRAPHITES**

**A Thesis  
Presented to  
the Faculty of the Department of Physics**

**In Partial Fulfillment  
of the Requirements for the degree  
Master of Science**

**by  
Robert J. Lanter  
June 1957**







This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E. Castetter  
DEAN

DATE June 4, 1957

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A Study of Current Noise in Cokes, Carbons, and Graphites

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This thesis, directed and supervised by the Hon. Mr. Justice  
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*June 4, 1967*

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A Study of Current Foreign Policy, Defense, and Foreign

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END



## TABLE OF CONTENTS

	PAGE
PART I - Introduction. . . . .	1
PART II - Experimental. . . . .	9
PART III - Results and Discussion. . . . .	18
PART IV - Conclusions . . . . .	22
REFERENCES . . . . .	42



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## TABLE OF CONTENTS

PART I - Introduction . . . . .	1
PART II - Experimental . . . . .	10
PART III - Results and Discussion . . . . .	15
PART IV - Conclusions . . . . .	22
REFERENCES . . . . .	23



# LIST OF TABLES

TABLE	PAGE
I. Total Noise Voltage Relative to Frequency, Current, Ambient Temperature, and Heat-Treat Temperature. . . . .	25
II. Values of the Frequency Exponent <u>n</u> . . . . .	26
III. Values of the Current Exponent <u>m</u> . . . . .	27
IV. Resistivity Relative to Ambient Temperature and Heat-Treat Temperature. . . . .	28
V. Energy Gap Relative to Heat-Treat Temperature . . . . .	29



TABLE

- I. Total Noise Voltage relative to  
Frequency, Current, Ambient Temperature,  
and Heat-Treat Temperature . . . . .
- II. Values of the Frequency component . . . . .
- III. Values of the Current component . . . . .
- IV. Resistivity relative to ambient  
Temperature and Heat-Treat Temperature . . . . .
- V. Energy gap relative to heat-treat  
Temperature . . . . .



## LIST OF FIGURES

FIGURE	PAGE
1. Typical Spectra of Noise in Germanium Single Crystal Filaments Carrying DC Current . . . . .	30
2. Schematic Diagram of the Energy Bands for Aromatic Solids . . . . .	31
3. a. Block Diagram of the Electronic Equipment b. Schematic Diagram of the Sample Test Section .	32
4. Noise Power Versus Frequency for Sample Heat- treated to 650 °C . . . . .	33
5. Noise Power Versus Frequency for Sample Heat- treated to 720 °C . . . . .	34
6. Noise Power Versus Frequency for Sample Heat- treated to 730 °C . . . . .	35
7. Noise Power at 40 Cycles Per Second Versus Current Through Sample. . . . .	36
8. Resistivity Versus Heat-treat Temperature . . . .	37
9. Current Versus Voltage for the Sample Heat-treated to 650 °C. . . . .	38
10. Current Versus Voltage for the Sample Heat-treated to 720 °C. . . . .	39
11. Current Versus Voltage for the Sample Heat-treated to 730 °C. . . . .	40
12. Noise Power at 40 cycles per Second Versus DC Power Dissipated in Sample . . . . .	41



# FIGURES

1. Typical spectra of noise in the sample circuit
2. Schematic diagram of the sample circuit
3. a. Block diagram of the measurement system  
b. Schematic diagram of the sample circuit
4. Noise Power Versus Frequency for Sample Circuit  
treated to 650 °C
5. Noise Power Versus Frequency for Sample Circuit  
treated to 750 °C
6. Noise Power Versus Frequency for Sample Circuit  
treated to 750 °C
7. Noise Power at 40 GHz for Sample Circuit
8. Current Through Sample
9. Resistivity Versus Temperature for Sample
10. Current Versus Voltage for the Sample
11. Current Versus Voltage for the Sample  
Heat-treated to 750 °C
12. Noise Power at 40 GHz for Sample Circuit  
Heat-treated to 750 °C
13. DC Power Dissipation in Sample



## PART I

### INTRODUCTION

Current noise, also referred to as excess noise,  $1/f$  noise, and semiconductor noise, is generated when an electric current passes through various conductors and devices such as carbon resistors,<sup>1</sup> thin metal film,<sup>2</sup> vacuum tubes,<sup>3</sup> silicon and germanium,<sup>4</sup> and even through insulators<sup>5,6</sup> subjected to very intense electric fields. In character, it differs markedly from the ordinary thermal or Johnson<sup>7,8</sup> noise which is common to all conductors and which results from fluctuations in the electronic velocity distribution which occur at any finite temperature. Johnson noise has a flat noise power spectrum and is present whether or not current flows, whereas current noise<sup>9</sup> has a spectrum such that the noise power rises with decreasing frequency (where the noise power values are usually stated in terms of watts per cycle per second of band pass of the measuring



Current noise, also referred to as random noise, is noise, and some consider noise, is generated when an electric current passes through various conductors and devices such as carbon resistors, tube resistors, vacuum tubes, silicon and germanium, and even insulators, subjected to very minute electric fields. In character, it differs markedly from thermally generated or Johnson noise which is common to all conductors and which exhibits the characteristics of any electronic velocity distribution which occurs in any finite temperature. Johnson noise has a flat power spectrum and is present whether or not current flows, whereas current noise has a spectral peak and the noise power rises with increasing frequency (where the noise power varies the square of the frequency). The noise power per octave of band width of the measuring



instrument) and is present only when there is a current flow, increasing with current approximately as  $I^m$ . However,  $m$  differs from one material to another, which may indicate that the dependence is more complicated than can be given by a simple power law. The noise power spectrum has been represented by the function  $1/f^n$  and a graph showing some typical germanium noise power spectra is given in Figure 1. The reported values of  $n$  are in the neighborhood of unity and average about  $3/2$ .

The function  $1/f^n$  has caused some concern<sup>10</sup> because its integral, the total noise power, diverges when taken over the frequency range of zero to infinity; however, the function can be changed to avoid this result, e.g., by letting  $n$  become less than one in the range of very low frequencies and greater than one in the range of very high frequencies. There is little experimental knowledge about the current noise spectrum at the low end. It has been reported in some cases to reach a maximum, while in others it has continued to rise to the limit of the experimental measurements. In pyrolytic carbon resistors,<sup>11</sup> for example, it was found<sup>1</sup> to be still rising at a  $10^{-4}$  cycles per second. Also, little is known about the dependence of current noise on ambient temperature, but for germanium, it was reported to be essentially independent of temperature<sup>9</sup> over the range from room temperature to about 70 °K.



instrument) and is shown in Figure 1. It is a curve of  
 flow, increasing with current in a non-linear manner,  
 in contrast to the linear relationship which would be expected  
 if the dependence of flow on current were linear. The curve is  
 by a simple power law. The curve is shown in Figure 1.  
 represented by the function  $y = ax^b$  and a straight line is  
 typical of the relationship between flow and current.  
 The reported values of  $b$  are in the neighborhood of unity  
 and average about 1.2.  
 The function  $y = ax^b$  has several advantages. It is  
 its integral, the total mass flow, diverges with time  
 over the frequency range of zero to infinity. However, the  
 function can be changed to avoid this difficulty, e.g., by  
 letting  $b$  become less than one in the range of very low  
 frequencies and greater than one in the range of very high  
 frequencies. There is little experimental knowledge about  
 the current noise spectrum at the low end. It has been  
 reported in some cases to reach a minimum at low  
 frequencies and to rise to the limit of the observable  
 measurement. In previous cases, the noise spectrum  
 it was found to be flat at low frequencies and to rise  
 at high frequencies. This is shown in the dependence of  
 current noise on current, shown in Figure 2.  
 It was reported to be very slightly dependent on current  
 over the range from zero to infinity.



Seemingly, current noise does not result from a purely random process as does Johnson noise. If it were assumed that the noise was due to a change in density of charge carriers, one possible mechanism would involve the capture and immobilization of carriers. The problem of explaining how they can be immobilized for times long enough to account for the observed low noise frequencies has not been solved. Two theoretical approaches to this problem have been made with reference to germanium, both involving the use of traps. A trap is defined (see Kittel<sup>12</sup>) as an impurity atom or other imperfection in the crystal capable of capturing an electron or hole; the captured carrier may be re-emitted at a subsequent time. One approach considers the traps as lying on the surface of the germanium and having various energy depths, the energy spectrum being such as to yield the observed noise spectrum<sup>13</sup>. The other approach considers the traps as existing in the oxide film covering the surface, thus an electron in a trap close to the germanium would escape in a shorter time than one further removed, thereby providing the long time constants necessary.<sup>14</sup>

There is considerable doubt that these approaches can apply generally since current noise has been observed in metal films, and metals have electronic characteristics much different from semiconductors. It has also been



Secondly, current noise can not be easily removed

randomly random processes as they are not stationary.

Assuming that the noise has the same statistical properties

charge carriers, one possible mechanism would involve the

capture and immobilization of carriers, the removal of

explaining how they can be immobilized for a long time

enough to account for the observed low noise frequencies

has not been solved. The theoretical approaches to this

problem have been made with reference to germanium, but

involving the use of traps, it is not clear how this

can be applied to other semiconductor materials.

Capacitance of capacitors as elements in noise circuits

carriers may be re-emitted as a consequence of the noise

processes considered the traps in the case of the carrier

the germanium and having various energy levels, the noise

spectrum being such as to yield the observed noise spectrum.

The other approach considers the traps as existing in the

oxide film covering the surface, then an electron in a trap

close to the germanium would escape in a shorter time than

one further removed, thereby providing the low noise spectrum

observed.

There is considerable doubt that these approaches

can apply generally since it is not clear how the noise spectrum

in metal films, and more a more general consideration

much different from semiconductor. I am not sure



observed in carbon resistors which are made from materials of widely varying characteristics. There are references to current noise in carbon resistors, but very little data has been published. Therefore, it seems desirable to make a study of the conditions under which noise in carbon and graphite does occur. Since the hypotheses about current noise are mostly based on germanium, a study based on carbon might assist in solving the problem by supplying additional information.

The differences between semiconductors, metals, and this family of carbons can be seen in their electronic properties.<sup>15</sup> In a metal<sup>15</sup> at absolute zero,  $N$  electrons will fill the  $N/2$  lowest energy levels (since two electrons of opposite spin can occupy each level). At temperatures above absolute zero, the probability of a level being occupied is given by the Fermi-Dirac distribution law

$$f = \left\{ \exp \left[ (E - E_F) / kt \right] + 1 \right\}^{-1}$$

where  $E$  is the energy level and  $E_F$  (the Fermi level) is the energy corresponding to the highest energy level filled at absolute zero.



observed in carbon compounds which are known to be  
materials of which the crystal structure is known  
and reference to the literature is a matter of course  
but very little data has been published. Therefore  
it seems desirable to make a study of the compounds  
under which notice is shown and perhaps their nature.  
Since the hypothesis about current flow and energy  
based on formulas, a study based on energy levels  
exists in solving the problem by analogy and is in  
information.

The difference between the two cases, in which  
and this family of carbon compounds can be seen in their electronic  
properties. In a solid, as in a gas, the electronic  
will fill the two lowest energy levels (since two  
electrons of opposite spin can occupy each level).  
temperatures above absolute zero, the probability of a  
level being occupied is given by the Boltzmann factor  
Boltzmann law

where  $E$  is the energy level and  $E_0$  the Fermi level, is  
the energy corresponding to the highest occupied level  
filled at absolute zero.



In a crystal, there are allowed and forbidden bands of electronic energy levels. If an allowed band is completely filled and there are no electrons in a higher band because the thermal energy  $kT$  is much less than  $E_g$ , the width of the forbidden band, there can be no conduction, for conduction requires increasing the energy of an electron, and there is no available higher state. Metals correspond to the case where the uppermost occupied band is only partially filled, and thus higher energy levels are available. Some materials are insulators at absolute zero but not at higher temperatures; these are materials in which the energy gap of the forbidden band is small, thus allowing electrons to be thermally excited from the filled band to the empty conduction band. The difference between insulators and semiconductors at ordinary temperatures is that the energy gap is too large in insulators for thermal activation to occur.

In an intrinsic semiconductor, the Fermi level lies at the middle of the forbidden band. When an electron is thermally excited into the conduction band, it leaves a hole in the valence band. The conductivity is determined by the number of carriers thus thermally activated, and is approximately related to the temperature by

$$\sigma = A \exp(-E_g/2kT)$$



In a crystal, the energy levels are discrete and the width of the forbidden band is small. If the energy level is high, the band is filled and there are no electrons in a higher band because the energy is much lower than the width of the forbidden band. There can be no conduction, for conduction requires increasing the energy of an electron, and there are no available states. Metals correspond to the case where the energy level is only partially filled, and the higher energy levels are available. Some materials are insulators at absolute zero but not at higher temperatures. These materials are in which the energy gap of the forbidden band is small, thus allowing electrons to be thermally excited from the filled band to the empty conduction band. The difference between insulators and semiconductors at ordinary temperatures is that the energy gap is too large in insulators for thermal activation to occur.

In an intrinsic semiconductor, the Fermi level lies at the middle of the forbidden band. When an electron is thermally excited into the conduction band, it leaves a hole in the valence band. The conductivity is determined by the number of carriers, which are electrons and holes, and is approximately related to the temperature by

$$\sigma = n e \mu$$



where  $A$  is a constant,  $E_g$  is the energy gap,  $k$  is Boltzmann's constant, and  $T$  is the temperature in degrees Kelvin.

If there are impurity atoms or imperfections in the crystal, impurity (or extrinsic) conductivity results. If the impurity (donor) atom has one valence electron more than neighboring atoms, the excess electron will be weakly bound to the atom, thus even at low temperatures thermal activation can occur, with n-type conductivity resulting. If the impurity (acceptor) atom has one fewer valence electrons than is required by the lattice structure, there are not enough electrons to fill the valence band and an unpaired hole will exist, resulting in p-type conductivity. A crystal defect such as a lattice vacancy will immobilize an electron, thus creating an unpaired hole, as will the crystal surface which is a region of a different potential from that inside the crystal, again resulting in p-type conductivity.

Graphite belongs to a family of substances which extends from graphite to crystals of benzene, graphite being a semiconductor with a zero energy gap and benzene having a large energy gap of several electron volts. Between these extremes lie the carbons and hydrocarbons having a structure built up of layers of condensed hexagonal carbon rings. According to Kozowski,<sup>16</sup> the electronic band







picture for this family has several features. First, the energy gap between the conduction band and the valance band decreases continuously with increasing crystallite size, going from several volts in benzene to zero in the infinite graphite crystal. Secondly, in the process of increasing the crystallite size by heating, hydrogen and other fragments of the molecule are driven off from the peripheral atoms, leaving unsaturated valence electrons. These become saturated by electrons from the highest occupied band, the pi band, which thus acquires excess holes. Because of the small size of the crystallites, and resulting large number of peripheral atoms, a large number of mobile holes are created, which eventually destroy the semiconductivity. Thirdly, after the valence electrons of the peripheral atoms are saturated, subsequent crystallite growth results in a decrease in the relative number of peripheral atoms, since each time two ring structures join, their total circumference to area ratio decreases. This results in a decrease in the number of holes. When the material reaches the graphite stage, the energy gap is so low that thermally activated electrons and holes are the predominant carriers. A schematic diagram of the energy band structure just described appears on Figure 2. Since the band structure is fairly well known in this family of



picture for this family and several features. First, the energy gap between the conduction band and the valence band decreases continuously with increasing crystallite size, going from several volts in polymers to zero in the infinite graphite crystal. Secondly, in the presence of increasing the crystallite size by heating, reduction and other treatments of the material, the energy gap decreases. Peripheral atoms, i.e., atoms with a low coordination number, become saturated by electrons from the adjacent occupied band, the  $\pi$  band, which then becomes empty holes. Because of the small size of the crystallites, and resulting large number of peripheral atoms, a large number of mobile holes are created, which eventually destroy the semiconductivity. Thirdly, since the valence electrons of the peripheral atoms are saturated, movement of crystallites results in a decrease in the relative number of peripheral atoms, since each time two ring structures join, their total circumference is equal to the circumference. This results in a decrease in the number of peripheral atoms. In the initial stages of the growth of the crystallites, the growth rate is low but eventually saturated crystallites are formed and the predominant current is a saturation current. The band structure just described appears in Figure 1. The band structure is fairly well known in that level of



materials, a study of their current noise properties might assist in clarifying the problem of current noise. Such a study is described in Parts II and III.



materials, a study of their chemical properties  
might assist in clarifying the nature of the  
Such a study is contained in the following table.

## TABLE I

### ANALYTICAL DATA

1.0000

1.0000



## PART II

### EXPERIMENTAL

The raw coke, carbon, and graphite samples were prepared by heat-treating pieces of molded phenol formaldehyde resin (Bakelite) in a helium atmosphere to various temperatures from about 500 to 3000 °C. The samples were 2 cm long and 0.1 by 0.25 cm in cross-section, with side arms to allow voltage drops to be measured without involving the current-carrying contacts. However, it was found that the contact resistances of connections to the sample were negligible so no further use was made of the side arms. The molded samples were heat-treated in a stainless steel tube in an electric furnace. The tube was sealed and pressurized to slightly over atmospheric pressure. The samples and a control thermocouple were placed in a closed graphite container in the furnace. The furnace temperature was controlled by a Wheelco Chronotrol and was made to rise at the rate of 100 °C per hour to a maximum of 900 °C. Samples were heat-treated to temperatures above 900 °C in a graphite



## PART II

### EXPERIMENTAL

The two cases, carbon, and graphite, were prepared by heat-treating pieces of material (graphite) in a vacuum furnace (Baker, 1960) at a constant temperature of various temperatures from 1000 to 1500 °C. The samples were 2 cm long and 0.1 cm diameter. section, with side view to show various areas to be measured without involving any special treatment. However, it was found that the contact resistance of connections to the sample were negligible and no further use was made of the side view. The heated sample was heat-treated in a stainless steel tube in an electric furnace. The tube was sealed and surrounded by nitrogen over atmospheric pressure. The samples and a thermocouple were placed in a closed electric container in the furnace. The furnace temperature was controlled by a Rheo-Chemical and was used to heat the sample of 100 °C per hour to a maximum of 1500 °C. Graphite was heat-treated to temperatures above 1000 °C in the furnace.



tube resistance furnace in which was maintained a helium atmosphere, the temperature being measured with a Leeds and Northrup optical pyrometer. Samples in the 600 to 900 °C range were vitreous, i.e., shiny, black, and quite brittle, and required considerable care in handling in order to avoid breakage. Those treated to temperatures of the order of 3000 °C had the appearance and physical properties usually associated with graphite.

The ends of the samples were sand-blasted and areal contacts made by applying indium solder by means of an ultrasonic soldering iron. Leads were then soldered to the sample with an indium-tin alloy solder, using an ordinary soldering gun. The solder appeared to adhere quite well; however, a few of the contacts came loose after several immersions in liquid nitrogen, this presumably being due to the difference in thermal expansion of the sample and the solder.

The arrangement of the electronic equipment used for the measurements is shown in the block diagram, Figure 3a. The schematic diagram of the sample test section is shown in Figure 3b. The current through the sample was varied by controlling the voltage output from







the regulated power supply. The filter section, composed of  $C_1$ ,  $L_1$ , and  $C_2$ , served to reduce the ac ripple and transient voltage effects from the power supply. The impedance of  $C_2$  at audio frequencies was small compared to that of the load resistor so the power supply impedance was negligible. Further reduction in the current through the sample was obtained by use of potentiometer  $R_1$ . The current noise in the sample caused a noise voltage to appear across the load resistor  $R_L$ . The noise voltage was amplified by a factor of 120 and then applied to the wave analyzer. The wave analyzer, which has a pass band of 4 cycles per second, regardless of the frequency setting in its 20 to 16,000 cycle per second range, gave a direct reading of the input voltage. The dc voltage across the sample was measured with a vacuum-tube voltmeter which was switched out of the circuit during the noise voltage measurements.

To determine the gain and frequency response of the system, a resistor was substituted for the sample and an ac voltage from a Hewlett-Packard Model 200I Interpolation Oscillator was applied across it. The system was found to be linear from 6 kilocycles per second (the upper limit of the oscillator) to about 20 cycles per second. To avoid any non-linearity, 40 cycles per second was the lowest frequency at which data were taken.



the regulated power supply. The latter consisted of 2, 10, and 100 ohms, and was connected in series with the load. The impedance of the load was determined by the ratio of the voltage across it to the current through it. The power supply was regulated by a potentiometer. The noise voltage was measured across the load resistor. The noise voltage was amplified by a factor of 100 and then applied to the wave analyzer. The wave analyzer, which has a gain of 100, gives a reading of the noise voltage. The noise voltage across the sample was measured with a vacuum tube voltmeter which was switched out of the circuit during the noise voltage measurements.

To determine the gain and frequency response of the system, a test tone was applied to the input and an output from a vacuum tube voltmeter was measured. Interpolation facilities for the output were used. The system was found to be linear from 10 to 100 cps (the upper limit of the noise) to 10,000 cps (the lower limit of the noise). The noise was measured with a vacuum tube voltmeter which was switched out of the circuit during the noise voltage measurements.



The noise voltages were recorded for samples heat-treated to 650, 720, and 730 °C, the data being taken with currents ranging from 2.5 to 40 milliamperes, at frequencies ranging from 40 to 1280 cycles per second, and at ambient temperatures of 300, 190, 80, and 3.9 °K, i.e., those of air, dry ice in acetone, liquid nitrogen, and liquid helium, respectively. Although noise voltages were observed when samples heat-treated to 820 and 900 °C were placed in the liquid helium cryostat, the actual sample temperatures were not known because boiling took place at all current values at which observable noise was produced.

The voltage indicated on the wave analyzer at any given frequency is the total effective voltage due not only to the signal developed by the sample, but also by the Johnson noise in both the sample and the load resistor and the background noise due to the amplifier and the wave analyzer. To determine the various noise voltage values, the sample was short circuited and 40 ma of dc current was passed through the load resistor. The combined Johnson noise and background noise was of the order of 0.08 millivolts input to the wave analyzer at 40 cycles per second, and dropped off slightly at higher frequencies. (The measured values



The noise voltage was measured for 100 sec. at  
 heat-treated to 300, 400, and 500 °C. The data were  
 taken with current density of 100 A/cm<sup>2</sup> in a helium  
 atmosphere, at temperatures ranging from 100 to 500 °C.  
 per second, and at constant temperature of 300, 400,  
 50, and 500 °C. A 1.0 A, source of air, 0.5 sec in duration,  
 liquid nitrogen, and liquid helium, respectively.  
 Although noise voltage was observed with samples  
 heat-treated to 300 and 500 °C were tested in the  
 liquid helium system, the noise level was higher than  
 were not known because cooling took place at all  
 current values at which considerable noise was produced.  
 The voltage indicated on the wave analyzer at any  
 given frequency is the total effective voltage due not  
 only to the signal developed by the sample, but also  
 by the Johnson noise in both the sample and the load  
 resistor and the amplifier noise due to the amplifier  
 and the wave analyzer. To determine the voltage  
 noise voltage values, the signal was short-circuited  
 and 50 ms of no current was passed through the load  
 resistor. The combined Johnson noise and amplifier  
 noise was of the order of 0.1 mV (rms) at 100 Hz  
 wave analyzer at 100 Hz per second, and changes of 1  
 slightly at higher frequencies. The measured voltage



are given in Table 1.) The Johnson noise developed in a resistor is

$$v_J^2 = 4 k T R \Delta f$$

where  $v_J$  is the Johnson noise voltage,  $k$  is Boltzmann's constant in watt-seconds per °K,  $T$  is the temperature in °K,  $R$  is the resistance in ohms and  $\Delta f$  is the pass band of the wave analyzer in cycles per second. So, for the 7500 ohm load resistor at 300 °K, the magnitude of the Johnson noise voltage was  $(2.23)10^{-8}$  volts. The comparison of this voltage to the background noise voltage is made by the following calculation, based on the procedures of Jenkins.<sup>17</sup> The total noise voltage (as read on the wave analyzer) is

$$v_t^2 = v_J^2 G^2 + v_o^2$$

where  $v_J$  is the Johnson noise voltage,  $G$  is the gain of the amplifier, and  $v_o$  is the background noise voltage. Substituting the known values of  $v_J$ ,  $v_t$ , and  $G$ ,

$$v_o^2 = (6.4)10^{-9} - (7.2)10^{-12}$$



are given in Table I. The corresponding values

in a resistor is

$$V_0 = \frac{1}{2} \Delta T \cdot \Delta T$$

where  $V_0$  is the Johnson noise voltage,  $\Delta T$  is the

constant in volt-seconds per °K,  $T$  is the temperature

in °K,  $R$  is the resistance in ohms and  $\Delta T$  is the

band of the noise amplifier in cycles per second, Hz.

For the 7500 ohm load resistor at 300 °K, the rms value

of the Johnson noise voltage was  $(8.33 \times 10^{-12})$  volts. The

comparison of this voltage to the maximum noise

voltage is made by the following calculation, based on

the procedure of Table I. The total noise voltage

(as read on the wave analyzer) is

$$V_0 = \frac{1}{2} \Delta T \cdot \Delta T$$

where  $V_0$  is the Johnson noise voltage,  $\Delta T$  is the

of the amplifier, and  $V_0$  is the Johnson noise voltage.

Substituting the known values of  $V_0$ ,  $V_0$  and  $R$

$$V_0 = (8.33 \times 10^{-12}) \cdot (1.5 \times 10^{-12})$$



The last term on the right is small, so  $\underline{v}_o^2$  is nearly equal to  $\underline{v}_t^2$ ; thus, the Johnson noise voltage contribution to  $\underline{v}_t$  is negligible. By a similar calculation, it can be shown that the Johnson noise developed in the sample itself is also small compared to the background noise and thus negligible in the noise power computations.

The voltage developed across the load resistor was that due to the current noise and Johnson noise in both the sample and the load resistor. The Johnson noise voltages were negligible, so

$$\underline{v}_t^2 = \underline{v}_n^2 G^2 + \underline{v}_o^2$$

Where  $\underline{v}_n$  is the voltage across the load resistor due to the current noise and the other terms are as previously defined.

It can be seen from the schematic diagram of Figure 3b that the noise voltage across the sample was related to that across the load resistance by

$$\underline{v}_N = \underline{v}_n (R_S / R_L)$$



The last term on the right is small, so  $V_{\text{noise}}$  is approximately equal to  $V_{\text{noise}}$ . The Johnson noise voltage density is  $V_{\text{noise}} = \sqrt{4kT/R}$ , where  $k$  is Boltzmann's constant,  $T$  is the absolute temperature, and  $R$  is the resistance. It can be shown that the Johnson noise voltage density is the same as the noise voltage density of a resistor. The noise voltage density is also small compared to the power.

The voltage developed across the load resistor was that due to the current, noise and Johnson noise. In both the case of the load resistor, the Johnson noise voltage was negligible, so

$$V_{\text{noise}} = \sqrt{4kT/R}$$

where  $V_{\text{noise}}$  is the voltage across the load resistor to the current noise and the other terms are negligible. This is defined.

It can be seen from the above that the noise voltage across the load resistor is related to the noise voltage across the load resistor by

$$V_{\text{noise}} = \sqrt{4kT/R}$$



where  $\underline{v}_N$  is the noise voltage across the sample,  $\underline{v}_n$  is the noise voltage across the load resistor,  $\underline{R}_S$  is the resistance of the sample, and  $\underline{R}_L$  is the resistance of the load resistor. Then the noise power in the sample is given by

$$\begin{aligned} P_N &= \underline{v}_N^2 / \underline{R}_S \\ &= \underline{v}_n^2 \underline{R}_S / 4 \underline{R}_L^2 \end{aligned}$$

The factor 1/4 is introduced because the wave analyzer has a four cycles per second pass band and it is desirable, for comparison purposes, to express the noise power in terms of power per cycle of band width. If it is assumed that the relation between the noise power per cycle and the frequency is of the form

$$P_N = B f^{-n}$$

where  $\underline{B}$  is a constant, then

$$n = (\log P_{N2} - \log P_{N1}) / (\log f_1 - \log f_2).$$

It can also be assumed that the relation between the noise power at any given frequency and the current through the sample is of the form



where  $V_1$  is the noise voltage across the resistor  $R_1$  in the noise voltage source. The noise voltage across the resistor  $R_1$  is the resistance of the sample, and  $V_2$  is the resistance of the first resistor. Then the noise power in the sample is given by

$$P = \frac{V_1^2}{R_1} = \frac{V_2^2}{R_2}$$

The factor  $kT$  is introduced because the noise power has a four cycles per second band and  $kT$  is the noise power, for comparison purposes, to express the noise power in terms of power, or cycles per second. It is assumed that the relation between the noise power and cycle and the frequency is of the form

$$P = kT \nu$$

where  $\nu$  is a constant, then

$$P = kT \nu = \frac{V_1^2}{R_1} = \frac{V_2^2}{R_2}$$

It can also be assumed that the relation between the noise power at any given frequency and the current through the sample is of the form



$$P_N(f) = C I^m$$

where C is a constant. Then m is given by

$$m = (\log P_{N2} - \log P_{N1}) / (\log I_2 - \log I_1).$$

These equations establish useful relationships between the measured values of current, noise voltage and frequency and the derived values of noise power per cycle.

To determine resistivities, current versus voltage measurements were made on a number of samples. From the measured resistance, the resistivity in ohm-cm was calculated, using the equation

$$\rho = (1.2)10^{-2}R$$

where R is in ohms and the constant was determined from the dimensions of the sample. The resistivity was measured on twelve samples ranging in heat-treat temperature from 600 to 900 °C. This was done using very small values of voltage and current to avoid any non-linear effects due to heating of the sample. Then sets of current versus voltage data were taken on the samples used in the noise voltage measurements, namely, the ones heat-treated to 650, 720, and 730 °C. These data included currents to 40 milliamperes and voltages to 250 volts.



$$f_p(\omega) = C \frac{1}{\omega^2}$$

where  $C$  is a constant. Then it is given by

$$n = (\log \frac{1}{f_p} - \log \frac{1}{f_{p0}}) / (\log \frac{1}{f_p} - \log \frac{1}{f_{p0}})$$

These equations established useful relationships between the measured values of current, voltage and frequency and the derived values of noise power per cycle. To facilitate resistivity, current versus voltage measurements were made on a number of samples. From the measured resistance, the resistivity in ohm-cm was calculated, using the equation

$$\rho = 0.314 \times R$$

where  $R$  is in ohms and the constant was determined from the dimensions of the sample. The resistivity was measured on twelve samples ranging in length from 0.5 to 1.0 cm. This was done using very small values of voltage and current to avoid any self-heating effects due to Joule heating of the sample. The measured current versus voltage data were then used in the noise voltage measurements. Current, the noise heat-treated at 500, 1000, and 1500 °C. These data are shown courtesy of Dr. J. H. Langer and Dr. J. H. Langer.



Assuming the variation of the resistivity to be of the form

$$\rho = A \exp(E_g/2kT)$$

where A is a constant, the electronic activation energy E<sub>g</sub> was calculated from the resistivity versus ambient temperature data. These values were calculated for samples heat-treated to temperatures in the 600 to 900 °C range.

Some cursory noise measurements were made using a point contact. The metal point consisted of a spring-loaded tungsten rod electrolytically etched in KOH solution to a sharp point. One connection was then made to the rod and the other to an areal contact on the sample. With about 10 ma of current flowing through the point, noise voltages were obtained at room temperature from several samples, including a piece of graphite which had been heat-treated to about 3000 °C.

On the basis of the experimentally determined data and the derived relationships involving them, it is possible to discuss some characteristics of current noise as determined in this investigation and compare them with characteristics reported in the literature. This is done in Part III.



Assuming the variation of the resistivity to be of the

form

$$\rho = \rho_0 (1 + \alpha \Delta T)$$

where  $\alpha$  is a constant, the resistance variation curve  $R$  was calculated from the resistivity versus distance temperature data. These values were calculated for temperatures heated-cooled to the vicinity of the 100 to 200 °C range.

Some curves were measured with the probe making a point contact. The point contact consisted of a tungsten loaded tungsten tip microscopically etched to form

a sharp point. One contact was made to the rod and the other to an axial contact on the sample. With about 10 mV of current flowing through the point, noise voltages were obtained at room temperature from several samples, indicating a high level of noise which had been heated-cooled to about 200 °C.

On the basis of the experimental data obtained and the derived temperature versus distance data, it was possible to discuss some characteristics of the point contact as determined in this investigation and compare them with characteristics reported in the literature. This is done in Part III.



### PART III

#### RESULTS AND DISCUSSION

Under the conditions described in the previous section, the current noise was measurable only in the cases where the heat-treatment temperature of the sample lay in the range from about 650 °C to around 730 °C; the resistance of samples treated to below 650 °C was much too high to allow passage of sufficient current. It is reasonably certain, however, that current noise would be found in samples outside of the 650 to 730 °C range under improved experimental conditions; a current dependent noise was observed by another investigator,<sup>18</sup> in an earlier unreported investigation, in a very thin specimen of pyrolyzed cellulose heat-treated to about 300 °C. The observed noise voltage values are given in Table I.

The variation of noise power with frequency for several samples is shown in Figures 4, 5, and 6. It is evident that the noise power is of the same type as was observed earlier for other materials,<sup>1,9</sup> i.e., the power spectrum varies with frequency as  $1/f^n$ , with the important



RESULTS AND DISCUSSION

Under the conditions described in the previous section, the current noise was measured in only 10 cases where the first-hand temperature of the sample lay in the range from about 300°U to 350°U. The resistance of samples treated as being 300°U was much too high to allow passage of sufficient current. It is reasonably certain, however, that current noise would be found in samples outside of the 300°U to 350°U range under improved experimental conditions. A current dependent noise not observed by other investigators in an earlier reported investigation, is a very faint specimen of irregular colored spots treated in about 300°U. The observed noise pattern within the given range is

Table 1.

The variation of noise power with frequency for several samples is shown in Figure 1, 2, and 3. It is evident that the noise power is of the same order of magnitude for all of the samples. The noise power observed earlier for other materials is of the same order of magnitude. The noise power is of the same order of magnitude for all of the samples.



difference, however, that the value of  $\underline{n}$  is not a constant (see Table II). For the sample heat-treated to 650 °C,  $\underline{n}$  is 1.4 at room temperature and increases to 4.8 at 80 °K. However, for the samples heat-treated to 720 and 730 °C, its value is larger at the ambient temperature of 190 °K than at 80 °K. These show that at least in this case,  $\underline{n}$  is a function of the ambient temperature. It seems noteworthy that the greatest similarity between the noise spectra of these samples and that of germanium occurs when the ambient temperature is around 300 °K. In this temperature region the values of  $\underline{n}$  have their best agreement.

The noise power (at a fixed frequency) dependence on current is shown in Figure 7. The dependence may be expressed in the form of  $\underline{I}^{\underline{m}}$ . From the slopes of the curves, values of  $\underline{m}$  were calculated and are presented in Table III. The values of  $\underline{m}$  here are, in general, larger than those reported for germanium at room temperature, going from 2.8 at 300 °K to several times that value at 80 °K. In Figure 7, it is apparent that as the current increases,  $\underline{m}$  becomes smaller. It is probable that this is a result of sample heating, since the boiling of the ambient liquid became evident at this stage; thus, the average temperature of the surface of the sample may have been considerably higher than that of the ambient liquid.



difference, however, and the value of  $\alpha$  is not a  
 constant (see Table II). For the range 5-10°C. the  
 to 650°C.  $\alpha$  is 1.4 at room temperature and increases  
 to 2.8 at 65°C. However, for the range heat-treat of  
 to 720 and 730°C. the value is larger at the highest  
 temperature of 730°C than at 720°C. These data show that  
 at least in this case,  $\alpha$  is a function of the absolute  
 temperature. It seems reasonable that the greatest  
 similarity between the noise spectrum of these samples  
 and that of germanium occurs when the absolute tempera-  
 ture is around 300°K. In this temperature region the  
 values of  $\alpha$  have their best agreement.

The noise power (at a fixed frequency) is known  
 on current is shown in Figure 7. The dependence may  
 be expressed in the form of  $I^{1/2}$ . With the slope of the  
 curves, values of  $\alpha$  were calculated and are presented in  
 Table III. The values of  $\alpha$  here are, in general, larger  
 than those reported for germanium at room temperature,  
 going from 2.8 at 300°C to several times that value at  
 65°C. In Figure 7, it is apparent that as the current  
 increases,  $\alpha$  becomes smaller. It is probable that this  
 is a result of sample heating, since the holding of the  
 constant light source evident at the same time, the  
 average temperature of the surface of the sample has  
 been considerably higher than that of the ambient liquid.



The resistivities of the samples are plotted in Figure 8 as functions of the heat-treatment temperature, and the tabulated data is given in Table IV. The curves show a large drop between 600 to 700 °C. This has been explained<sup>16</sup> as due to the creation of excess carriers (holes) during devolatilization of the sample, and decreasing electronic activation energy with increasing crystallite size. The reason for the break at around 720 °C is not evident in the light of the energy band picture, however. Energy gap values calculated from resistivity versus ambient temperature data are presented in Table V. They are in agreement with those reported in the literature<sup>16</sup> and as indicated in Figure 2. It should be remarked, however, that they should not be taken too exactly because of the unaccounted-for effect of the increasing number of excess holes produced as the heat-treatment temperature increases.<sup>19</sup>

As Figures 9, 10, and 11 show, the relationship between current and voltage becomes non-ohmic as the current increases. The non-linearity is especially interesting in the cases where the voltage drop across the sample becomes independent of the current; the sample then acts as a voltage-regulating element. The non-linearity definitely seems to be the result of the sample becoming heated due to power dissipation and the large



The resistivity of the material is  
Figure 8 as function of the heat-treatment temperature  
and the annealed state is given in Table IV. The curves  
show a large drop between 300 and 400 °C. This has been  
explained<sup>18</sup> as due to the disappearance of oxygen centers  
(holes) during deoxygenation of the material and  
decreasing electronic activation energy with increasing  
crystallite size. The temperature for the onset of the  
TNO<sup>+</sup> is not evident in the light of the energy band  
picture, however. Energy gap values calculated from  
resistivity versus temperature for annealed state and  
in Table V. They are in agreement with those reported  
in the literature<sup>19</sup> and as indicated in Figure 9.  
It should be remarked, however, that they should not be taken  
too exactly because of the uncertainty in the value of the  
inducting number of oxygen holes formed in the material.  
The temperature dependence of the resistivity  
As Figures 8, 10, and 11 show, the resistivity  
between current and voltage becomes non-linear at low  
current intensities. The non-linearity is especially  
interesting in the case where the voltage is constant  
the sample becomes the source of the current. The sample  
then acts as a voltage-regulating element. The non-  
linearity definitely seems to be due to the sample  
becoming unable to govern the current and the voltage



negative coefficient of resistance of the sample. Measurements across the sample side arms showed that contact resistance was negligible and that the non-linearity was not a contact phenomenon, but was a bulk property. Furthermore, current-voltage non-linearities of the type associated with metal--semiconductor contacts exhibits the departure from Ohm's Law most strongly at low values of current and voltage and tend to become more linear at higher values.

It is interesting and suggestive that the onset of measurable current noise coincides approximately with the departure from Ohm's Law as the current is increased, and that in the cases where the samples showed no appreciable departure from linearity, no current noise was observed.

The coincidence between the occurrence of current noise and the non-ohmic behavior which is connected with sample heating suggested a direct comparison between noise power and power dissipation. The results of such a comparison are presented in Figure 12. They show that the noise power increases rapidly with power dissipation, but not in an easily interpreted manner. It would be very informative, if the noise power spectrum were known, to plot the integrated noise power for the entire spectrum against the power dissipated in the sample.



negative correlation of the noise  
noise power and the signal power  
contact resistance to the noise  
linearity was not a constant parameter, but as a  
property. Furthermore, the noise power  
of the type associated with noise power  
noise exhibits the behavior from which the noise power  
at low values of current and voltage was found to decrease  
more linearly at higher values.

It is interesting and suggestive that the noise of  
generable current noise (noise power) with  
the departure from linearity as the current is increased,  
and that in the cases where the noise is shaped to a  
noise departure from linearity, no current noise was  
observed.

The correlation between the departure of current  
noise and the non-linear behavior which is connected with  
noise heating suggests a direct relationship between noise  
power and power dissipation. The relationship of noise  
generation and dissipation is shown in Fig. 1. The noise  
the noise power increases rapidly with power dissipation,  
but not in an easily identifiable manner. It would be  
interesting, if the noise power were shown to  
plus the intensity of noise power for the noise power  
against the power dissipation in the sample.



## PART IV

### CONCLUSION

The current noise properties of condensed aromatic solids (formed from phenol formaldehyde resin) ranging from raw cokes to graphites were studied, and, within the current, voltage, and sensitivity limitations of the experimental equipment, current noise was found only in samples in the heat-treatment range up to about 900 °C, i.e., only in raw cokes and those undergoing transition to carbon. However, a cursory study using point contacts was made on material which had received heat-treatment above this range, including a well graphitized sample heat-treated to about 3000 °C., and a frequency-dependent current noise was observed.

The conditions under which the current noise was studied in this work were probably more extensive than those under which current noise in germanium was studied. First, the current noise power spectrum was found to be representable by  $1/f^n$ , with  $n$  having values in most cases outside the range reported for germanium;<sup>9</sup> however, at room temperature, the correspondence is quite good. For ambient temperatures lower than 300 °K, the value of  $n$







is larger, ranging in value from around two to about four. Secondly, the noise power per cycle depends very strongly on the ambient temperature, increasing as the ambient temperature decreases, with samples of lower heat-treatment showing a stronger dependence. This result is quite different from published data on germanium semiconductors, e.g., Montgomery<sup>9</sup> reported only a weak dependence, but in his study he used germanium which contained many excess carriers; the resistivity of such material changes rather slightly with temperature in comparison to the raw cokes. Raw coke, on the other hand, is essentially an intrinsic semiconductor with an energy gap of the order of 0.1 electron volts. Therefore, if the current noise were due to a fluctuation in the carrier concentration, the effect of a change in concentration occurring at a low ambient temperature would be greater in an intrinsic semiconductor such as the raw coke than in an extrinsic semiconductor such as germanium. Thirdly, the noise power per cycle can be represented by  $I^m$ , with  $m$  taking values from two to several times that value, and in general increasing when the ambient temperature is lowered. As was the case for the power spectrum, the current dependence is about the same as for germanium at 300 °K.



is larger, ranging in value from about 10 to 20  
four. Secondly, the noise power per cycle depends very  
strongly on the ambient temperature, increasing as the  
ambient temperature decreases, with a maximum of about  
best-constant showing a stronger dependence. This  
result is quite different from the results of the  
noise measurements, e.g., the noise power is reported  
only a weak dependence, but in the study of the noise  
which contained many peaks, the noise power is  
such material changes rather slightly with temperature  
compared to the low noise. The noise, on the other hand,  
is essentially an intrinsic phenomenon with an  
gap of the order of 0.1 electron volt. Therefore, all  
the current noise were due to a fluctuation in the carrier  
concentration, the effect of a change in concentration  
occurring at a low ambient temperature would be greater in  
an intrinsic semiconductor than in the low noise case in  
an extrinsic semiconductor, such as germanium. Finally, the  
noise power per cycle can be represented by  $I_n$ , with a  
value of about 10 to 20 in germanium, and in  
general increasing with the ambient temperature as shown.  
As was the case for the noise power, the current noise  
once is about the same as for germanium at 300 °K.



This study shows that current noise occurs when there is a deviation from Ohm's Law, i.e., when the applied voltage and resultant current are no longer proportional. Since most, and perhaps all, cases of occurrence of frequency and current dependent noise are associated with non-linear devices, e.g., semiconductors, diodes, vacuum tubes, insulators near breakdown, it seems reasonable to seek a mechanism involving non-linearity as an important feature. Even though it may not be justifiable to seek a single mechanism to explain all of the occurrences of current noise,<sup>20</sup> nevertheless, the fact that in the cases studied and discussed herein the non-linearity is not a barrier layer phenomenon<sup>21</sup> (as in semiconductor devices), nor a space-charge effect (as in vacuum tube devices), but simply a result of heating the sample does seem to point to some single underlying cause.



This study shows that current noise occurs when

there is a deviation from Ohm's law, i.e., when the

applied voltage and resultant current are no longer

proportional. This point, and others still, must be

occurrence of frequency and current dependent noise and

associated with non-linear elements, e.g., semiconductor

diodes, vacuum tubes, and various other electronic devices

responsible for such a mechanism involving non-linearity

as an important feature. Even though it may not be

justifiable to seek a single mechanism to explain all

of the occurrence of current noise, nevertheless, the

fact that in the cases studied and discussed herein the

non-linearity is not a primary factor is significant.

In semiconductor devices, for a noise-current effect

(as in vacuum tube devices), one usually finds a

heating the sample does tend to point to some single

underlying cause.



TABLE I

## TOTAL NOISE VOLTAGE RELATIVE TO FREQUENCY

$T_{HT}$ (°C)	$T_A$ (°K)	I (ma)	Frequency (Cycles per second)					
			40	80	160	320	640	1280
*		40	0.08	0.06	0.05	0.05	0.05	0.05
650	300	20	0.16	0.15	**	---	---	---
		40	0.50	0.35	0.20	0.10	---	---
	190	5	0.30	---	---	---	---	---
		10	6.0	2.0	0.50	0.12	---	---
		20	120	34	13	3.5	1.4	0.50
		25	190	58	28	8.0	2.8	0.80
	80	0.3	1.6	0.50	0.20	---	---	---
720	300	40	---	---	---	---	---	---
	190	20	1.1	.30	---	---	---	---
		40	90	20	4.0	1.0	0.35	---
	80	2.5	13	6.0	1.9	---	---	---
		5	26	11	4.0	1.3	---	---
		10	110	52	24	8.0	1.8	0.70
		20	210	100	38	15	4.0	1.2
		28	250	110	45	18	5.0	2.4
730	300	40	---	---	---	---	---	---
	190	40	3.2	0.60	---	---	---	---
	80	2.5	2.7	---	---	---	---	---
		5	14	4.0	1.4	---	---	---
		10	85	31	9.0	4.0	0.8	---
		20	210	60	20	7.0	2.2	0.80
		36	380	110	42	15	9.0	3.0

\* Values under "Frequency" in this line are for  $v_o$ .

\*\* A dash indicates  $v_t$  was not above background.

NOTE:  $T_{HT}$  is the heat-treat temperature.

$T_A$  is the ambient temperature.

I is the current through the sample.







TABLE II

VALUES OF THE FREQUENCY EXPONENT  $\underline{n}$ 

$T_{HT}$ (°C)	$T_A$ (°K)		
	300	190	80
650	1.4	3.4	4.8
720	---	4.2	3.0
730	---	4.8	3.5

NOTE:  $T_{HT}$  is the heat-treat temperature. $T_A$  is the ambient temperature.



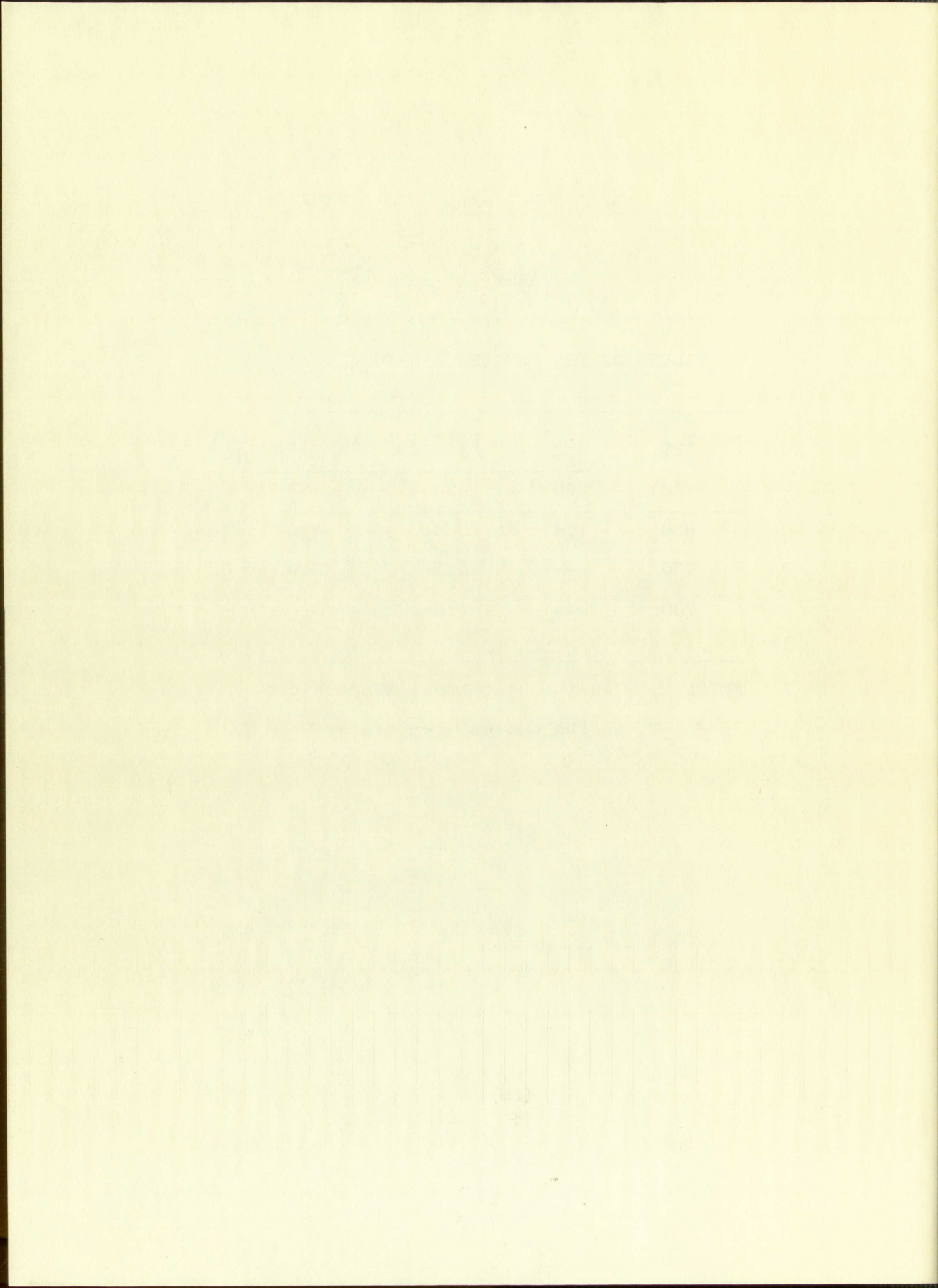




TABLE III

VALUES OF THE CURRENT EXPONENT  $\underline{m}$ 

$T_{HT}$ (°C)	$T_A$ (°K)		
	300	190	80
650	2.8	4.7	---
720	---	9.5	1.6
730	---	---	4.9

NOTE:  $T_{HT}$  is the heat treat temperature. $T_A$  is the ambient temperature.



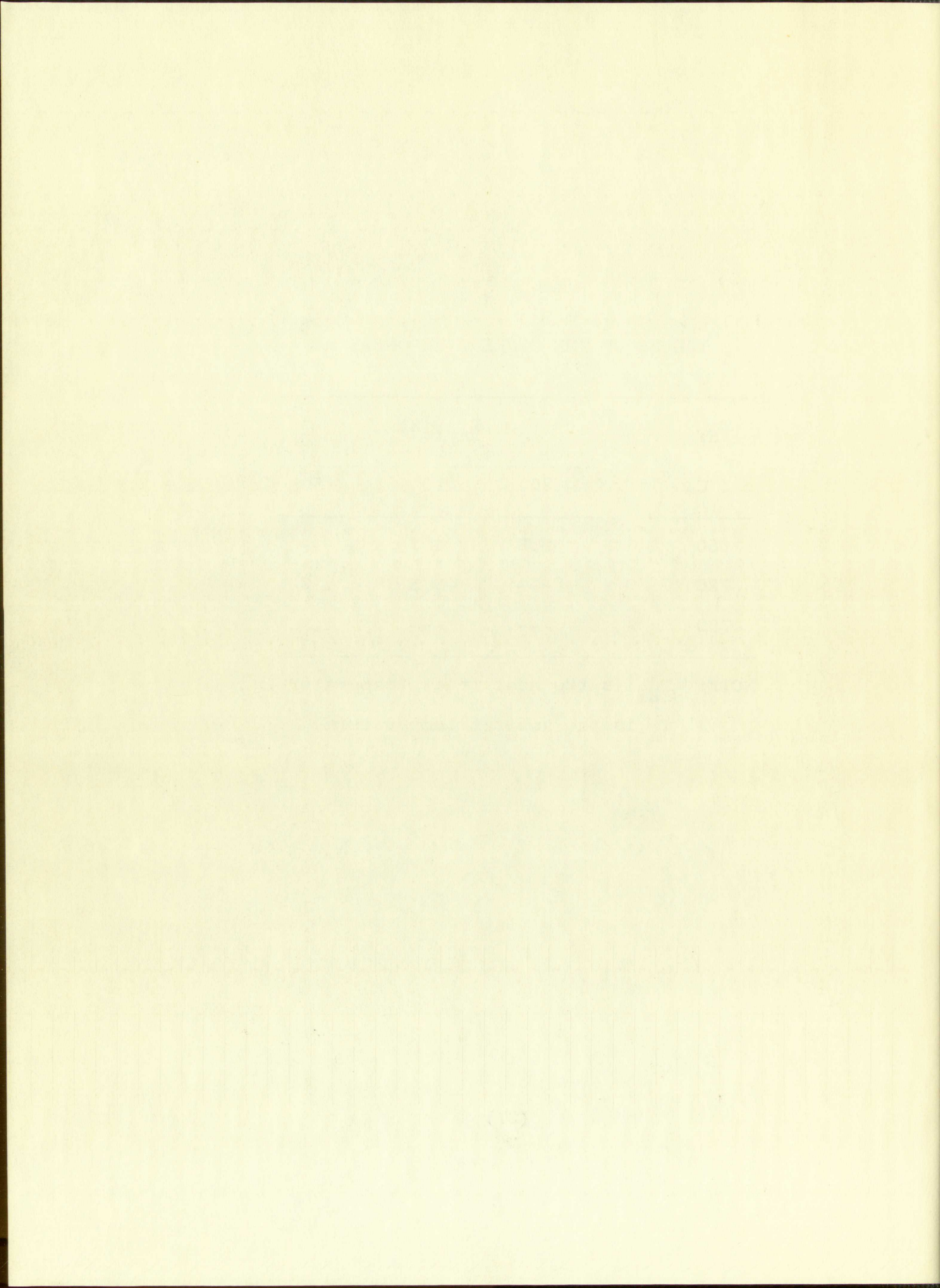




TABLE IV  
RESISTIVITY RELATIVE TO AMBIENT TEMPERATURE  
AND HEAT-TREAT TEMPERATURE

$T_{HT}$ (°C)	$T_A$ (°K)			
	300	190	80	3.9
620	9,600	---	---	---
635	69.6	492	75,600	---
650	43.2	264	24,000	---
680	15.0	66.0	3,720	---
720	4.56	15.6	456	---
730	1.50	4.32	72.0	---
735	1.06	3.00	22.2	---
750	0.192	0.408	2.64	---
820	0.0684	0.111	0.396	31,200
900	0.0144	0.0204	0.0288	0.134

NOTE:  $T_{HT}$  is the heat-treat temperature.

$T_A$  is the ambient temperature.







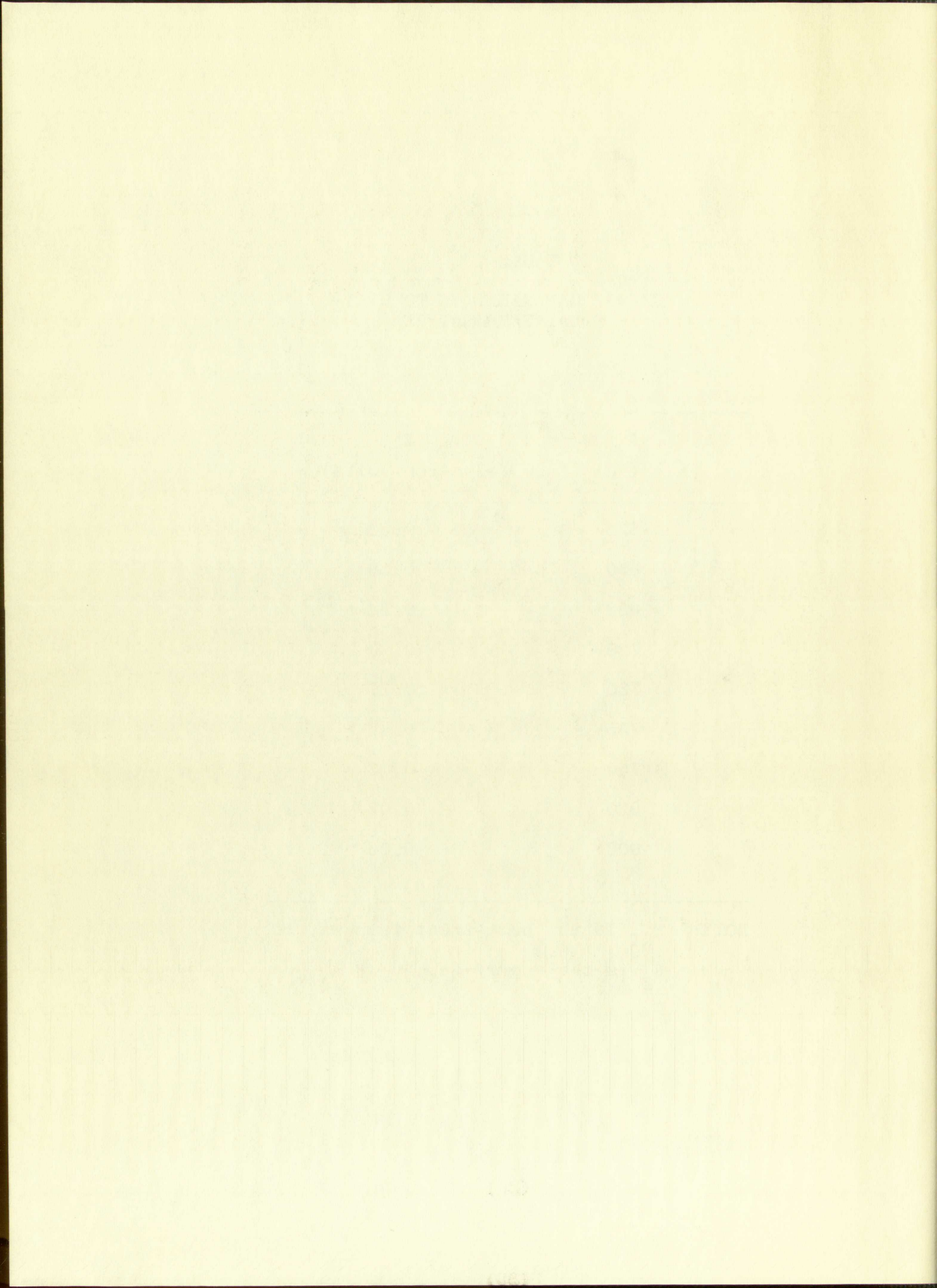
TABLE V  
ENERGY GAP RELATIVE TO HEAT-  
TREAT TEMPERATURE

$T_{HT}$ (°C)	$E_g$ (electron-volts)
635	0.32
650	0.30
680	0.24
720	0.20
730	0.17
735	0.16
750	0.12
820	0.08
900	0.06

NOTE:  $T_{HT}$  is the heat-treat temperature.

$E_g$  is the energy gap.







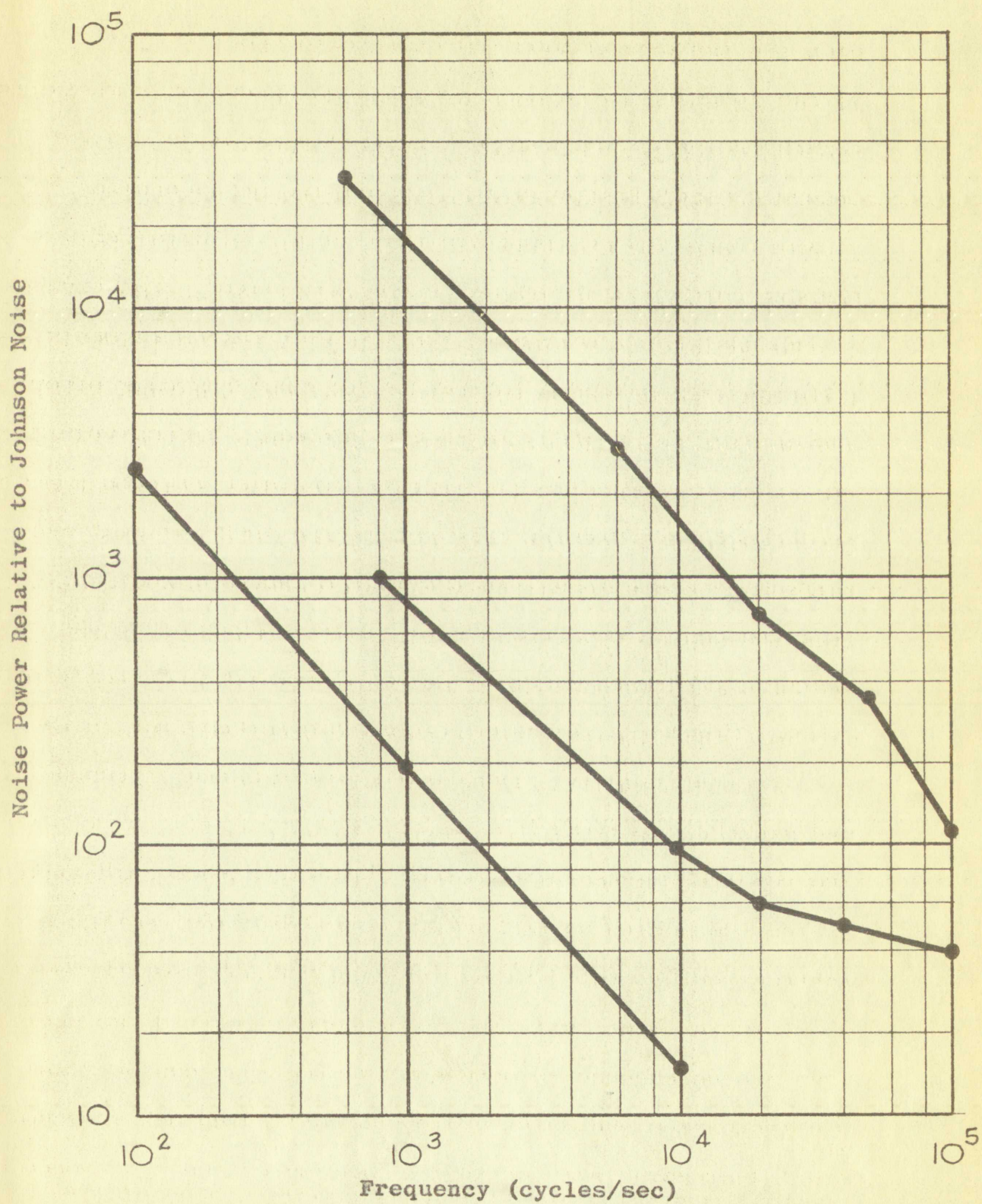


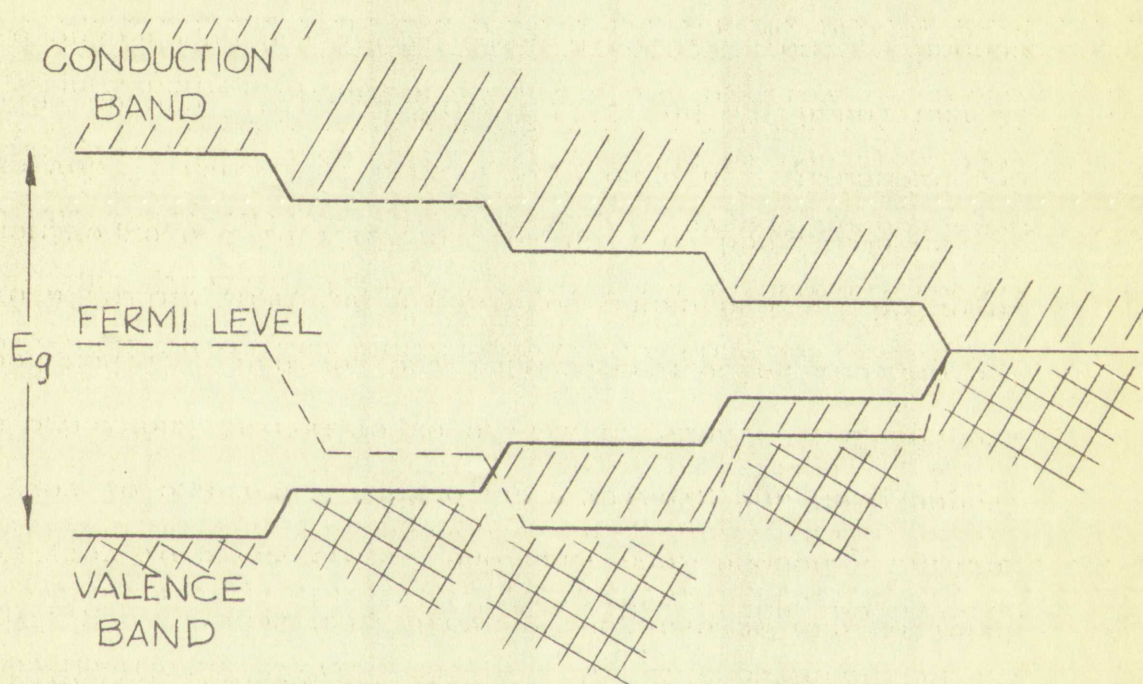
Fig. 1 Typical spectra of noise in germanium single crystal filaments carrying dc current. (After Montgomery.<sup>9</sup>)







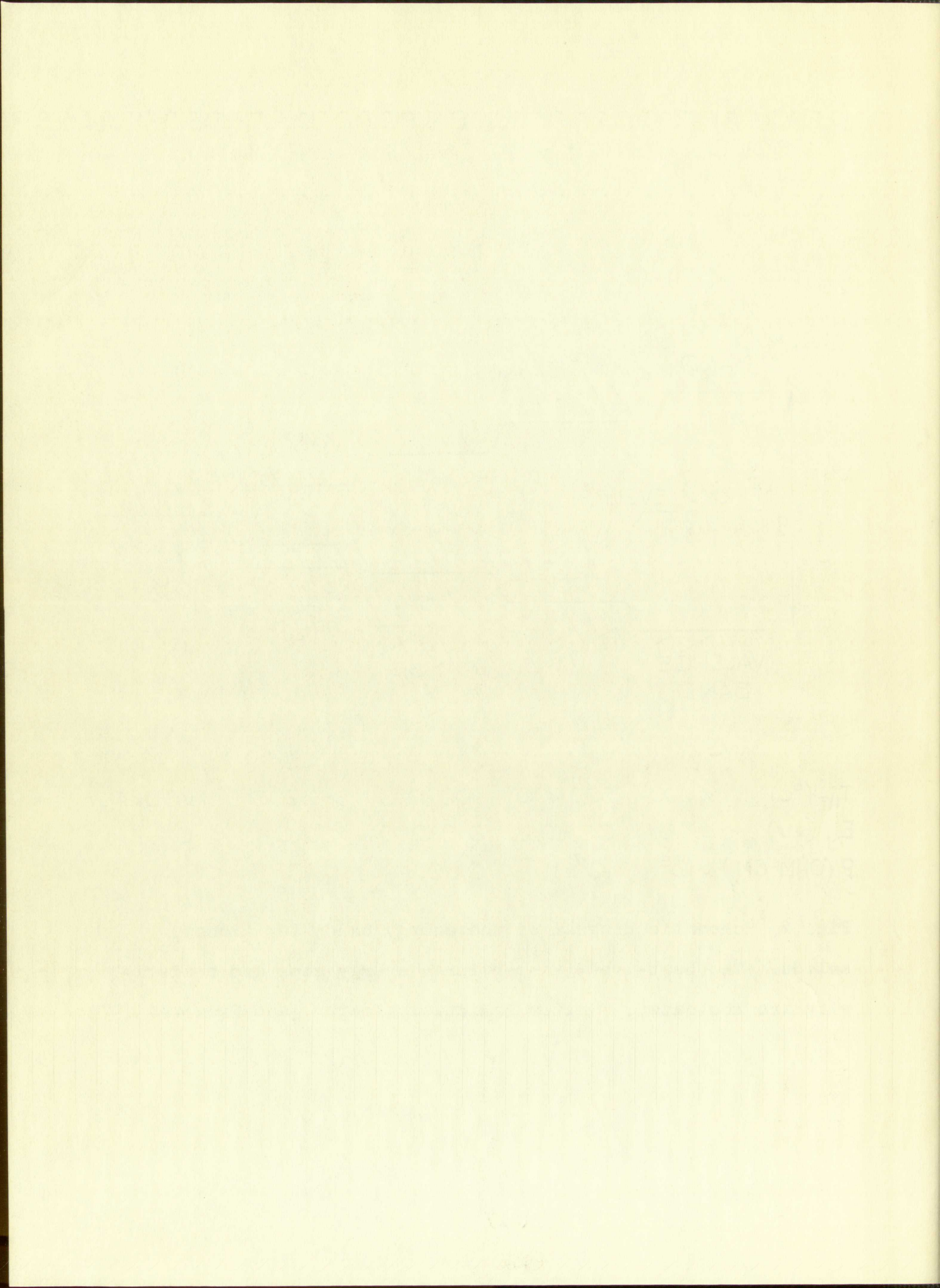
(a) MOLECULAR SOLID (b) RAW COKE (c) BAKED CARBON (d) POLYCRYSTAL- LINE GRAPHITE (e) NATURAL GRAPHITE



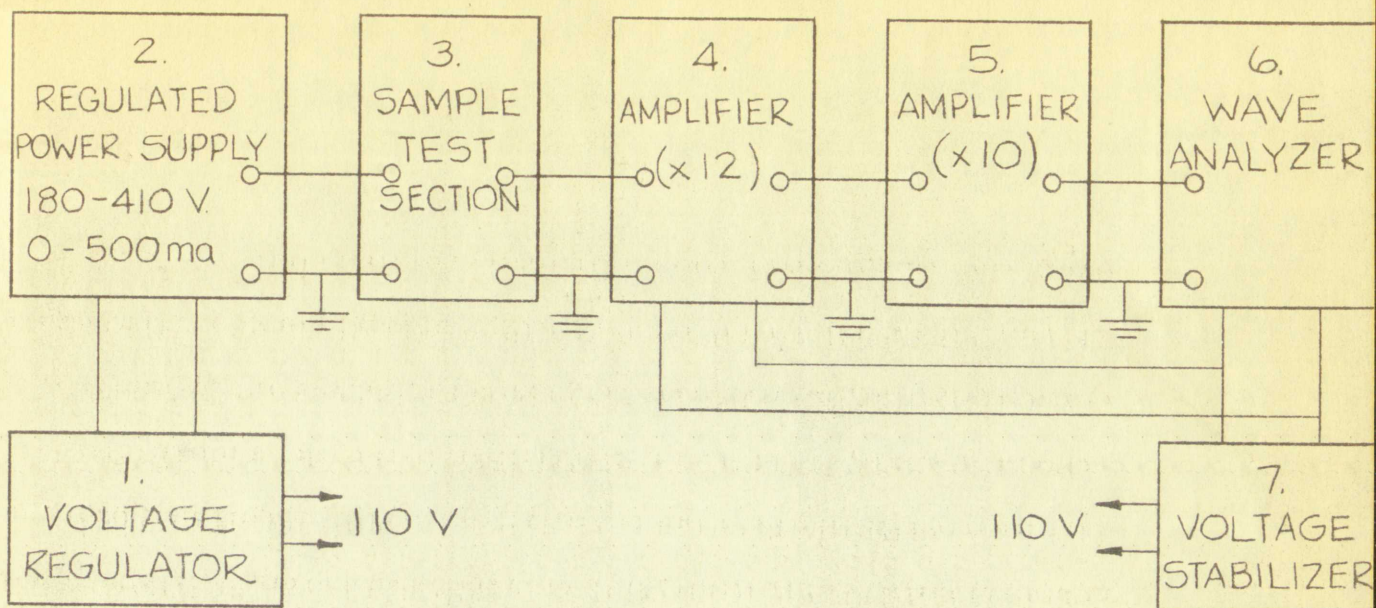
$T_{HT} (^{\circ}C)$	<600	500-700	900-1700	> 2200	NATURAL
$E_g$ (ev)	>0.3	0.5 - 0.2	0.15 - 0.03	< 0.01	$\leq 0$
$P$ (OHM-CM)	$>10^5$	$10^7-1$	0.005	$\leq 10^{-3}$	$\leq 5 \times 10^{-5}$

Fig. 2 Schematic diagram of the energy bands for aromatic solids. The heat-treat temperature, energy gap, and resistivity are indicated. (After McMichael, Kmetko, and Mrozowski.<sup>22</sup>)









UNIT 1. STABILINE TYPE 1E5101  
 UNIT 2. NATIONAL RADIO SERVICE CO.  
 UNIT 4. SOUTHWEST INDUSTRIAL ELECTRONICS MODEL R1.  
 UNIT 5. BALLENTINE MODEL 220  
 UNIT 6. GENERAL RADIO MODEL 736-A  
 UNIT 7. RAYTHEON MODEL VR6115

Fig. 3a Block diagram of the electronic equipment.

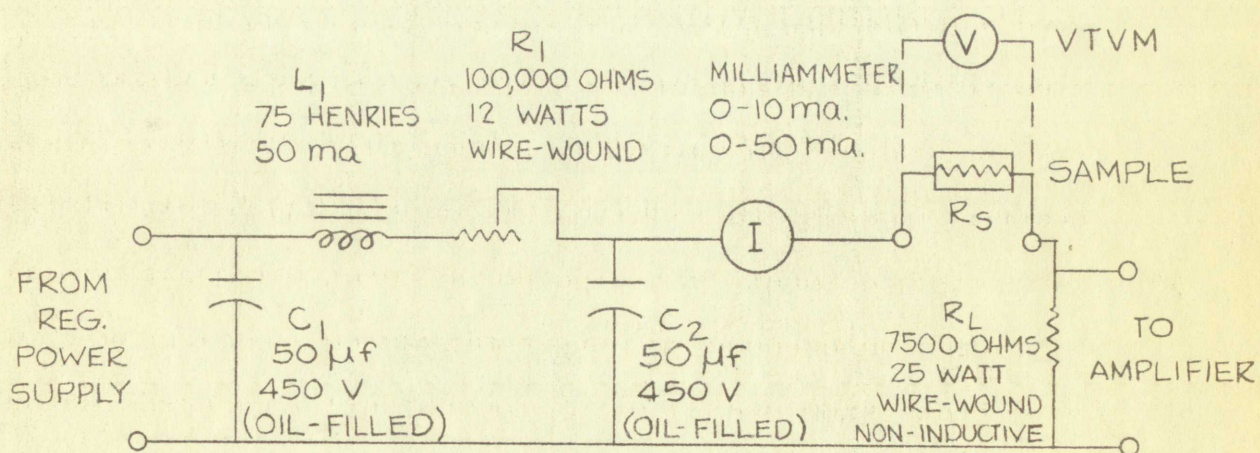


Fig. 3b Schematic diagram of the sample test section.







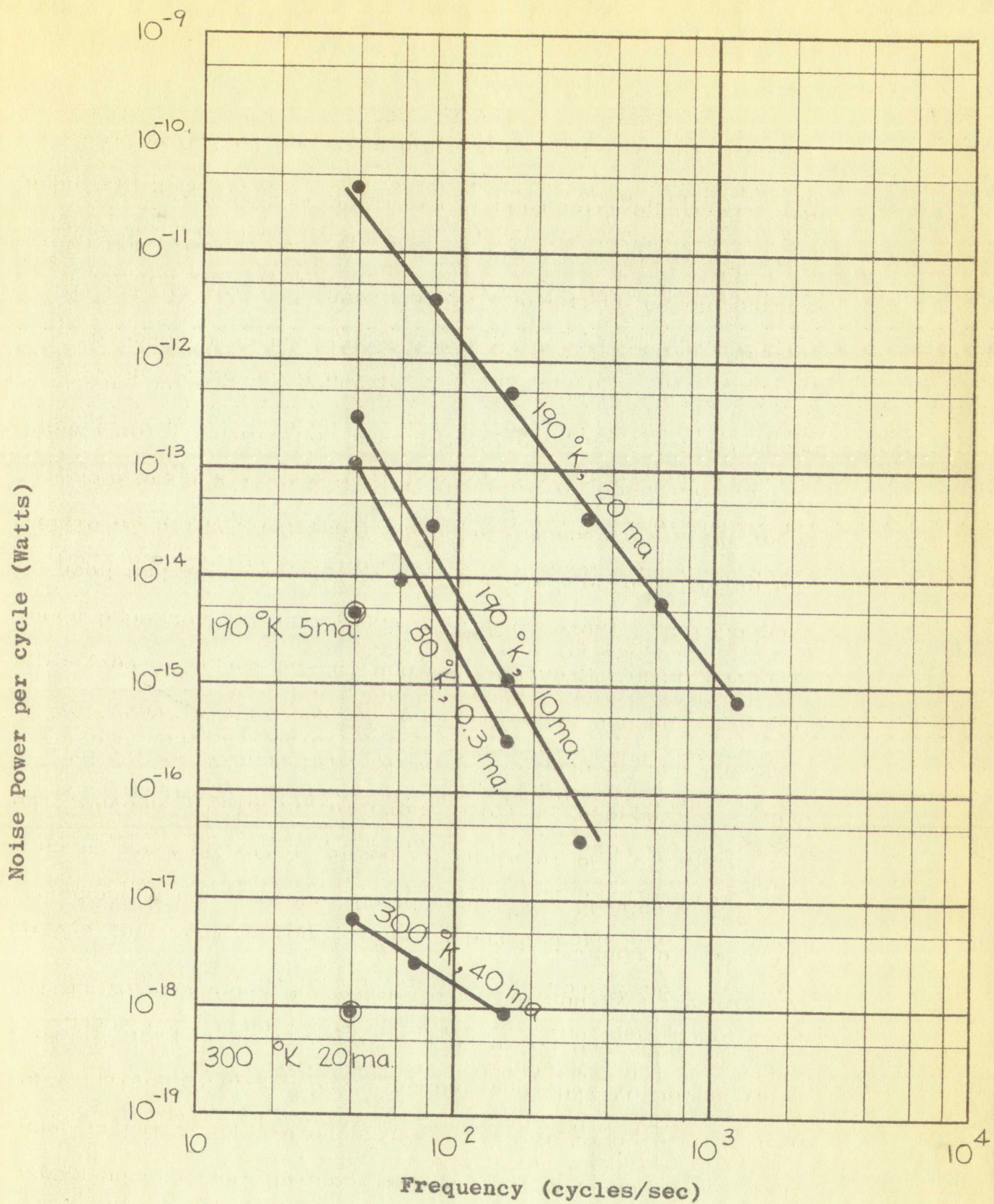
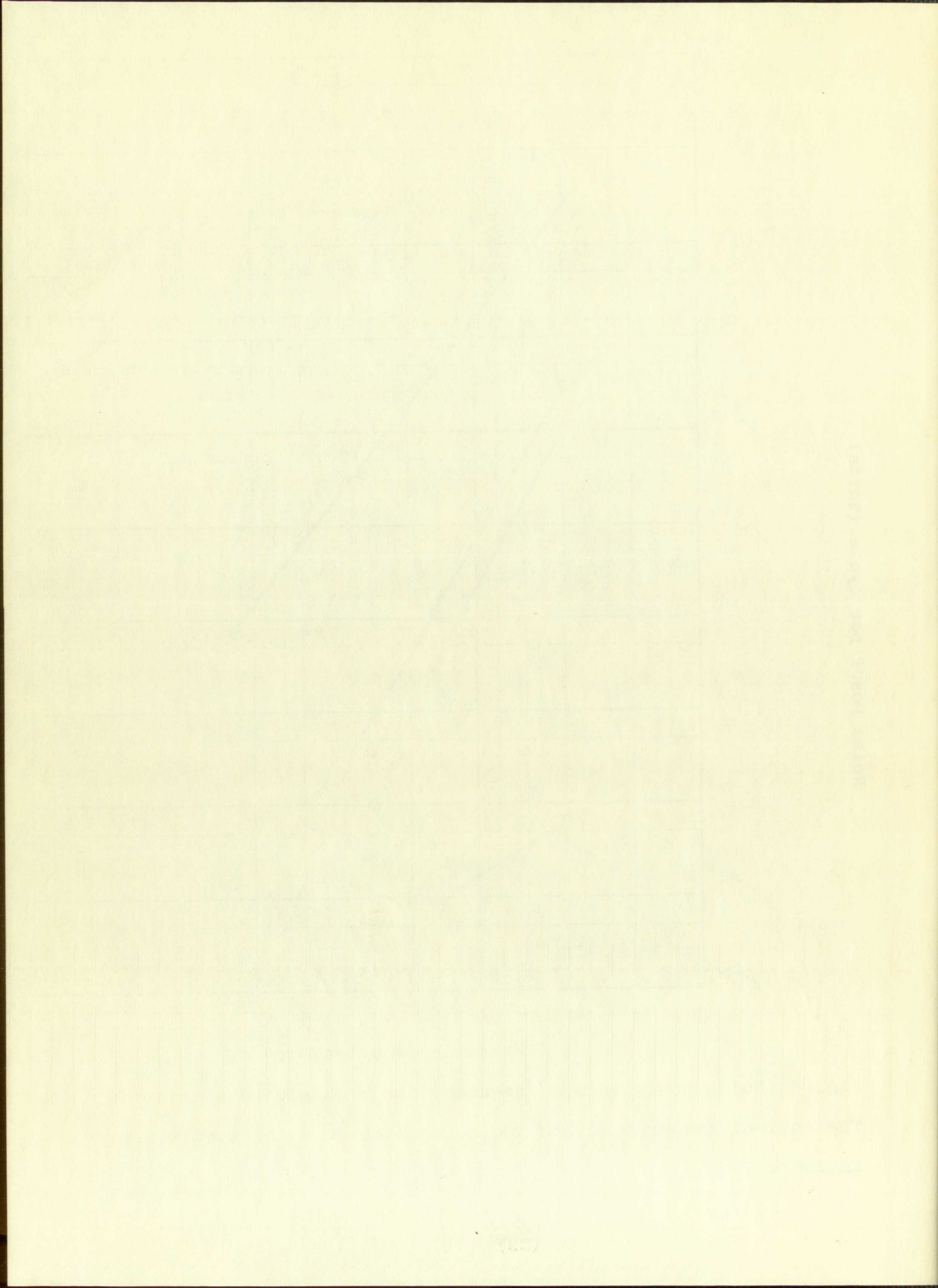


Fig. 4 Noise power versus frequency for a sample heat-treated to 650 °C. The ambient temperature and the current through the sample are indicated.







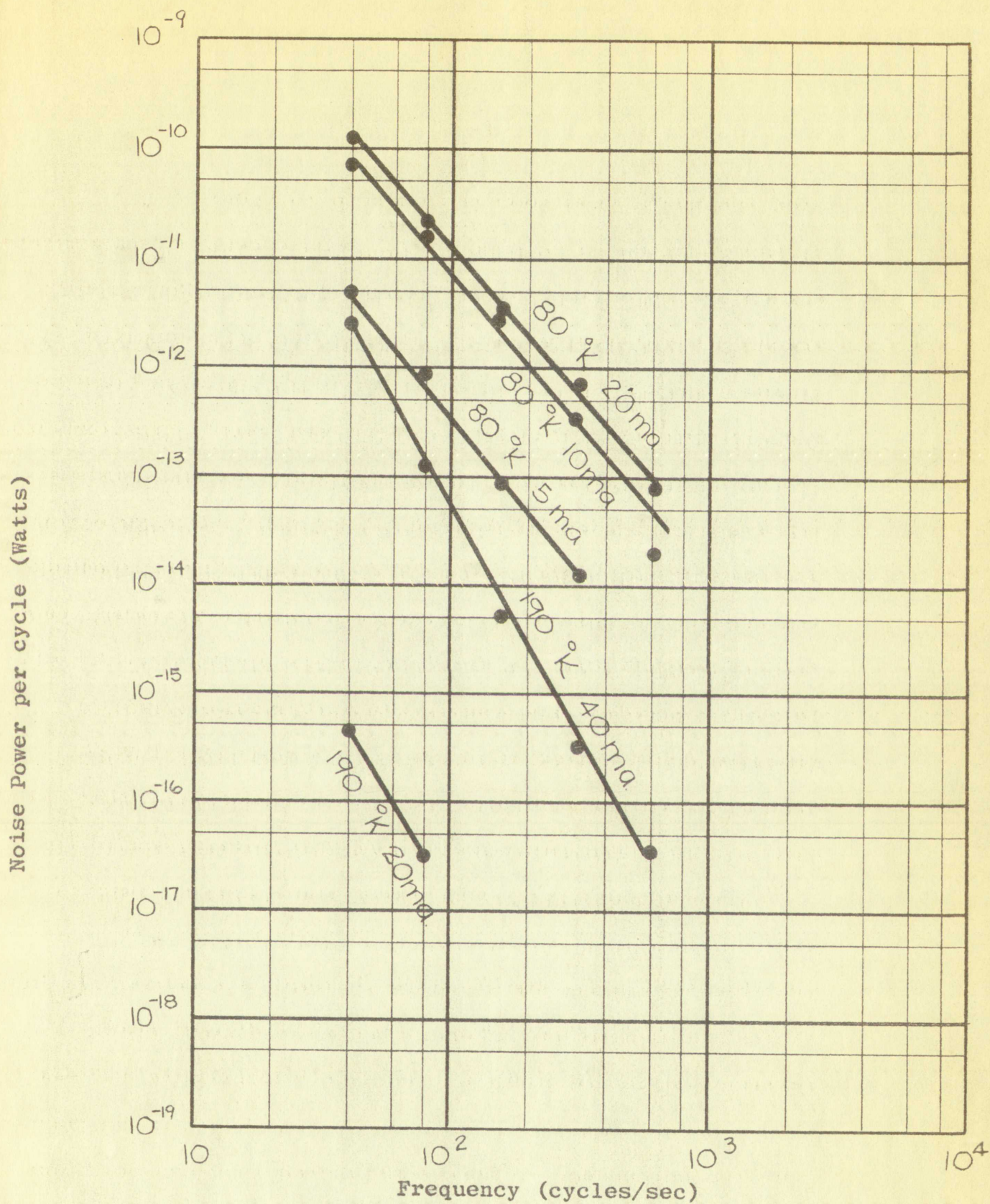


Fig. 5 Noise power versus frequency for a sample heat-treated to 720 °C. The ambient temperature and the current through the sample are indicated.







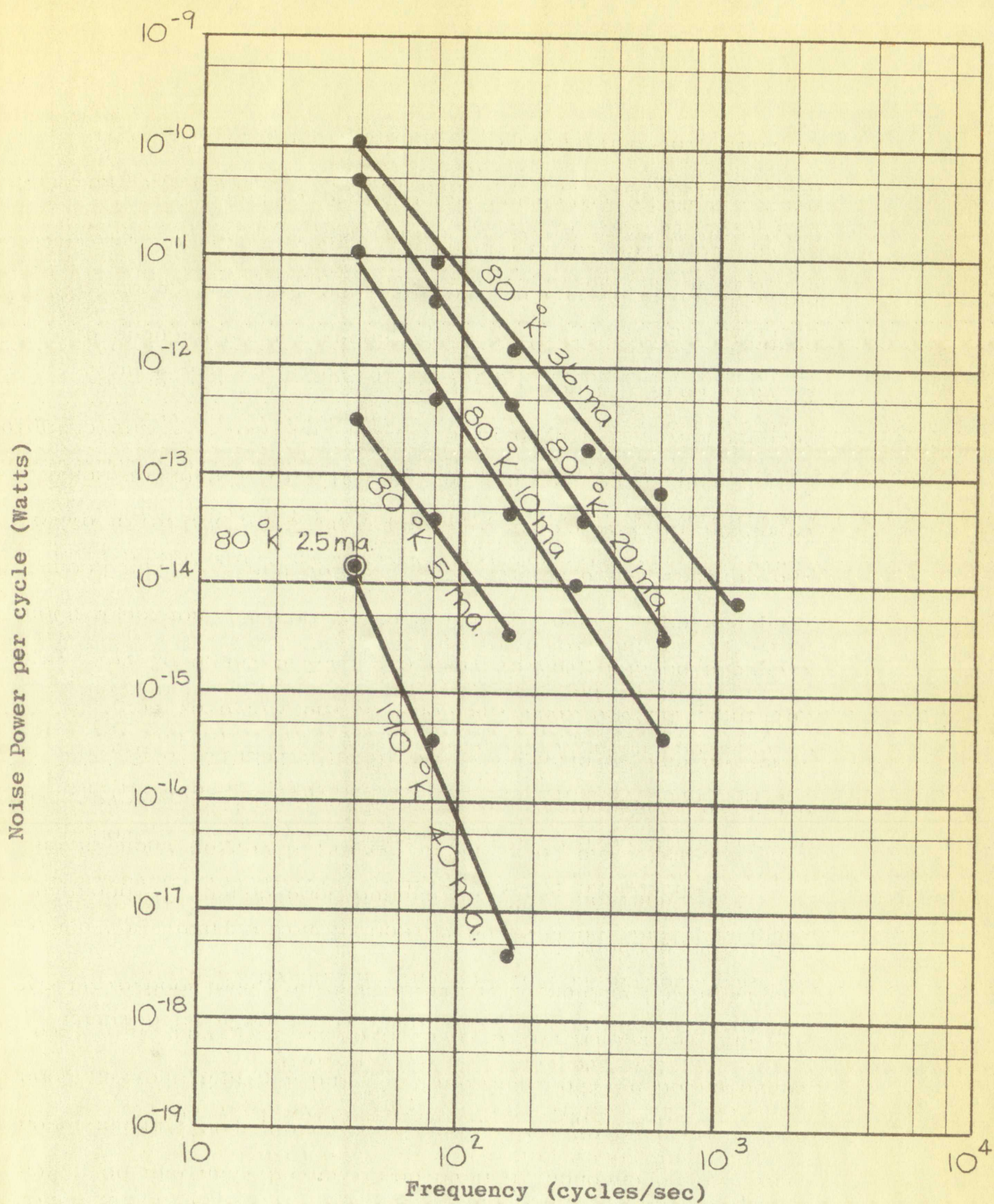


Fig. 6 Noise power versus frequency for a sample heat-treated to 730 °C. The ambient temperature and the current through the sample are indicated.







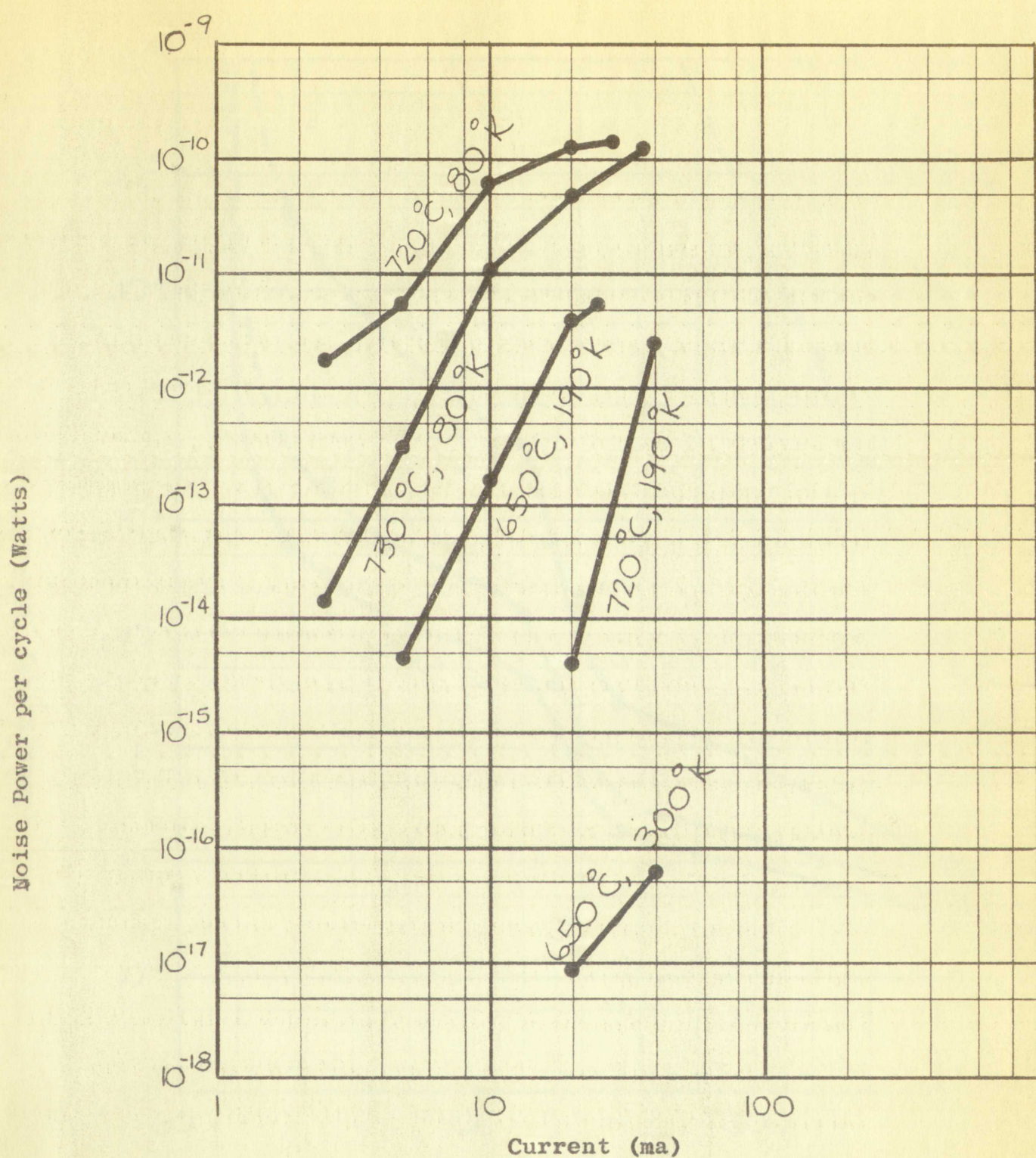


Fig. 7 Noise power at 40 cycles per second versus current through the sample. The heat-treat temperature in °C and the ambient temperature in °K are indicated.







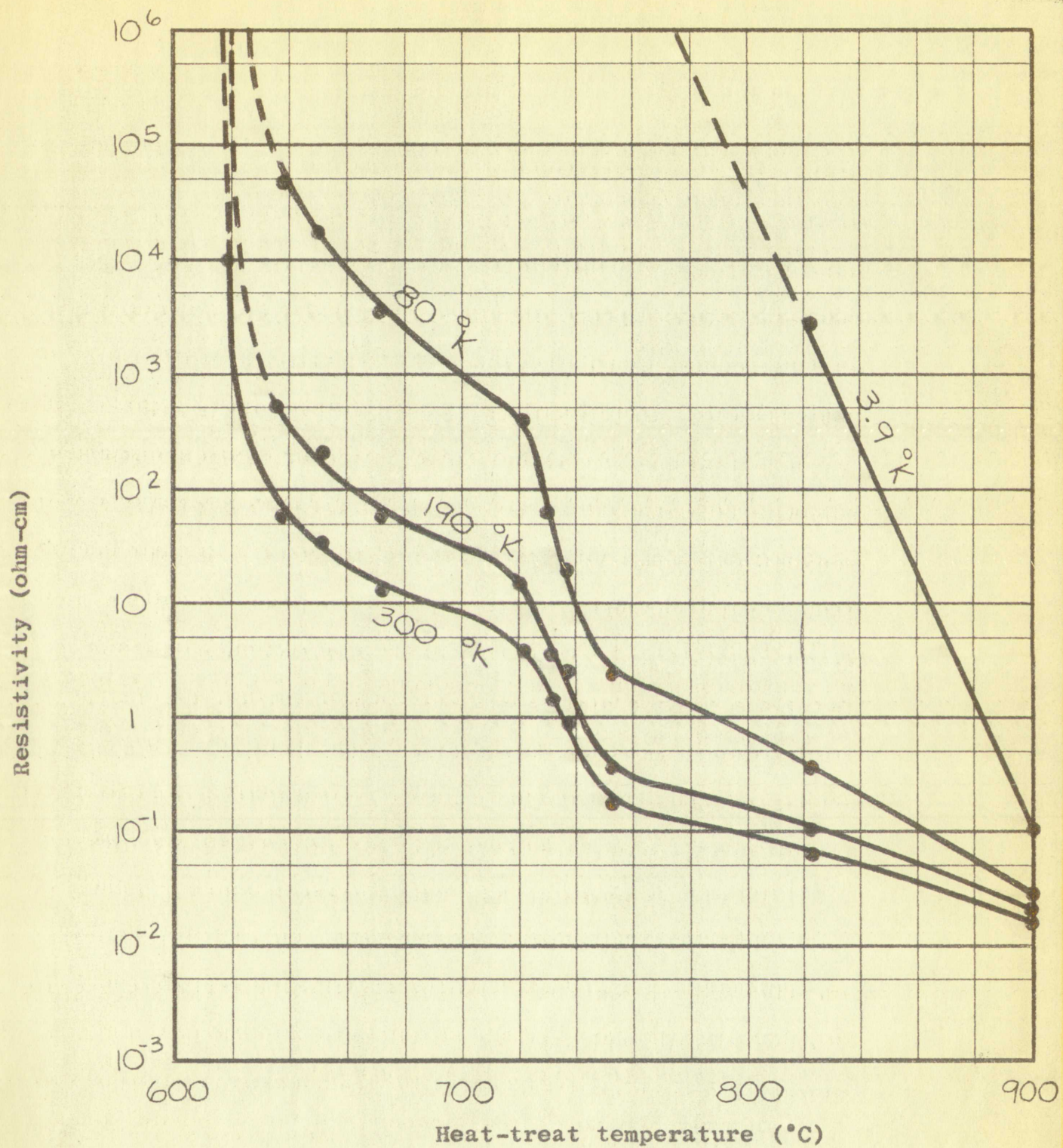


Fig. 8 Resistivity versus heat-treat temperature. The ambient temperature is indicated.







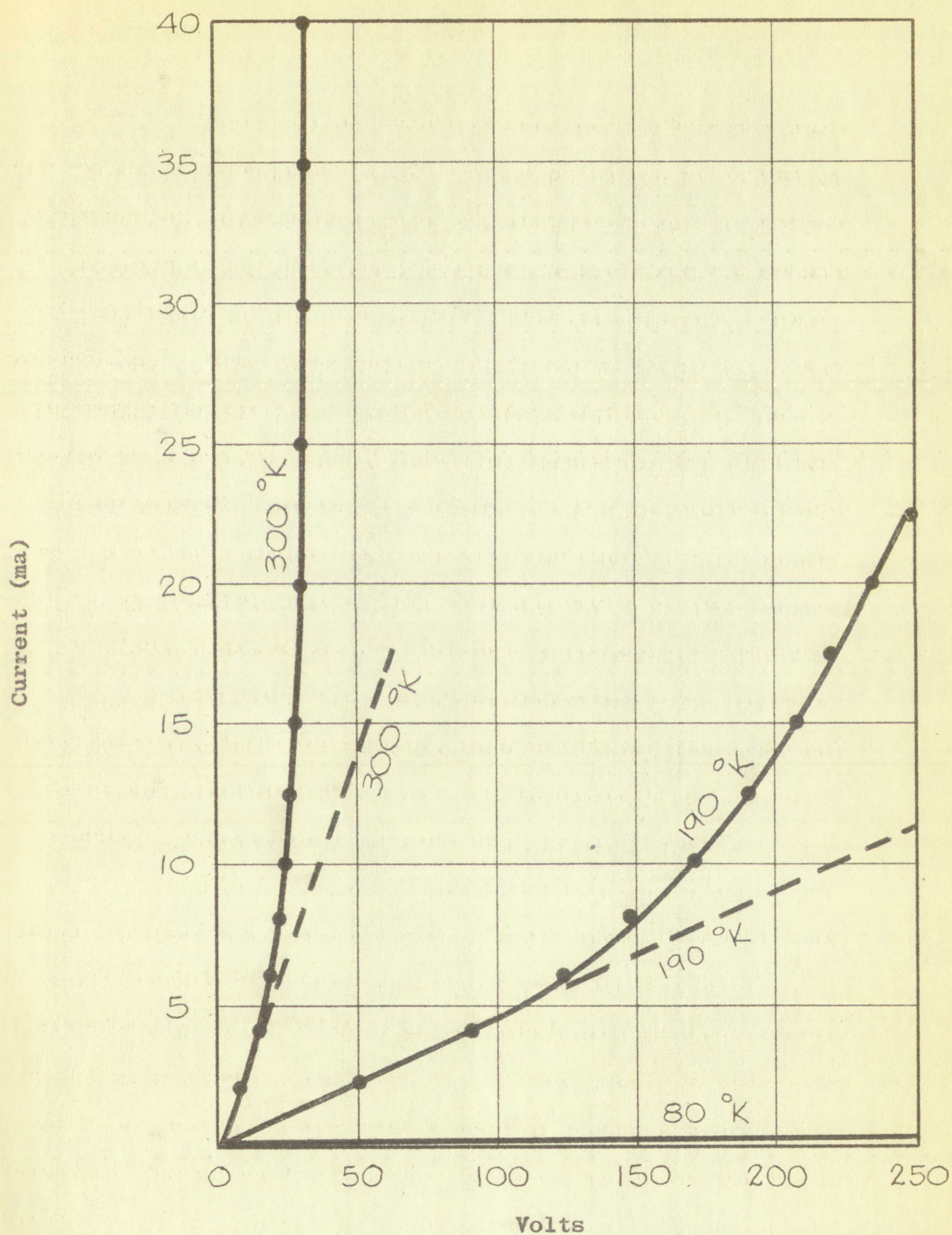
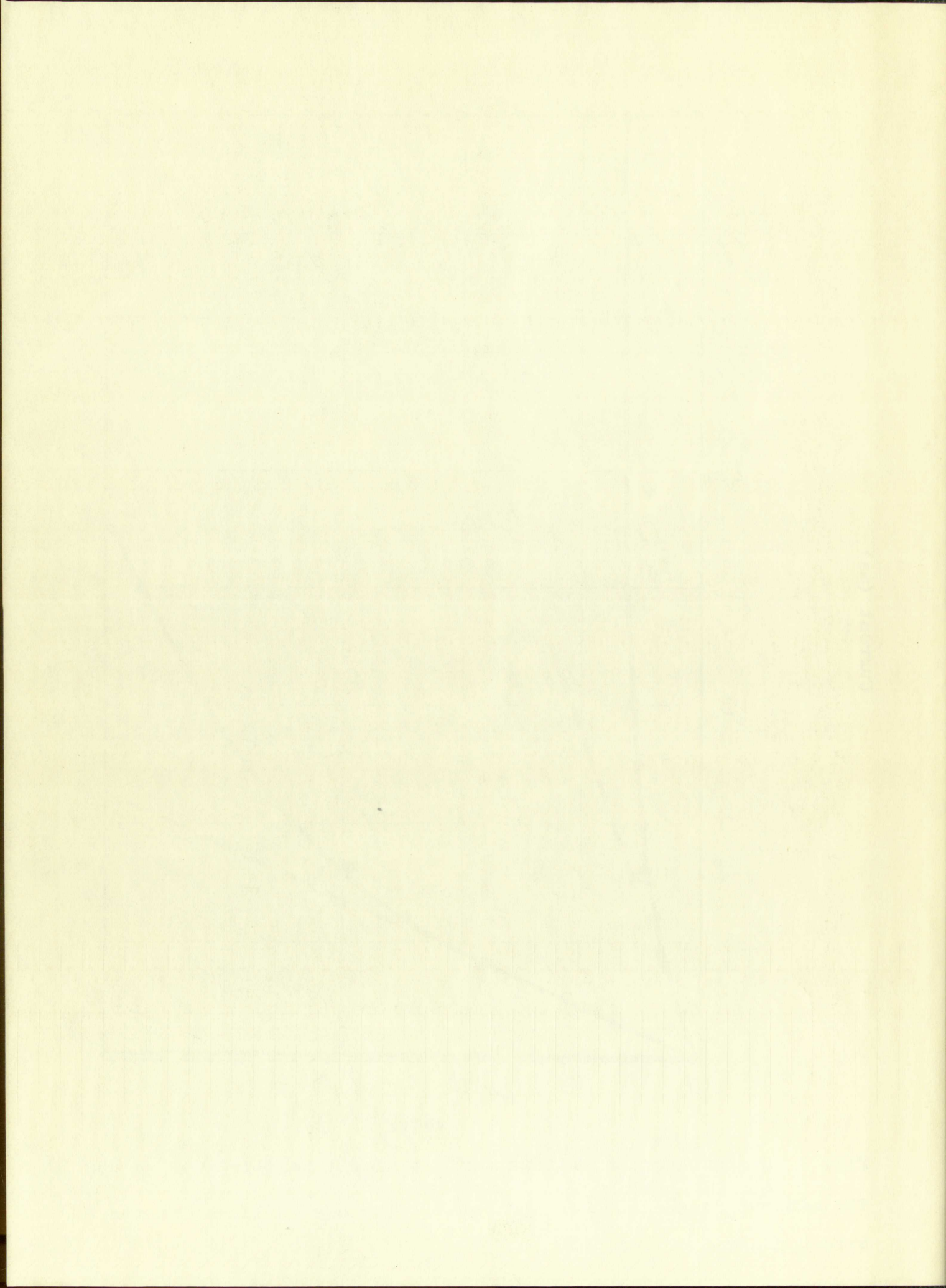


Fig. 9 Current versus voltage for the sample heat-treated to 650 °C. The ambient temperature is indicated. The dashed lines are the extended ohmic values.







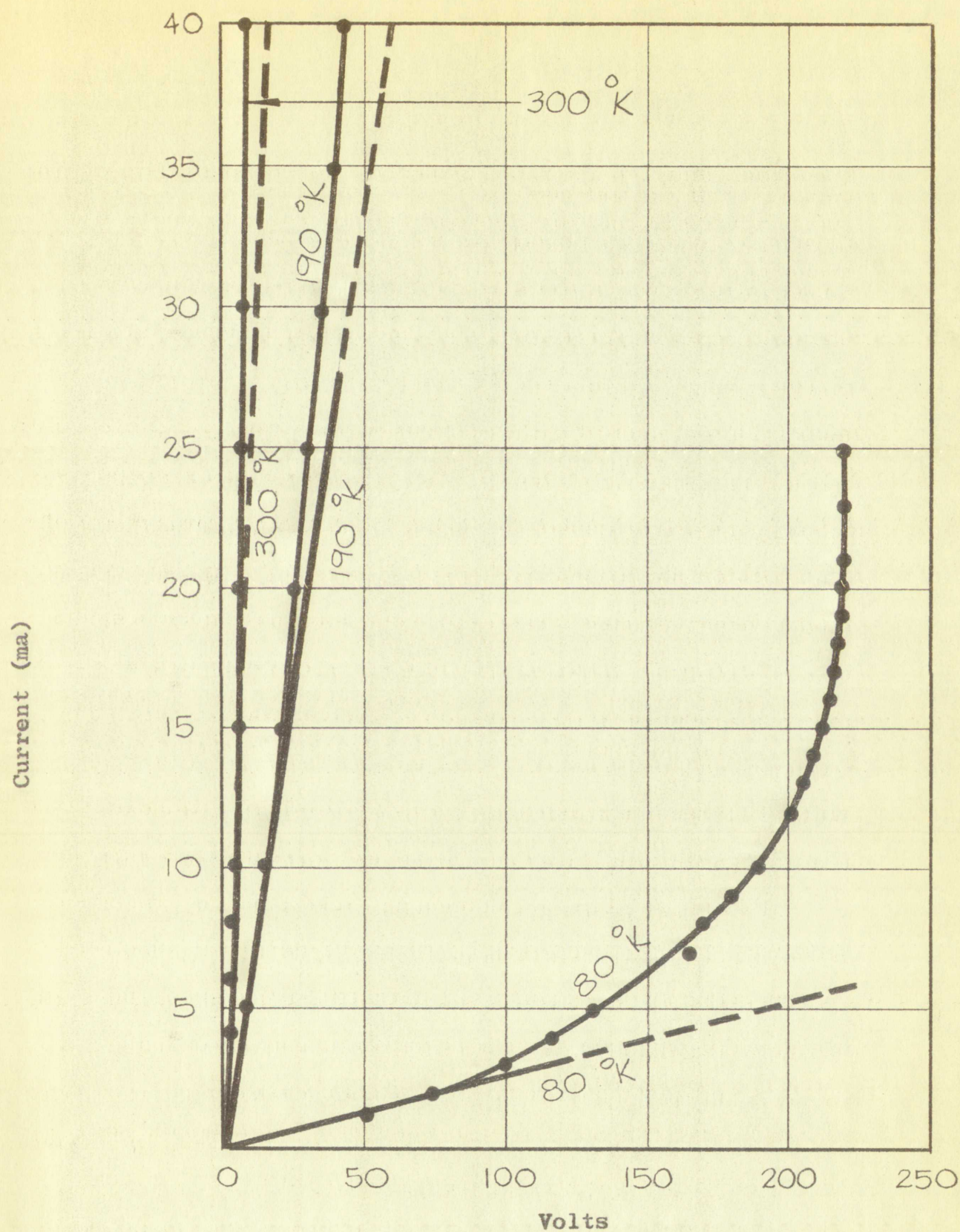


Fig. 10 Current versus voltage for the sample heat-treated to 720 °C. The ambient temperature is indicated. The dashed lines are the extended ohmic values.







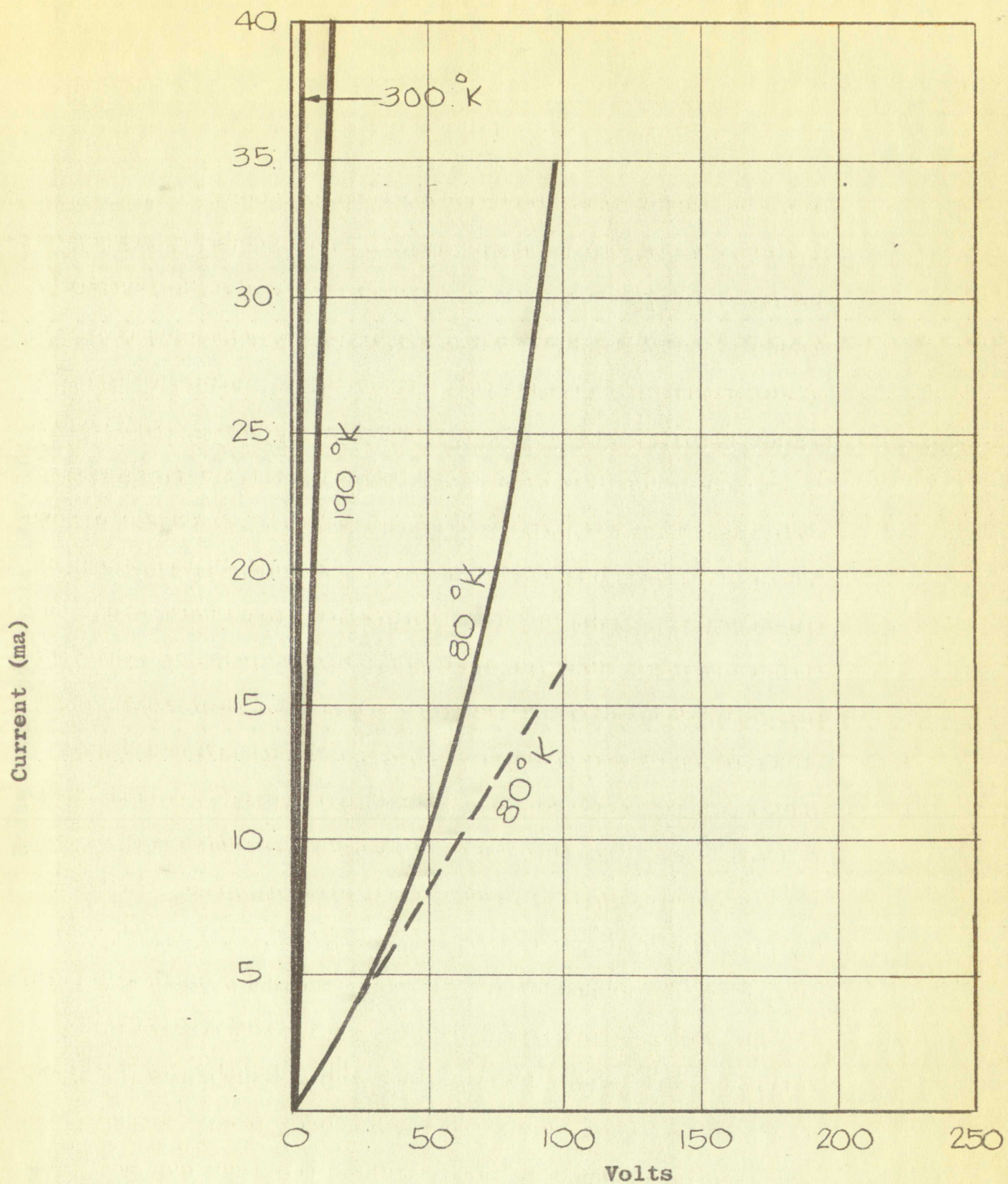
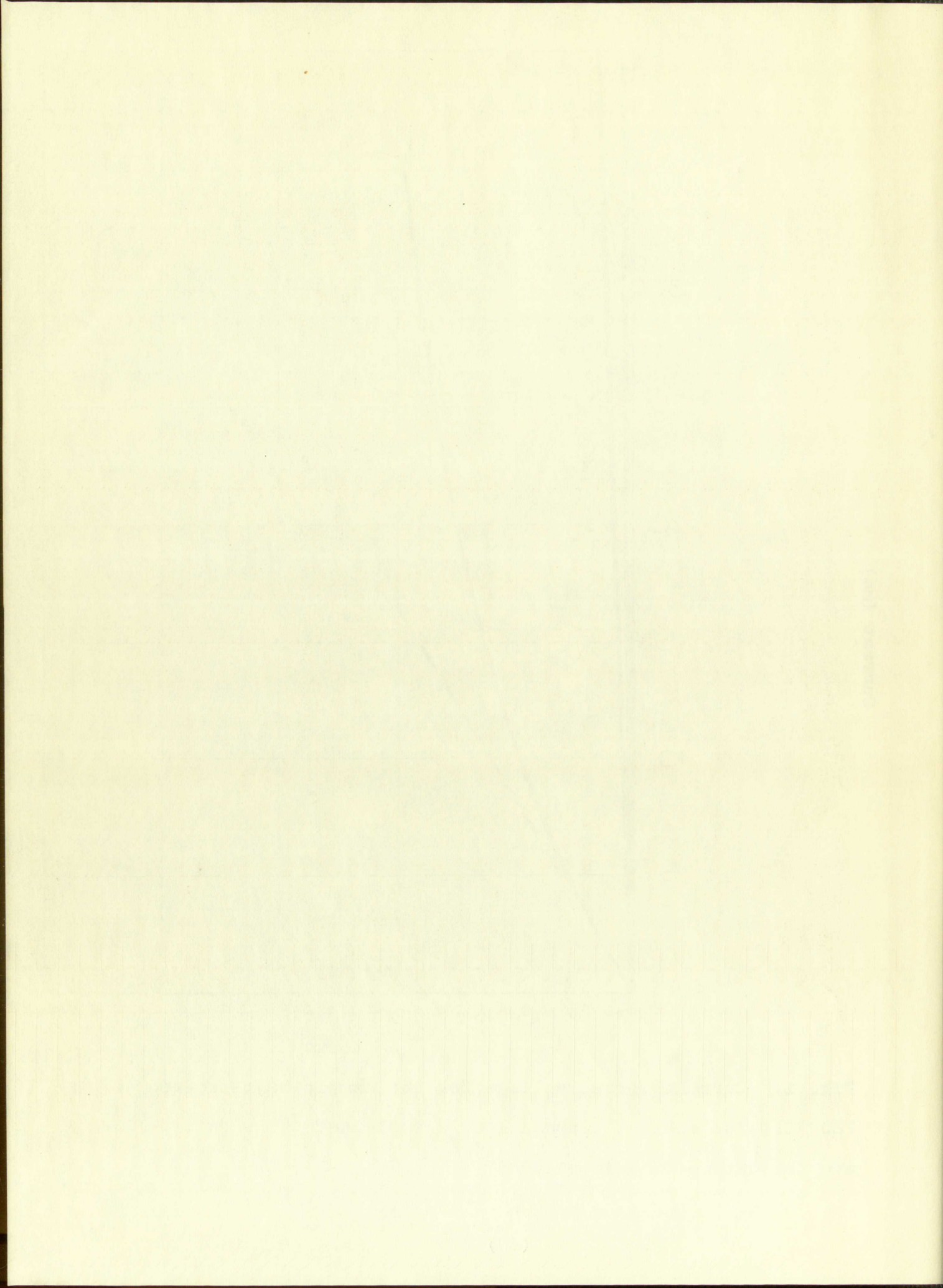


Fig. 11 Current versus voltage for the sample heat-treated to 730 °C. The ambient temperature is indicated. The dashed lines are the extended ohmic values.







Noise Power per cycle (Watts)

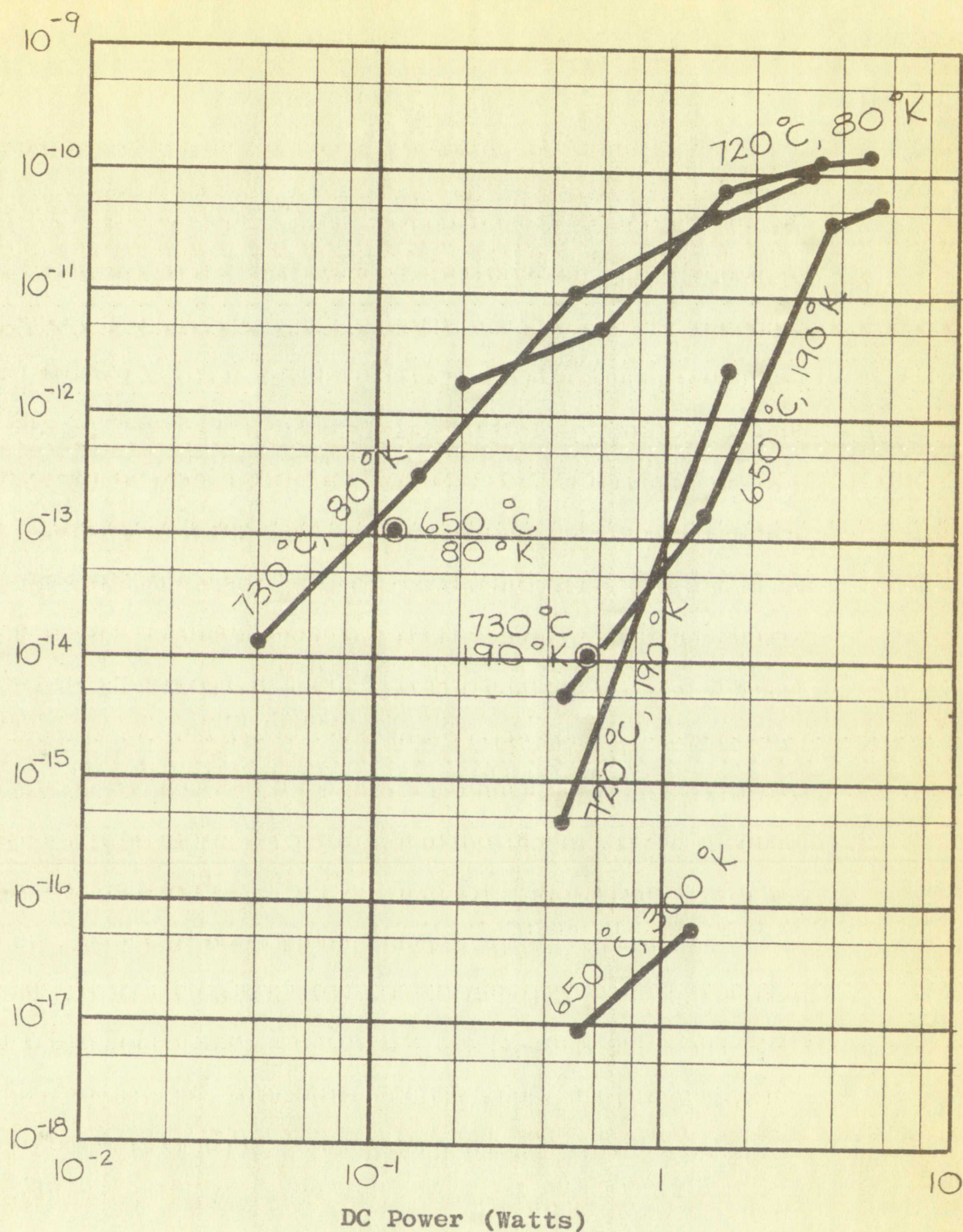
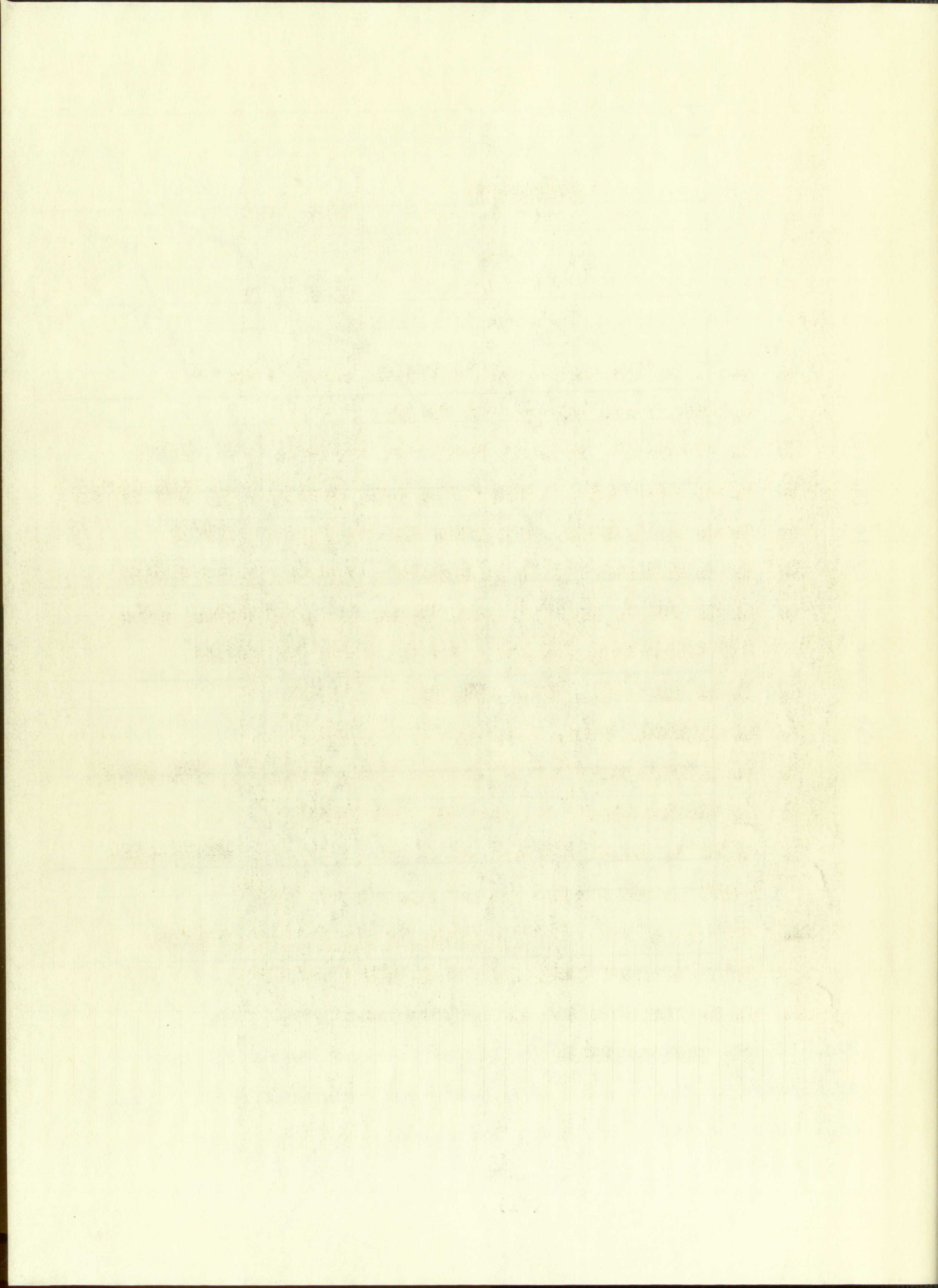


Fig. 12 Noise power at 40 cycles per second versus dc power dissipated in the sample. The heat-treat temperature in °C and the ambient temperature in °K are indicated.







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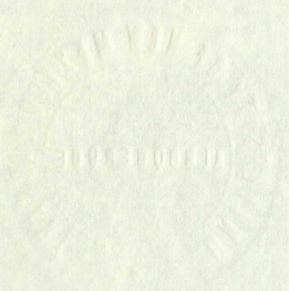






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MADE IN USA

MADE IN  
USA  
EAGLE A  
TIGER BRAND  
COTTON CLOTHING USA

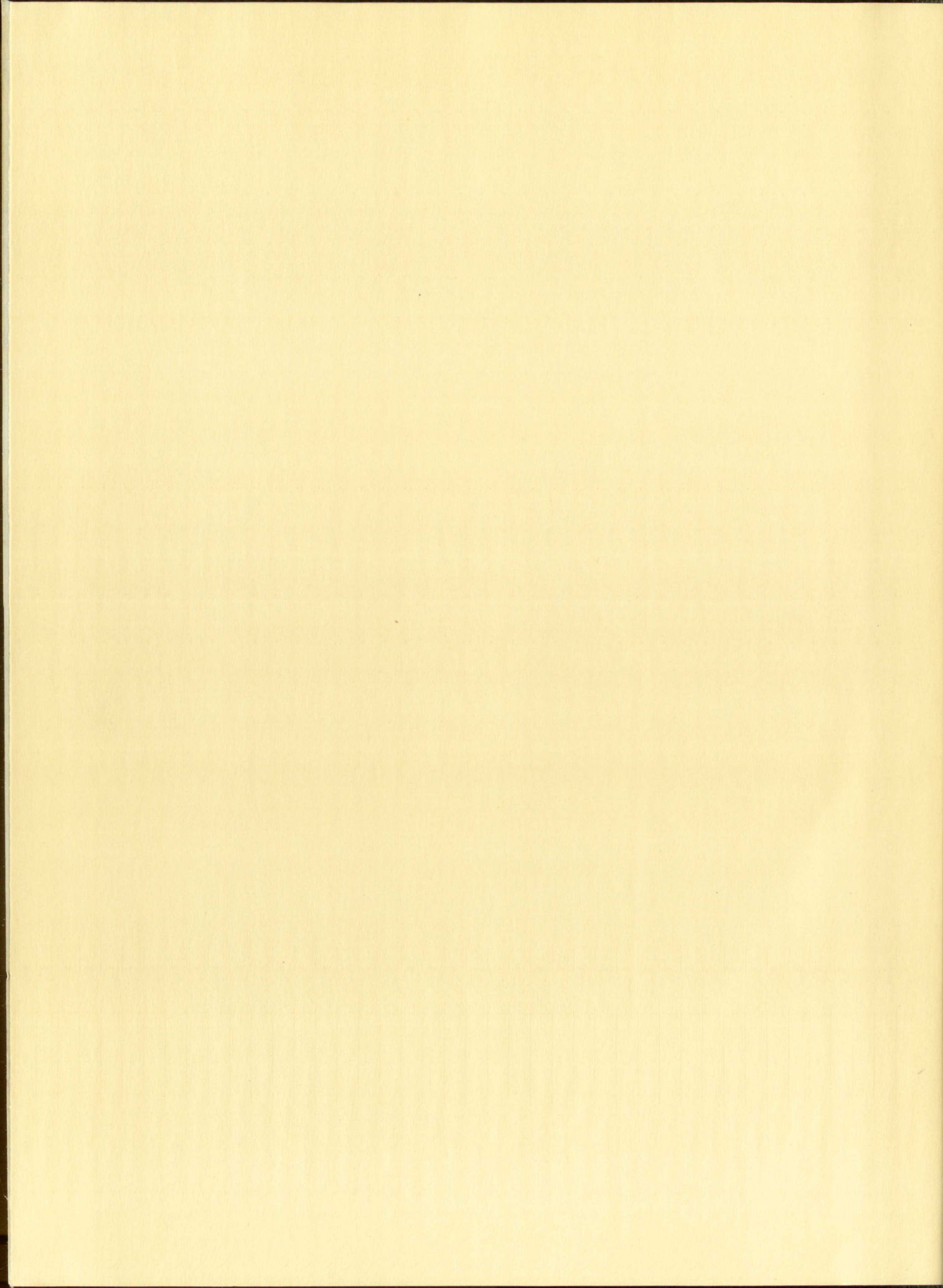




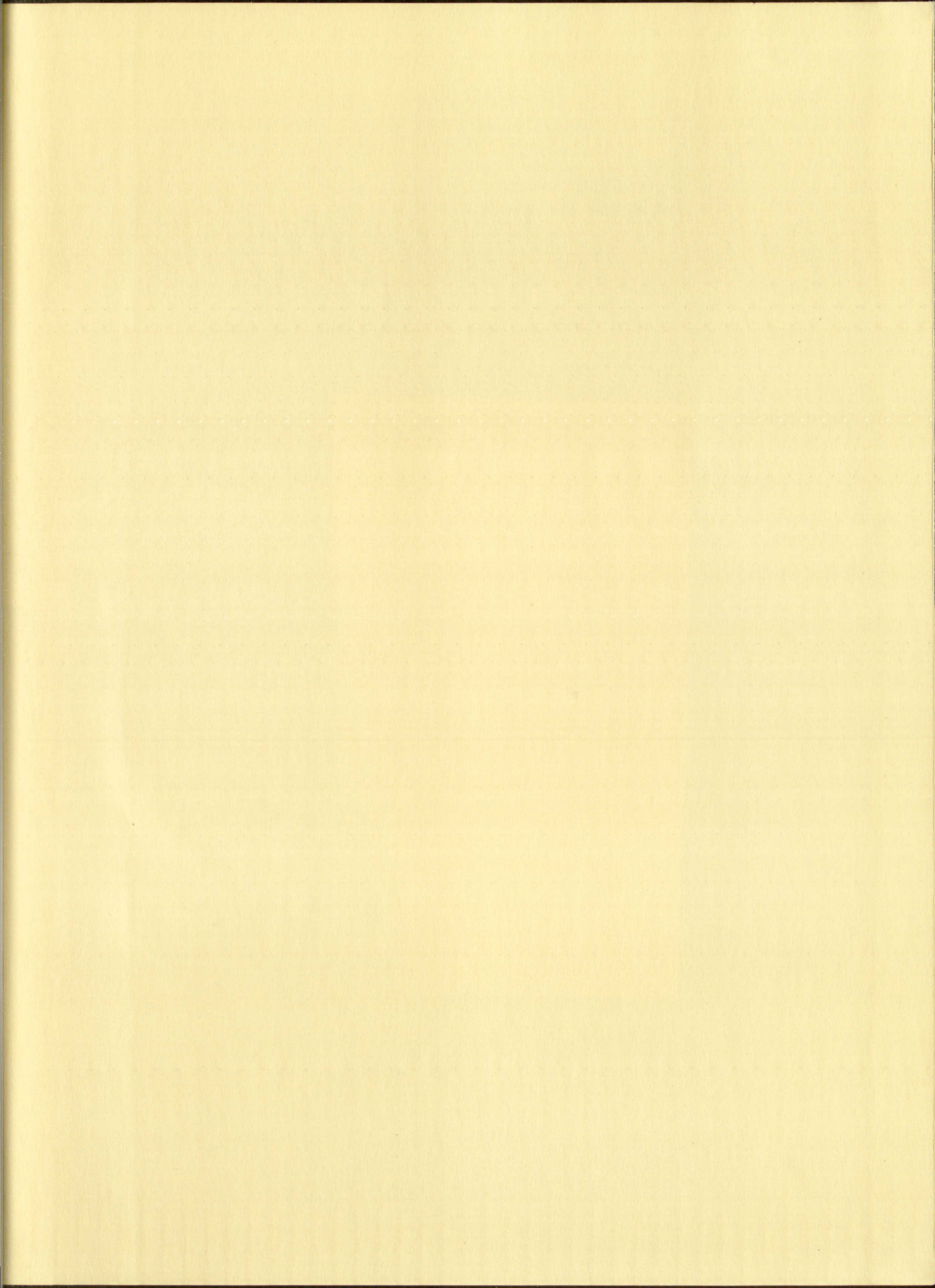














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