1961

Backswitch characteristics of indium films

Ammer, Henry G.

Monterey, California: U.S. Naval Postgraduate School

http://hdl.handle.net/10945/11722

BACKSWITCH CHARACTERISTICS OF INDIUM FILMS

HENRY G. AMMER
and
WILLIAM F. WOLFF

BACKSWITCH CHARACTERISTICS
OF
INDIUM FILMS

* * * * * *

Henry G. Ammer

and

William F. Wolff

BACKSWITCH CHARACTERISTICS
OF INDIUM FILMS

by

Henry G. Ammer

Major, United States Marine Corps

and

William F. Wolff

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 6 1

BACKSWITCH CHARACTERISTICS OF INDIUM FILMS

by

Henry G. Ammer

and

William F. Wolff

This work is accepted as fulfilling
the thesis requirements for the degree of
MASTER OF SCIENCE
IN
PHYSICS
from the
United States Naval Postgraduate School

ABSTRACT

The characteristics of the switch from the resistive to the superconducting state (backswitch) of a strip film of indium, driven resistive by a short current pulse, are investigated. The relationship of the time interval from pulse cessation to the time of reaching the complete superconducting state is explored against parameters of temperature and the DC measuring current for a moderately thick $(\sim 6\mu)$ film. An empirical equation for the relationship is developed and the technique for the derivation demonstrated.

Additional observations of phenomena encountered in the course of experiments are recorded without attempt at explanation.

The writers wish to express their gratitude to Professor J. N. Cooper of the U. S. Naval Postgraduate School for his advice, encouragement and assistance in this project. The technical aid rendered by Mr. Kenneth C. Smith was invaluable in reducing the equipment problem to a manageable level.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Table

1. Introduction

The growing interest in solid state physics and in particular the aspect of superconductivity in metals has led to wide research in the area of superconductivity in thin films. Areas of "normal" and "anomolous" behavior have been investigated[1] without a satisfactory explanation therefrom. Local work in this field has been conducted utilizing a direct current as reference and upon which is superimposed a larger pulsed current to drive the specimen resistive. In this fashion the resistance characteristics of the specimen, after the cessation of the pulsed current, have been investigated. This thesis attempts to determine the effect of this reference current on the backswitch for relatively thick films.

---

[1] A. C. Lauer and J. K. Nunneley, Transition Time from Resistive to Superconducting State for Thin Indium Films and John A. Eckert and Robert G. Donnelly, Temperature Dependence of the Normal-To-Superconducting Transitions, U. S. Naval Postgraduate School Theses, 1959 and 1960, respectively.

2. Definitions of Terms and Parameters

At extremely low temperatures, certain metals exhibit the phenomenon of superconductivity, i. e., no apparent resistance. To achieve the necessary temperatures, the specimen under investigation is bathed in liquid helium in the cryostat. By varying the pressure over the helium, and thus its vapor pressure, the temperature of the bath can be controlled. The temperatures used in these investigations were lower than that of liquid helium at one atmosphere, so it was necessary to reduce the pressure over the helium.

Thin films are used so that their resistance is great enough to be measured readily by standard equipment, without having the other two dimensions so great as to create a handling problem. The principle specimen used was prepared at the Space Technology Laboratories by evaporating 159.8 mg of indium at an initial pressure of 1×10^{-7} mm Hg, onto a polished glass substrate 4 9/16 inches distant. The substrate was cooled to a temperature of 138°K.

The physical characteristics of the film are:

Resistance at 300°K	1.5 ohms
Resistance at 4.2°K	0.13 ohms
Length	0.594 cm
Width	0.0076 cm
Thickness (approximate)	6.2×10^{-4} cm
Designation	G-232

Approximately 500 mg of Sn was evaporated on the ends for good contact. See Figure 1.

For a typical experiment, the specimen was immersed in liquid helium under reduced pressure, and carried a reference DC current, less than the steady current required to destroy the superconductivity. From a pulse generator, pulses at a preset frequency and size were superimposed on the DC current. With sufficient DC current and pulse amplitude, the specimen would become normally resistive within the duration of the pulse. If the DC current was set low enough, as explained later, the specimen would return to a superconducting state before the next pulse arrived. This transition from the resistive back to superconducting state - the backswitch transition - was the problem under investigation.

Figure 2 illustrates the typical oscilloscope trace for both input and output of the specimen. The time scales for the two traces are the same, however the voltage scales typically differ by two orders of magnitude from input to output.

Parameters not described or defined in Figure 2 include:

a. I_{DC} - Steady current maintained through the specimen.

b. PPS - Repetition rate of pulses, in pulses per second.

c. I_C^* - The minimum DC current that when applied to a specimen receiving pulses of a specific amplitude, repetition rate and duration will first cause the specimen to remain resistive between pulses.

d. $I_C'^*$ - The minimum DC current that will maintain the resistive state of the specimen between pulses, once this state has been established by a DC current equal to or greater than I_C^*.

The parameters which determine the backswitch characteristics of metal films are numerous. Included among them as a reasonable minimum estimate are the following:

a. I_{DC} - Applied DC current.

b. V_P - Voltage amplitude of input pulse.

c. PPS - Repetition rate of pulse input in pulses/sec.

d. PW - Width of input pulse.

e. Temperature.

f. Film properties.

  (1) Thermal.

  (2) Dimensions.

  (3) Crystalline structure.

  (4) Electromagnetic.

  (5) Non-uniformity, dimensional irregularities, epitaxic layer, etc.

g. Substrate Properties.

(1) Thermal.

(2) Dimensions.

In view of the morass of parameters, it was impossible to investigate the effect of each of these on the backswitch characteristics. By limiting the investigation to one specimen, the physical properties of the film and substrate are effectively eliminated from variance during the course of the project. A trial run indicated the most sensitive parameters affecting the decay time were reference DC current, pulse height, pulse width and temperature; the least sensitive was the repetition rate over the range of 50 to 20,000 pulses/sec so this parameter was not varied. It was initially planned to include pulse height as a variable, but time has not permitted.

Although many of our conclusions and graphs are derived from a single specimen, we obtained data on a second sample, G-233, which seemed to verify the general behavior of the principle specimen. This specimen was also indium and had the dimensions: 0.5913 cm long, 0.0042 cm wide and about 7 μ thick.

3. Equipment and Techniques

The test film and its electrical connections were immersed in liquid helium in a Dewar cryogenic container connected to a vacuum system which could maintain constant pressure by utilizing a pressure-regulating valve. However, constant pressure does not necessarily mean constant temperature at the specimen which may be from around 5 to 25 cm below the surface of the helium. To insure temperature equilibrium within the helium column, it must be boiling to create turbulence. This can be achieved by constantly and slowly decreasing the pressure over the helium. A technique described in Section 4 was used in returning to high temperatures from low ones.

Electrical pulses were produced by a Teletronics Laboratory Pulse Generator, Model #PG-200AA. The DC current was produced by a locally constructed DC generator with 0-500 volt range. Measurements of pulses and sample response were taken with a Tektronix Type 541A Oscilloscope with Type DA Plug-in Unit. The horizontal time scale could be varied from 0.02 μ sec/cm to 5 sec/cm; the vertical scale could be varied from 0.05 to 20 volts/cm.

Data were obtained by utilizing the circuit shown in Figure 3.

To insure minimum and uniform contact resistance in the mounted specimen, it was necessary to clean the contact

surfaces of oxides before each run; failure to do so made results worthless.

The technique employed in obtaining data consisted of impressing across the specimen fixed values of pulse width and height (PW and V_P) at 100 pulses/sec. The pulse height was chosen so that the specimen would be at least partially resistive at the lowest temperature investigated. For the results reported, $V_P = 10$ volts, and the corresponding pulse current about 200 milli-amperes. The pulse width was 5 μ sec. An I_{DC} value was selected and the back-switch time, τ , was measured as a function of temperature. This procedure was then repeated with different values of I_{DC}. Log τ was plotted as a function of I_{DC}, which yielded a family of approximately straight lines (Figure 4) with temperature as the parameter.

4. Results

The 5 μ sec pulse width yielded the family of lines shown in Figure 4 of the approximate form $\tau = \tau_0 e^{mI_{DC}}$. The slope of each line was computed with results as shown in Table 1. An irregular variation of the slope was noticed in these results as well as the fact that for a given temperature, the points associated with the lower values of I_{DC} fell somewhat below the plotted line. It was found that the equation of the form $\tau = \tau_0 (e^{mI_{DC}} - 1)$ fits the data much better. With the equation in this form, τ would become zero at $I_{DC} = 0$, which is known generally not to be the case. Thus this equation is not universally valid, although it fits the data of Figure 4 well.

The lesser value of m in Figure 4 and Table 1 were averaged, giving an $\bar{m}$, and the ratio of the slopes of the curve $e^{\bar{m}I_{DC}}$ to the curve $e^{\bar{m}I_{DC}} - 1$ determined at various values of I_{DC}. A mid-value I_{DC} was selected for each of the lines of Figure 4, and the appropriate ratio applied to each m of the family. These adjusted slopes were then plotted as a function of temperature. A least squares analysis of this plot indicated a small positive change in the slope with increasing temperature. A new value of $\bar{m}$ was then obtained by averaging the corrected slopes and new correction factors determined. After the initial m's were corrected by this factor, a least squares analysis

as before, indicated a very small negative change in $\overline{m}$ with increasing temperature. Subsequent iterations of the above process suggested that the slope $\overline{m}$ was independent of temperature.

A template of the equation $\tau = 1(e^{\overline{m} I_{DC}} - 1)$ was utilized to connect the data points, resulting in the curves shown in Figure 5. Clearly these curves fit the data much better than do the straight lines of Figure 4. The values of the asymptotic intercept with the $I_{DC} = 0$ line were designated τ_0 and determined graphically from Figure 4 and tabulated in Table 1. The value of log τ_0 thus was found to have a linear relationship to the fourth power of the temperature as shown in Figure 6.

The final relationship determined was found to be

$$\tau = (e^{0.103\,T^4 - 8.26})(e^{62.7\,I_{DC}} - 1)$$

with τ in microseconds and I_{DC} in amperes. The relationship between temperature and current was determined for a constant value of τ. These relationships are shown in Figure 7 and in Table 2, and are of the form $T^2 = aI_{DC} + b$. Attempts to correlate the values of a and b to available parameters directly proved futile; however the graphic results are shown in Figures 8 and 9. The derived parameters a and b are quite far removed from the basic data, and curve fitting at this point is of nebulous significance. It may be worthy of mention that the best fit for our a and b may be some function of $1/\tau$.

Incomplete data indicate that the slope of the family of lines $\overline{m}$ is a function of the pulse width and pulse height. In particular, $\overline{m}$ seems to decrease with increasing pulse width.

In addition, limited data seems to bear out the general features of our empirical equation for another specimen, G-233.

The DC current I_C^* for which the sample remains resistive between pulses (at V_P = 10 volts) is plotted as a function of temperature in Figure 10. This corresponds to the trace of the upper termini of the family in Figure 5. The lower line of Figure 10 is the minimum current $I_C'^*$ which will maintain the resistive state between pulses once the resistive state has been achieved.

It was found that Figure 10 was quite useful in temperature control, one of our most onerous problems. Control of descending temperature was quite accurate. However, after any upward move in temperature, the exact temperature of the specimen was not known for periods as long as 15 minutes. If it was necessary to go to a higher temperature after a series of decreasing temperature measurements, the pressure over the helium was slowly increased and the constant inputs of Figure 10 applied (V_P = 10 volts, PW = 5 μ sec). Then it was only necessary to check periodically I_C^*. When an I_C^* was found that corresponded to the desired or higher temperature, descending temperature

readings could be resumed.

When the specimen is driven resistive between pulses by increasing I_{DC}, the backswitch time τ increases regularly to some maximum value, which is small compared to the interval between pulses. Any further increase in I_{DC} results in what appears to be a discontinuous jump in the value of τ to the full period between pulses. This discontinuous jump is from the upper terminal points of Figure 5. In the range of input parameters where we made most of our observations, the voltage drop across the specimen, with time, after it was resistive between pulses, was as shown in Figure 11. Figures 4 and 5 of the thesis of Eckert and Donnelly seem to indicate a similar response for their thinner films. If our thicker specimens are acting similar to their thin ones, the fact that they could not observe a backswitch for some specimens, and no I_{max} for others may be explained by this phenomenon. That is, their Figures 4 and 5 may actually represent the situation after the specimen was resistive between pulses. We observed that the trough of Figure 11 would act somewhat like the normal backswitch decay, and with the application of sufficient I_{DC} it would be straightened out to what may be considered the normal pattern with no decay, but of course raised above ground. When only one pulse is displayed on the CRO, the minimum of the trough may be on the extreme right and a first glance may appear to be the

normal backswitch. However, if the pulse rises from a point higher at the left of the CRO screen than the lowest point of the trace to the right of the pulse, then this phenomenon is being observed and the specimen is resistive between pulses.

5. Observations

A distinct instability was noted in the decay time at various values of temperature and current. By tracing the instability to higher frequencies and displaying several pulses on the oscilloscope, it was found that the specimen had in essence two "modes of decay" in returning to the superconducting state for some values of temperature and DC current.

By adjustment of the sweep speed, it was possible to have the CRO sweep trigger so as to display these "modes" as alternate pulses in a series. Whenever the "double decay" was observed, it could always be displayed as an alternate arrangement and never in any other distribution. This double decay can be traced for any single input parameter to values of interest by setting in an initial value of the parameter, and adjusting the other input variables until "double decay" is observed. If the parameter in question is then changed slightly, stopping the "double decay," then it can be re-obtained by a relatively small adjustment of one or more of the other input variables. Further, it was noted that there were areas that remained in "double decay" for a fairly wide range of the input parameters. Hence there appears to be some continuous relationship between this phenomenon and certain combinations of the input parameters. See Figure 12. A limiting case of this "double decay" was observed where the

specimen was alternately fully resistive and superconducting between pulses. This was an extremely unstable condition, unlike the "double decay" described above. When observed, this phenomenon occurred at I_C^*.

During the taking of data for the lower temperatures where the pulse height was insufficient to drive the specimen fully resistive, it was noted that this in no way influenced the pattern of decay time observed. Even though full resistance was not achieved at the lower temperatures during the pulse, the specimen appeared to be fully resistive to the measuring current immediately after the pulse terminated. Figure 13 illustrates this.

6. Conclusions

If pulse width, pulse current and temperature are constant, the backswitch time varies as an exponential function of the reference current.

If the pulse width, pulse current and reference current are constant, the backswitch time varies as an exponential function of the fourth power of the temperature.

For specimen G-232, this leads to the equation:

$$\tau = (e^{0.103T^4 - 8.26})(e^{62.7 I_{DC}} - 1)$$

The constants of this empirical equation are functions of the pulse width and the pulse current as well as the various physical parameters of the system.

7. Recommendations for Further Work

Additional data be taken to determine the correlation between the constants of the empirical equation and pulse width and pulse current.

Sufficient data of improved accuracy at a single pulse width should be taken for a statistical determination of the possible higher order dependence of $\overline{m}$ on temperature.

The above should be repeated for additional pulse widths, and a plot of $\overline{m}$ vs pulse width made and checked to see if it correctly extrapolates into predicting the backswitch anomaly.

This same procedure should then be applied to other specimens of similar thickness and the results correlated.

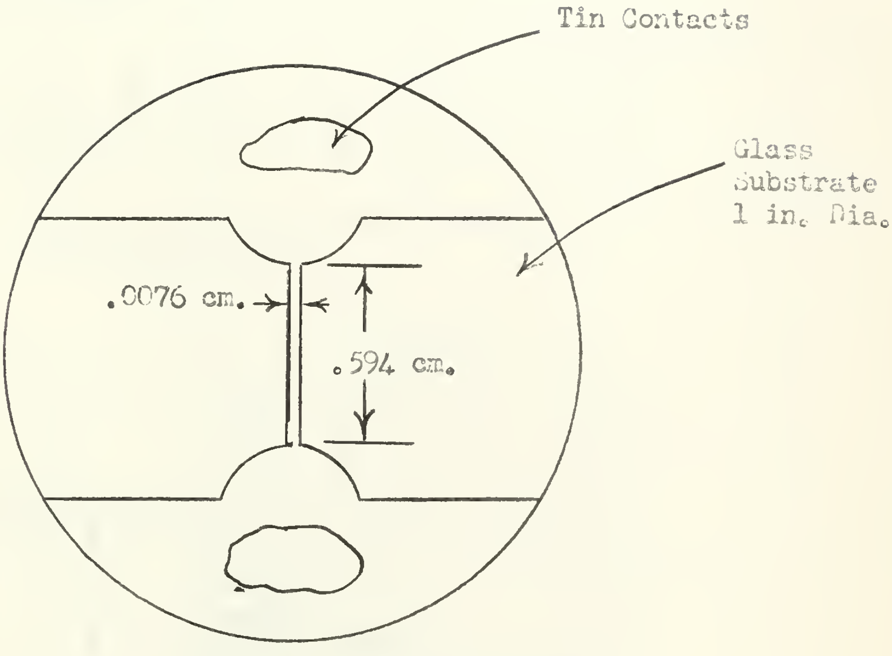
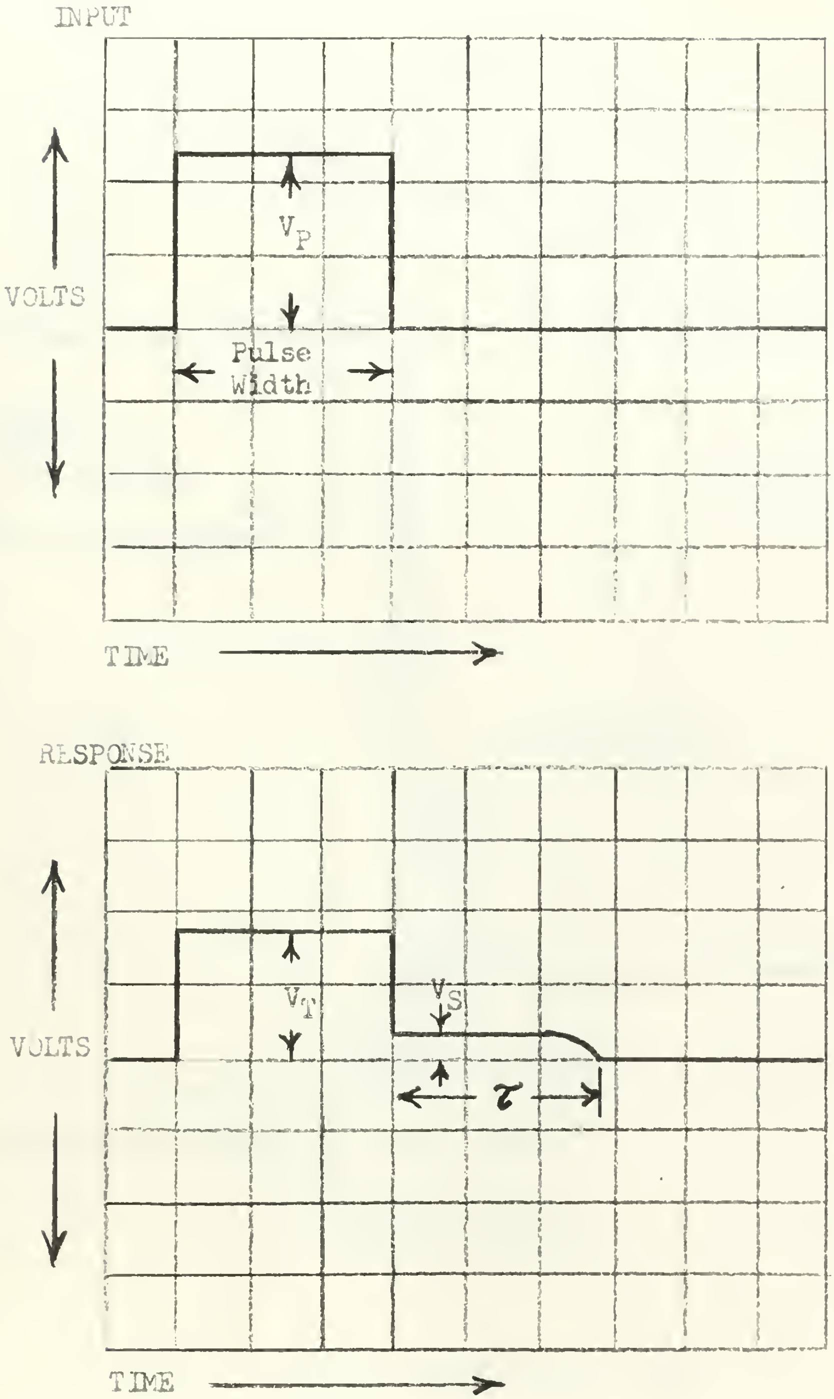


Figure 1.

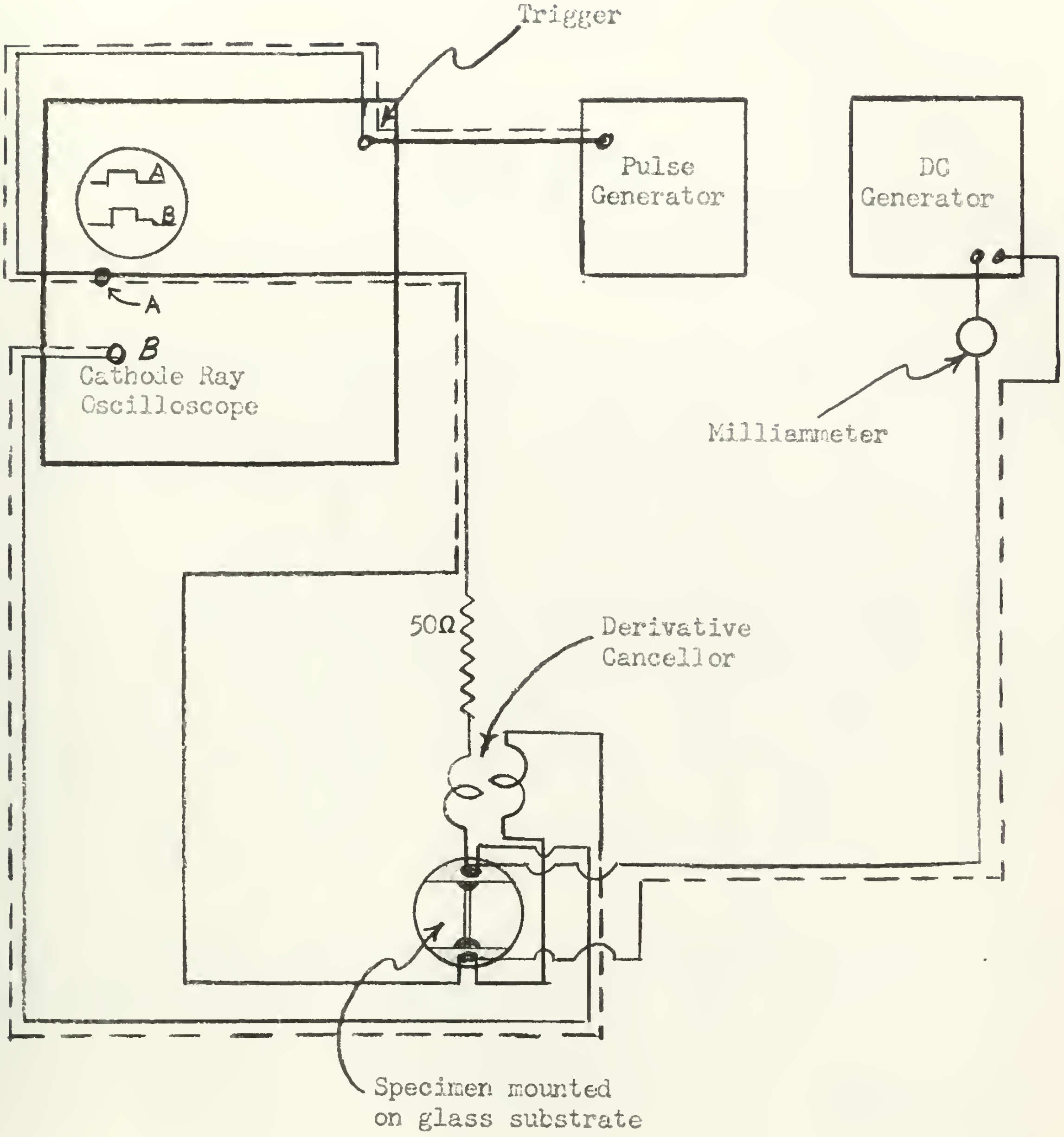
Specimen Configuration

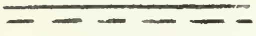


$V_T = [I_{DC} + I_P]\,R$

$V_S = [I_{DC}]\,R$

Figure 2
Input and Response Features





Shielded coaxial lead [50Ω]

Figure 3

Block Circuit Diagram

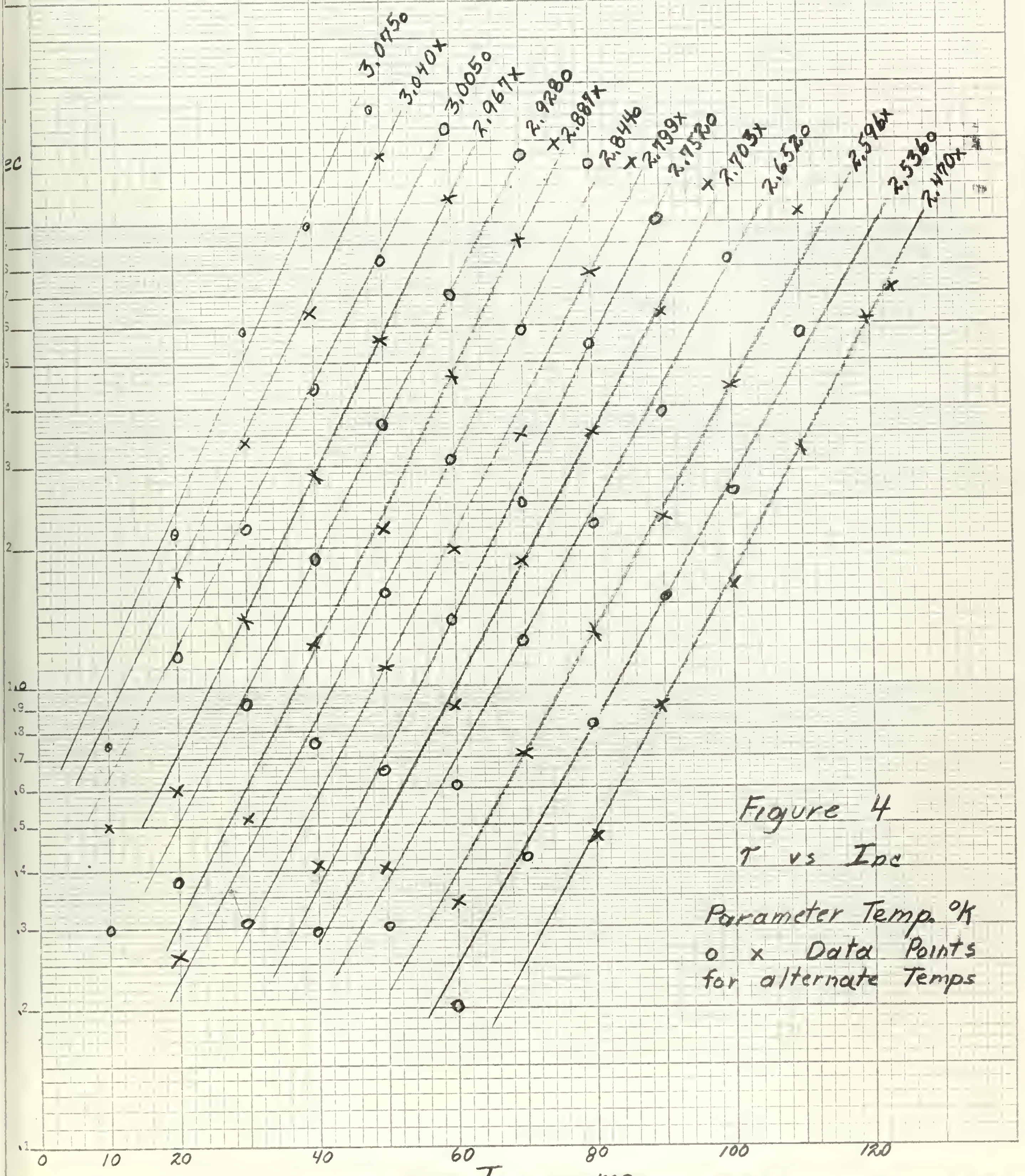


Figure 4

τ vs I_{DC}

Parameter Temp. °K

o x Data Points
for alternate Temps

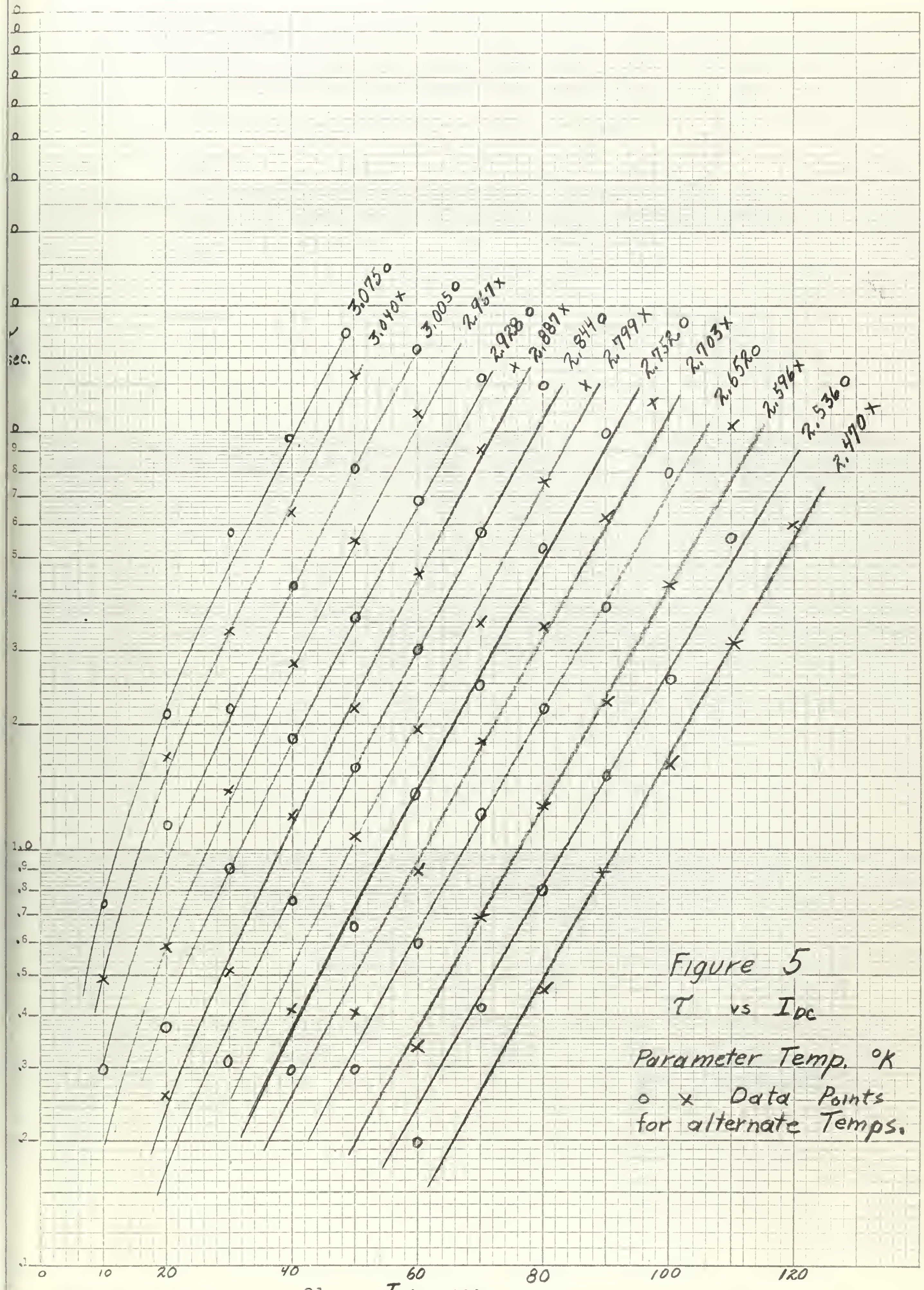


Figure 5
τ vs I_{DC}

Parameter Temp. °K
o x Data Points for alternate Temps.

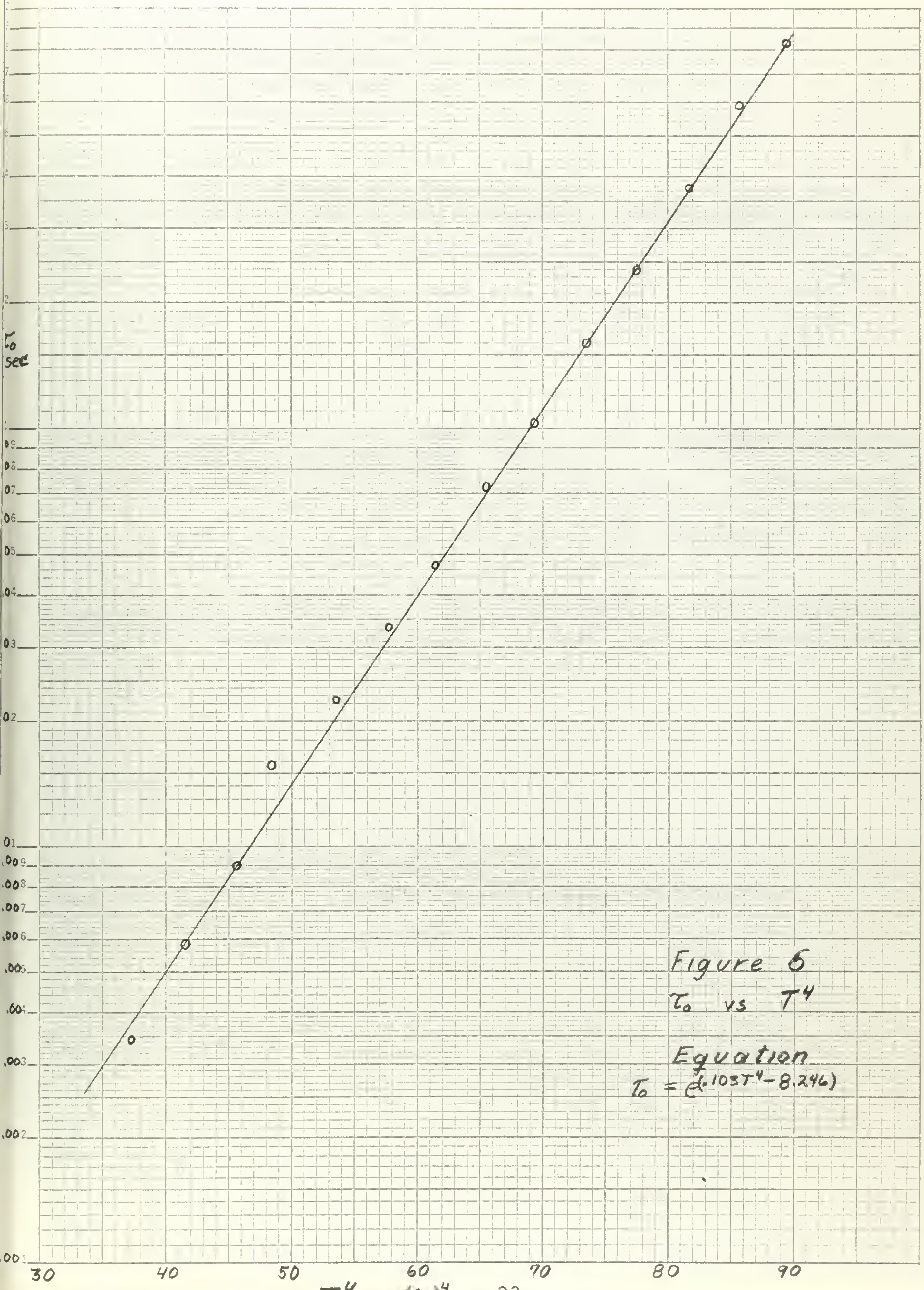


Figure 6

τ_0 vs T^4

Equation

$\tau_0 = e^{(.103T^4 - 8.246)}$

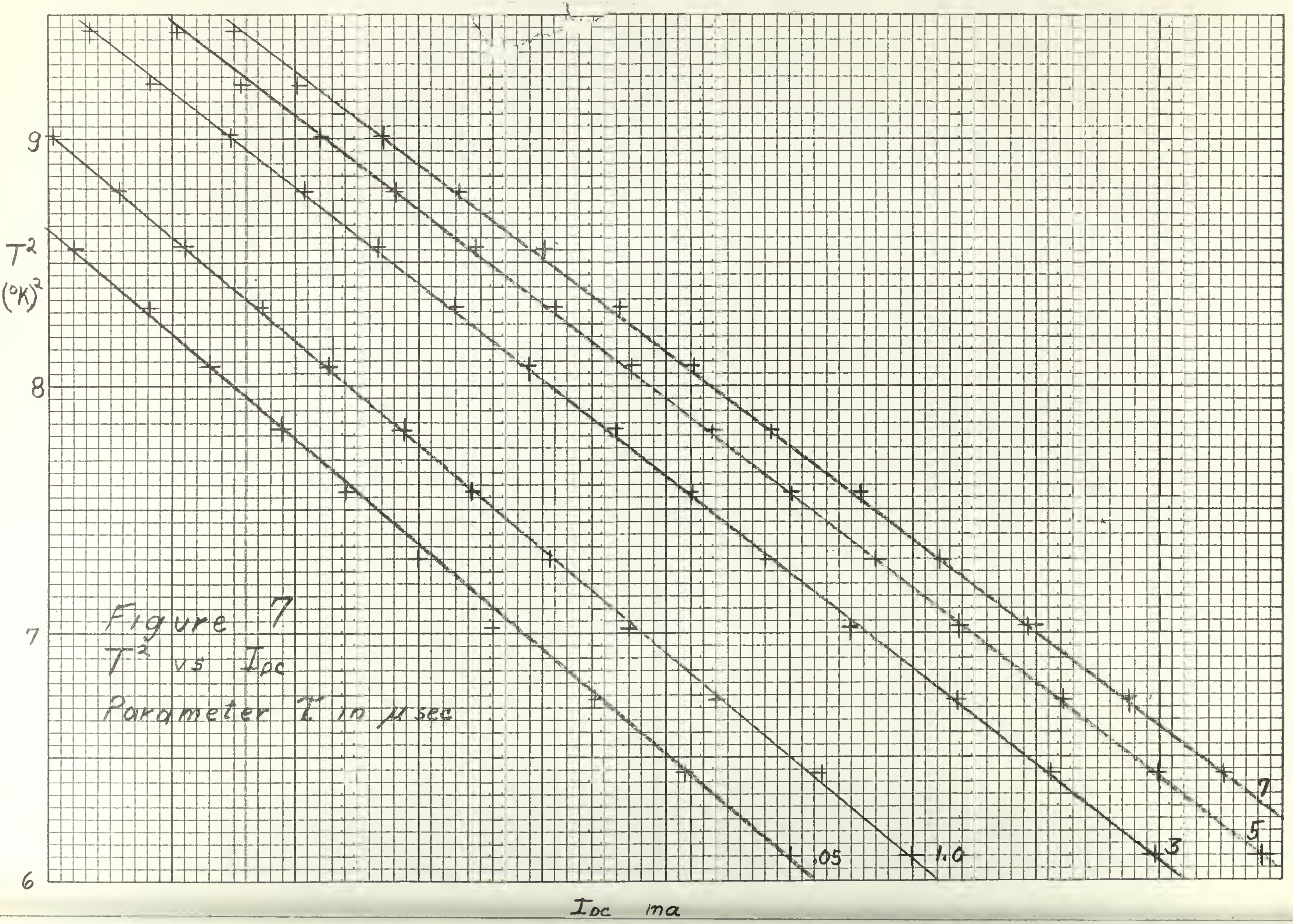


Figure 7
T^2 vs I_{DC}
Parameter τ in μsec

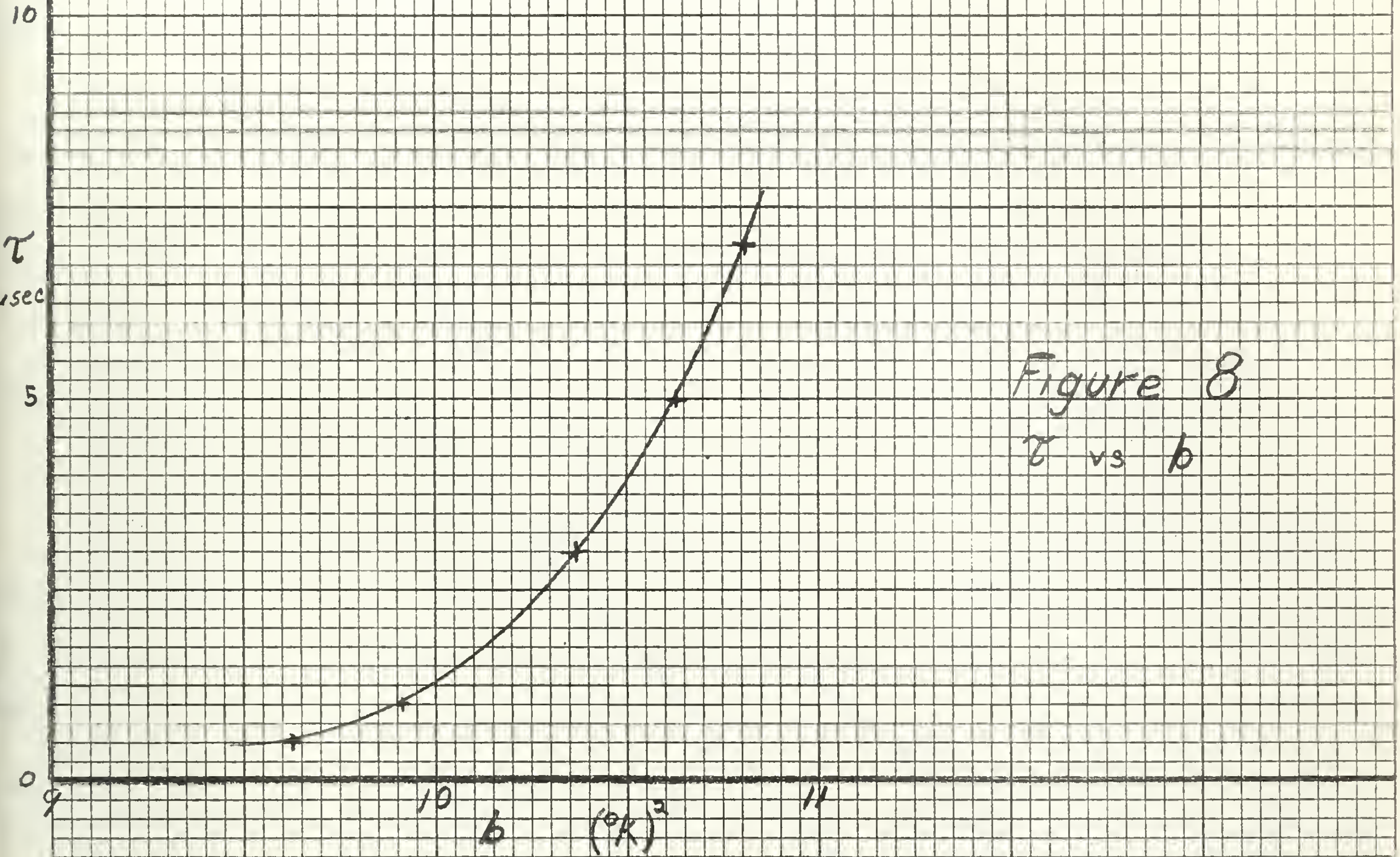


Figure 8

τ vs b

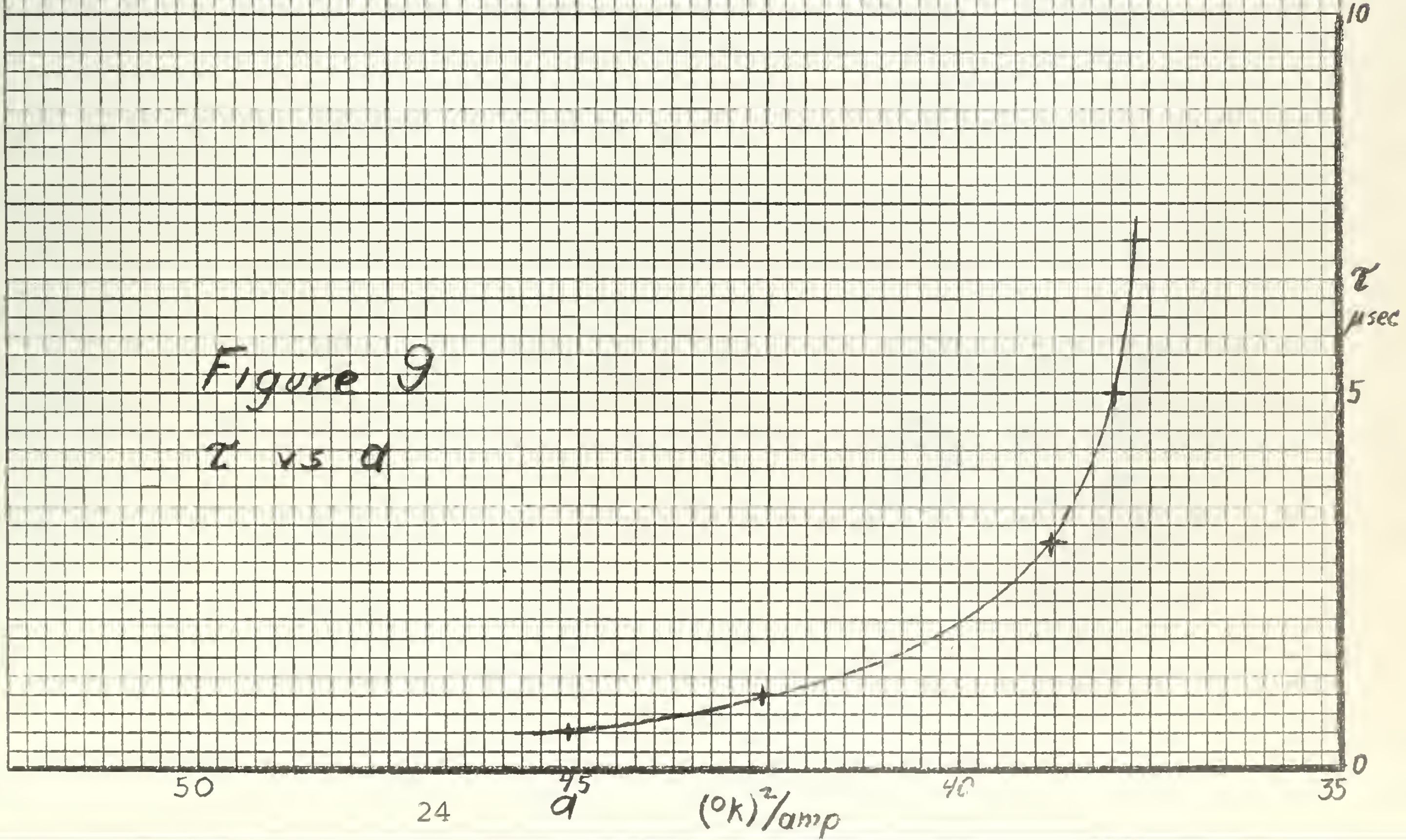


Figure 9

τ vs a

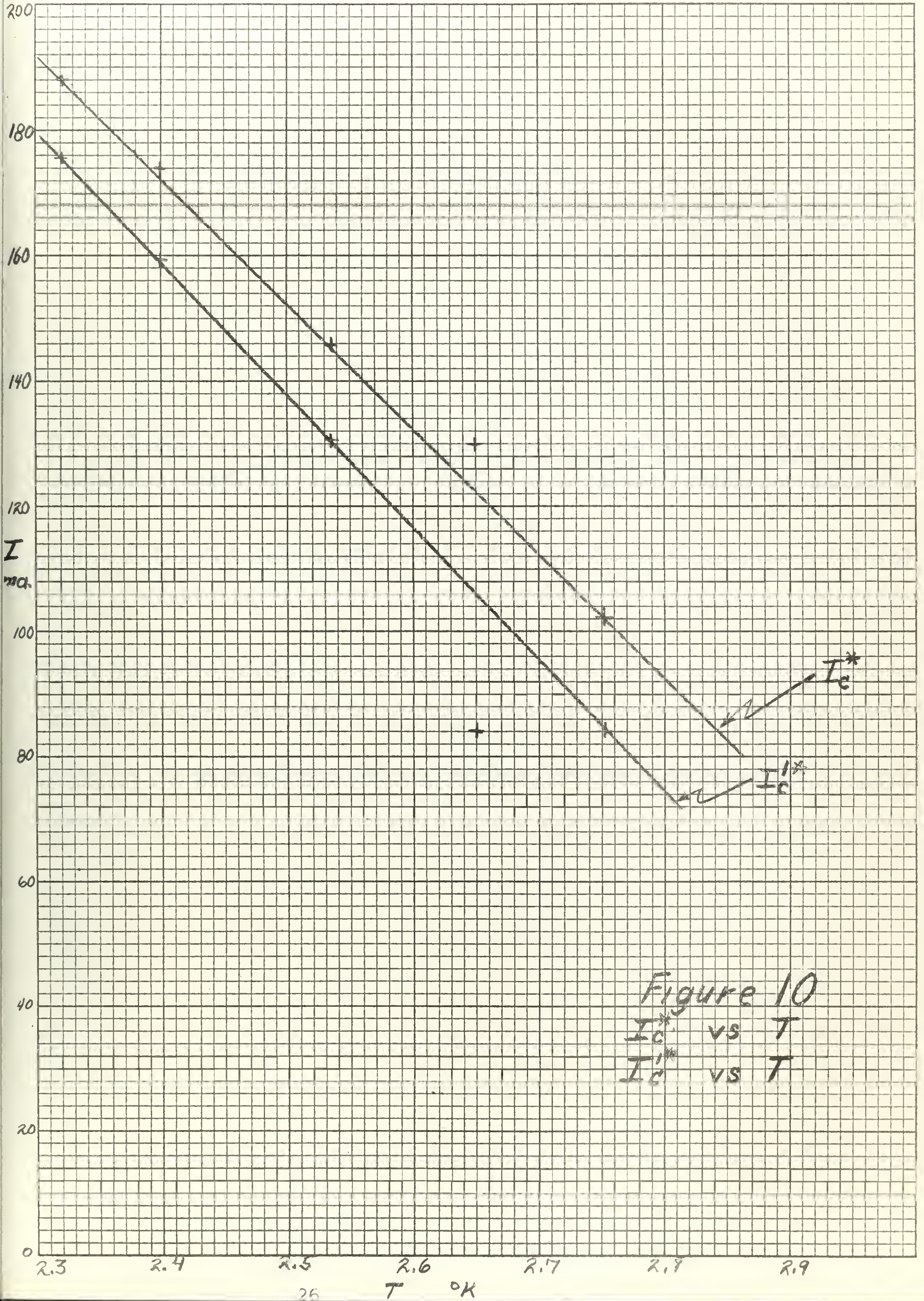


Figure 10

I_c^* vs T

$I_c'^*$ vs T

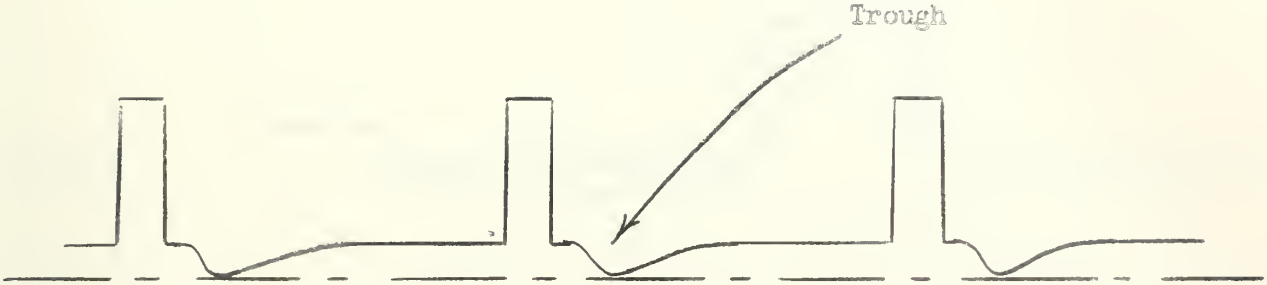


Figure 12

Typical Voltage Trace of Specimen, Resistive between Pulses

Superimposed

Separated

Figure 12

Diagram of Oscilloscope Trace Illustrating
Double Decay of Specimen Resistance

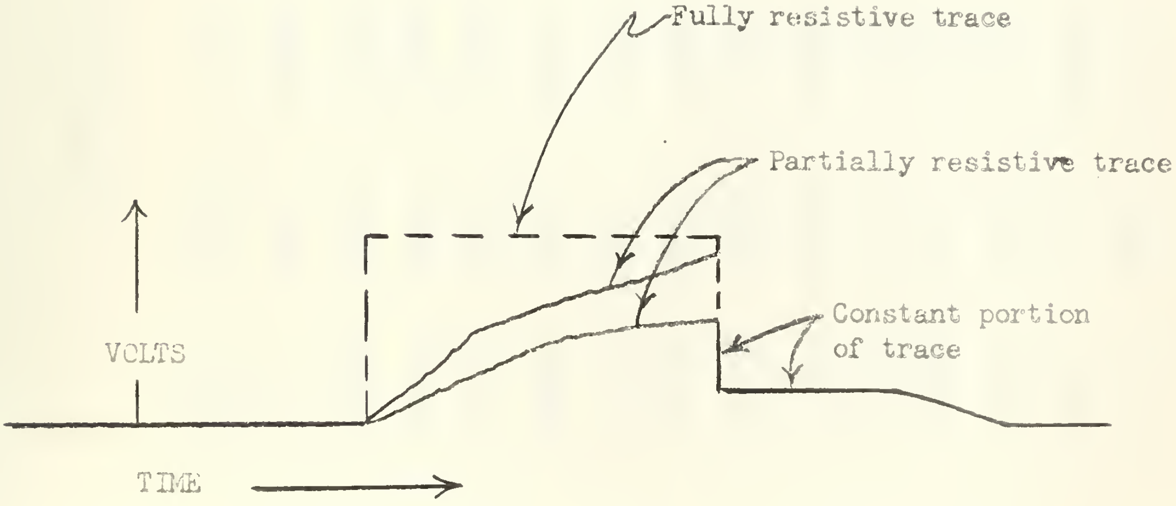


Figure 13

Diagram of Specimen Voltage at low Temperature

TABLE 1

Tabulation of Values Used in Computations

T (°K)	m (Fig 4)	m (corr)	T^2	I_{DC} in milliamperes at $\tau =$					τ_0
				0.5 μsec	1 μsec	3 μsec	5 μsec	7 μsec	(μ sec)
3.075	73.85	61.7	9.456	7.0	12.1	23.5	30.2	35.0	0.835
3.040	70.10	61.0	9.241	10.0	15.5	28.4	35.3	40.2	0.600
3.005	66.15	60.1	9.030	13.5	20.3	35.0	42.3	47.3	0.380
2.967	70.25	65.3	8.803	18.0	26.0	41.0	48.5	53.6	0.240
2.928	66.75	64.2	8.573	22.2	31.2	47.0	55.0	60.5	0.160
2.887	67.25	64.7	8.329	28.4	37.7	53.3	61.2	66.5	0.103
2.844	65.90	64.1	8.088	33.3	43.0	59.5	67.5	72.8	0.0725
2.799	66.15	64.8	7.834	39.5	49.1	66.0	73.9	79.0	0.0470
2.752	67.45	65.4	7.574	44.5	54.6	72.3	80.5	86.0	0.0332
2.703	61.85	61.0	7.306	49.8	60.8	78.3	87.0	92.6	0.0230
2.652	59.90	59.5	7.033	56.1	67.2	85.2	94.0	99.5	0.0154
2.596	59.70	59.5	6.739	64.8	74.2	94.0	102.5	108.0	0.0089
2.536	59.75	59.5	6.431	71.8	83.0	101.5	110.0	116.0	0.0059
2.470	62.30	62.1	6.101	80.8	90.1	110.0	118.8	124.3	0.00328

$\overline{m} = 62.7$

Table 2

Tabulation of Temperature - I_{DC} Relationships at Constant τ

τ (μ sec)	a	b
0.5	-45.1	9.63
1	-42.6	9.92
3	-38.8	10.4
5	-38.0	10.6
7	-37.7	10.8

Equation:

$$T^2 = aI_{DC} + b$$

(T in ^oK, I_{DC} in amperes)