DIELECTRIC RECOVERY OF SHORT A-C ARCS

BETWEEN HIGH-BOILING-POINT ELECTRODES

Thesis by

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SUMMARY

Continuing work done by an earlier investigator, the reignition characteristics of short arcs between copper and iron electrodes were studied in detail. Current, pressure, and arc length were varied to obtain curves of restriking voltage versus time at current zero. Data were obtained by making use of an oscillating circuit, varying the rate of rise of voltage across the arc terminals by varying the circuit constants, and observing and recording the voltage phenomena by the use of a cathode ray oscilloscope.

Results were obtained which check previous work on brass electrodes as to the kind of voltage recovery characteristic obtained for short arcs. The previously held theory that high melting point electrodes have a dielectric recovery directly proportional to arc length for short times, is shown to be false. An optimum arc length for dielectric strength for both copper and steel electrodes is seen to exist between 1.0 and 2.05 mm.. Temperatures calculated for the arc space agree in order of magnitude with results for earlier determinations.

The method used is held to be particularly appropriate, because average values were obtained in all cases, and results obtained with the apparatus were consistently checked over time intervals of more than two years.

The circuit used was the same as used by Dr. T. E. Browne, Jr.* The same method of obtaining the data was used and his thesis should be consulted for a more detailed analysis of the circuit.

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* Browne, "Dielectric Recovery of Short A-C Arcs between Low-Boiling-Point Electrodes", Thesis for Ph.D. degree, C.I.T., (1936).

I. INTRODUCTION

In a remarkable paper published in 1892,[1] Mr. A. J. Wurtz described his experimental discovery of the fact that metals fall into two main classes in their arc-supporting characteristics. Between electrodes of a metal of one group, he found that an arc burned freely with considerable noise, light, and movement. Metals of this group, including carbon, tin, and lead; iron, cobalt, and nickel; and copper and aluminum, all having boiling points between 1500°C. and 3600°C., he designated as "arcing" metals. Between electrodes of lower boiling point, such as zinc, cadmium, and mercury, he found that an arc was maintained with difficulty, and that if it did burn, there was little noise or light. These, he designated as the "non-arcing" metals and used their arc-quenching properties in a multigap type of lightning arrester. Mr. Wurtz was also the first to discover the almost paradoxical fact that as the electrode separation decreased, a higher voltage was required to maintain an arc between zinc or antimony electrodes.

Many workers have since studied this effect in more detail[2,3], showing some dependence on electrode boiling point and electrode separation. However, a satisfactory and complete theory of short-

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1. Wurtz, "Lightning Arresters", Trans. A.I.E.E. 9, p. 102 (1892).

2. Browne, "Extinction of Short A-C Arcs", Trans. A.I.E.E., 50, p. 1461, (1931).

3. Slepian and Strom, "Arc in Low-Voltage A-C Networks", Trans. A.I.E.E., 50, p. 847, (1931).

arc performance has not yet been proposed. As pointed out by Darrow[4], the work of many researchers in conduction in gases is of little or no use for purposes of correlation, because their data were taken under such varying conditions, and results often given with the omission of some necessary parameter information, that it cannot be correlated into a theory of arc performance. For example, much data have been taken on arcs between cylindrical electrodes as in the common carbon arc. In such cases the arc is usually bowed out at an edge so that no true figure can be used for arc length and actual separation of electrodes has little meaning.

Browne[5] with an exhaustive set of tests started a very systematic study on brass electrodes. Using the same apparatus built by Browne, the same set of tests was made by the author on copper and steel, two high boiling point metals, in an attempt to obtain further data on the subject. Current, electrode separation, and pressure were varied to obtain their effect on the restriking voltage of an arc. All results are given in the form of curves between arc reignition voltage and time after current zero. When the current goes through zero in an A-C arc, it does not immediately start flowing in the opposite direction. Instead a quite considerable voltage of the order of hundreds of volts is usually required to initiate current flow through the arc in the new direction.

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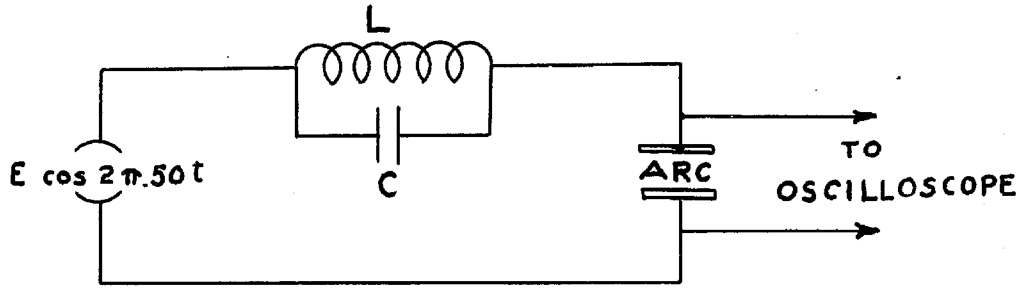
4. Darrow, "Electrical Phenomena in Gases", (a book) Williams & Wilkins Co. (1932).

5. Browne, "Dielectric Recovery of Short A-C Arcs between Low-Boiling-Point Electrodes", Thesis for Ph.D. degree, C.I.T., (1936).

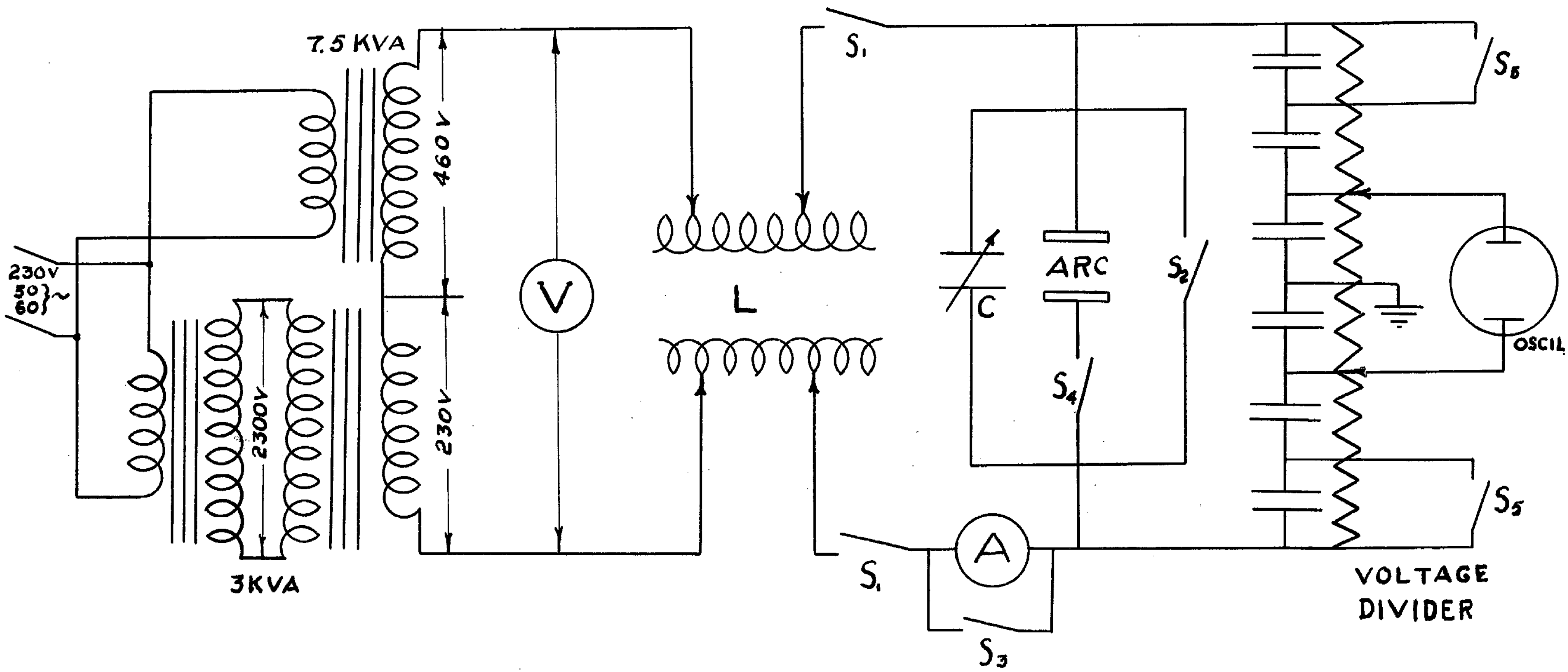
This is the voltage known as the reignition restriking, or recovery voltage. The rise of this voltage across the arc space is, of course, a function of the circuit parameters and time. The ability of an arc space to withstand breakdown; i.e., its dielectric strength, is also a function of time so that by varying the circuit constants, the time of breakdown of the arc space was varied, thus giving a measure of dielectric recovery with time.

This subject is of vital importance in electrical engineering. Short arcs are found in all circuit breakers, such as knife and snap switches used on low voltages and in fuses. In modern secondary networks the fault must burn clear. Present day industrial welding is a field intimately bound up with short-arc behavior. The deion circuit breaker and the autovalve lightning arrester are excellent examples of the use of the extinction characteristics of short arcs.



L
C
E cos 2π.50t
ARC
TO
OSCILLOSCOPE

Fig. 1.



7.5 KVA
460V
230V
230V
50
60
2300V
3KVA
V
L
S1
S1
C
ARC
S2
S4
A
S3
S5
S5
OSCIL
VOLTAGE
DIVIDER

Fig. 4.

II. THEORY

A most complete summary of the theories underlying and explaining short arc phenomena is to be found in Browne's thesis[5]. He has made use of seven principal references on the subject from 1923 to 1936 to give a comprehensive discussion and summary under the following heads:

1. Arc Reignition.
2. Space Charge Formation.
3. Dielectric Strength of Space Charge Sheath.
4. Conditions Affecting Dielectric Strength.
5. Rate of Dielectric Recovery.
6. Phenomena at the Anode.
7. Ionizing Activity.

There has been no departure in theory from those presented since 1936, so that it is felt unnecessary to reproduce this phase of the subject in this thesis.

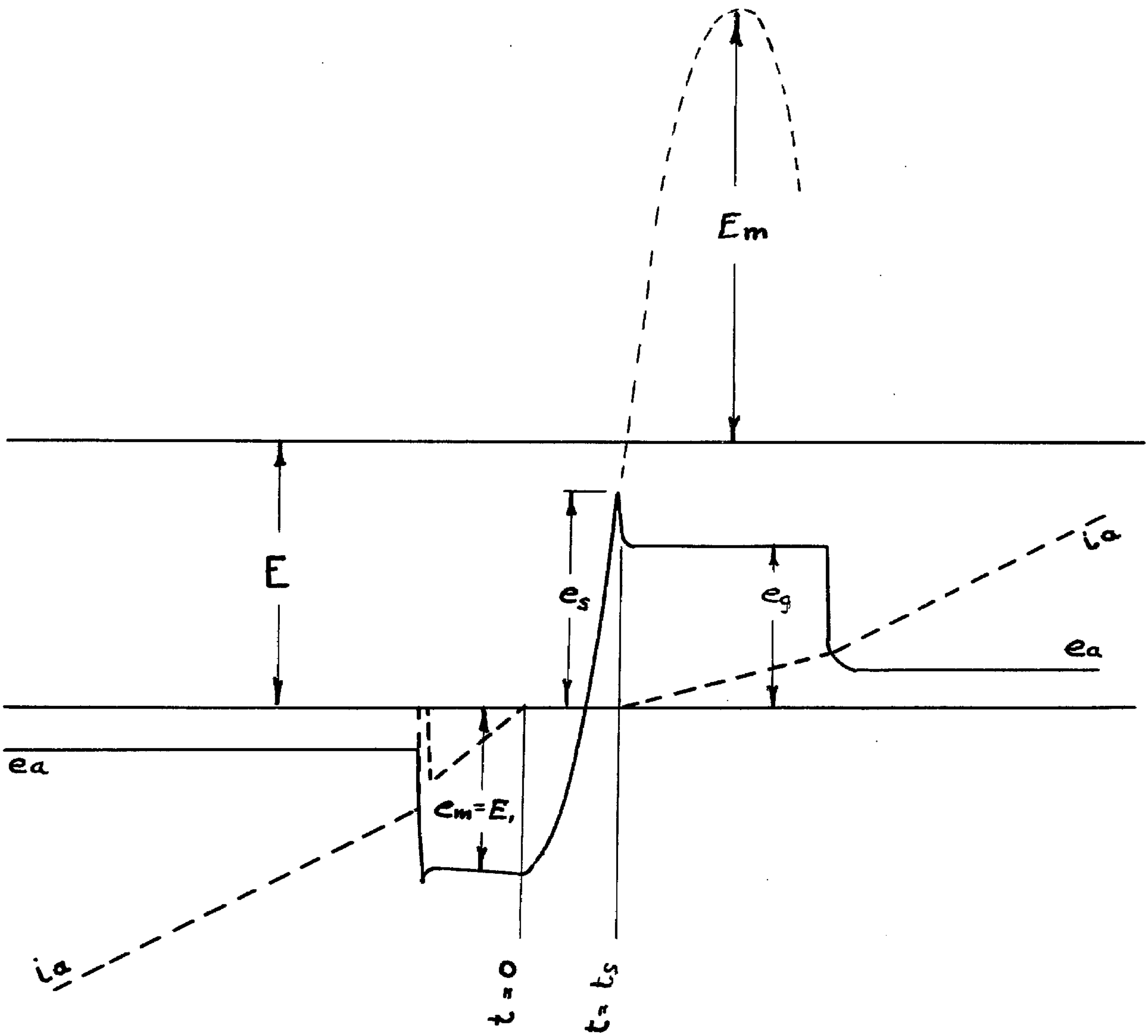


Fig. 2.

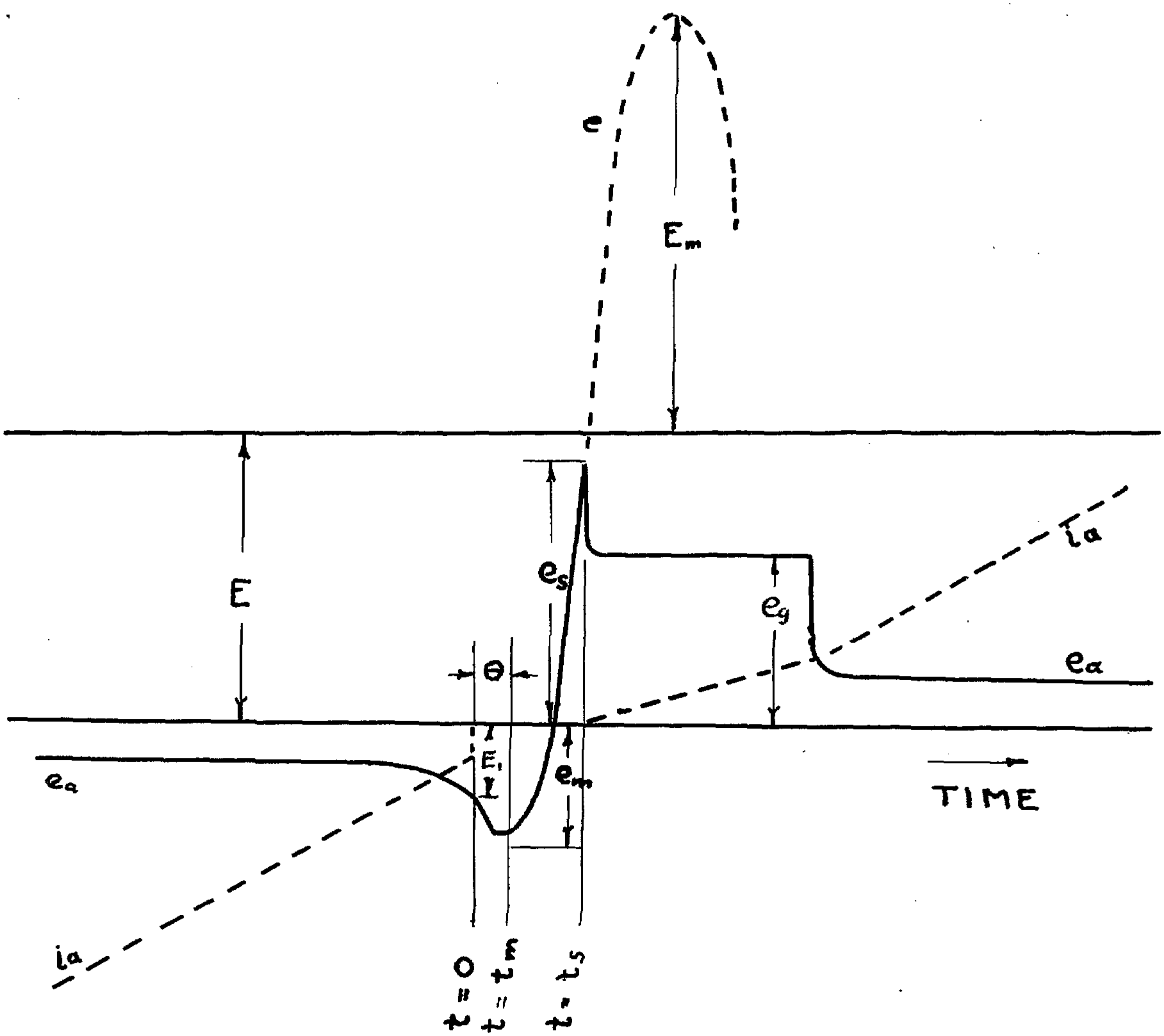


Fig. 3.

III. EXPERIMENTAL PROCEDURE

The apparatus used for the taking of data was the same as that used by Browne[5]. As shown in Fig. 1, current from a 690 volt circuit was limited by almost pure reactance, L, placed in series with the arc. All readings were taken in air on continuously-burning arcs between plane parallel metal electrodes. The metals were copper and steel; the currents 12.5, 25, and 50 amps.; the electrode separations 0.45, 1.0, 2.05, and 4.13 millimeters, and the pressures 1/4, 1/2, and 1 atmosphere. Condensance, C, (Fig. 4) was placed across the arc to vary the natural frequency of the circuit, and so give varying rates of voltage rise across the arc. A cathode ray oscilloscope of the Braun type (R.C. 104) with fluorescent screen was connected across the arc and gave a visual picture of the voltage wave at the time of current zero from which <u>AVERAGE</u> amplitude readings were taken.

The time relationships existing between supply voltage e_s, of maximum value E, arc voltage e_a, and arc current i_a, are shown in Fig. 2. Due to the very expanded scale of the figure, (the interval $t = o$ to $t = ts$, representing a maximum time of about 250 micro-seconds) the applied voltage which is at its maximum, appears as a horizontal straight line. Except near current zero, the current wave is a pure sine wave lagging the applied voltage by ninety degrees. As the arc current, approaching zero sinusoidally, reaches a small value of the order of 0.1 amps., it suddenly fails, falling immediately to zero, where it remains until a reignition voltage is reached so that at $t = t_s$ it starts to flow in the opposite sense.

The current in the inductance cannot drop instantly when the arc current fails and it surges into the capacity in the circuit, the reactors' distributed capacity which is in parallel with the capacity across the arc. Due to oscillations, then, the voltage across the inductance and capacity in parallel, rises from the value it had at $t = o$, to e_m at $t = t_m$ and e_s at $t = t_s$. The boundary conditions obtaining at $t = o$ are the values of E_1 the arc voltage and I_1 the arc current. The former is quite constant but the latter is subject to fairly large random variations with consequent variations in e_m.

At $t = t_s$ reignition occurs, the voltage across the arc falls to the glow voltage, and a glow discharge characterized by low current density and high cathode drop occurs. As the current increases, the glow turns into an arc the current then follows a sine wave and the arc voltage remains substantially constant for the next half cycle.

From $t = o$ to $t = t_s$ the arc voltage can be computed quite simply by the circuit equations since the current is zero. This has been done by Attwood, Dow and Krausnick[6]. See Appendix A.

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6. Attwood, Dow and Krausnick, "Reignition of Metallic A-C Arcs in Air", Trans. A.I.E.E., 50, p. 949, (1931).

$$e_a = E - E_m \cos(w\,t + \theta)$$

where e_a = the arc voltage during the period of $t = o$ to $t = t_1$.

E = maximum value of the applied A-C wave.

$E_m = E - e_m$ = amplitude of the voltage oscillation about E.

$w = 2\pi \frac{1}{\sqrt{LC}}$ = 2π times the natural frequency of the circuit.

e_m = the negative maximum of the oscillation.

$\theta = \tan^{-1} \frac{I_1/wC}{E - E_1}$ = the phase angle by which the negative maximum lags behind the time $t = o$.

The above equation can be solved for t_s by substituting e_s for e and obtain:-

$$t_s = \sqrt{LC} \quad \cos^{-1} \frac{E - e_s}{E - e_m} + \tan^{-1} \sqrt{\frac{E - e_m}{E - E_1} - 1}$$

With L in henries, C in microfarads, - t is given in microseconds.

Two kinds of negative maxima occur; viz. the negative glow, and the no-glow cases. The former is shown in Fig. 2 and occurs when the current fails earlier in the cycle and so drops from a larger negative value to zero. The negative electrode voltage falls very sharply to a sufficient value to produce a negative glow which lasts for a few microseconds. The same effect occurs for low values of C, as may be seen from the equations:

$$|e_m| = |E_m| - |E|$$

and

$$E_m = \sqrt{(E - E_1)^2 + \left(\frac{I_1}{W\,C}\right)^2}$$

so that an increase in I_1 or a decrease in C both tend to increase E_m and e_m. For this negative glow case, the initial voltage E_1 is identical with the negative maximum e_m, so that the inverse tangent term disappears in the expression for ts and

$$t_s = \sqrt{LC} \quad \cos^{-1} \frac{E - e_s}{E - e_m} \quad .$$

For each value of arc current and gap spacing, readings were taken, with values of capacity across the arc from zero to the highest possible at which the arc was stable. For each of these readings t_s was calculated and plotted against e_s giving a curve of reignition voltage versus time after current zero.

The method used for obtaining the data plotted on the accompanying curves was to adjust the gap spacing and current to the desired values. The value of the condenser, C, (Fig. 4) was then varied. This change in the value of the condenser changed the time required for the voltage to reach its reignition potential. This is the time t_s. Knowing the value of the condenser and of the inductance, the time t_s was calculated from the equation alone.

IV. RESULTS.

Results are given for copper electrodes under the following Figure numbers:-

COPPER ELECTRODES

	Separation	Pressure in Atmos.			Fig. Nos.
Effect of Current	4.13 mm.	1	1/2	1/4	5,6,7
	2.05 mm.	1	1/2	1/4	8,9,10
	1.0 mm.	1	1/2	1/4	11,12,13
	0.45 mm.	1	1/2	1/4	14,15,16
	Separation		**Current**		**Fig. Nos.**
Effect of Pressure	4.13 mm.	50,	25,	12.5	17,18,19
	2.05 mm.	50,	25,	12.5	20,21,22
	1.00 mm.	50,	25,	12.5	23,24,25
	0.45 mm.	50,	25,	12.5	26,27,28
	Pressure		**Current**		**Fig. Nos.**
Effect of Arc Length	1 atmosphere	50,	25,	12.5	29,30,31
	1/2 "	50,	25,	12.5	32,33,34
	1/4 "	50,	25,	12.5	35,36,37

Figures 38 and 39 are representative curves which are given to show the correlation between the actual data and the curves drawn through them.

A. Copper Electrodes

1. Data

Figures 5 to 38 show 34 sets of curves. In all, 589 readings were taken on copper, - about 15 points making up one curve. About 90 of these readings were made to re-check data in order to make certain that the apparatus gave consistent results and to check probable mistakes.

Data were taken for all possible combinations of 50, 25, and 12.5 amps.; 4.13, 2.05, 1.0, and 0.45 mm.; and pressures of 1, 1/2, and 1/4 atmosphere. It was impossible to get consistent results with 50 amps. at 1 atmos. and 0.45 mm. separation, though a portion of the curve is shown.

The number of curves is too large to include them all on separate sheets, so that the results are given under three main heads:-

(1) Figures 5 to 16 show the effect of current on dielectric recovery;

(2) Figures 17 to 28 show the effect of pressure, and;

(3) Figures 29 to 37 show the effect of arc length.

Figures 38 and 39 are submitted to show how, in general, calculated points agree with the final curve drawn through them. They are representative examples. In all cases the curves drawn follow the data points very closely.

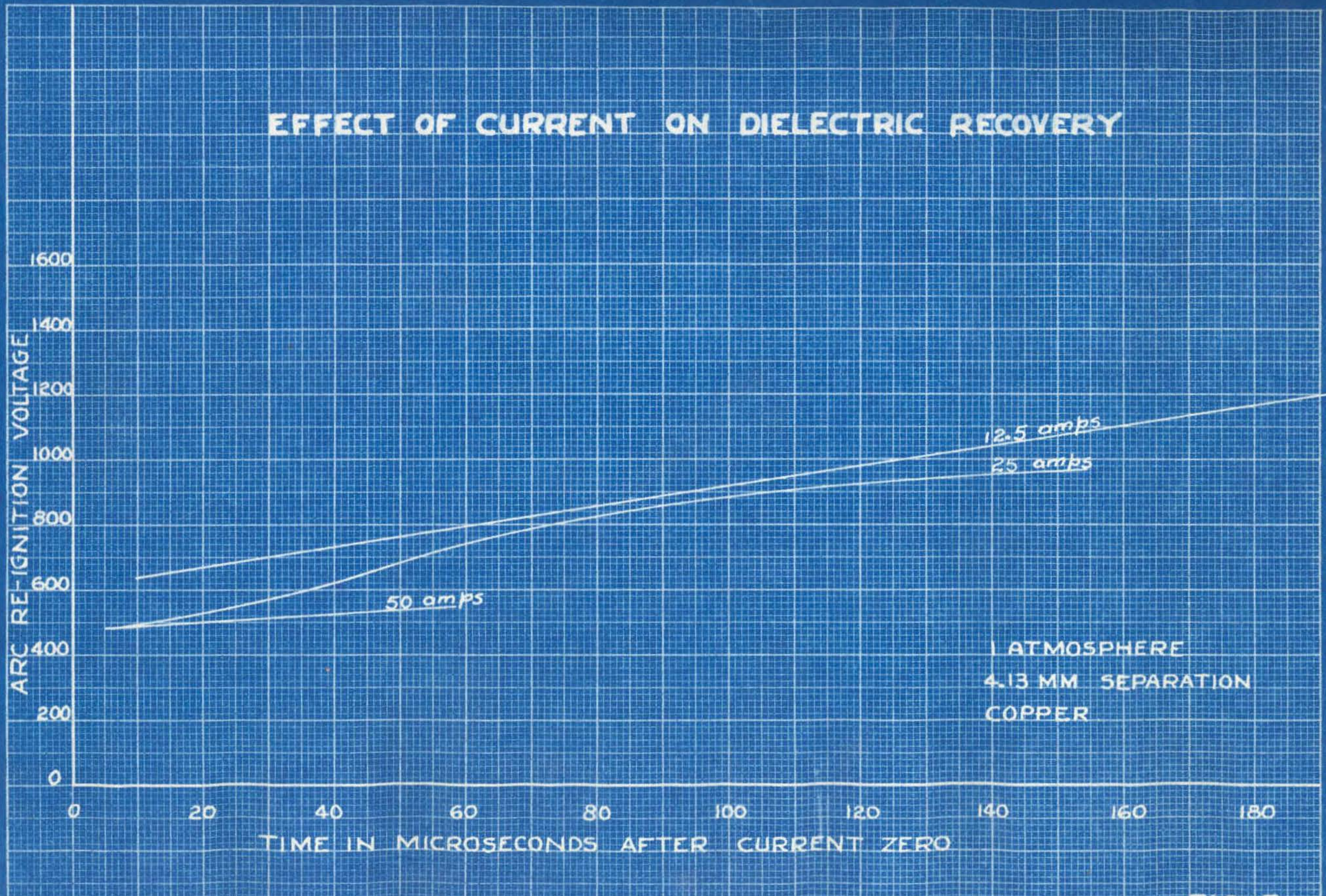

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
12.5 amps
25 amps
50 amps
1 ATMOSPHERE
4.13 MM SEPARATION
COPPER

FIG. 5.

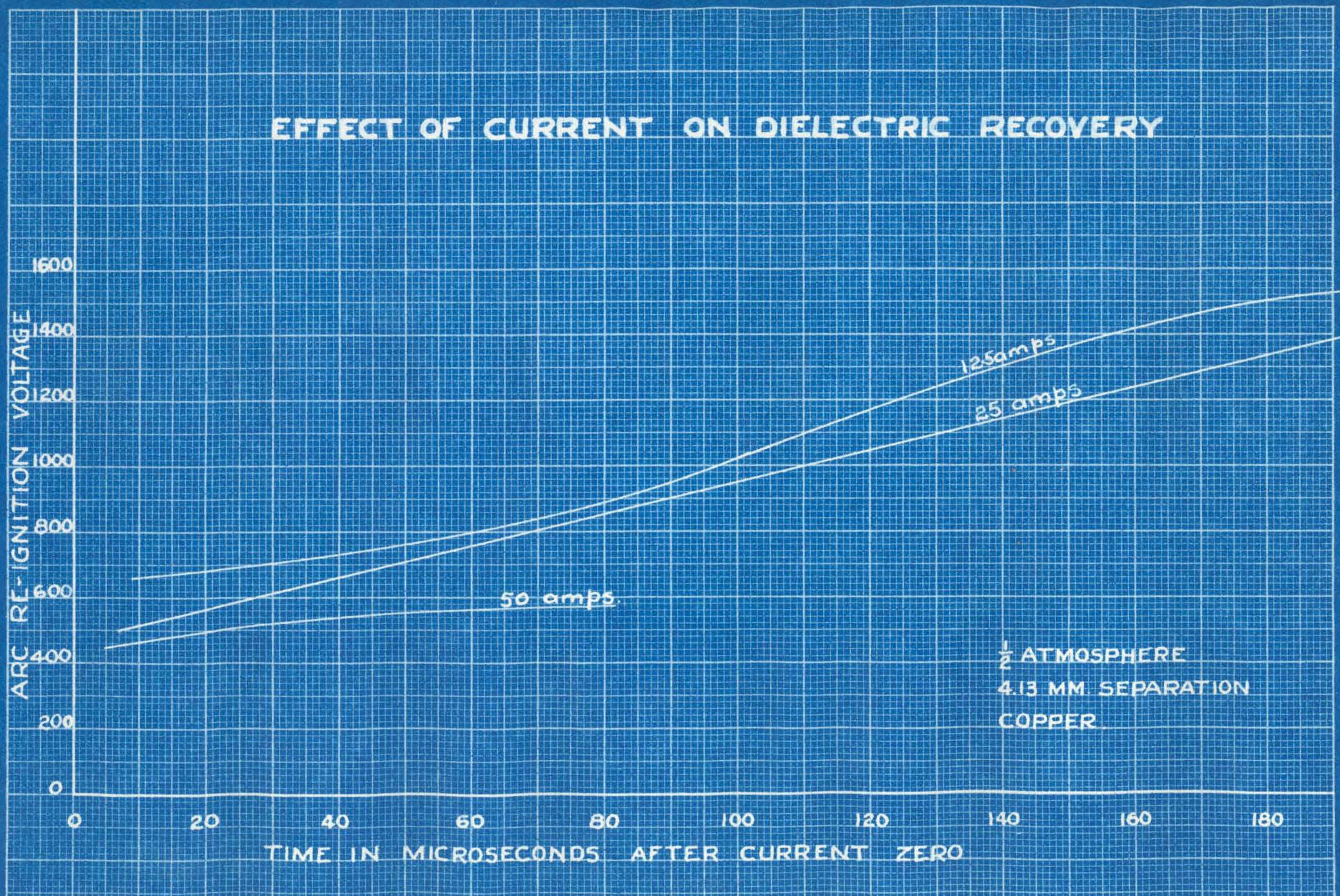

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
12.5 amps
25 amps
50 amps.
½ ATMOSPHERE
4.13 MM. SEPARATION
COPPER.

FIG. 6.

EFFECT OF CURRENT ON DIELECTRIC RECOVERY

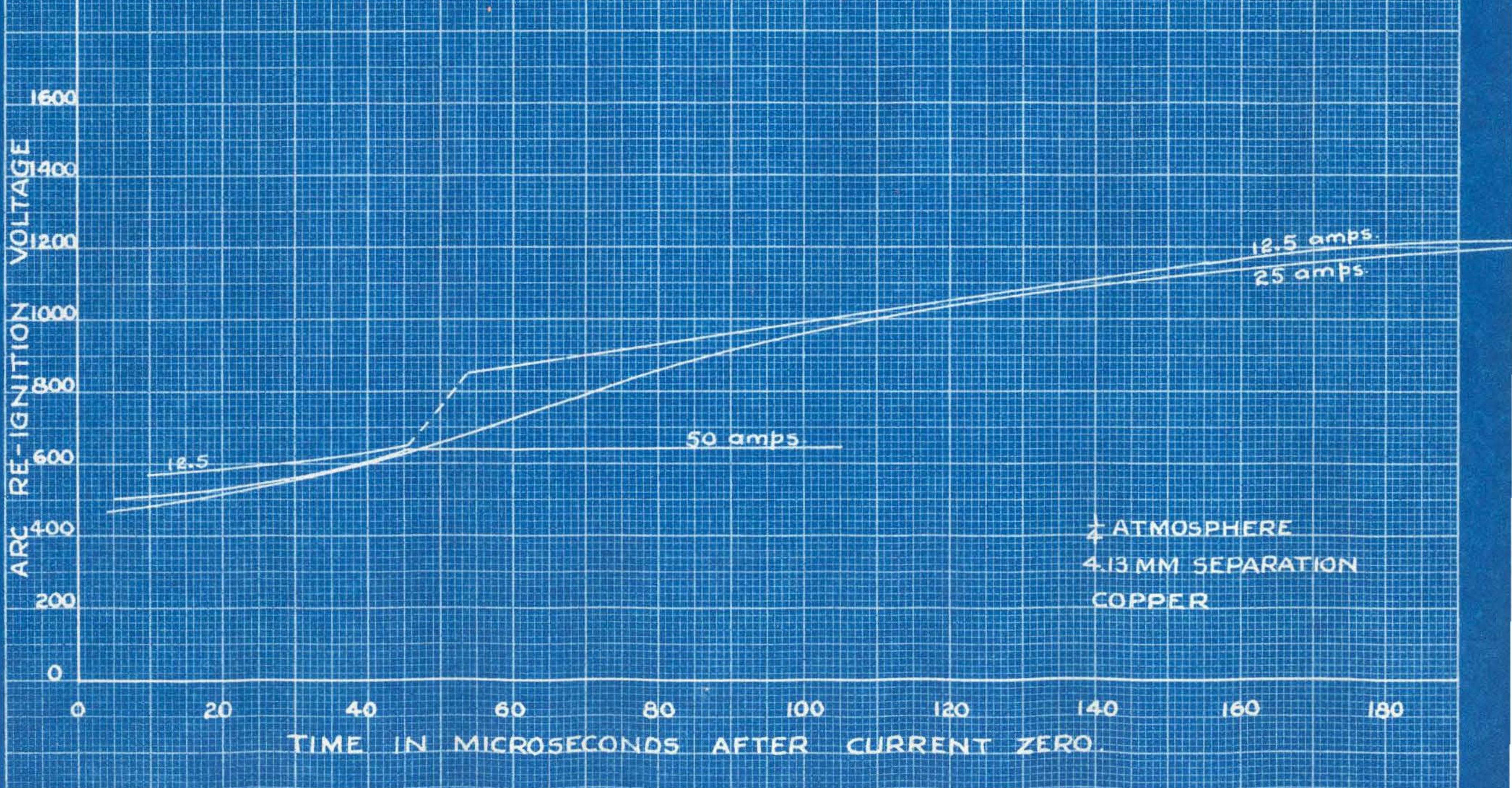


FIG. 7.

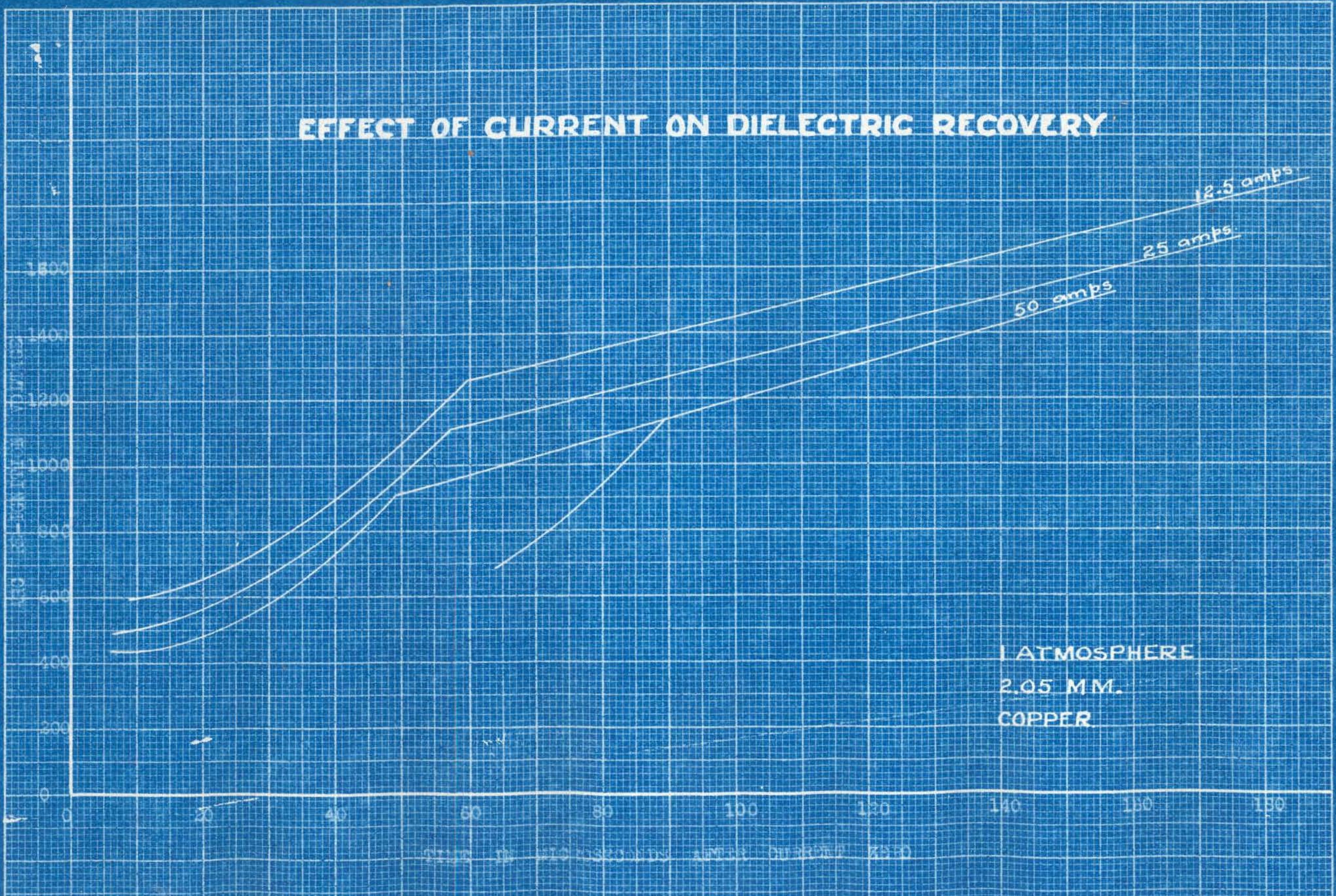

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
12.5 amps
25 amps
50 amps
1 ATMOSPHERE
2.05 MM.
COPPER
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 8.

EFFECT OF CURRENT ON DIELECTRIC RECOVERY

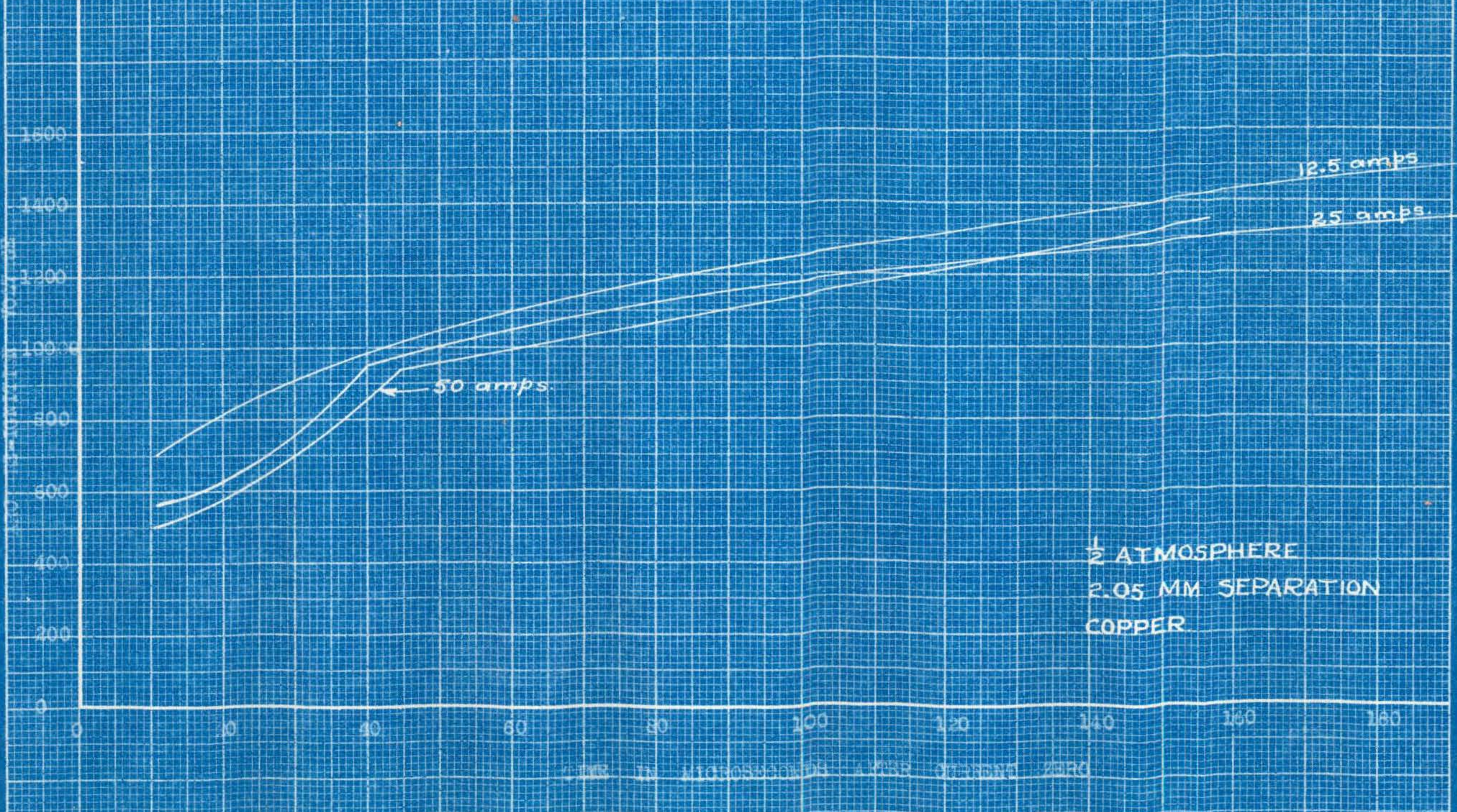


FIG. 9.

EFFECT OF CURRENT ON DIELECTRIC RECOVERY

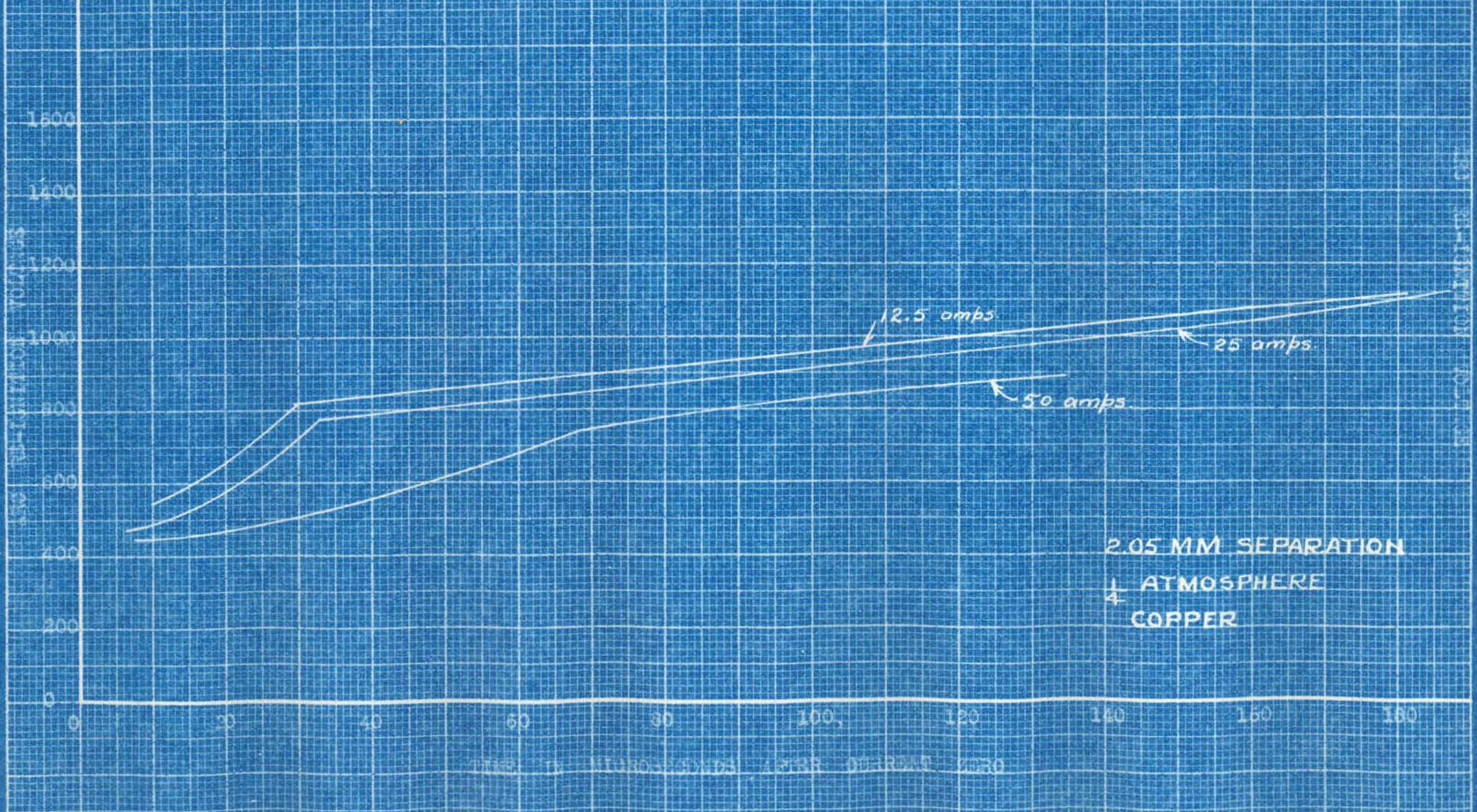


FIG. 10.

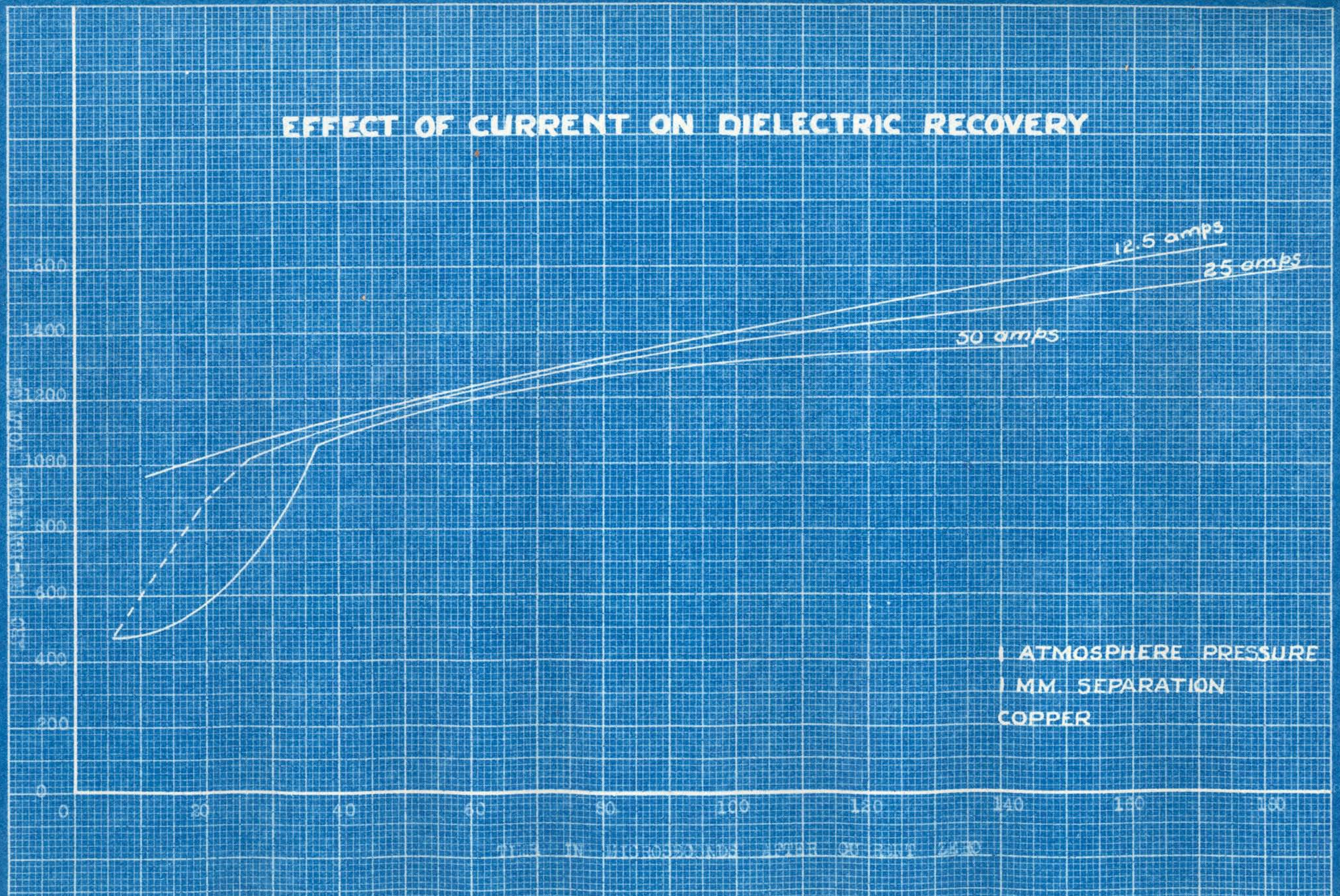

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
12.5 amps
25 amps
50 amps
1 ATMOSPHERE PRESSURE
1 MM. SEPARATION
COPPER
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 11.

EFFECT OF CURRENT ON DIELECTRIC RECOVERY

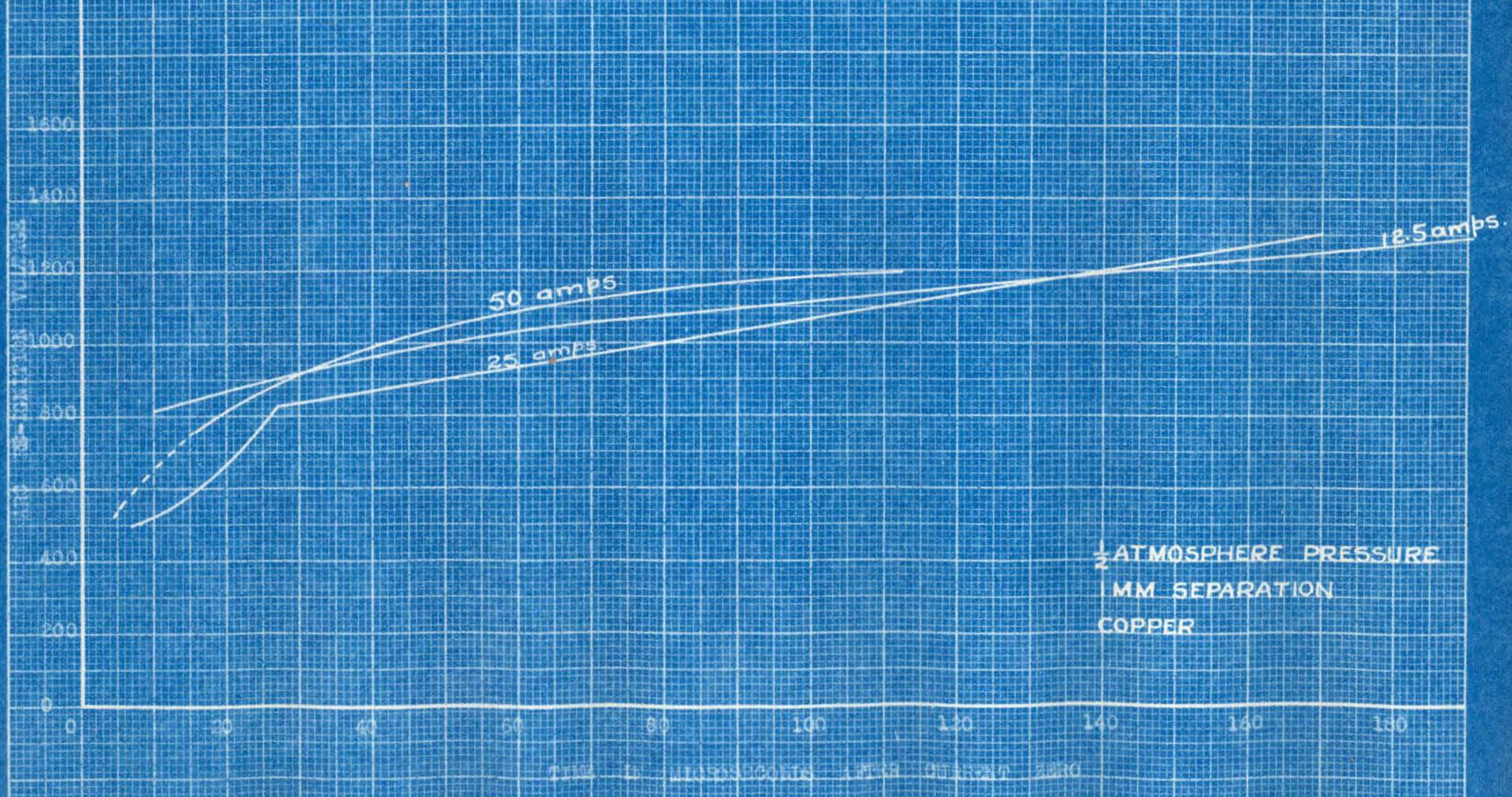


FIG. 12.

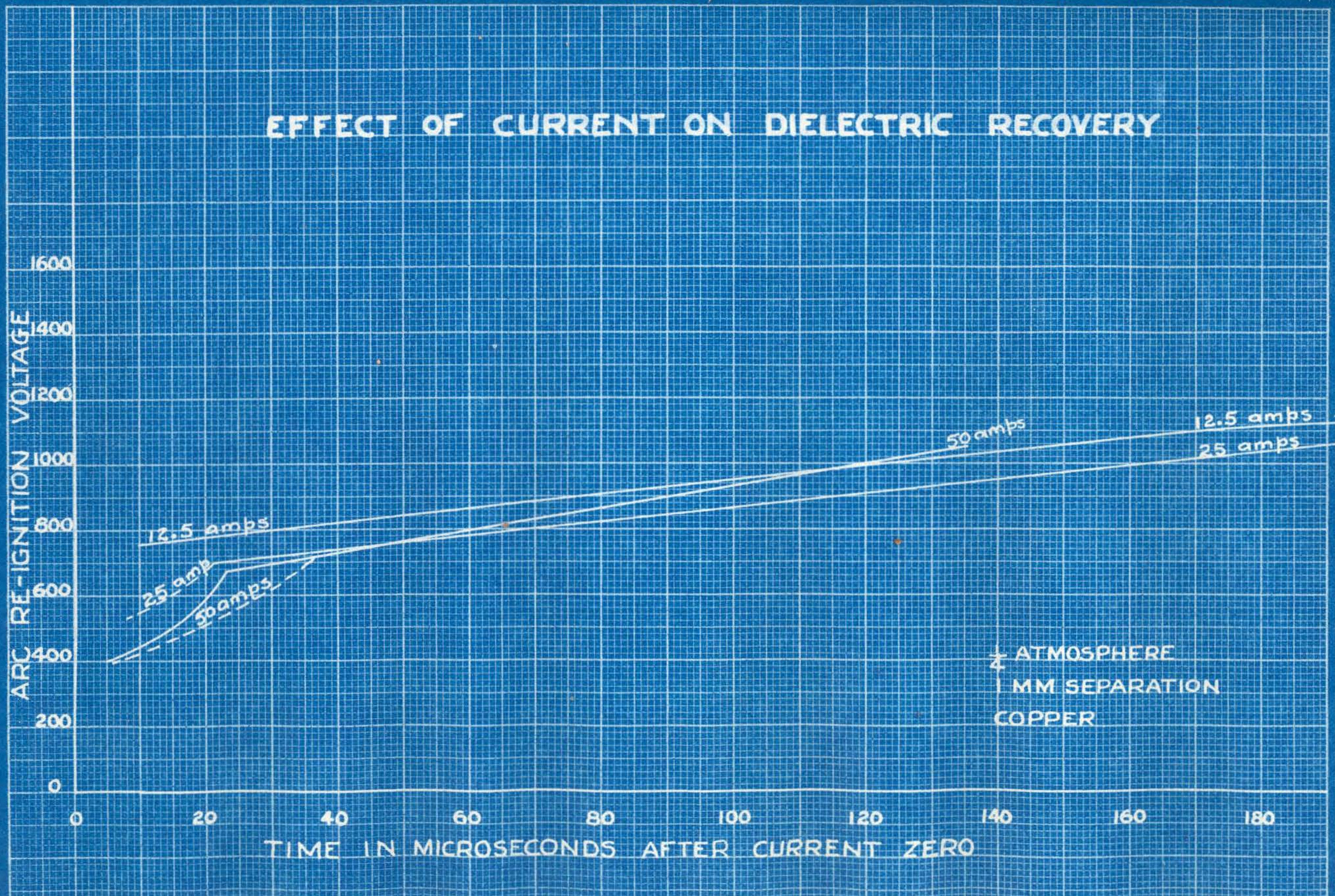

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
12.5 amps
25 amp
50 amps
50 amps
12.5 amps
25 amps
1/4 ATMOSPHERE
1 MM SEPARATION
COPPER

FIG. 13.

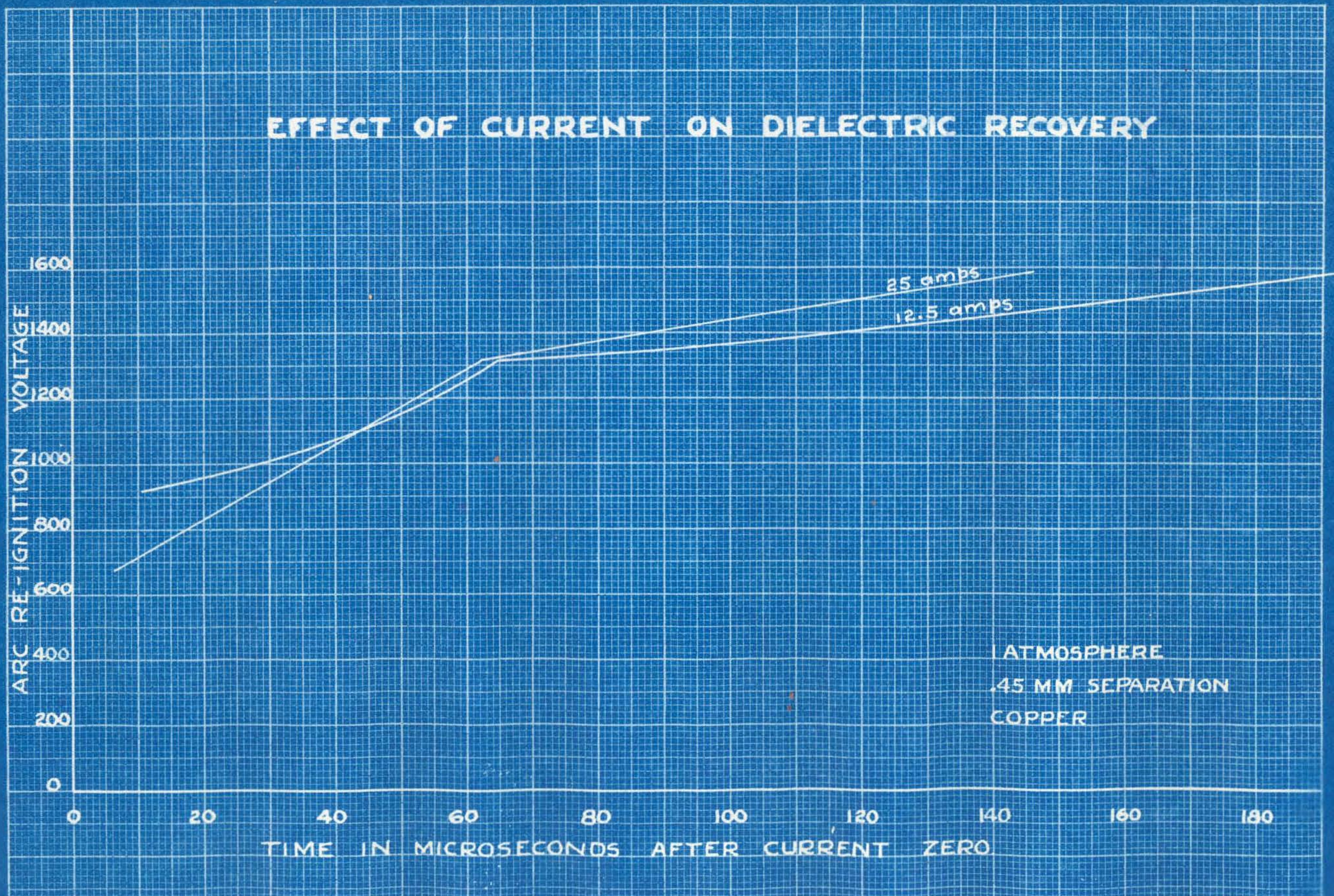
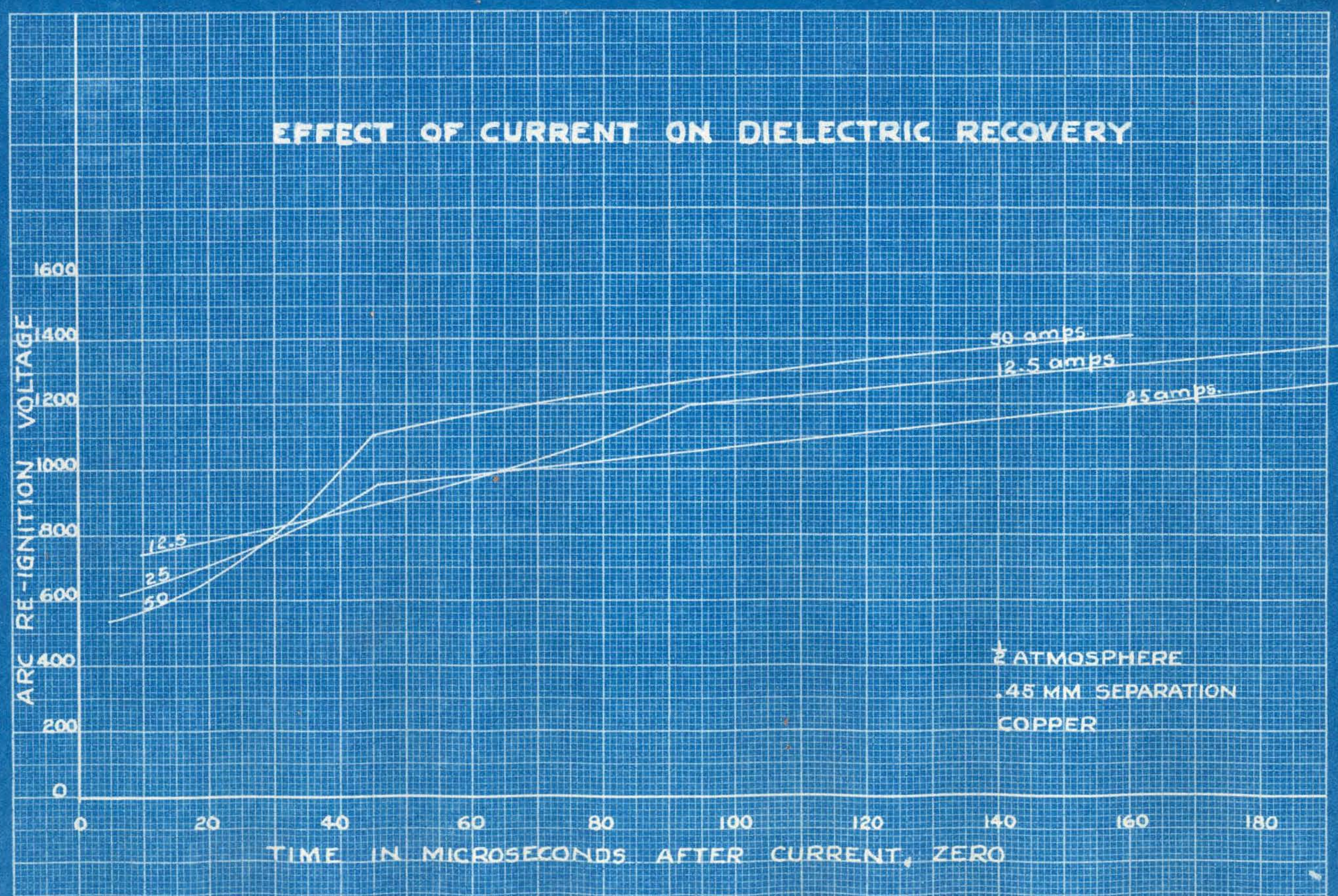
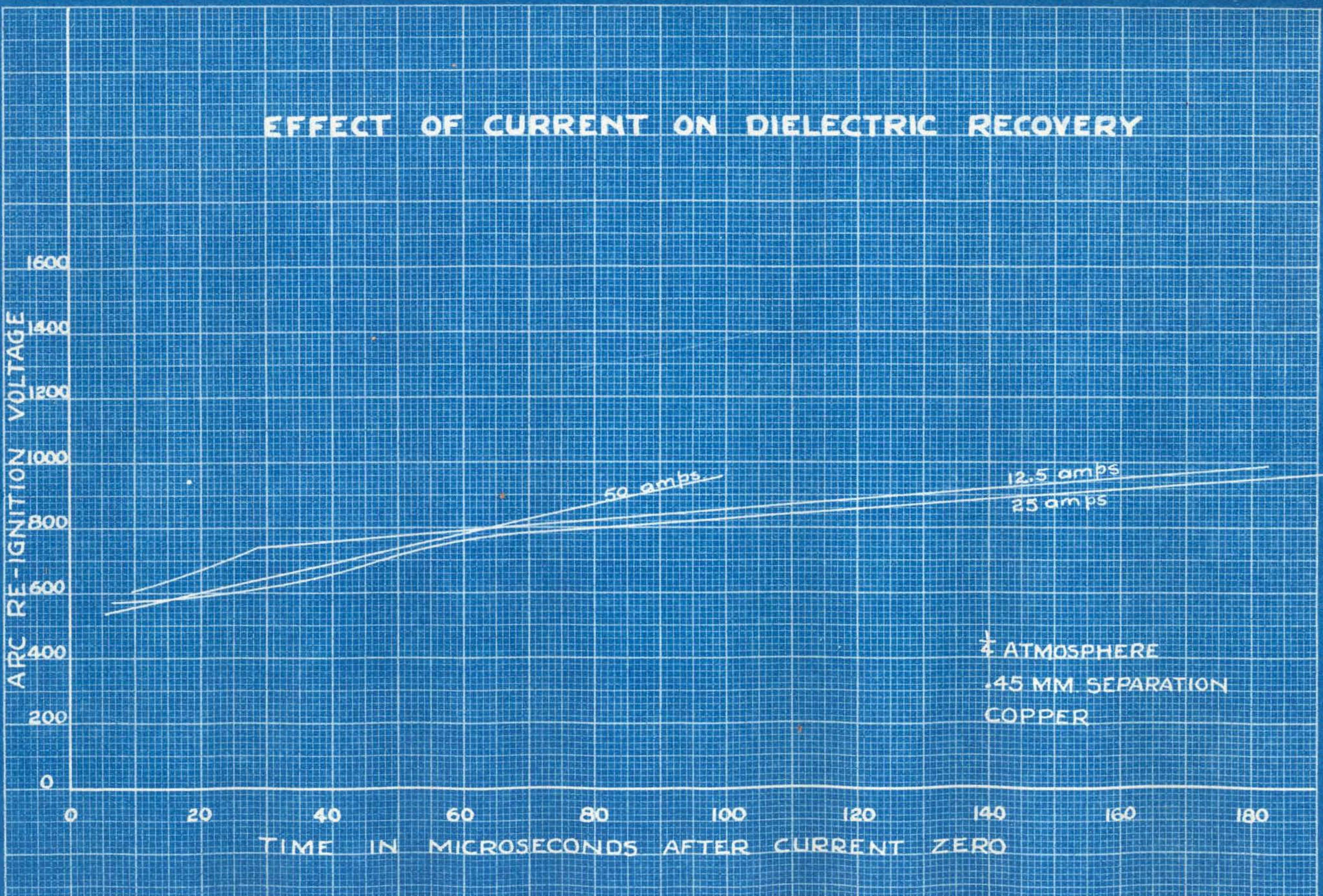

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
25 amps
12.5 amps
1 ATMOSPHERE
.45 MM SEPARATION
COPPER

FIG. 14.



EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
50 amps.
12.5 amps.
25 amps.
12.5
25
50
½ ATMOSPHERE
.45 MM SEPARATION
COPPER

FIG. 15.


EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
50 amps
12.5 amps
25 amps
¼ ATMOSPHERE
.45 MM SEPARATION
COPPER
FIG. 16.

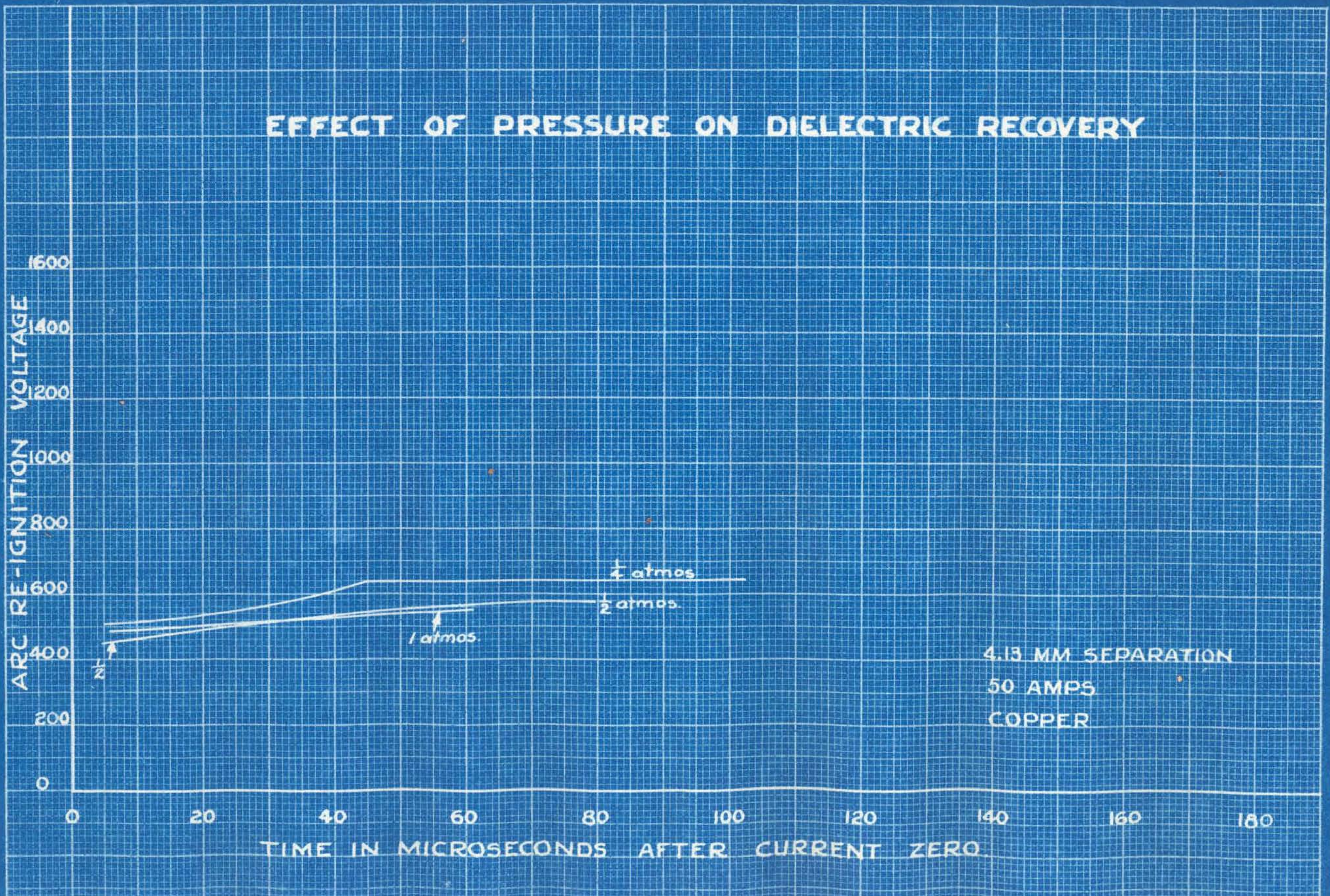

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
$\frac{1}{4}$ atmos
$\frac{1}{2}$ atmos.
1 atmos.
$\frac{1}{2}$
4.13 MM SEPARATION
50 AMPS
COPPER

FIG. 17.

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

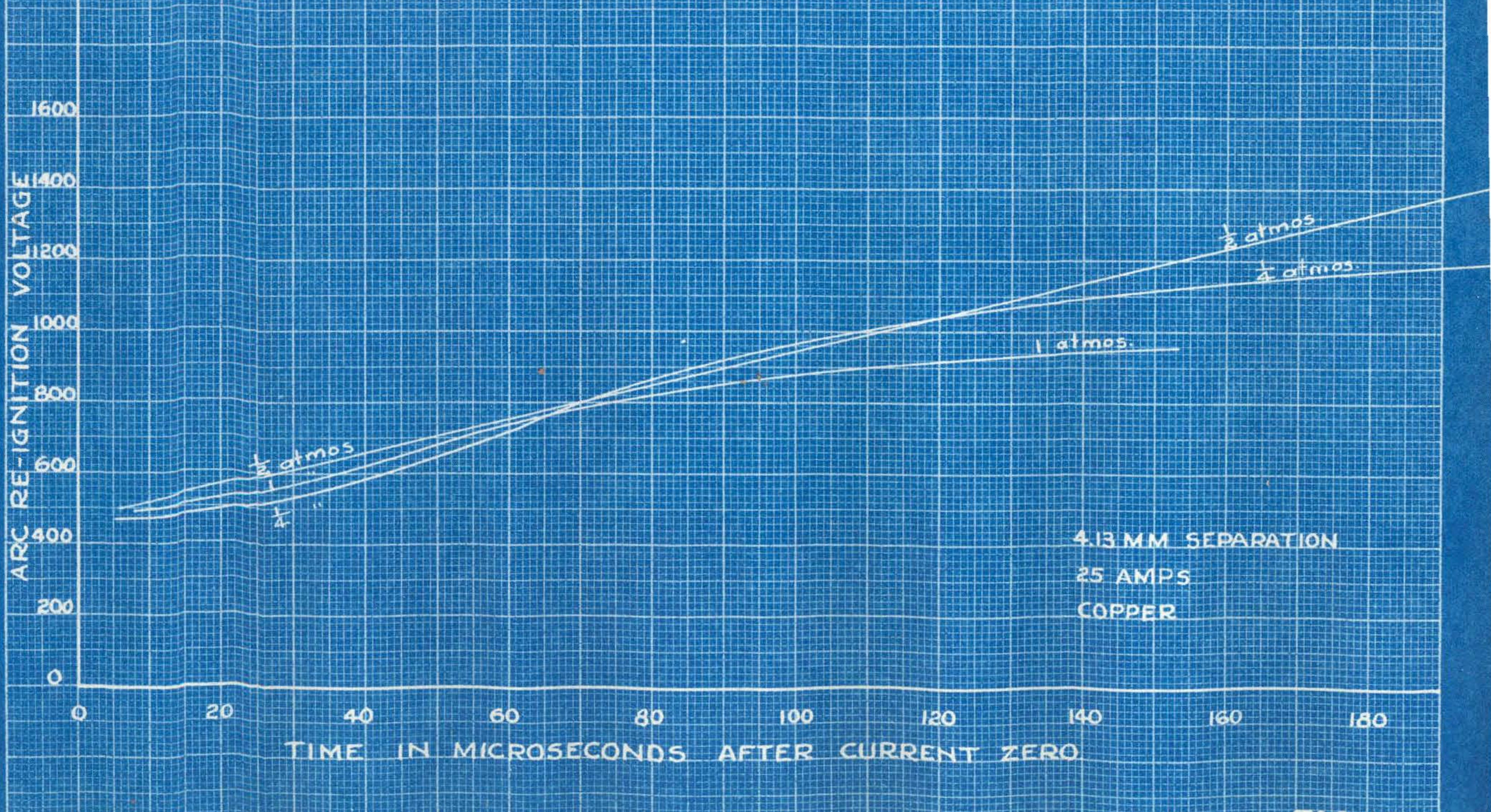


FIG. 18.

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

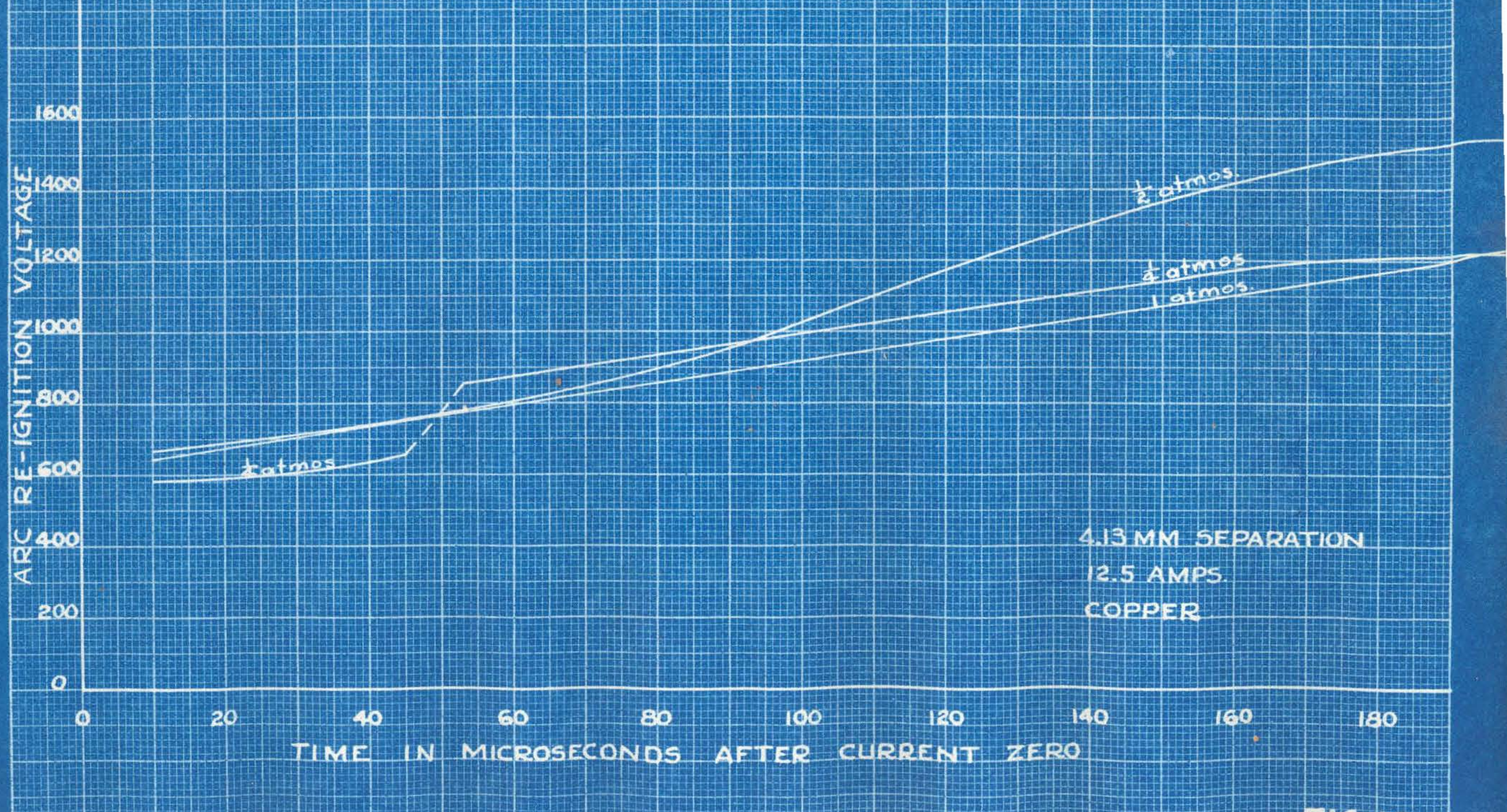


FIG. 19.

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

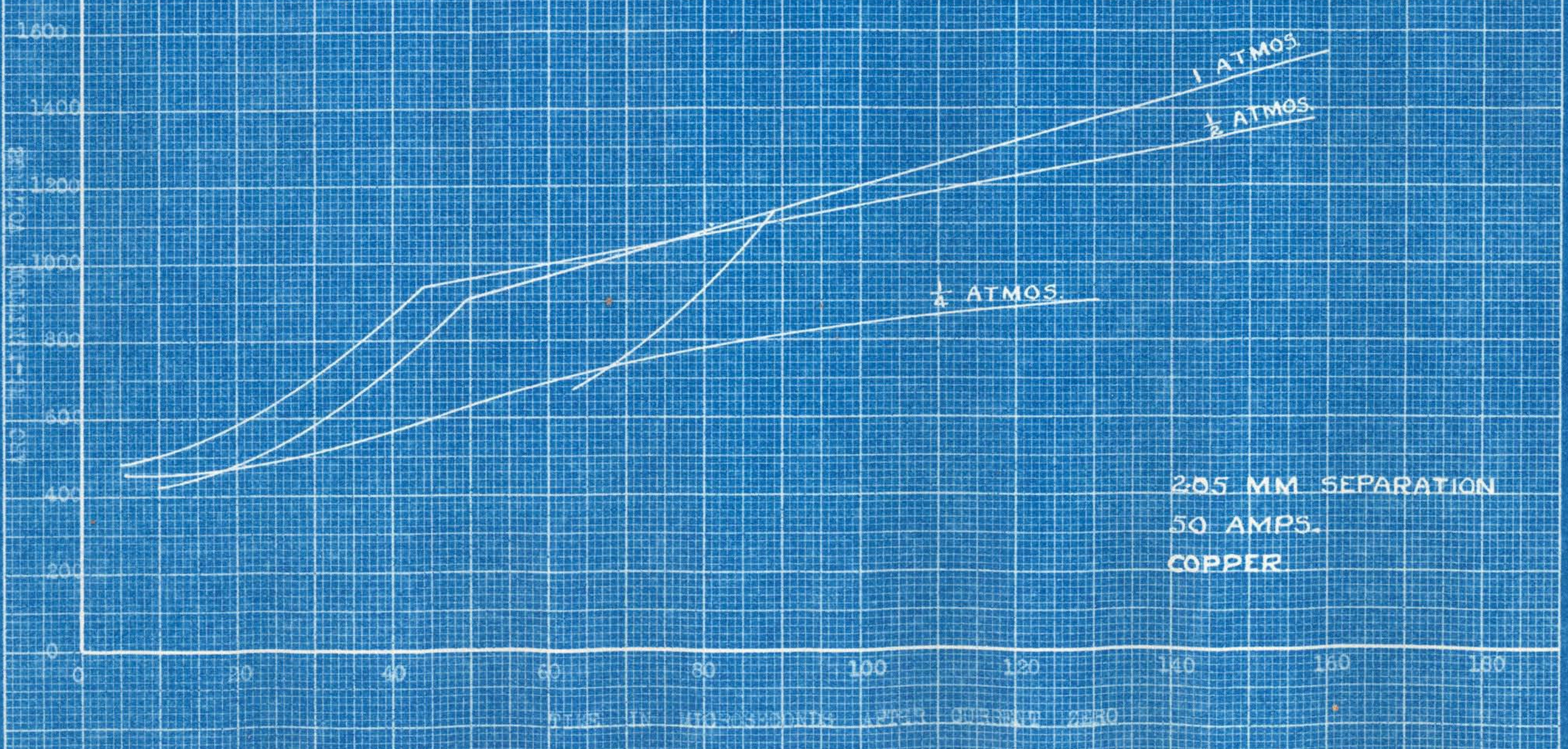


FIG. 20.

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

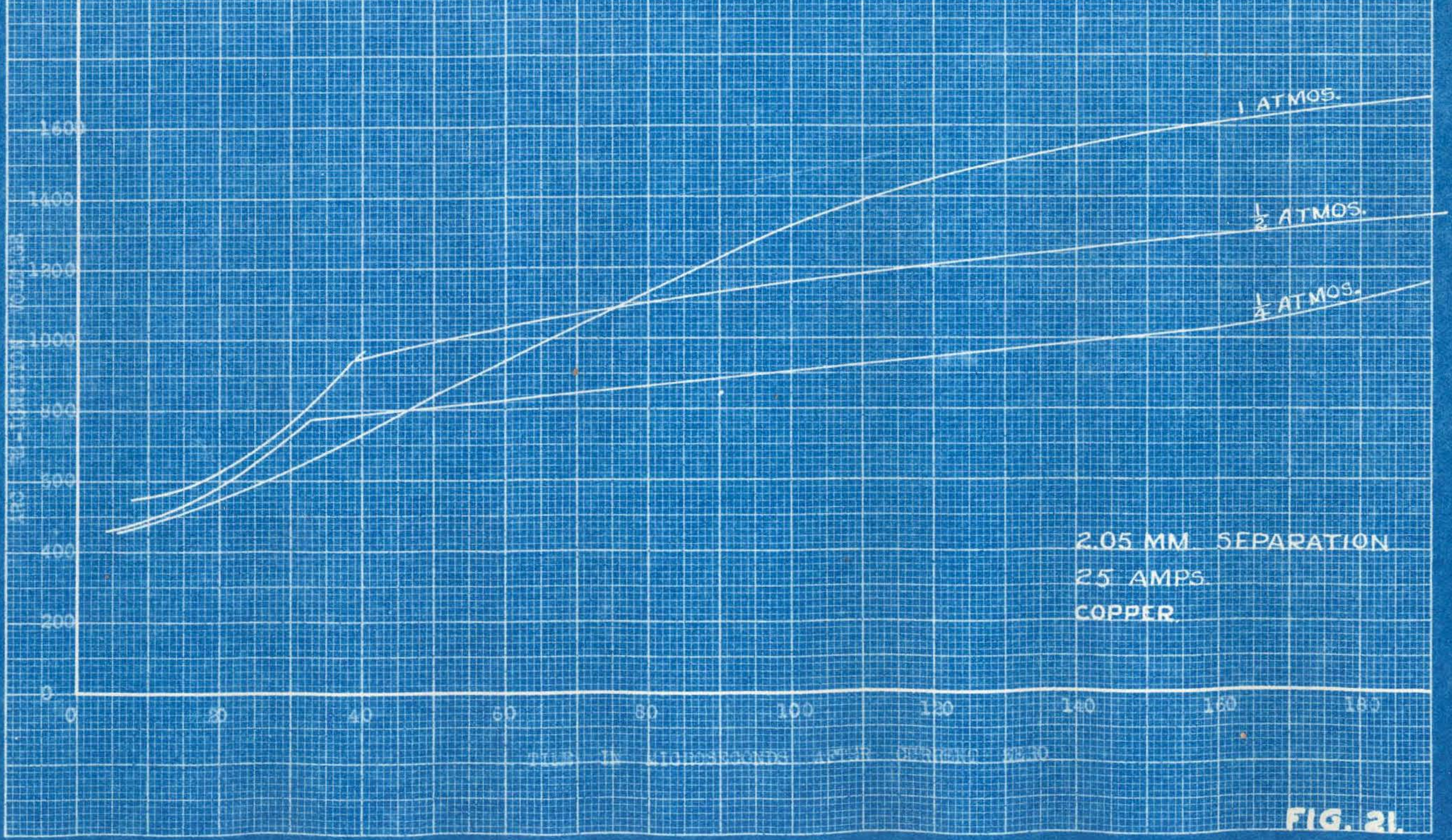
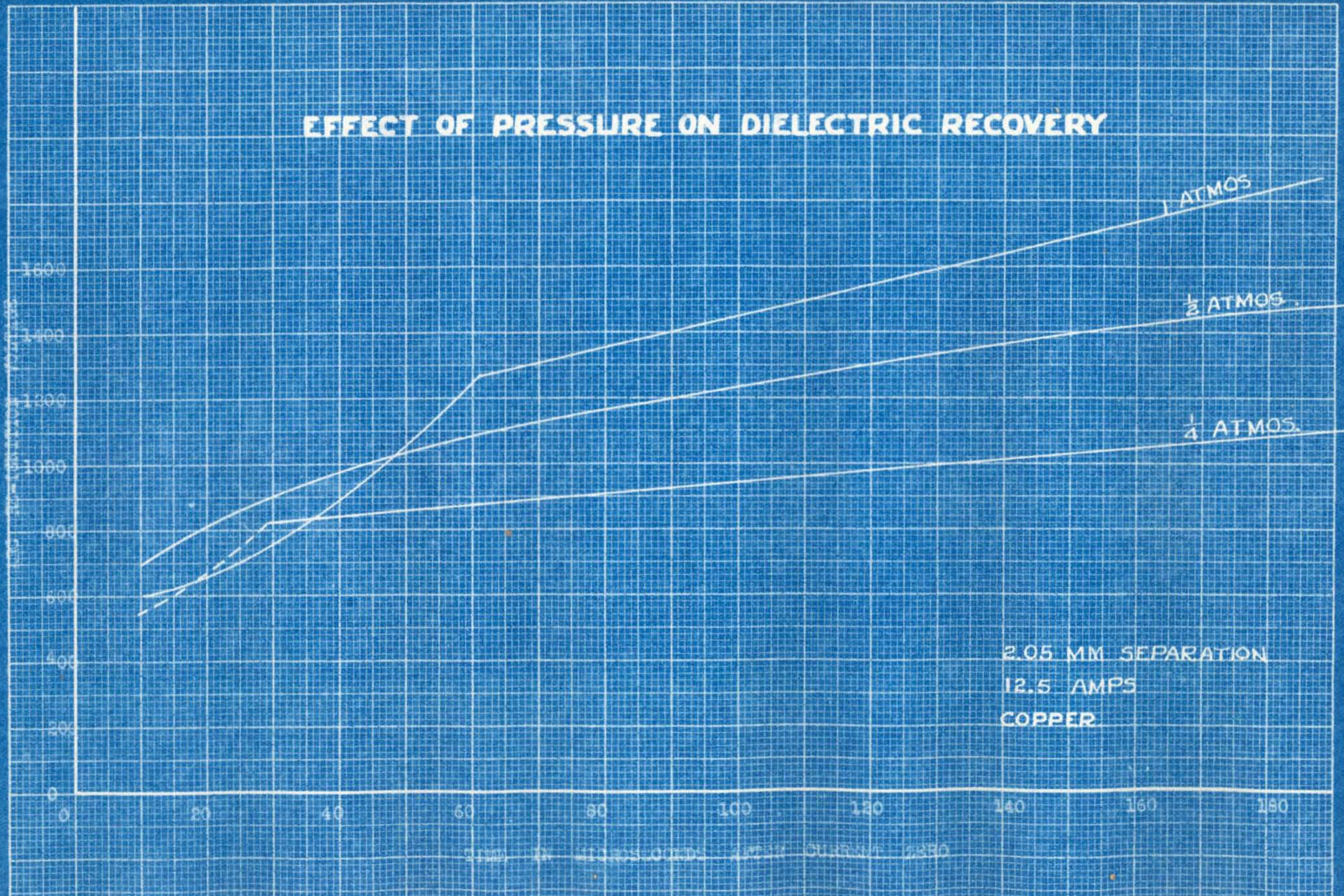


FIG. 21.



EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
1 ATMOS
½ ATMOS.
¼ ATMOS.
2.05 MM SEPARATION
12.5 AMPS
COPPER
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 22.

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

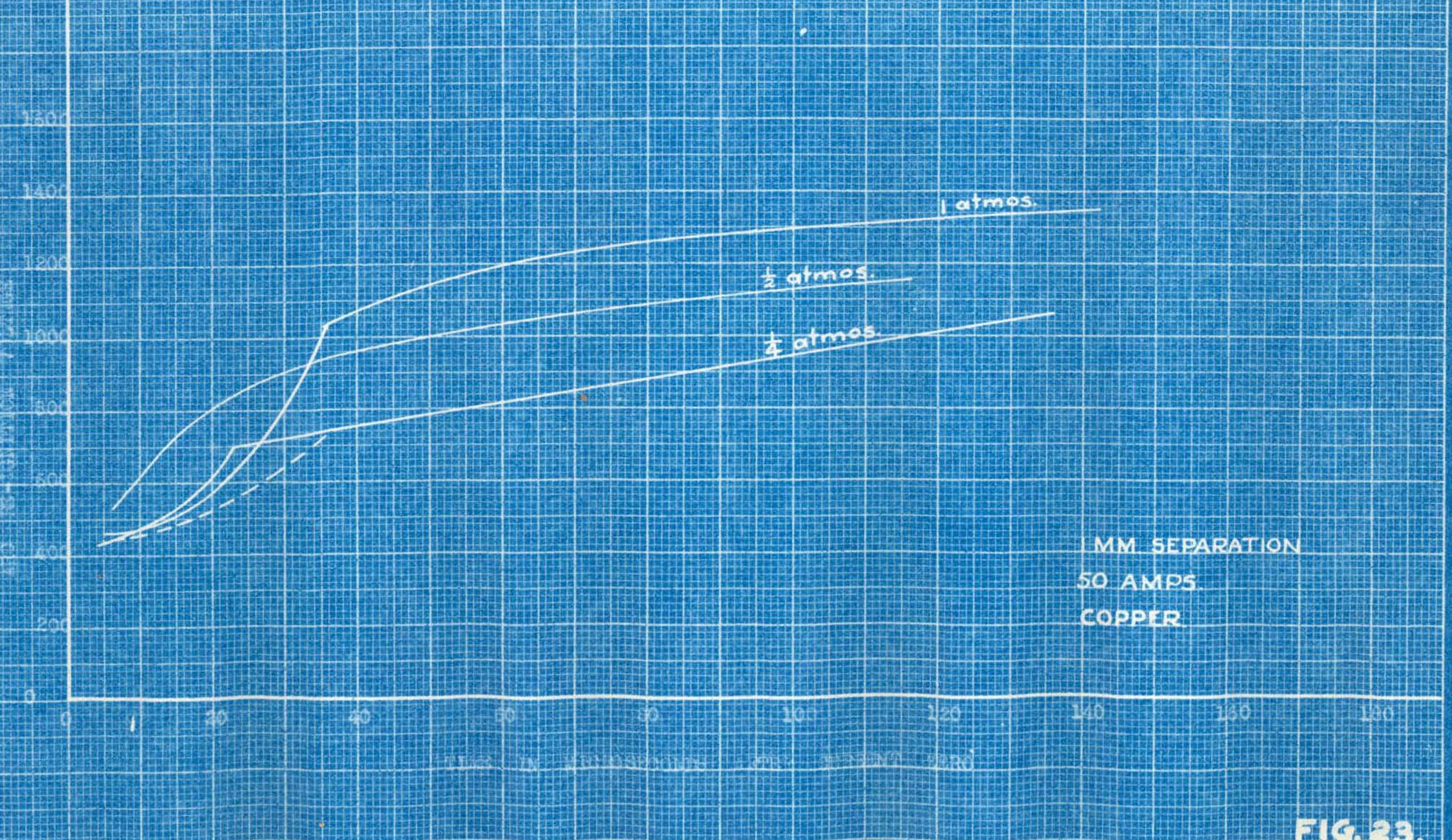


FIG. 23.

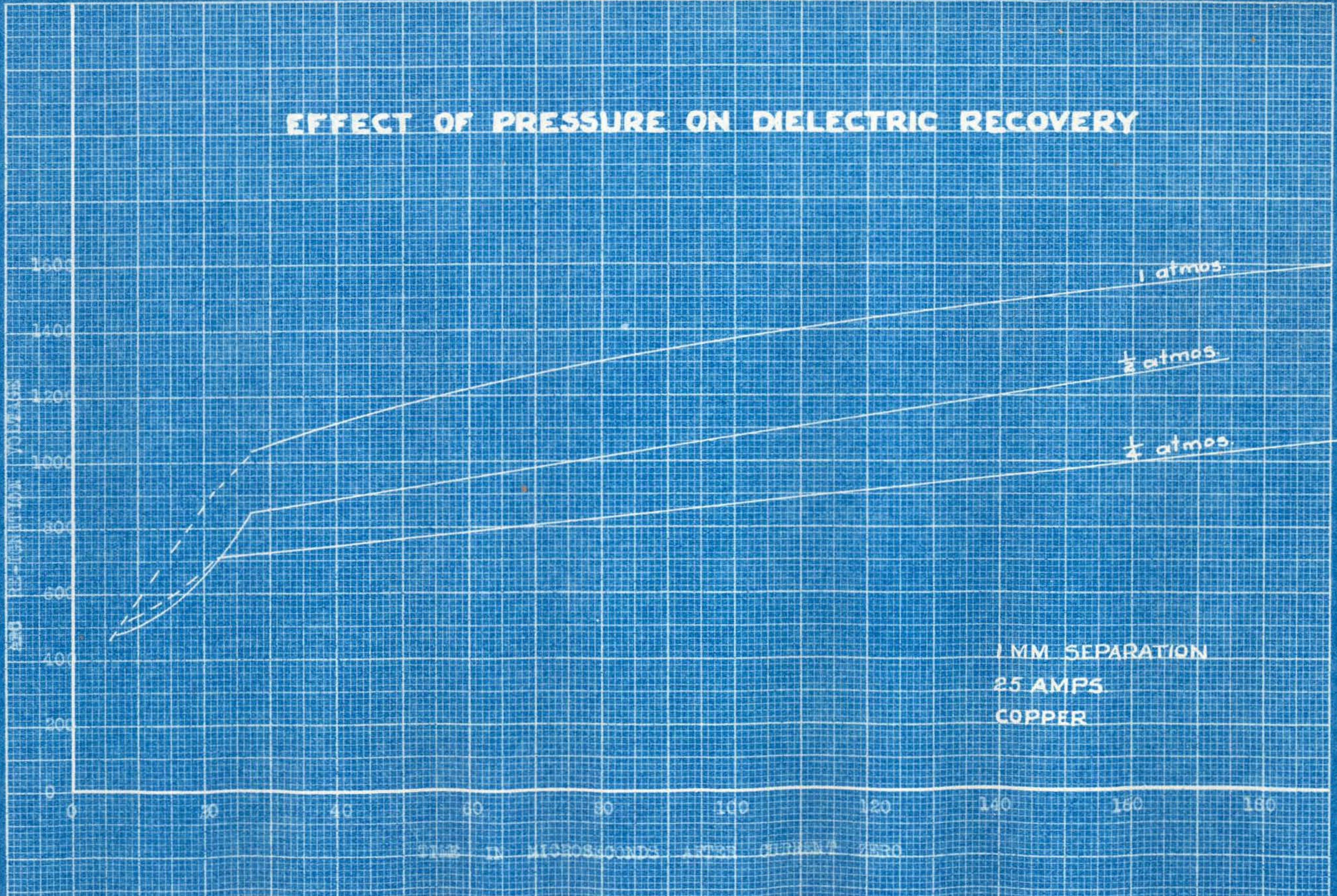

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
1 atmos.
½ atmos.
¼ atmos.
1 MM SEPARATION
25 AMPS
COPPER

FIG. 24.

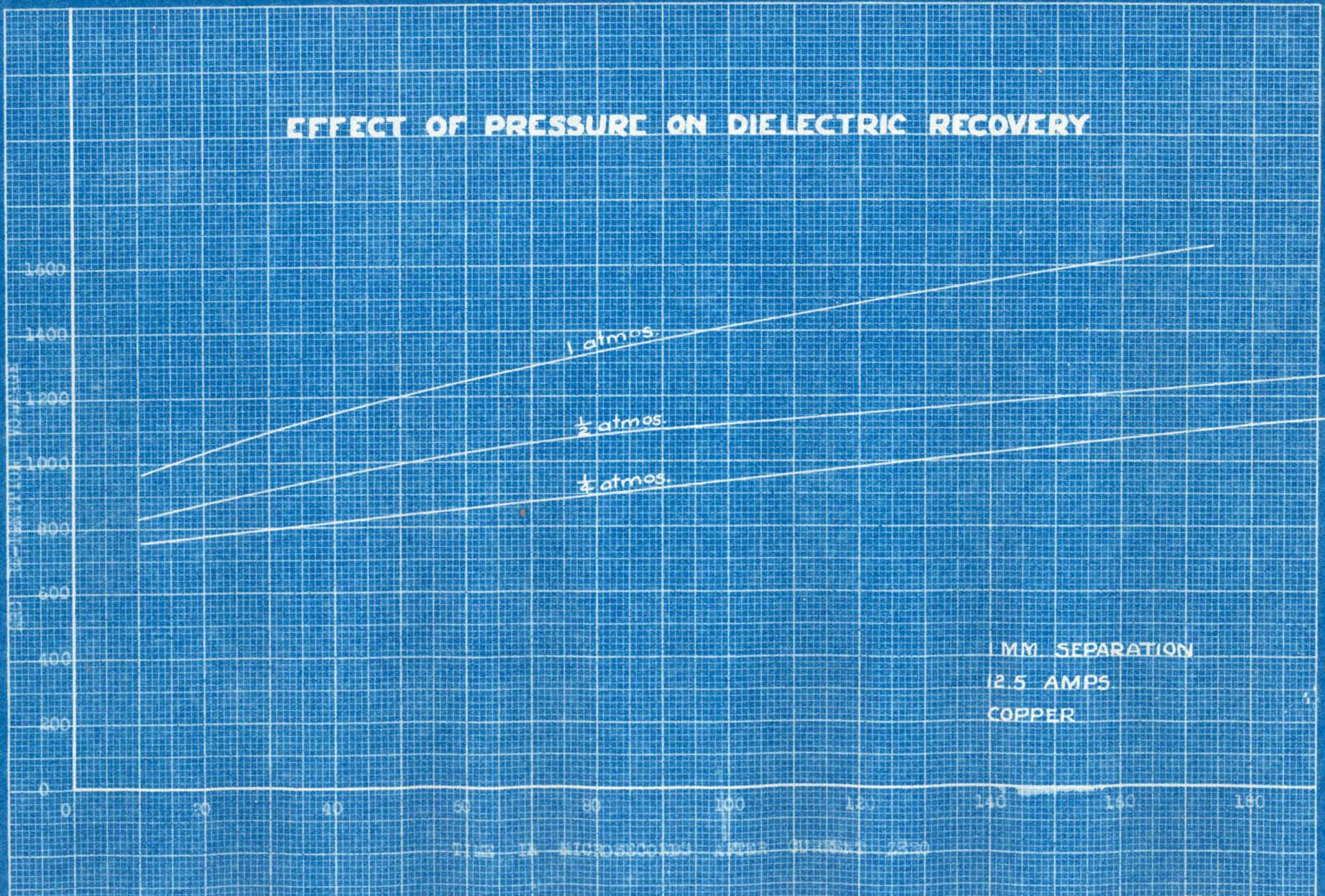

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
1 atmos.
½ atmos.
¼ atmos.
1 MM. SEPARATION
12.5 AMPS.
COPPER
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 25

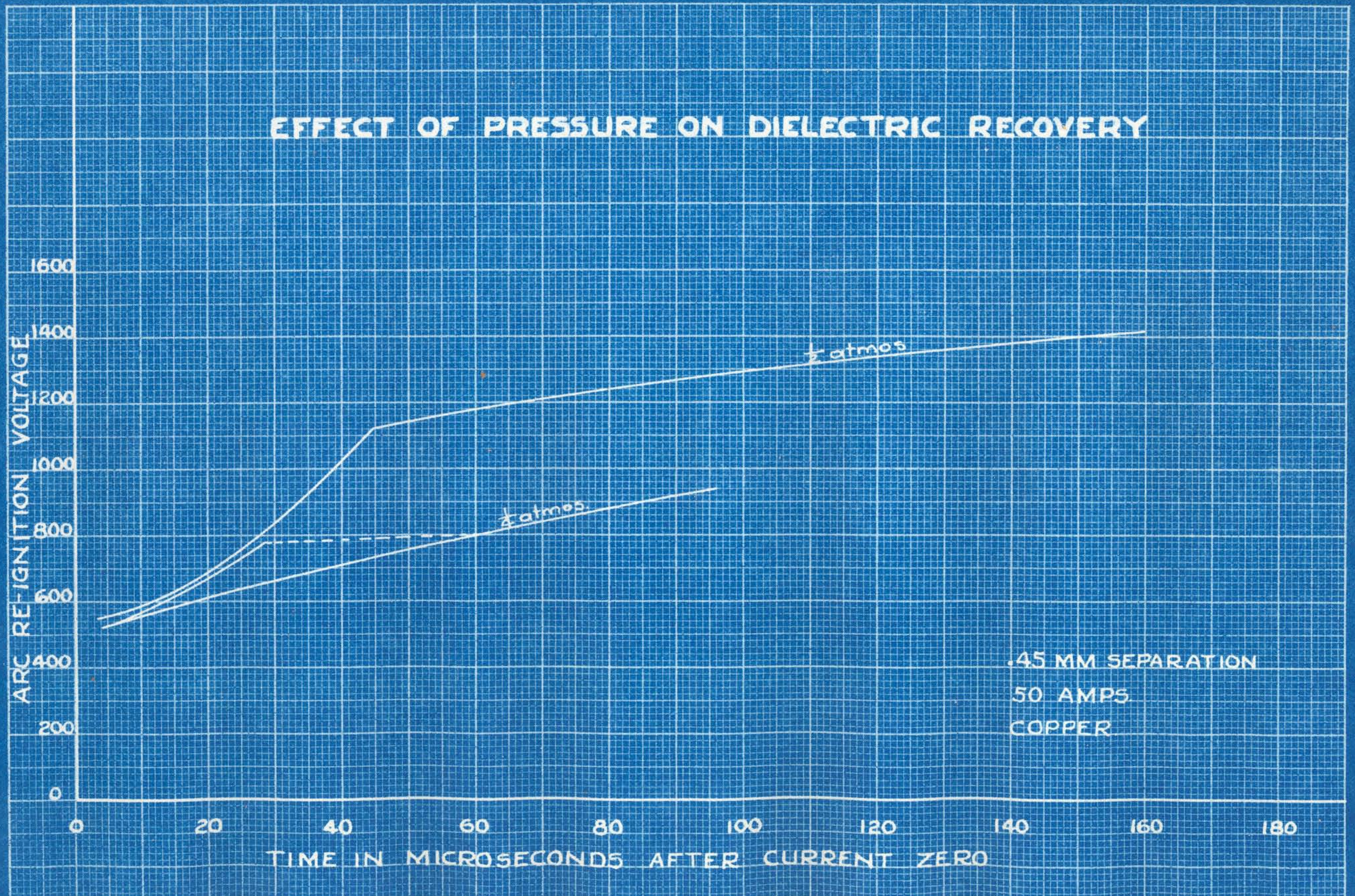

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
atmos
atmos.
.45 MM SEPARATION
50 AMPS
COPPER
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 26.

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

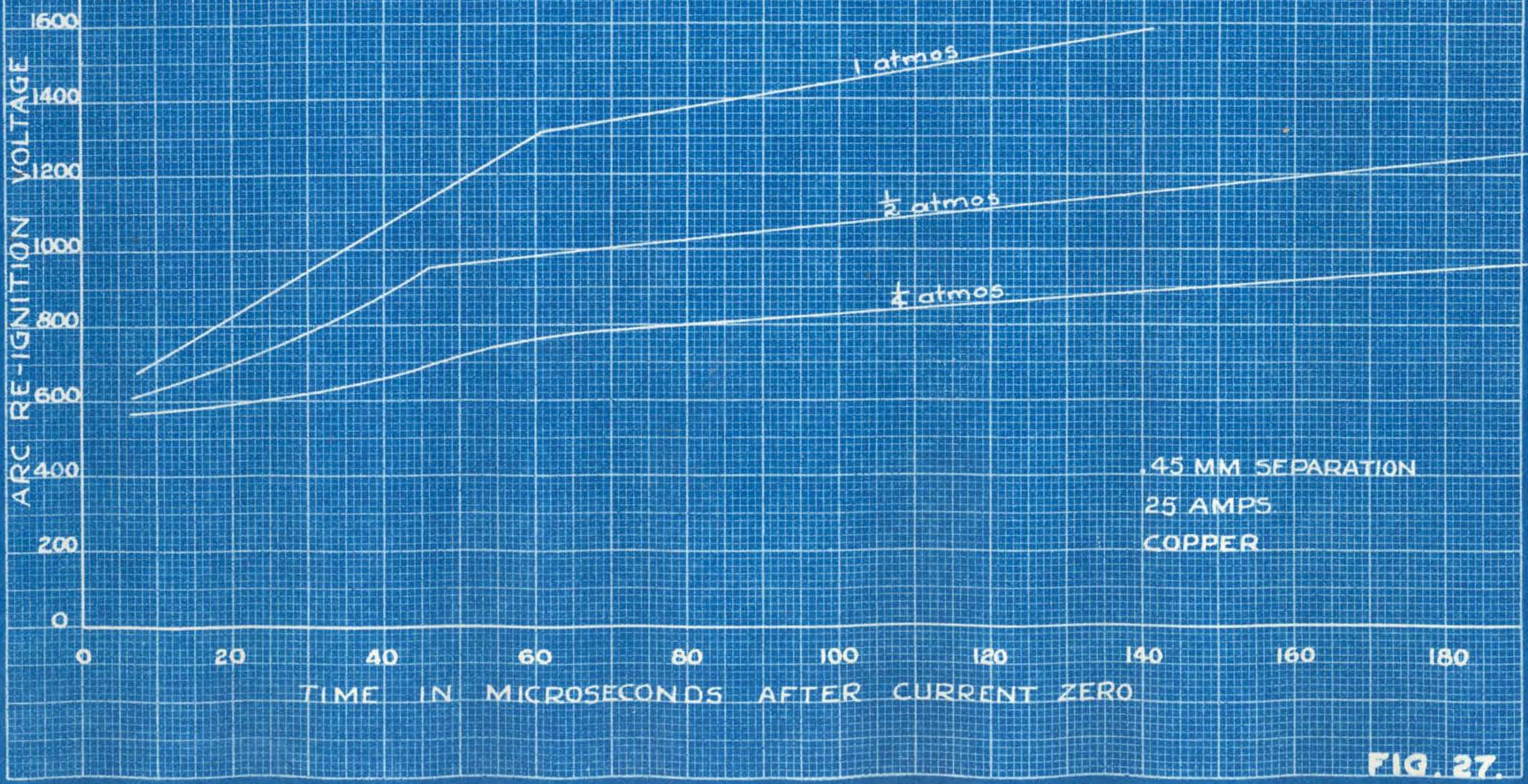


FIG. 27.

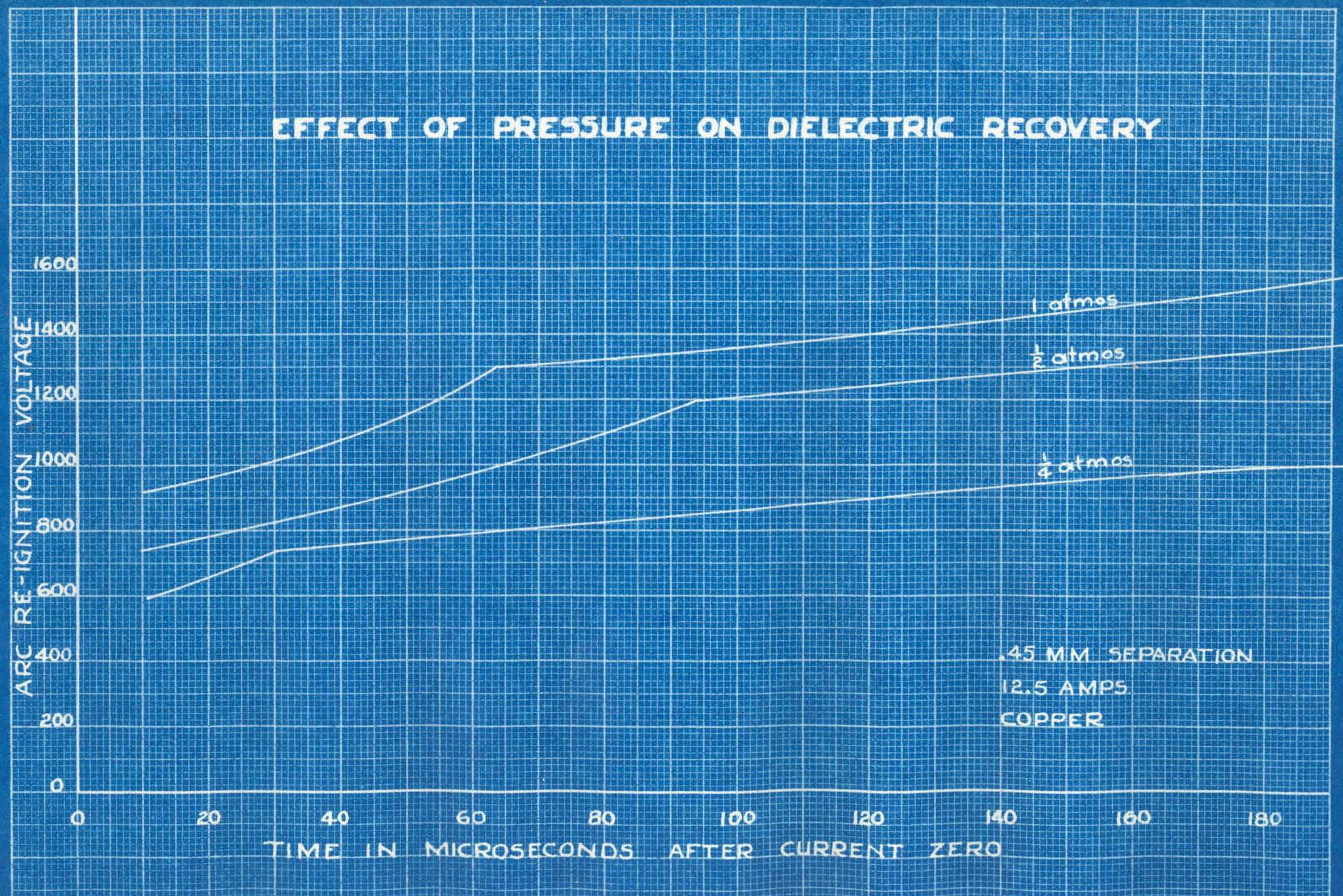

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
1 atmos
½ atmos
¼ atmos
.45 MM SEPARATION
12.5 AMPS
COPPER

FIG. 28.

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY

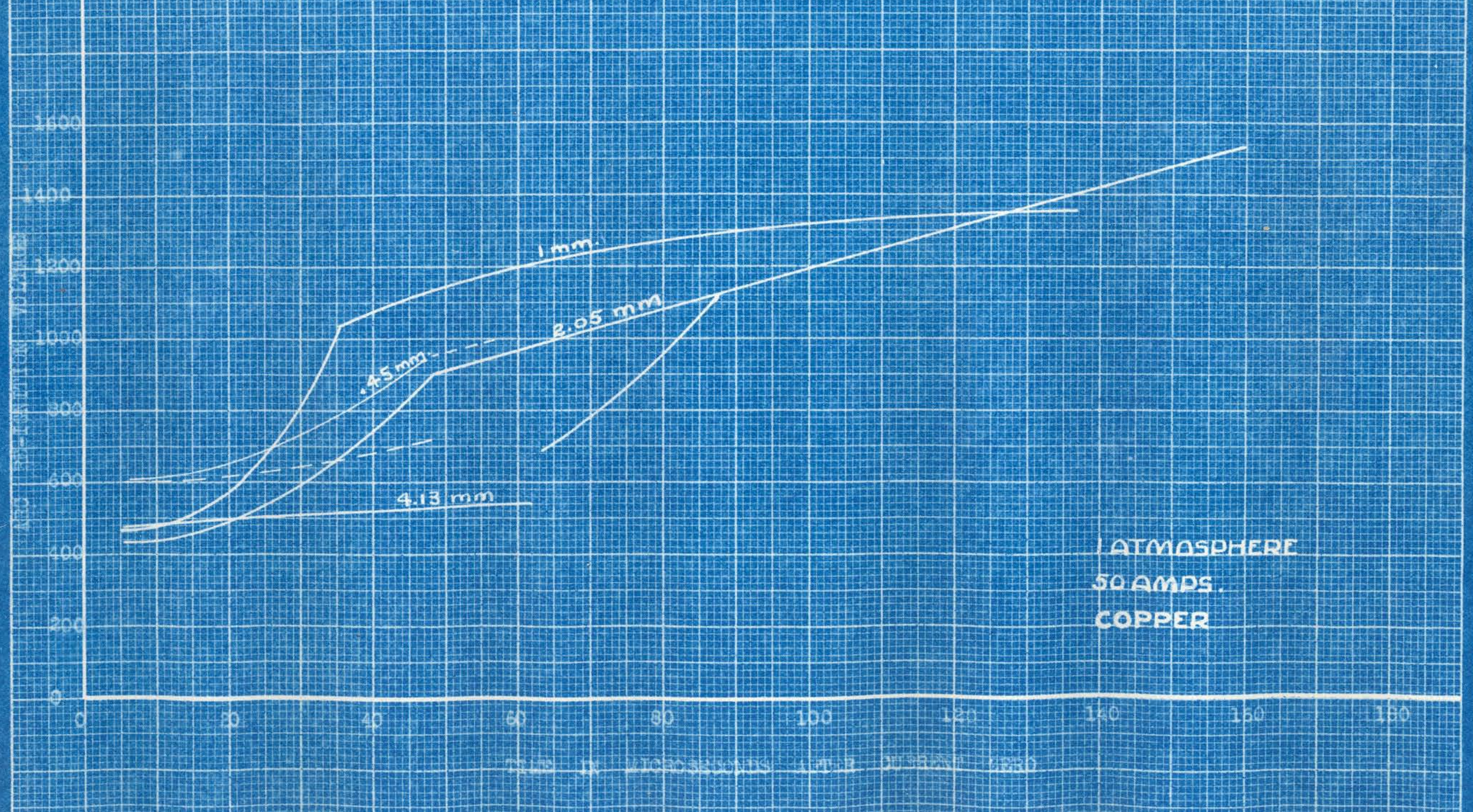


FIG. 29.

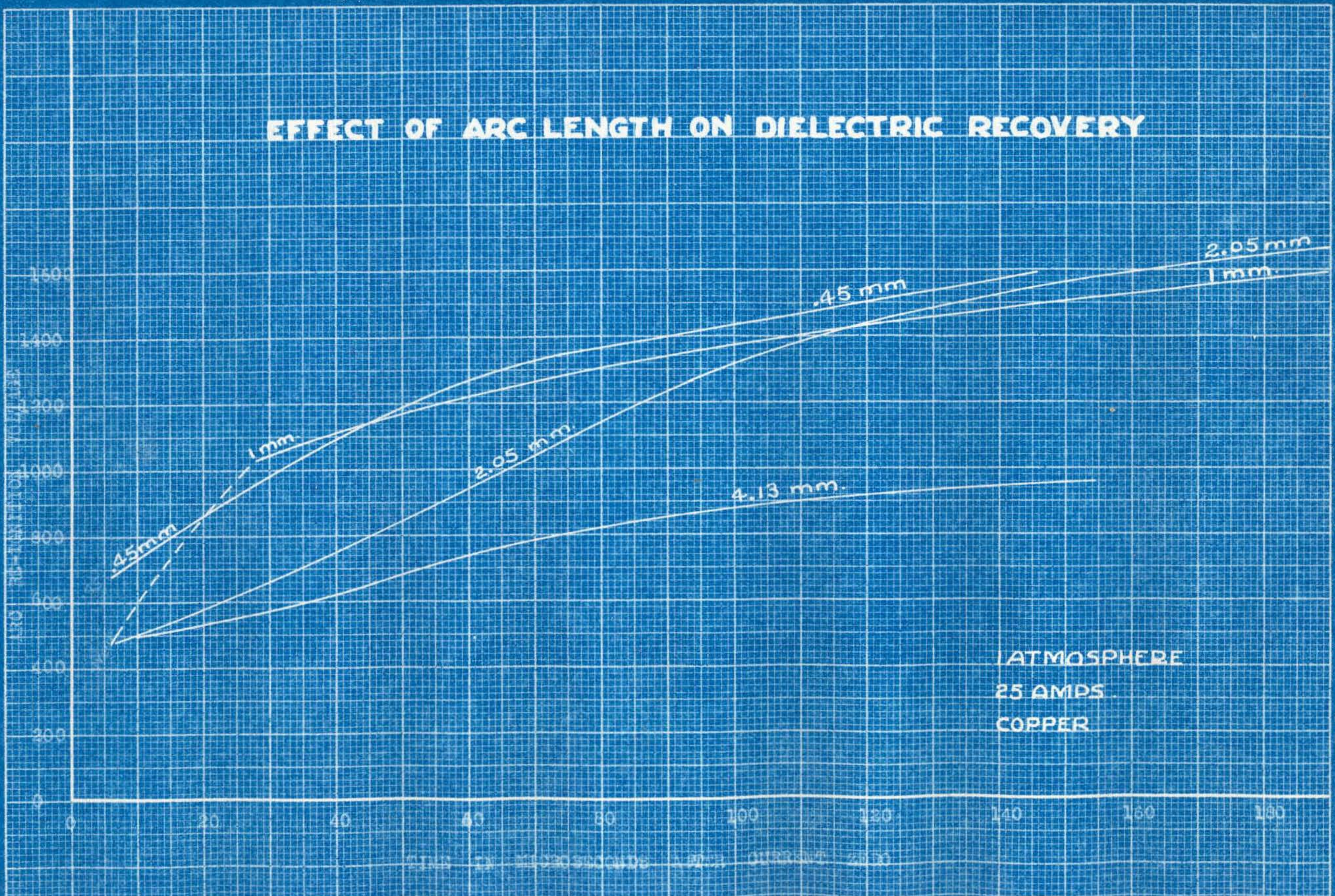
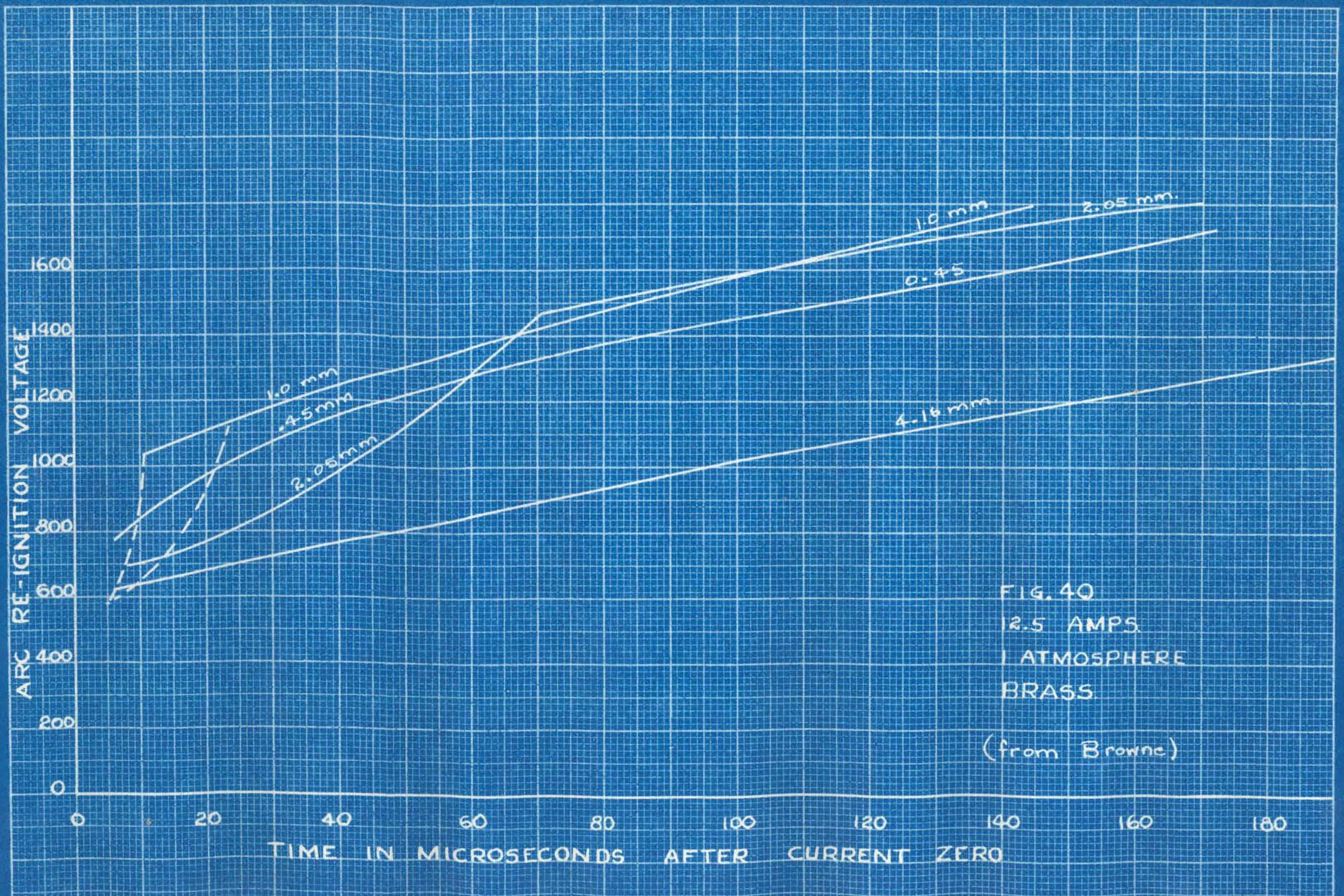

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
2.05 mm
1 mm.
.45 mm
1 mm.
2.05 mm.
4.13 mm.
.45 mm
1 ATMOSPHERE
25 AMPS.
COPPER

FIG. 30



1600
1400
1200
1000
800
600
400
200
0
ARC RE-IGNITION VOLTAGE
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
1.0 mm
.45 mm
2.05 mm
1.0 mm
2.05 mm.
0.45
4.16 mm
FIG. 40
12.5 AMPS.
1 ATMOSPHERE
BRASS.
(from Browne)

FIG. 30a

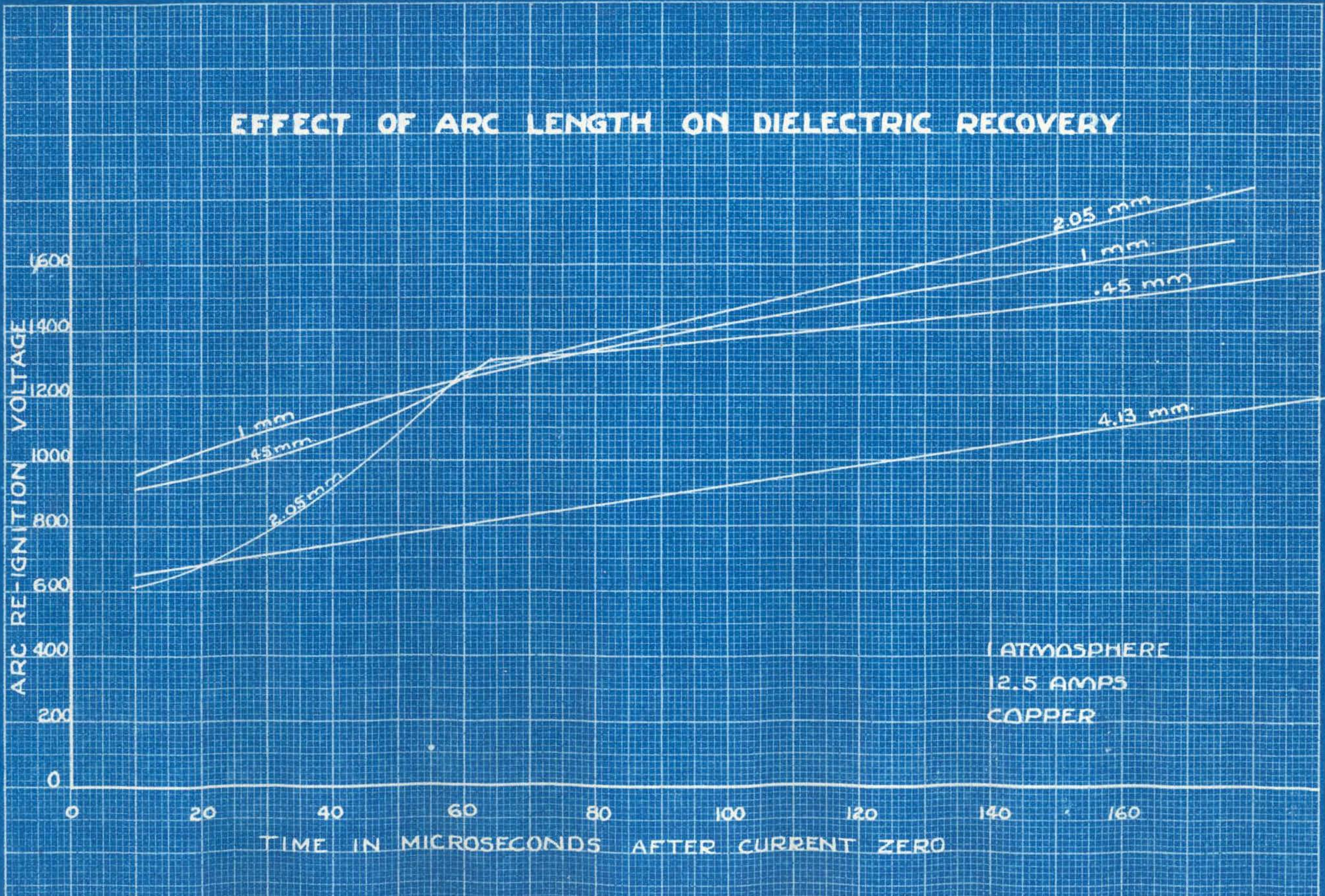

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
2.05 mm
1 mm.
.45 mm
4.13 mm.
1 mm
.45mm.
2.05mm
1600
1400
1200
1000
800
600
400
200
0
ARC RE-IGNITION VOLTAGE
0
20
40
60
80
100
120
140
160
TIME IN MICROSECONDS AFTER CURRENT ZERO
1 ATMOSPHERE
12.5 AMPS
COPPER

FIG. 31

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY

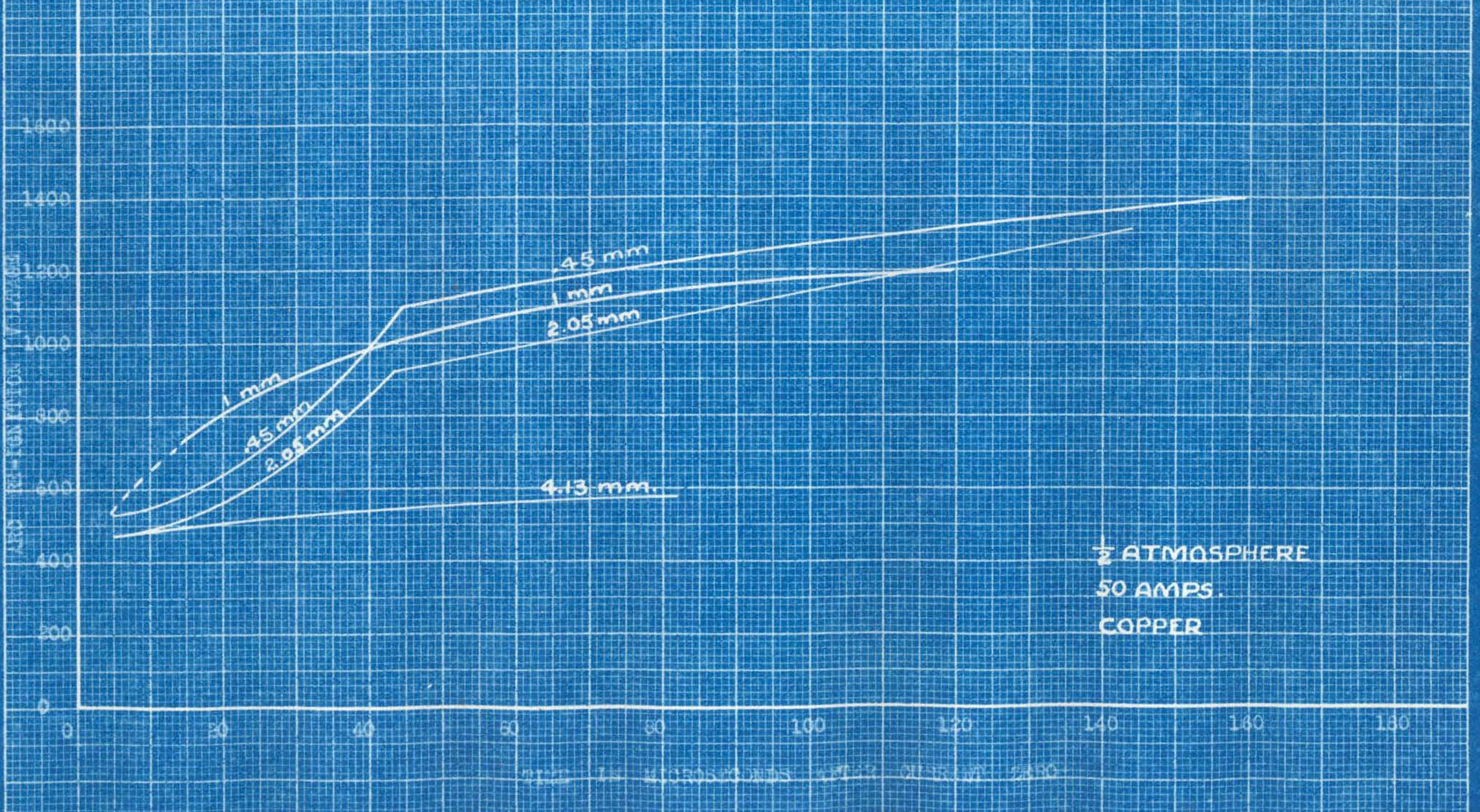


FIG. 32.

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY

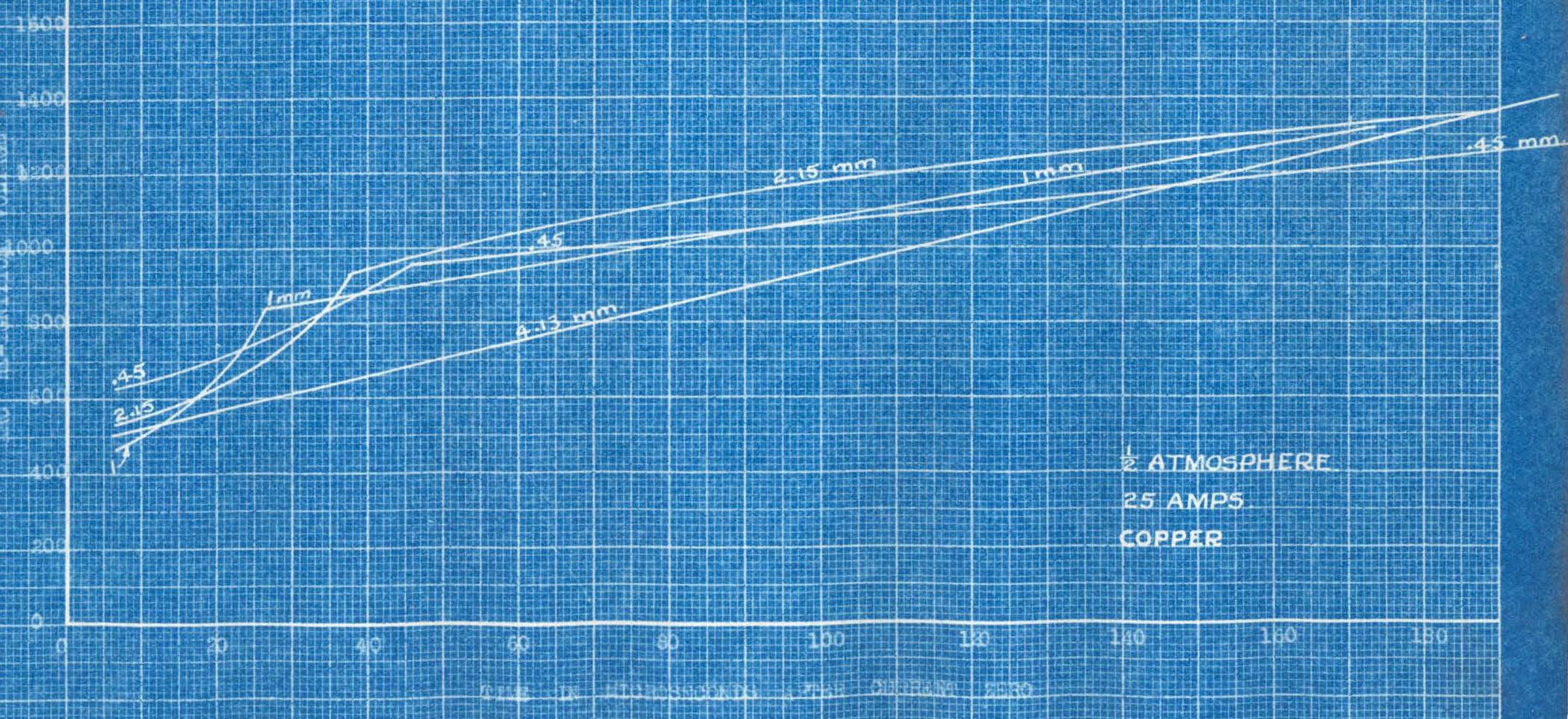


FIG. 33

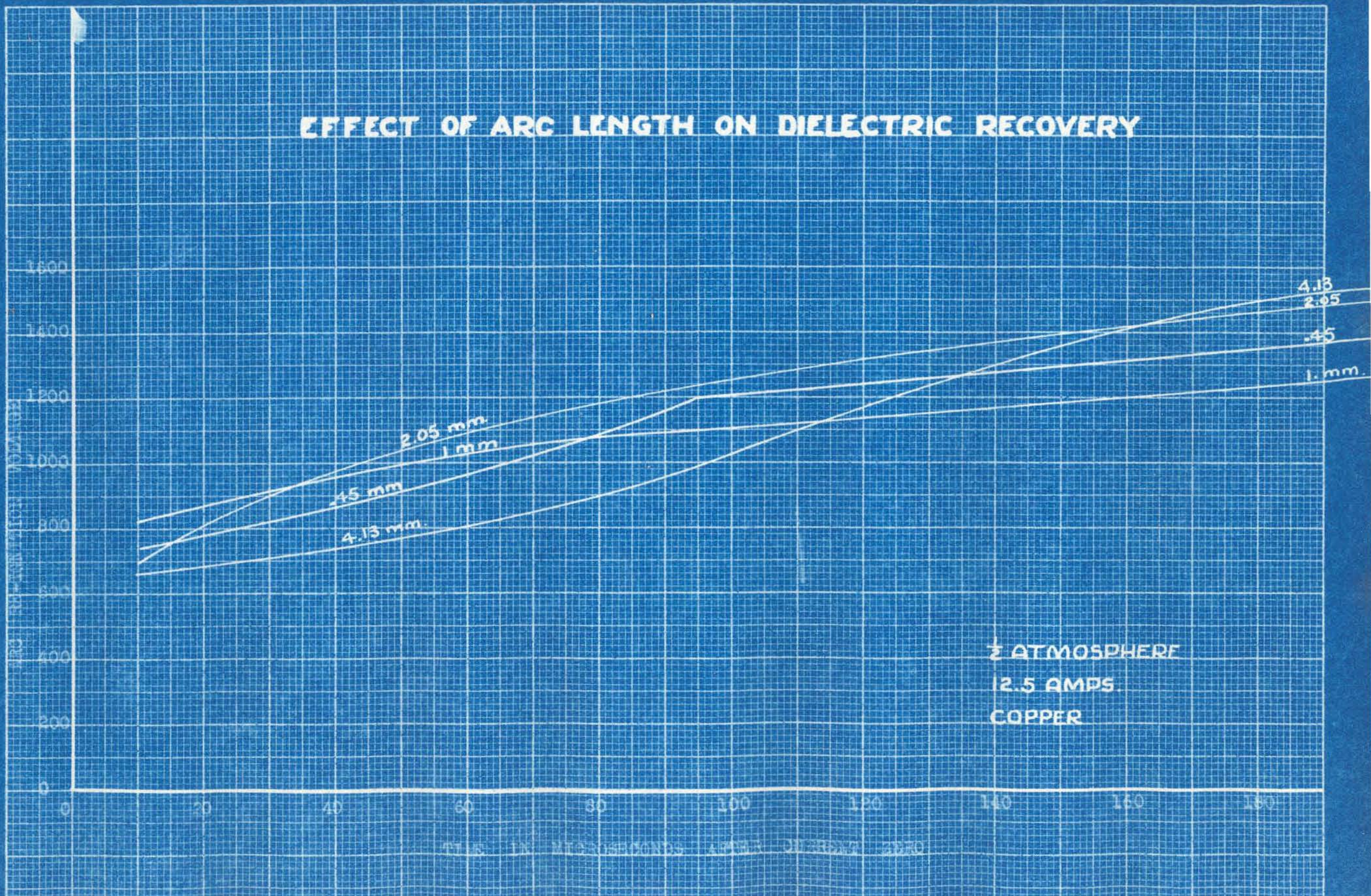

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120
140
160
180
2.05 mm.
1 mm.
.45 mm
4.13 mm.
4.13
2.05
.45
1. mm.
½ ATMOSPHERE
12.5 AMPS.
COPPER

FIG. 34

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY

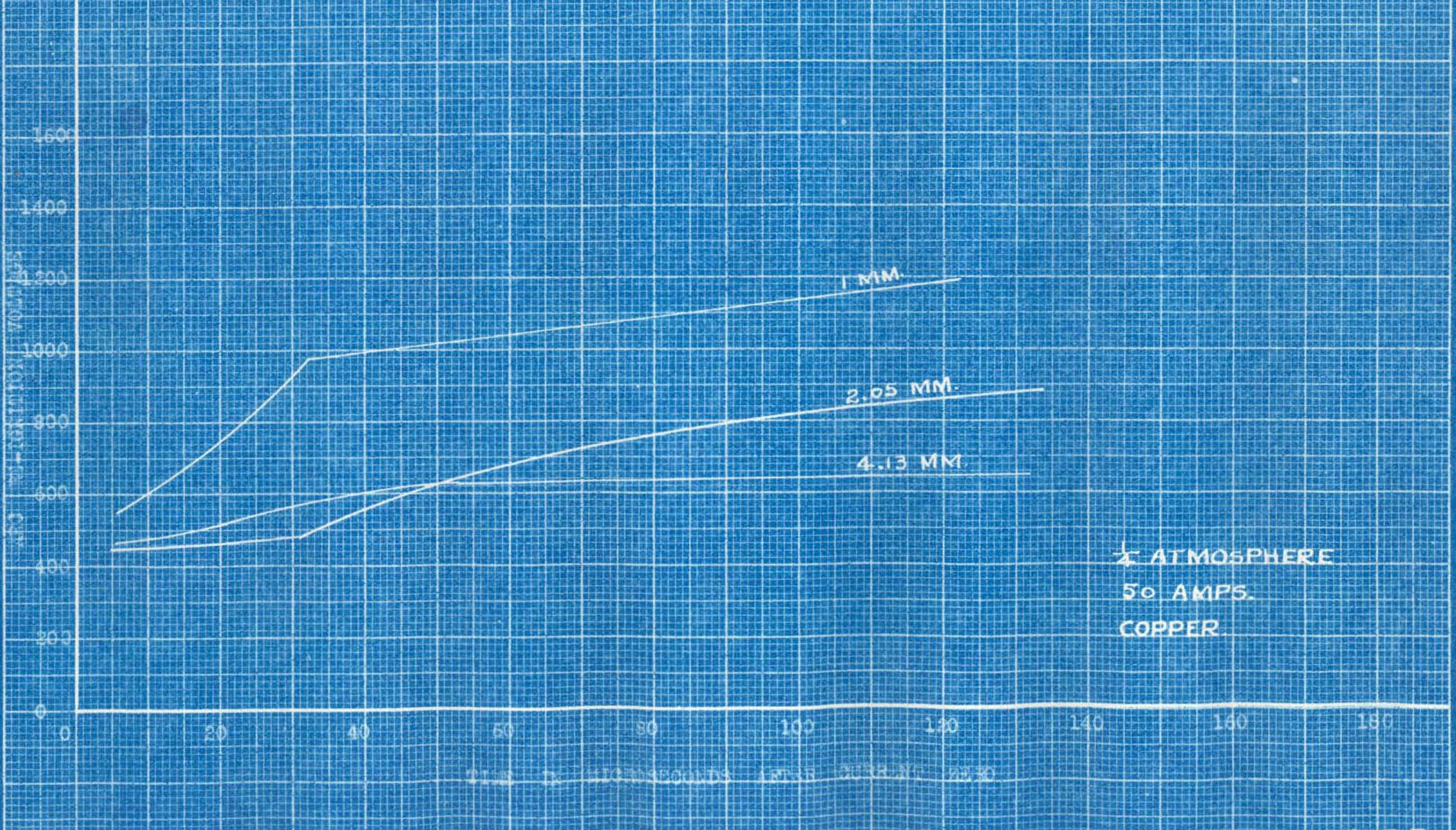


FIG. 35

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY

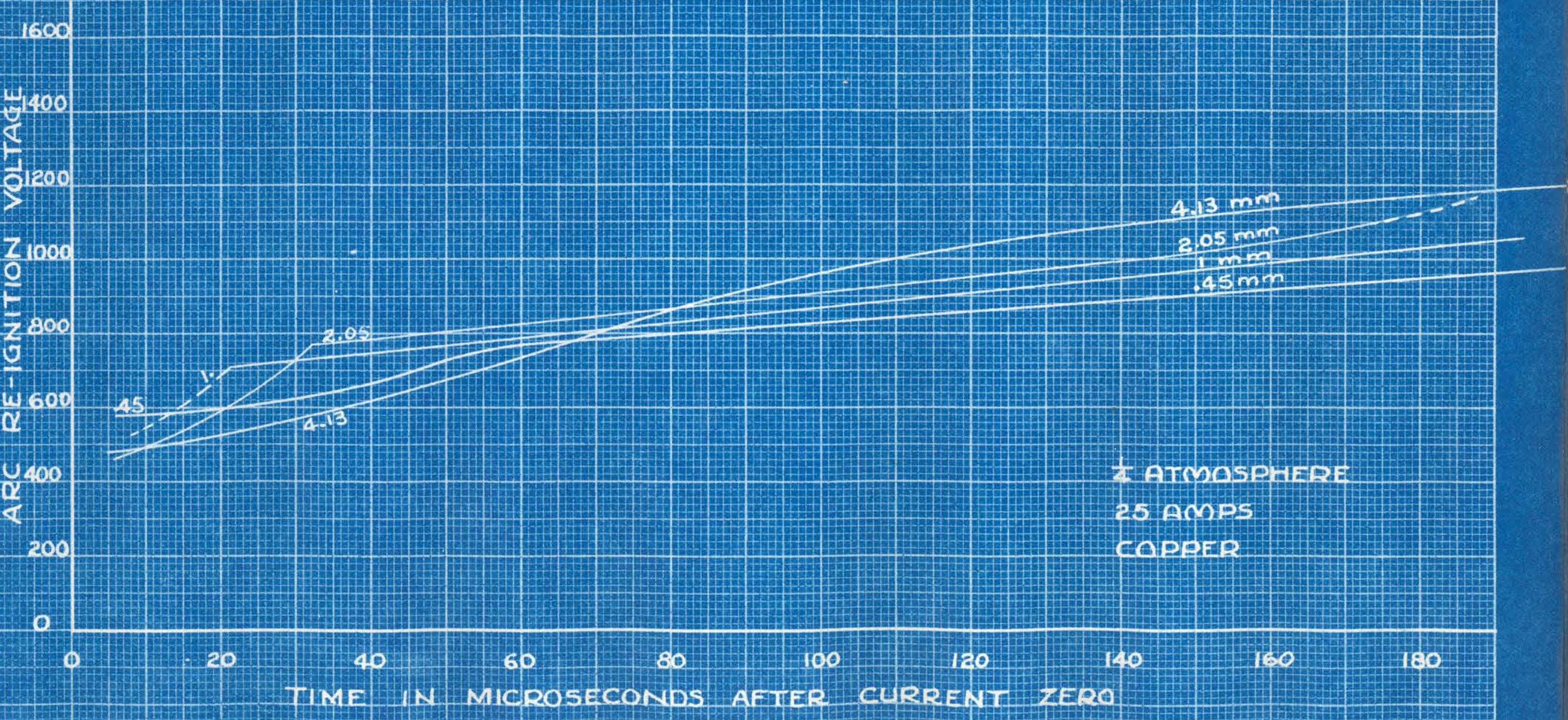


FIG. 36.

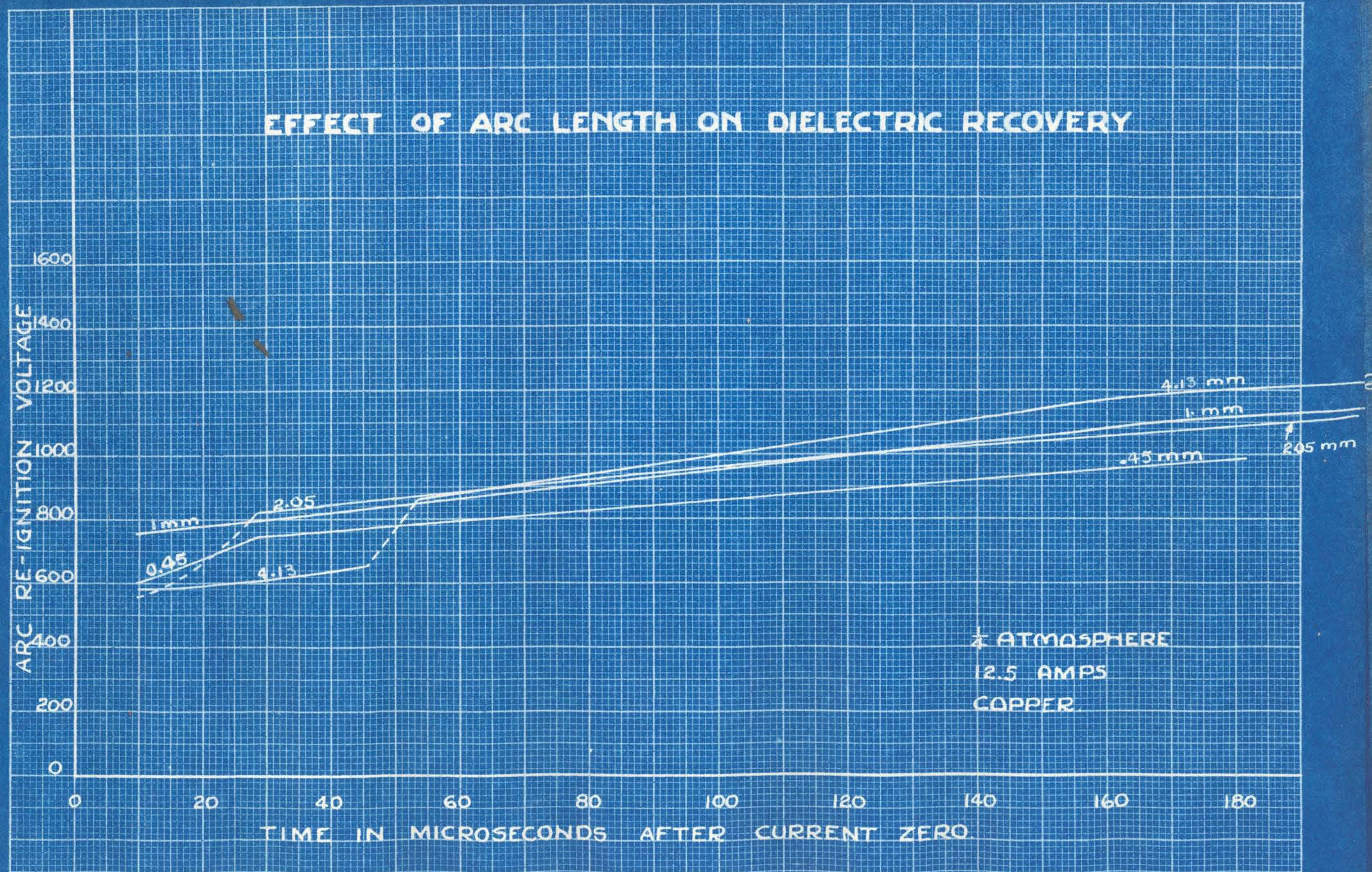

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
4.13 mm
1. mm
2.05 mm
.45 mm
2.05
1 mm
0.45
4.13
¼ ATMOSPHERE
12.5 AMPS
COPPER.

FIG. 37.

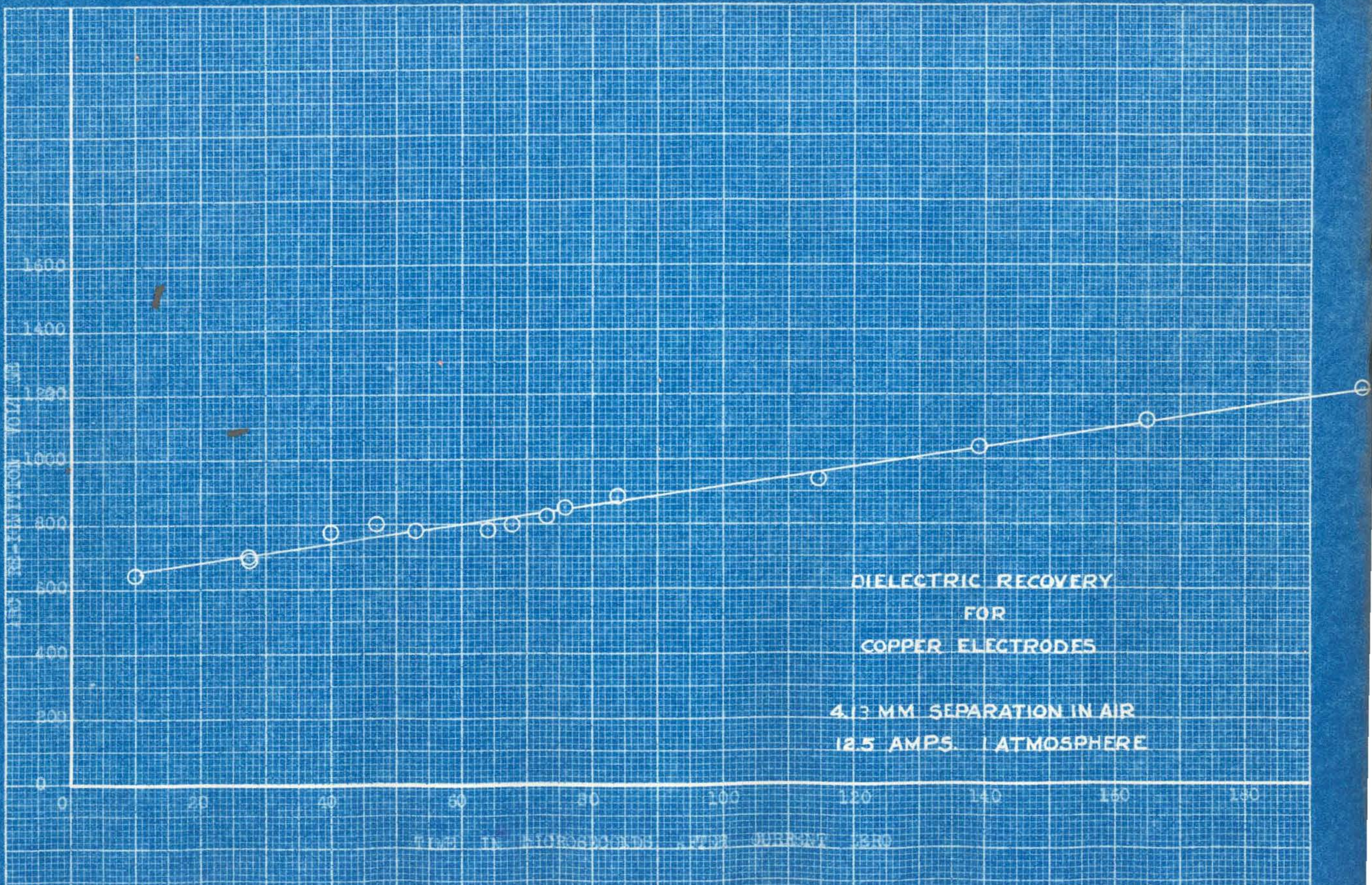

DIELECTRIC RECOVERY
FOR
COPPER ELECTRODES
4.13 MM SEPARATION IN AIR
12.5 AMPS. 1 ATMOSPHERE
ARC RE-IGNITION VOLTAGE
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 38.

2. Effect of Current - (Copper)

Figures 5 through 11, show the definite effect that increasing the current lowers the initial recovery voltage and also the subsequent sparking voltage. However, at 1/2 atmos. and 1 mm. (Fig. 12), the dielectric recovery curve for 50 amps. is higher than that for 12.5. Figure 13 (1/4 atmos. and 1 mm.) and Figure 14 (1 atmos. and 0.45 mm.) show this same effect.

The curves shown on Figures 15 and 16 show the anomalous relation that the dielectric recovery curve for 12.5 amps is higher than that for 25 amps. but less than that for 50 amps. The initial recovery rate, however, is still smaller for the higher currents. It should be noted that with the exception of Figure 12, these latter results all occur at 0.45 mm. separation.

Assuming that current density is invariant in the arc, neglecting lateral diffusion from the ionized core, and treating diffusion and cooling as one-dimensional processes, then the reignition curves for various currents should all coincide. The results obtained show then the variations in these assumptions. Lateral diffusion must be appreciable for the longer arcs - 4.13, 2.05, and 1.0 mm. For, still assuming uniform current density, the ratio of core perimeter to core area is greater for 12.5 amps. than for a greater current, so that diffusion is relatively more important for the smaller currents.

The effect occurring in Figures 13 to 16, that of a higher recovery curve for 50 amps. than for 12.5 amps., can be explained by the fact that it was very difficult to maintain an arc at 0.45 mm. and 1/2 or 1/4 atmos. with 12.5 or 25 amps. Almost immediately after initiation the arc appeared as a diffuse discharge and quickly (in less than a second) changed to a glow discharge. For these cases then, the relations existing were obviously very different from those holding at the other spacings and there could be no assumption of uniform current density.

3. Effect of Pressure - (Copper)

Figures 17 through 28 show the effect of gas pressure on dielectric recovery, all other quantities being kept constant for any set of curves. The Figures show that in general the curves cross at some point, showing that the effect of pressure is different for the first and the latter part of the curves. Equation (5), Appendix (E), shows that the dielectric strength of the space charge sheath should vary directly with the pressure (since pressure varies inversely as temperature) and inversely as the ion density. Because of the relation existing between the ion density and coefficient of diffusion, Equation (5) shows that for deionization by diffusion the early recovery rate should be almost independent of pressure. After deionization of the space, the only effect of pressure is upon the density of the gas between the electrodes.

For the same temperature the dielectric strength should be higher for the higher pressure and directly proportional to it. The fact that this condition does not hold for later recovery times, shows that the temperatures are different, which is easily appreciated since the cooling rate is higher for a lower pressure. These relations of low dielectric strength for short reignition times and of high dielectric strength for later times with increasing pressure are well shown in the curves of this set.

Figures 18, 21, 24, and 27 agree identically in form with Browne's Figures 45, 44, 43, and 42, respectively, for brass, differing only somewhat in magnitude.

4. Effect of Arc Length - (Copper)

Figures 29 through 37 show the effect of arc length on dielectric recovery. With only the exceptions noted below, the shorter arcs are seen to have a higher short-time voltage strength than the longer ones. Inasmuch as this property has hitherto been held to hold only for the low-boiling-point electrodes, this is a very significant fact.

Considering first the 50 amp. curves at 1, 1/2, and 1/4 atmosphere (Figures 29, 32, and 35) as being of most practical interest, it is seen that the 4.13 mm. arc has the lowest restriking voltage. In Figure 35 (50 amps. 1/4 atmos.) deionization takes place for all spacings at 30 microseconds. Both in these curves (Figure 35) and in those of Figure 32, the 4.13 mm. arc has a slightly higher recovery voltage than the 2.05 mm. arc but the difference is within the range of possible experimental error. In Figures 29 and 32, complete deionization does not take place for the 4.13 mm. spacing within the time range shown. It was impossible to continue this curve further, because of the explosive violence with which the arc behaved. For as the arc shunting capacity was increased to obtain longer reignition times, the arc movement became very rapid often reaching the electrode edges and bowing out into an arc length of a foot or more. It is unfortunate that readings were not taken on spacings between 2.05 mm. and 4.13 mm., for there appears to be a rather significant large variation in dielectric recovery between these curves (Figures 29 and 32). Figures 29, 30, and 32 show that as the time gets longer the dielectric strength of the 2.05 mm. space becomes greater than that of the 1 mm. or 0.45 mm. arcs. At still later times it is to be expected, as shown in subsequent curves, that the 4.13 mm. arc strength will rise to a value greater than any of the others shown.

The 25 amp. curves at 1, 1/2, and 1/4 atmosphere (Figures 30, 33, and 36) are also very interesting. They show again that for short times the breakdown voltage varies inversely as the arc length, and then as diffusion becomes more important the long arc spaces reassert their higher voltage strength. Figure 36 is indeed an excellent presentation of these phenomena.

Figures 31, 34, and 37 for the 12.5 amp. arcs show another effect which is also evident on Figure 35. It is that even for short recovery times the 1 mm. arc has a higher dielectric strength than the 0.45 mm. This shows very definitely that for 12.5 amps. at least, there is a separation between 1.0 mm. and 2.05 mm. at which the dielectric strength of a copper arc is a maximum.

Figures 30, 31, and 33 of this thesis agree very closely with data taken under the same conditions for brass[5]-(Figures 39, 40, and 41, respectively). These Figures 40 and 41 also show that an optimum spacing exists between 1 mm. and 2.05 mm. These results show that short time dielectric recovery is not dependent on boiling points, as far as copper and brass are concerned, unless indeed their boiling points are not sufficiently different, - which is a rather untenable hypothesis since the boiling point of zinc is only 930°C. and that of copper is 2310°C.

The extremely close relation between Figure 31 for copper and Figure 40 for brass is a good check on the consistency of the experimental apparatus, for data, for these curves were taken exactly eighteen months apart.

Results are given for steel electrodes under the following Figure numbers:-

STEEL ELECTRODES

	Separation	Pressure Atmos.			Fig. Nos.
Effect of Current	4.13 mm.	1	1/2	1/4	40,41,42
	2.05 mm.	1	1/2	1/4	43,44,45
	1.0 mm.	1	1/2	1/4	46,47,48

	Separation	Current			Fig. Nos.
Effect of Pressure	4.13 mm.	50,	25,	12.5	49,50,51
	2.05 mm.	50,	25,	12.5	52,53,54
	1.0 mm.	50,	25,	12.5	55,56,57

	Pressure	Current			Fig. Nos.
Effect of Arc Length	1 atmosphere	50,	25,	12.5	58,59,60
	1/2 "	50,	25,	12.5	61,62,63
	1/4 "	50,	25,	12.5	64,65,66

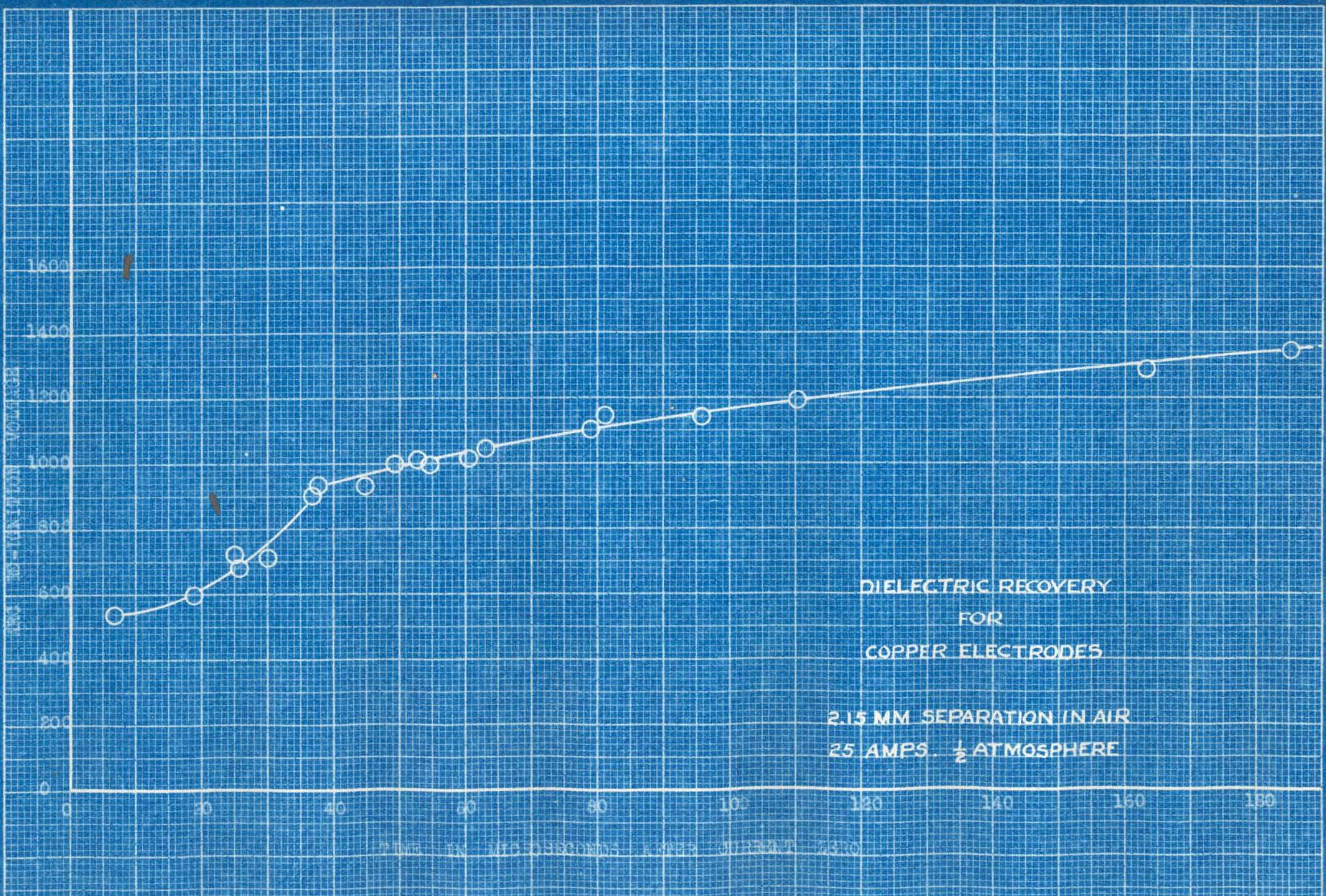

DIELECTRIC RECOVERY
FOR
COPPER ELECTRODES
2.15 MM SEPARATION IN AIR
25 AMPS. ½ ATMOSPHERE
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 39.

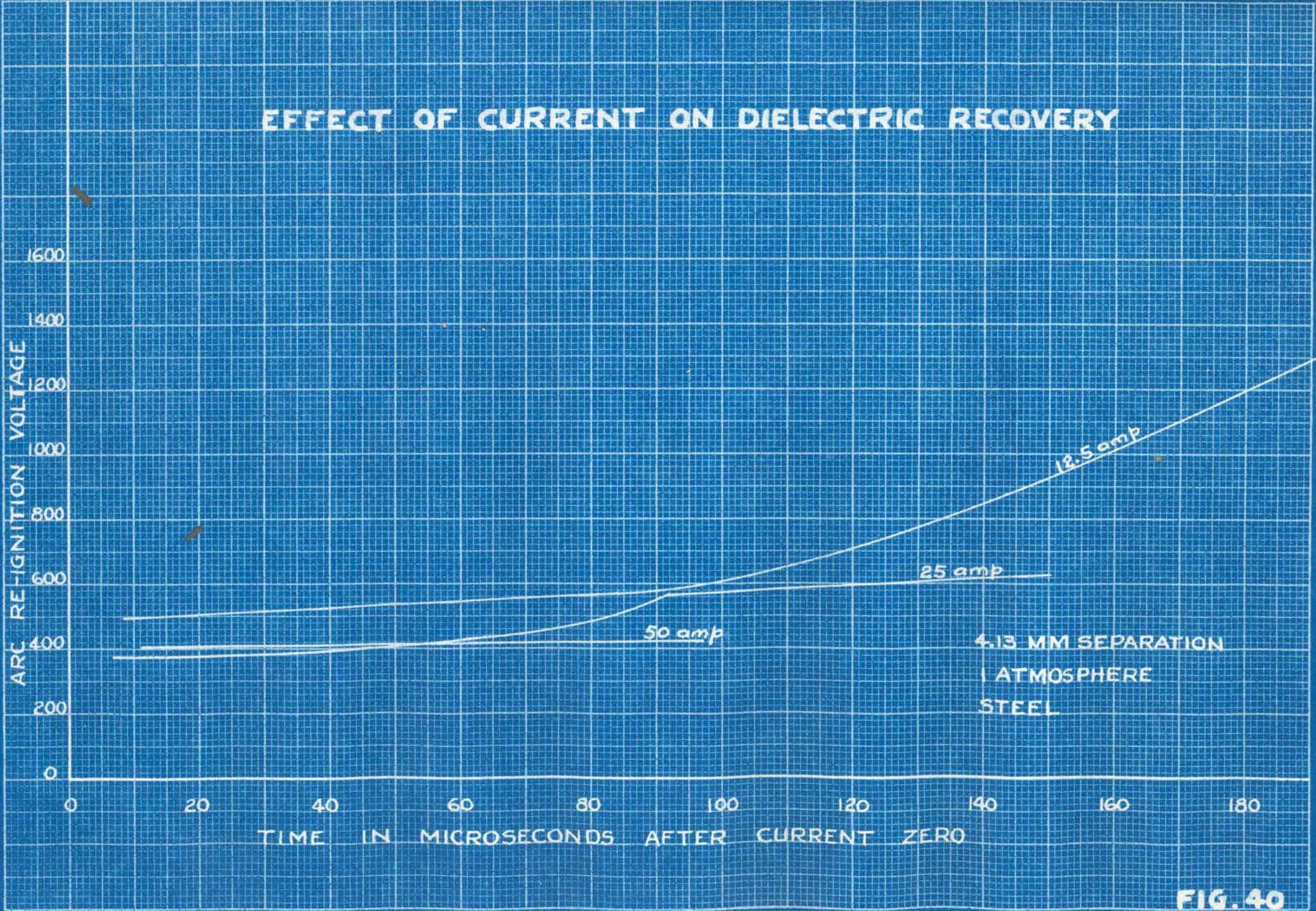

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
12.5 amp
25 amp
50 amp
4.13 MM SEPARATION
1 ATMOSPHERE
STEEL

FIG. 40

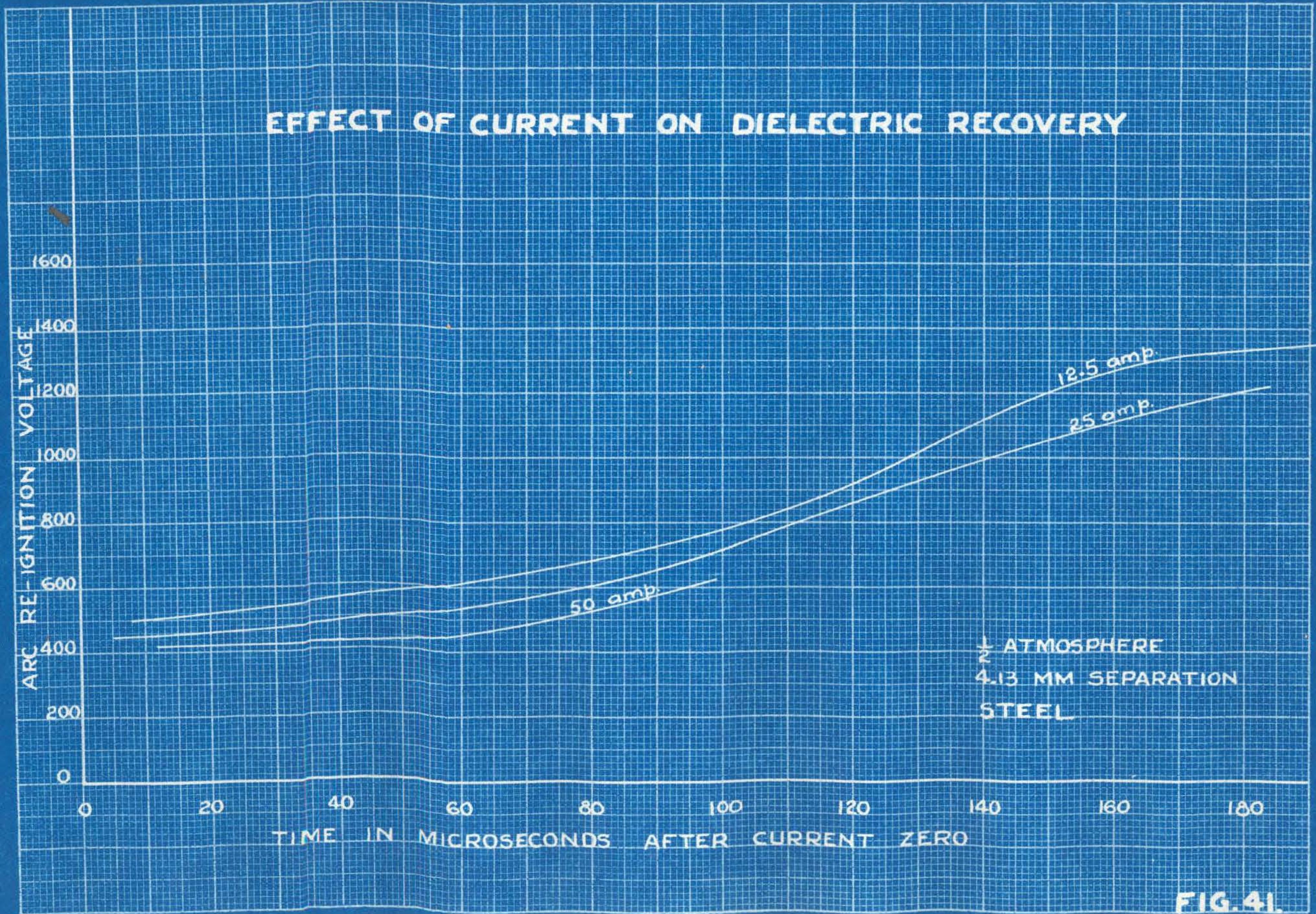

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
12.5 amp.
25 amp.
50 amp.
½ ATMOSPHERE
4.13 MM SEPARATION
STEEL

FIG. 41.

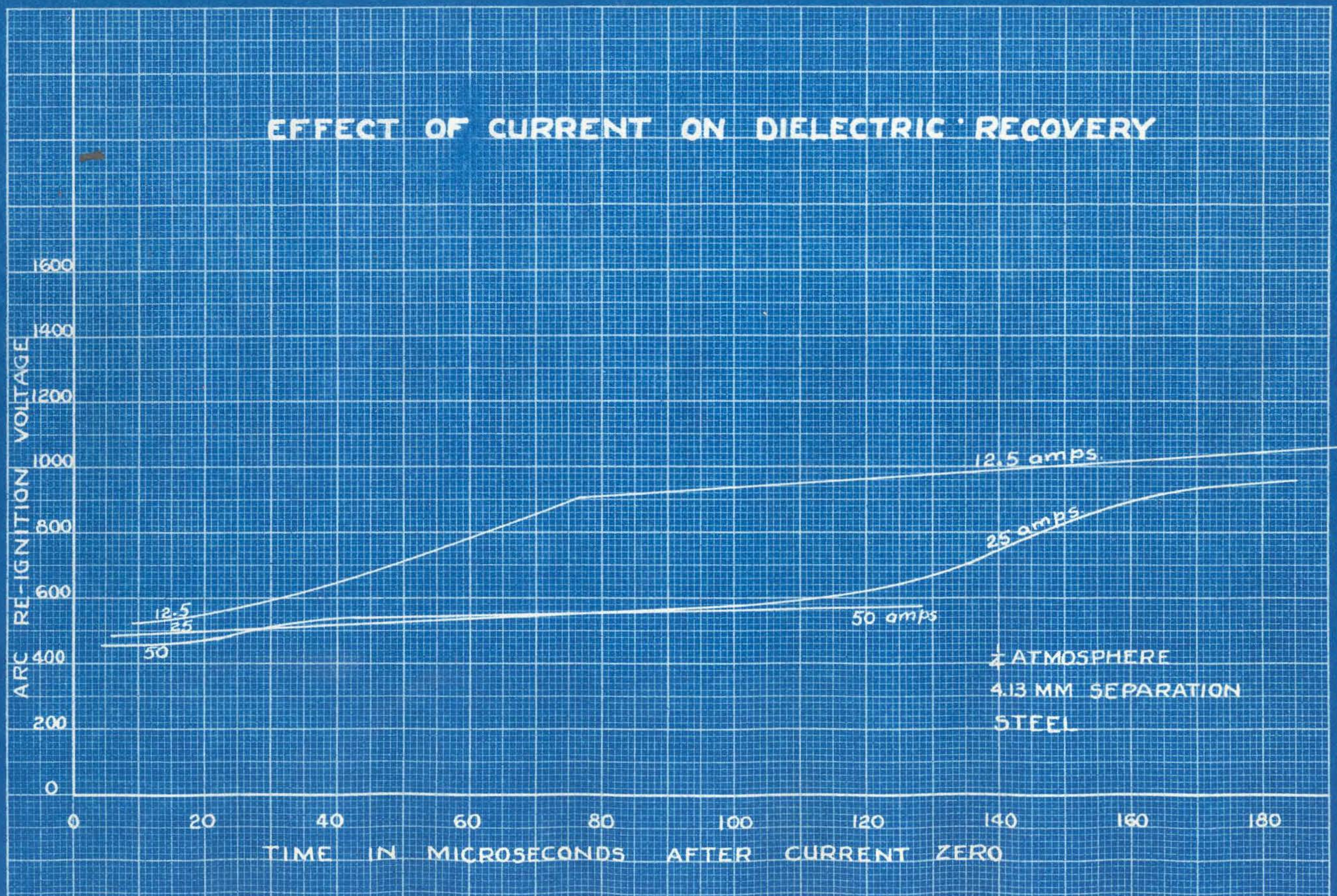

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
12.5 amps.
25 amps.
50 amps
12.5
25
50
¼ ATMOSPHERE
4.13 MM SEPARATION
STEEL

FIG. 42.

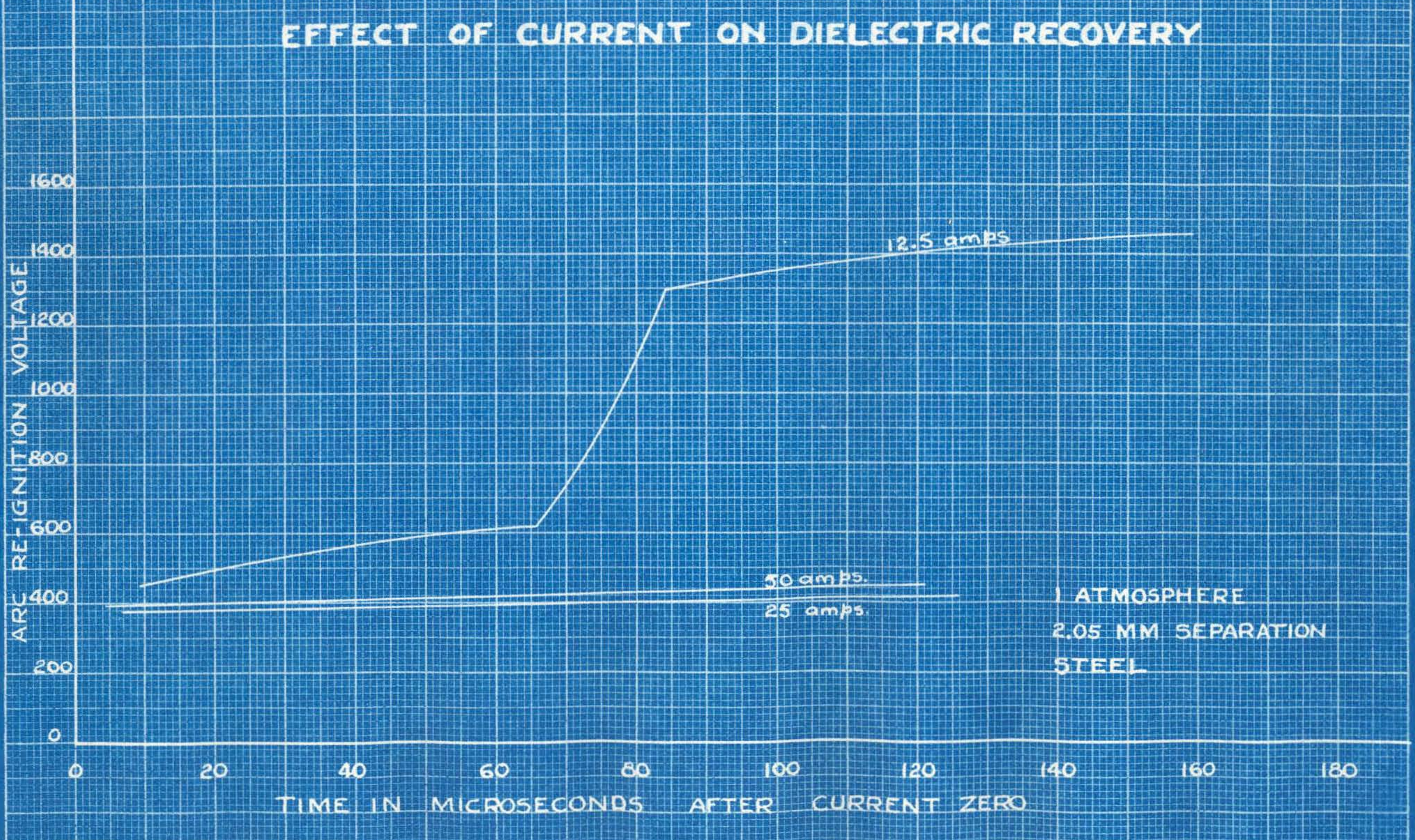

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
12.5 amps
50 amps.
25 amps.
1 ATMOSPHERE
2.05 MM SEPARATION
STEEL
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG.43.

B. Steel Electrodes

1. Data

Figures 40 through 46 show 27 sets of curves. These curves were made up from 472 readings. As for copper, all combinations of 50, 25, and 12.5 amps; 4.13, 2.05, and 1 mm.; and pressures of 1, 1/2, and 1/4 atmosphere were used. These Figures are divided into three main groups:-

(1) Figures 40 to 48 show the effect of current on dielectric recovery;

(2) Figures 49 to 57 show the effect of pressure on dielectric recovery;

(3) Figures 58 to 66 show the effect of arc length on dielectric recovery.

2. Effect of Current - (Steel)

The nine sheets, Figures 40 to 48, show definitely that increasing the current does not have much effect on the initial voltage-time recovery rate but that after a short time, of the order of 30 microseconds, the recovery voltage rises very much more rapidly for the 12.5 amp. arc.

In none of the curves, except perhaps in Figure 41 (1/2 atmos. 4.13 mm.), did complete deionization take place for the 50 amp. arc up to 130 microseconds. All 26 curves, if projected back to cut the zero time axis, show an initial arc reignition voltage

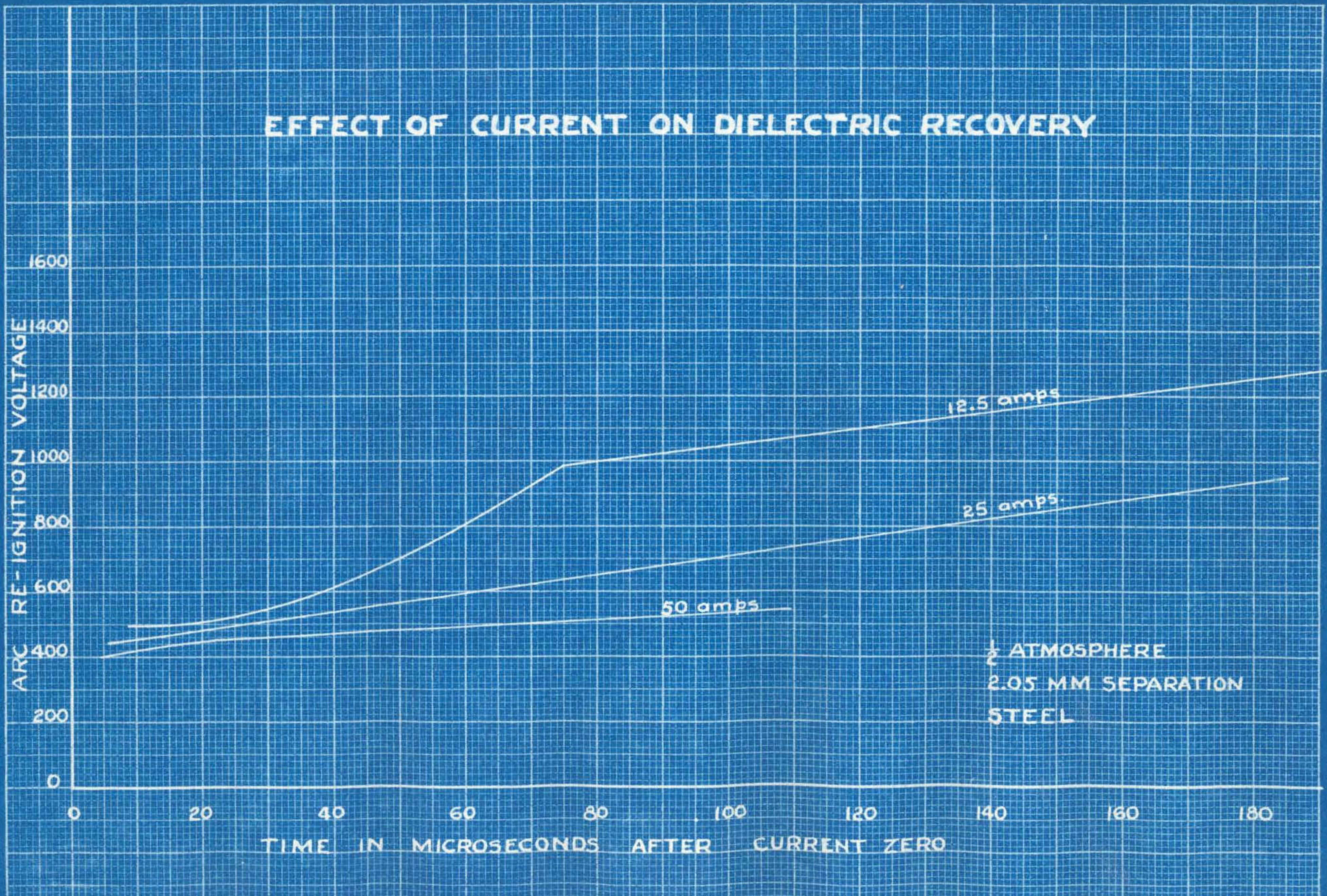

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
12.5 amps
25 amps.
50 amps
½ ATMOSPHERE
2.05 MM SEPARATION
STEEL
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 44.

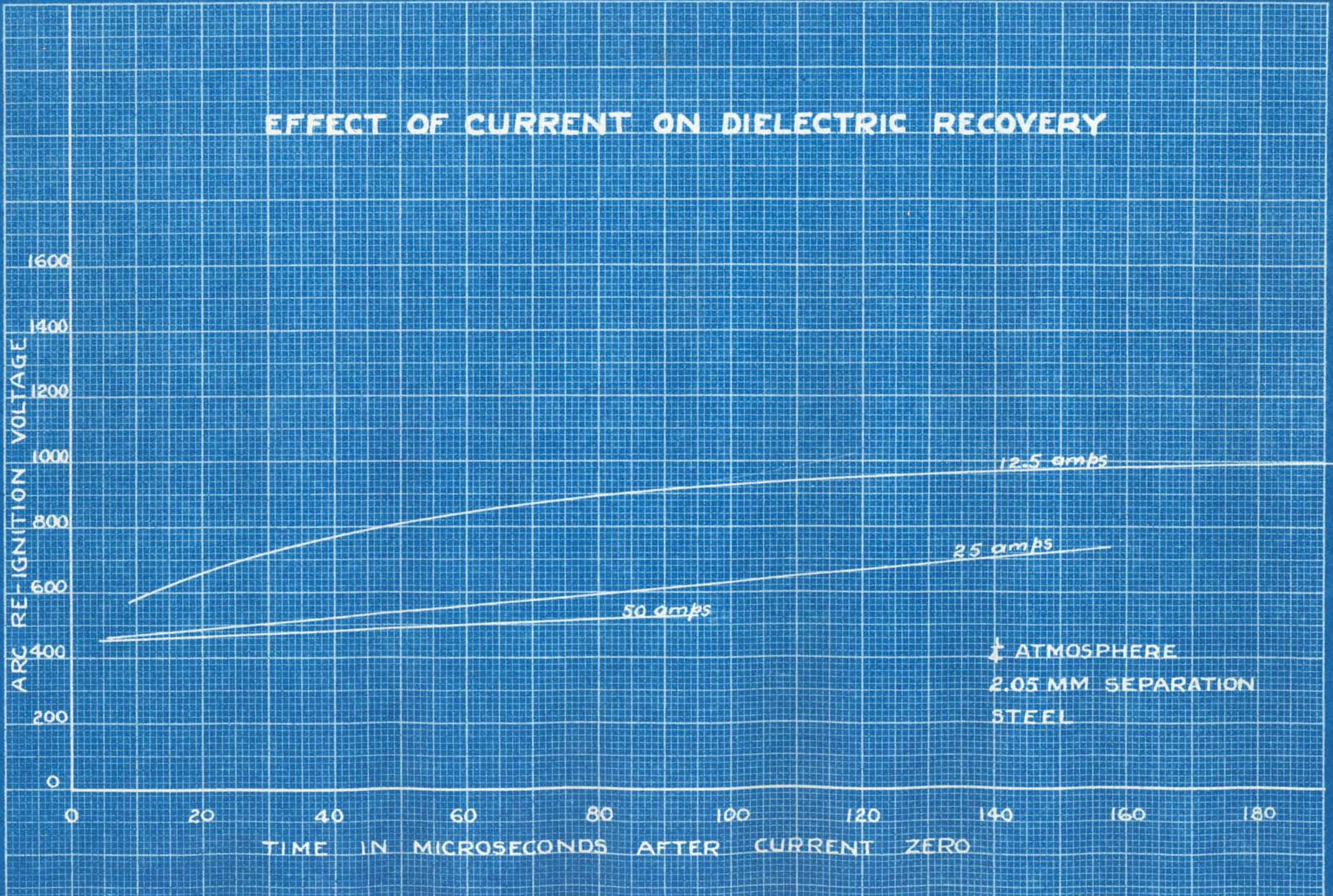

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
12.5 amps
25 amps
50 amps
¼ ATMOSPHERE
2.05 MM SEPARATION
STEEL

FIG. 45.

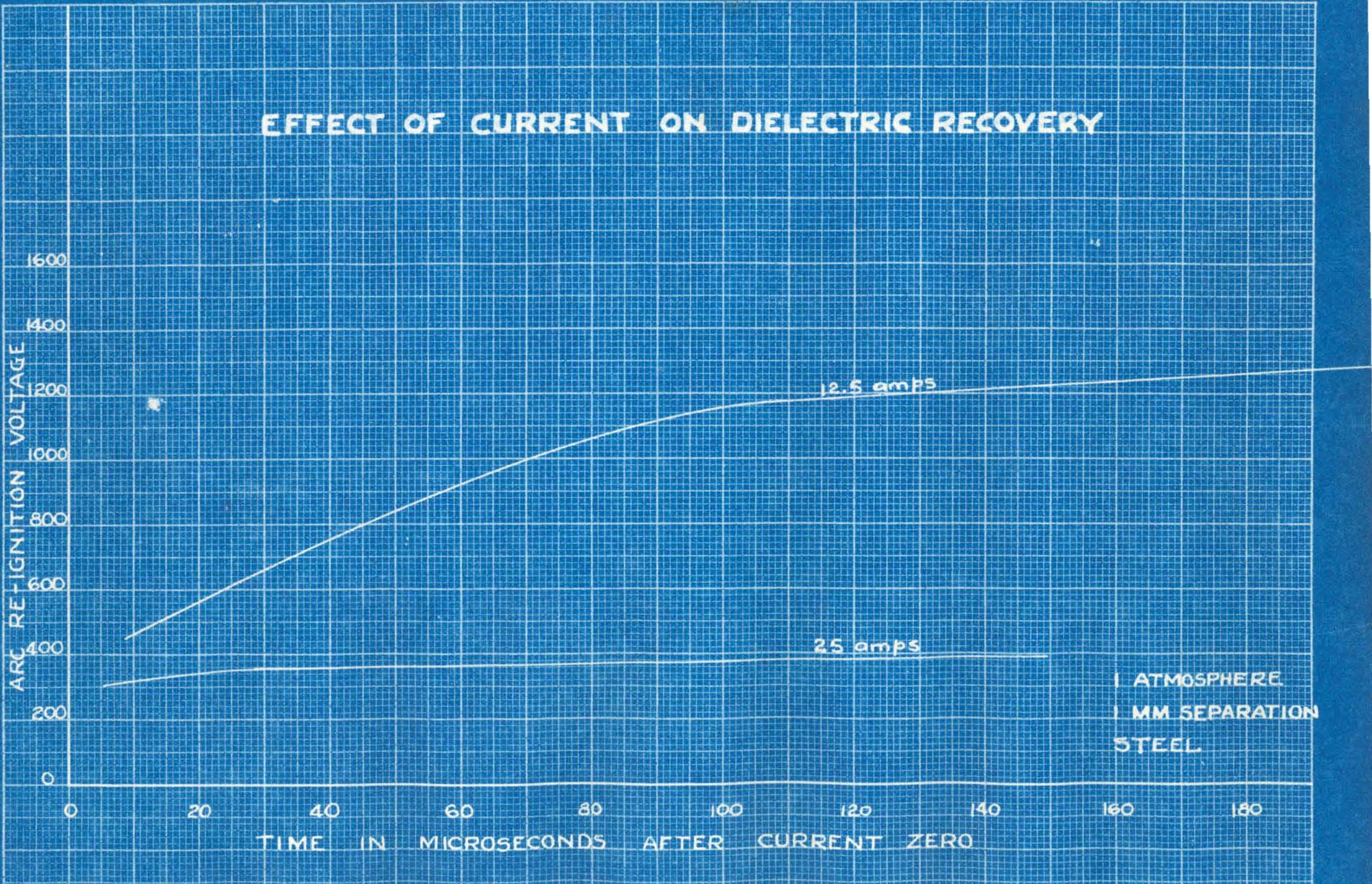

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
12.5 amps
25 amps
1 ATMOSPHERE
1 MM SEPARATION
STEEL

FIG.46.

between 400 and 500 volts. This value is of the order of the minimum sparking potential for air and undoubtedly represents that value for iron electrodes in air. These variations of voltage with current show definitely that no simple one-dimensional process of cooling or diffusion is adequate to explain recovery rates. However, the observations made for the case of the copper electrodes apply with equal force to this case.

3. Effect of Pressure (Steel)

Figures 49 through 57 show the effect of pressure on dielectric recovery for the 50, 25, and 12.5 amp. arc at 4.13, 2.05, and 1.0 mm. separations.

Looking first at Figures 49, 52, and 55 (50 amps.; 4.13, 2.05 and 1.0 mm.), it is seen that the dielectric recovery curves are practically horizontal. The dielectric strength is greater for 1/4 atmos. than for 1/2 or 1 atmos., but the difference is indeed small, being principally the difference existing at earliest restriking. For this case it is true that the initial striking voltage should be slightly higher for the lower pressure, since cooling takes place in the arc space immediately after current zero at a rate depending on the mean free path which is inversely proportional to the pressure. Complete deionization does not occur for any of the 50 amp. curves up to 130 microseconds. It was impossible to obtain points beyond this time, because of the very unstable arc which then existed.

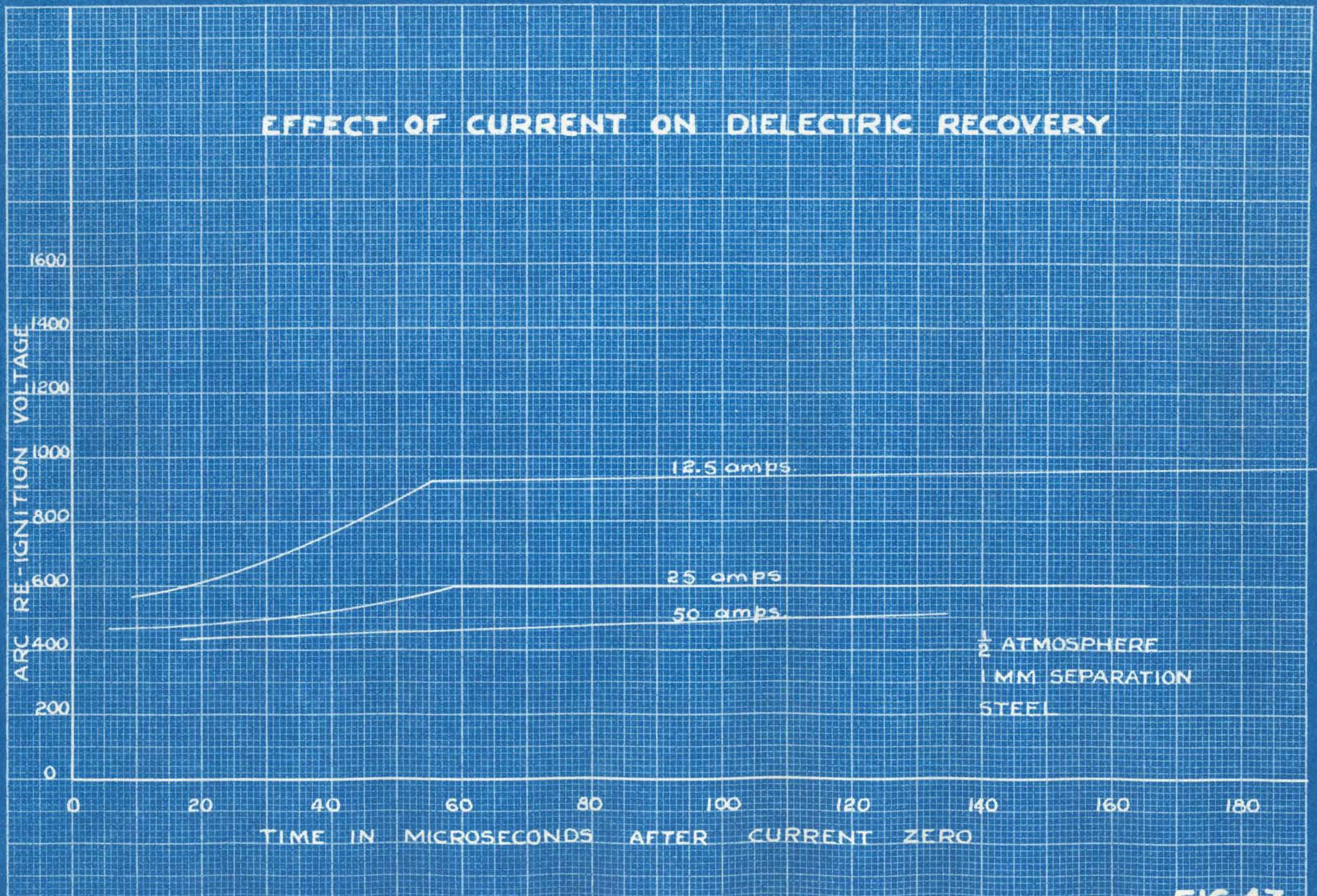

EFFECT OF CURRENT ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
12.5 amps.
25 amps
50 amps.
½ ATMOSPHERE
1 MM SEPARATION
STEEL
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 47.

EFFECT OF CURRENT ON DIELECTRIC RECOVERY

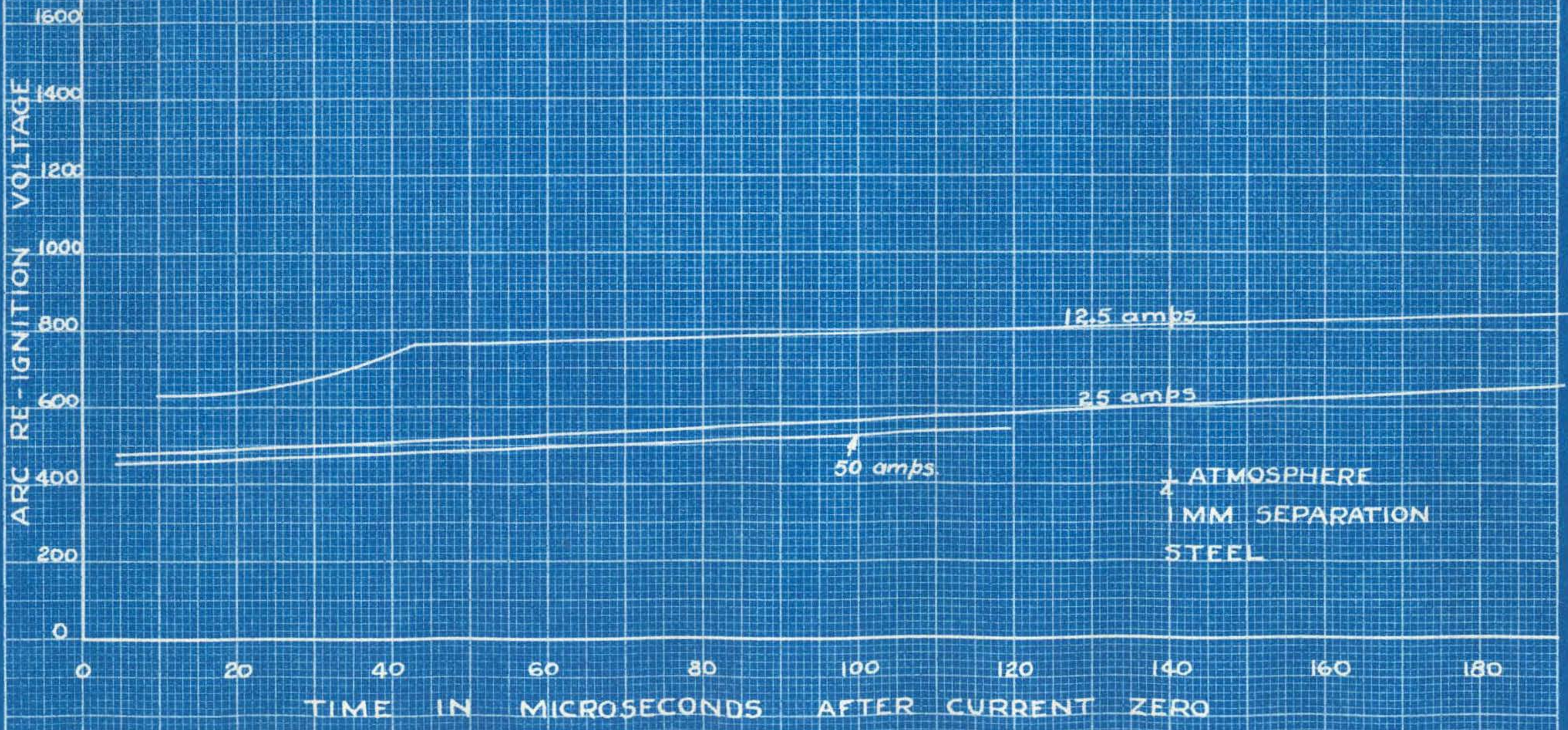


FIG. 48

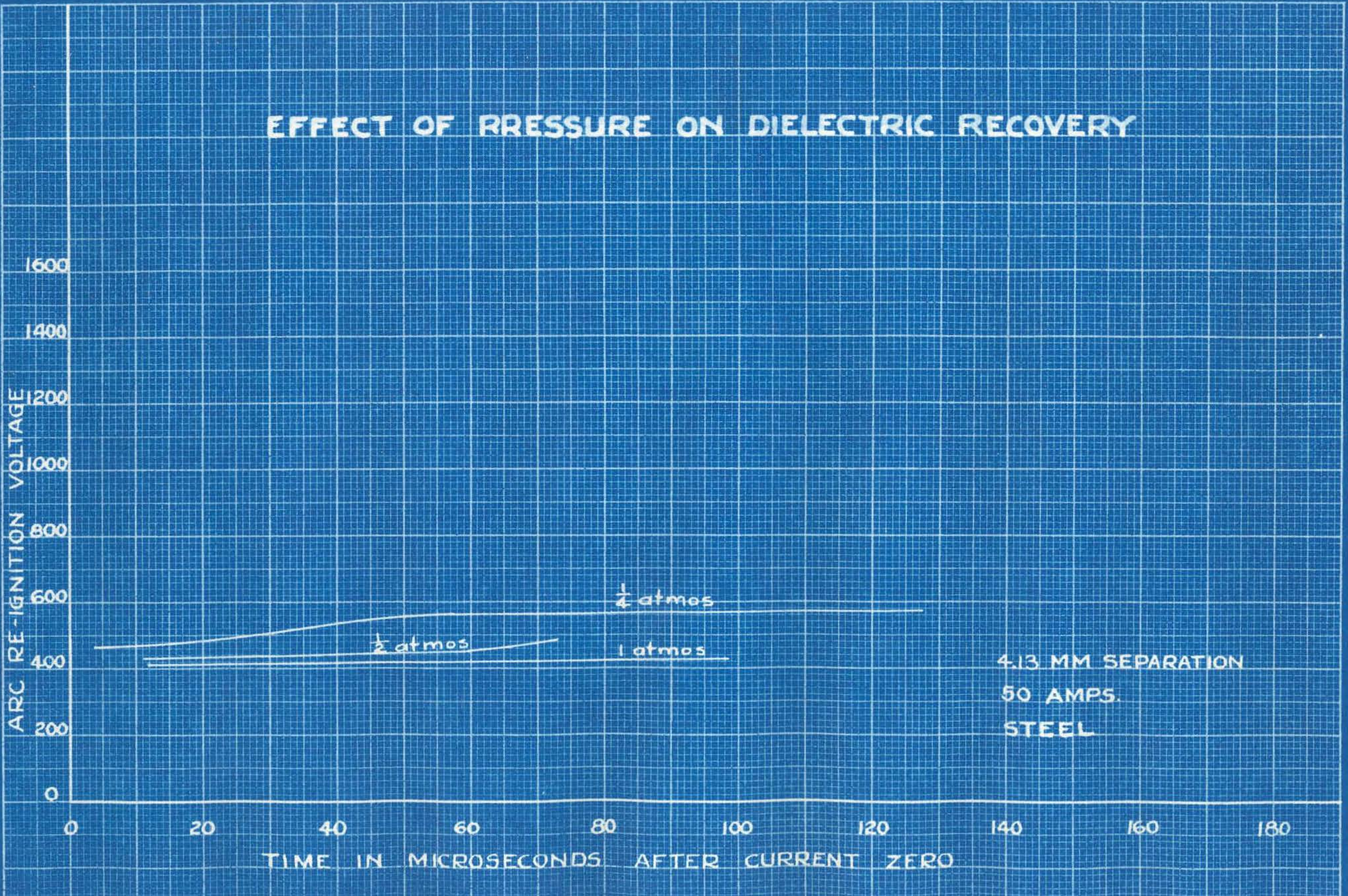

EFFECT OF RRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
$\frac{1}{4}$ atmos
$\frac{1}{2}$ atmos
1 atmos
4.13 MM SEPARATION
50 AMPS.
STEEL

FIG. 49.

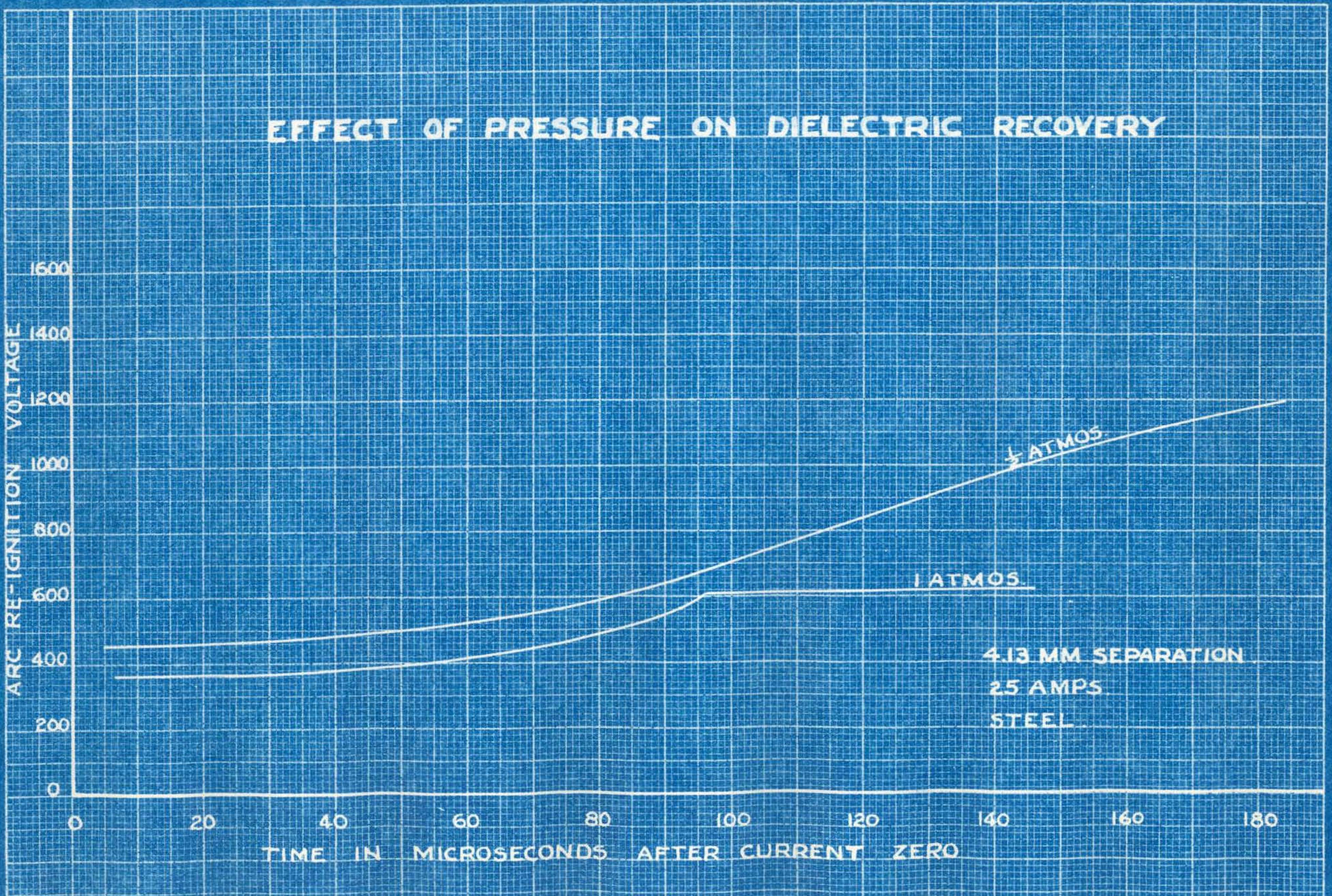

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
½ ATMOS.
1 ATMOS.
4.13 MM SEPARATION.
2.5 AMPS.
STEEL.
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 50.

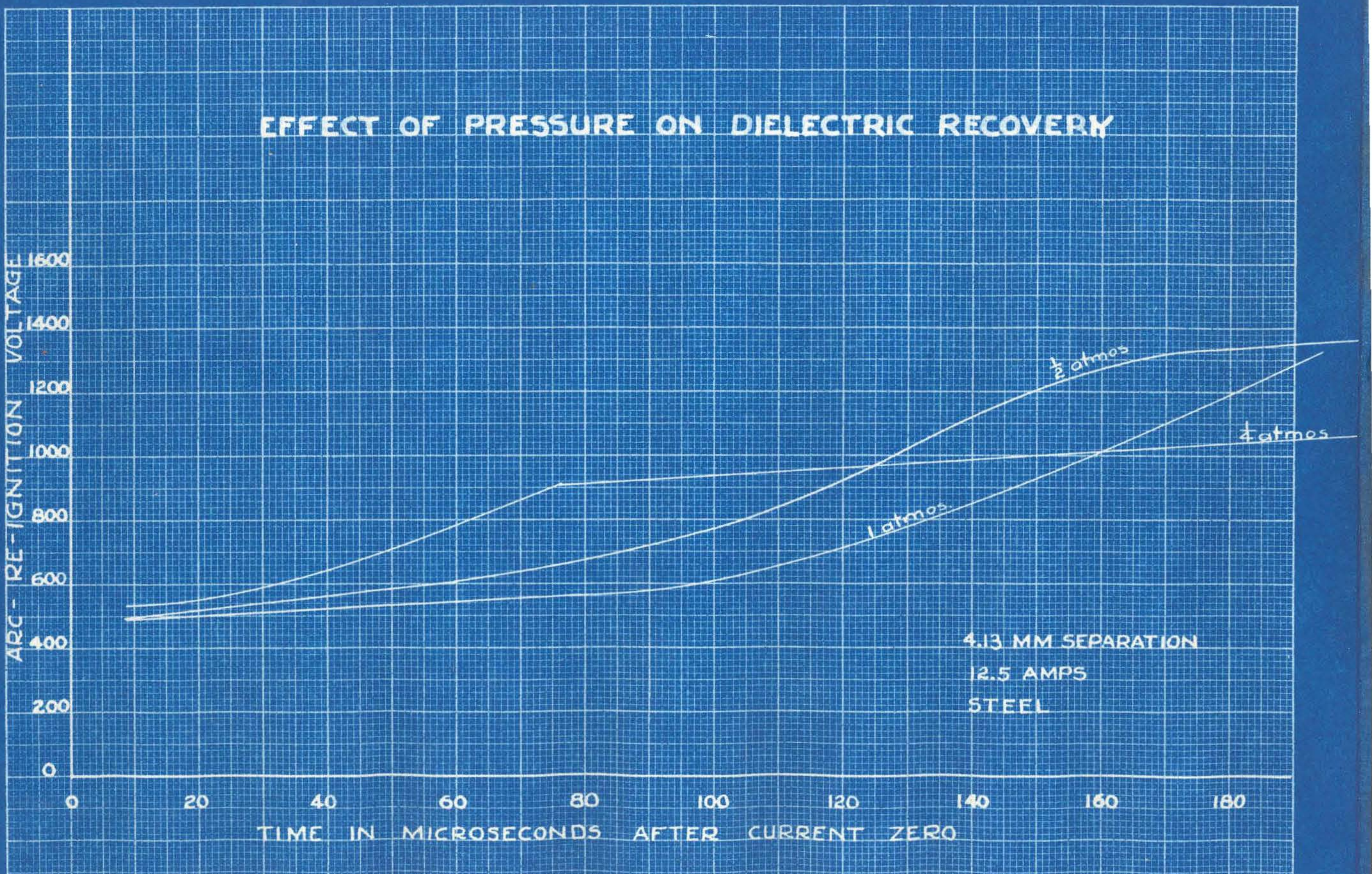

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC - RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
½ atmos
¼ atmos
1 atmos.
4.13 MM SEPARATION
12.5 AMPS
STEEL

FIG. 51

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY

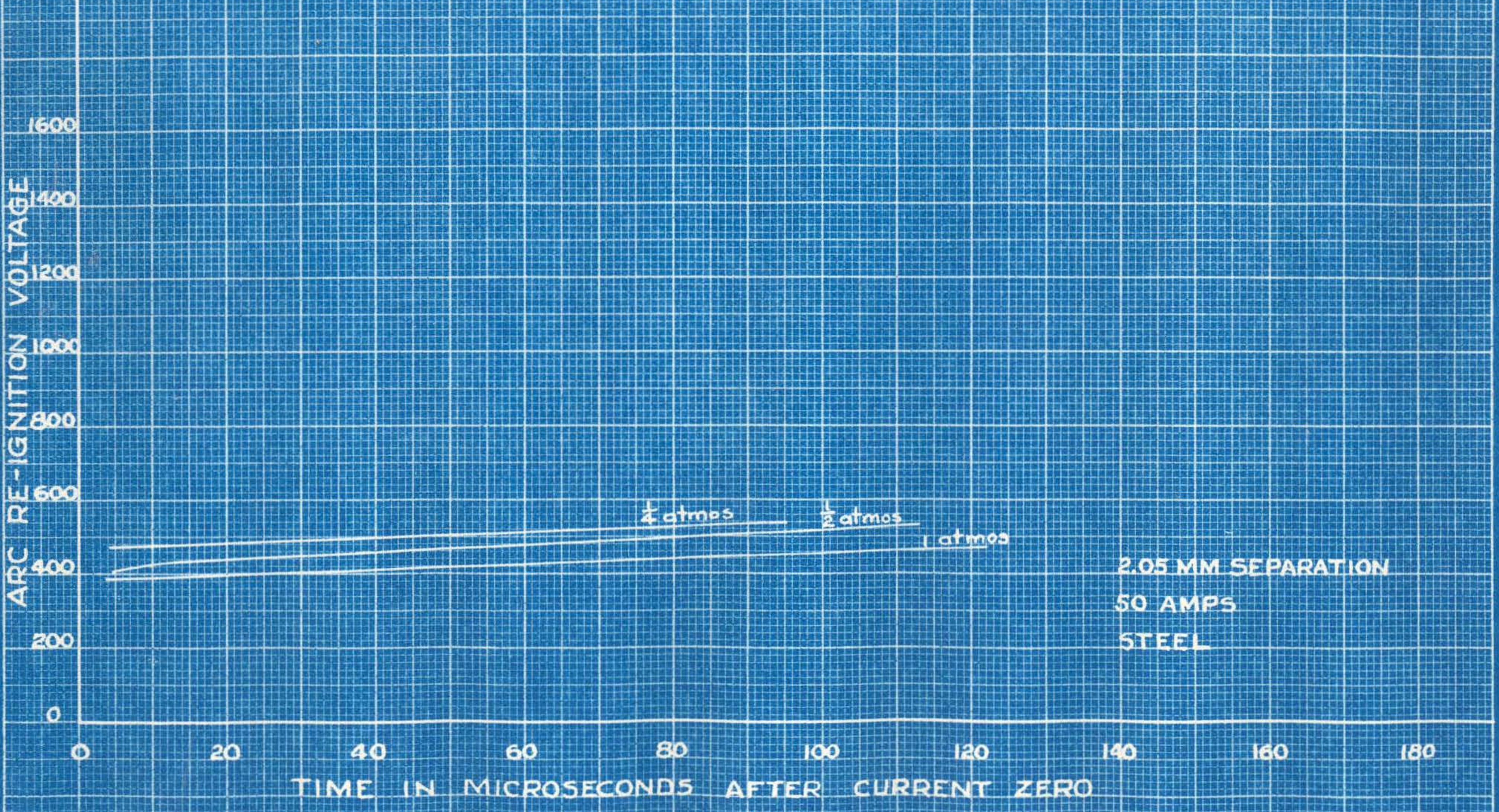


FIG. 52.

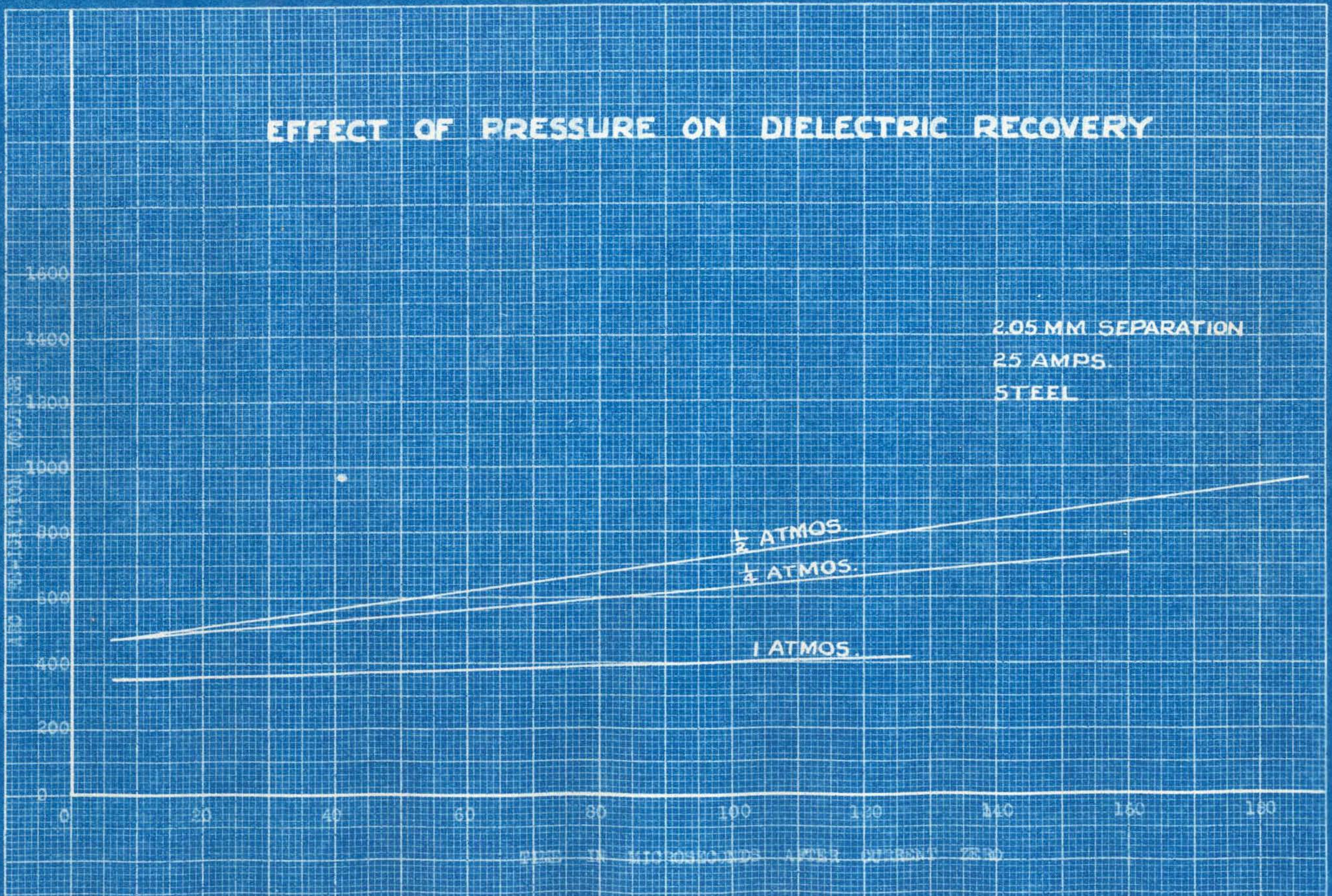

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
2.05 MM SEPARATION
25 AMPS.
STEEL
½ ATMOS.
¼ ATMOS.
1 ATMOS.
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 53.

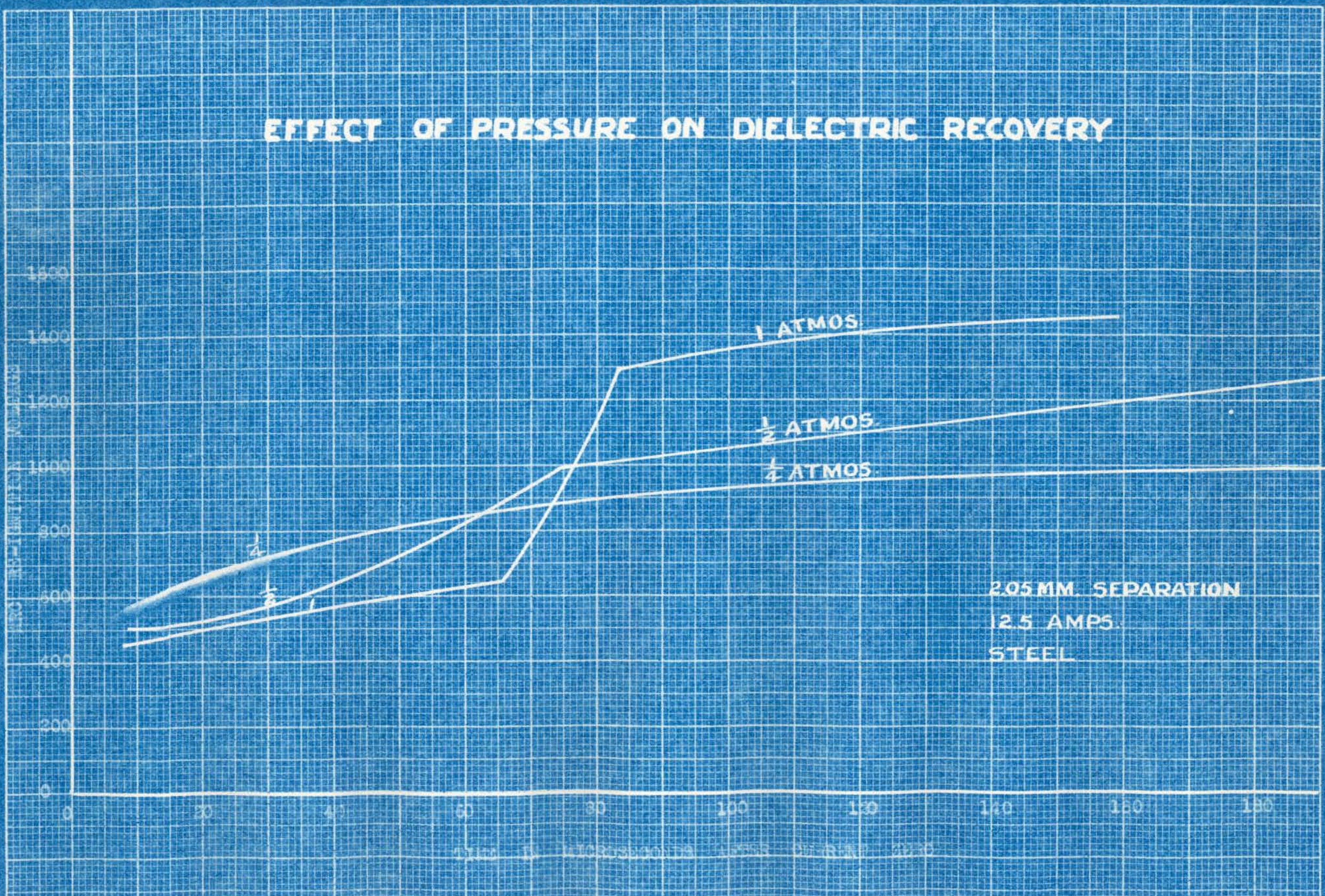
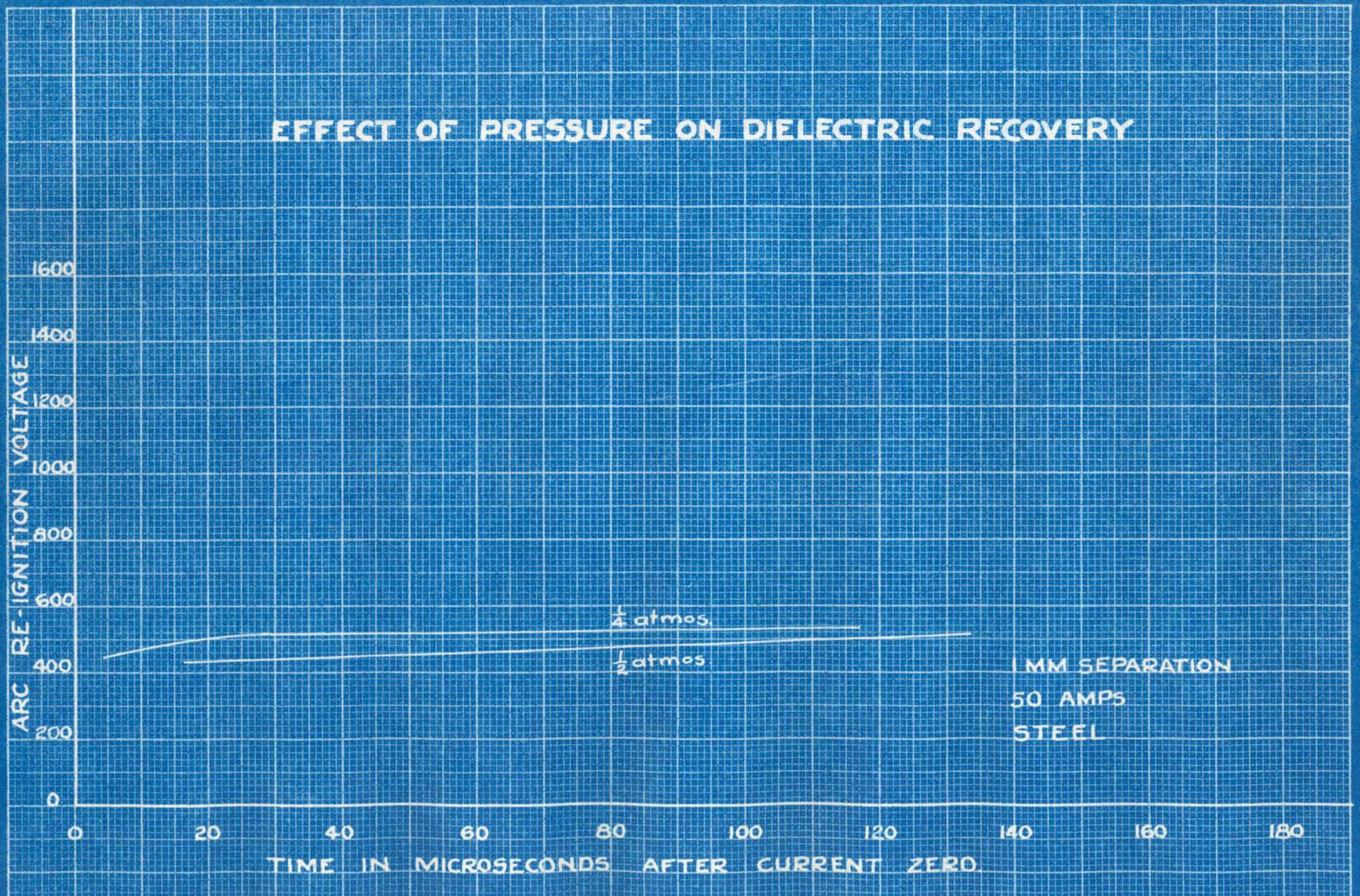
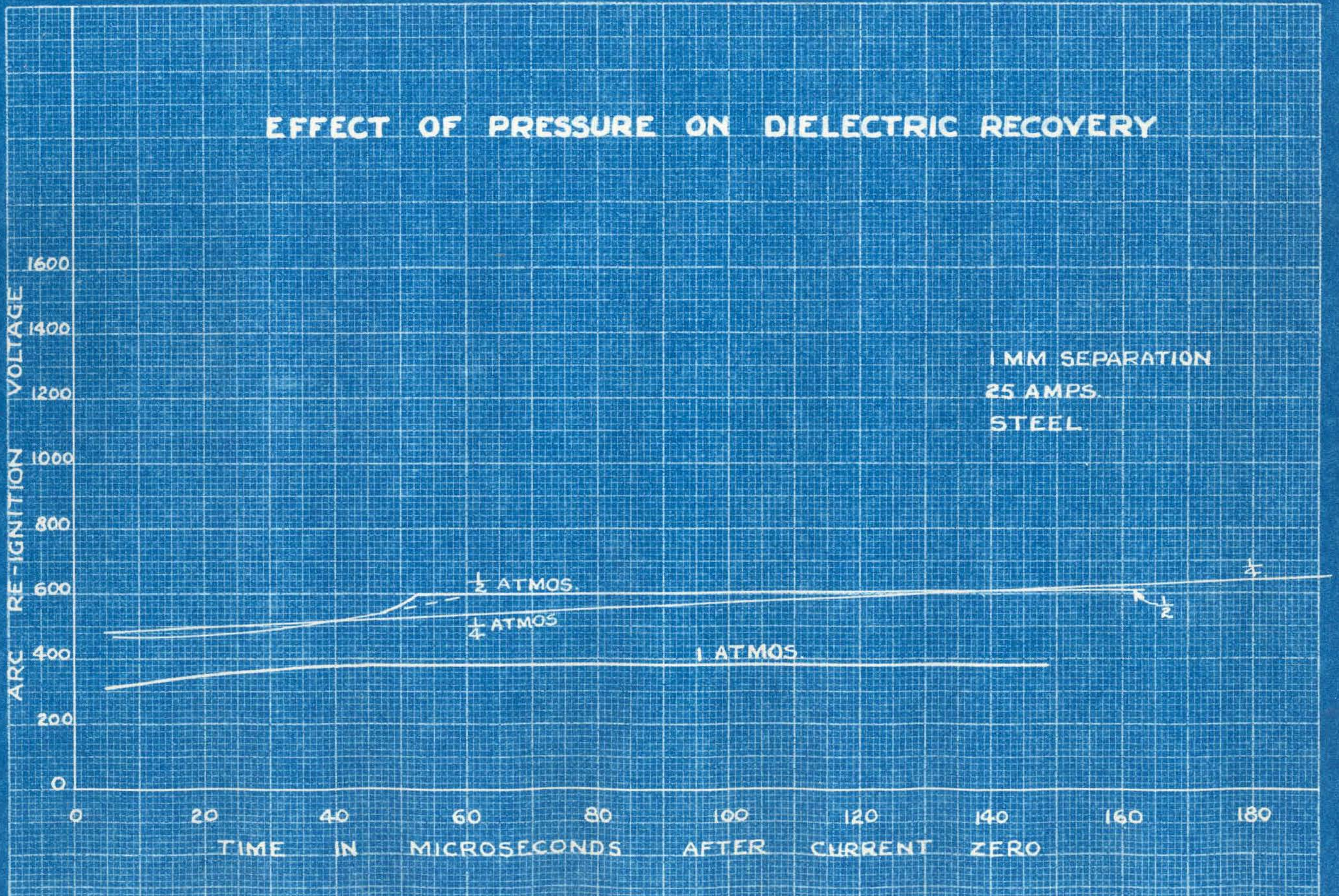

EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
1 ATMOS.
1/2 ATMOS.
1/4 ATMOS.
1/4
1/2
1
2.05 MM. SEPARATION
12.5 AMPS.
STEEL
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180

FIG. 54.



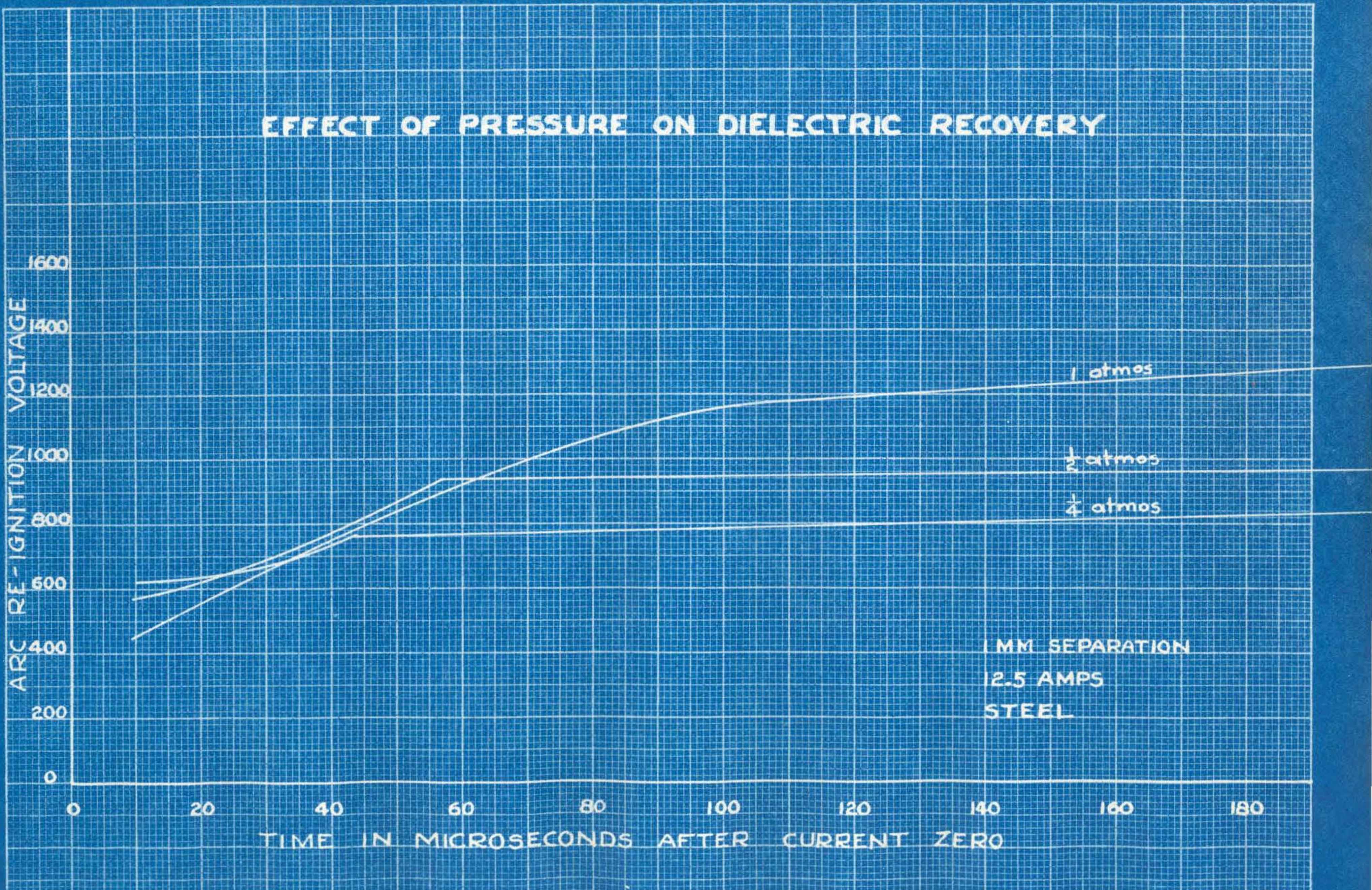
EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
$\frac{1}{4}$ atmos.
$\frac{1}{2}$ atmos.
1 MM SEPARATION
50 AMPS
STEEL
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 55.



EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
1 MM SEPARATION
25 AMPS.
STEEL.
$\frac{1}{2}$ ATMOS.
$\frac{1}{4}$ ATMOS
1 ATMOS.
$\frac{1}{4}$
$\frac{1}{2}$

FIG. 56.



EFFECT OF PRESSURE ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
1 atmos
½ atmos
¼ atmos
1 MM SEPARATION
12.5 AMPS
STEEL

FIG. 57.

Proceeding now to a consideration of Figures 50, 53, and 56 ((25 amps.; 4.13, 2.05 and 1 mm.), we find that the 4.13 mm. arc shows complete deionization at about 80 microseconds. The 2.05 mm. gap shows a somewhat greater gain in dielectric strength for the 1/2 atmos. case, deionization appearing to take place very quickly. For 1 atmos. pressure, however, as for 50 amps., deionization is not completed in 130 microseconds. The minimum breakdown voltage, which we should expect to be independent of current, is very nearly the same for 50 as for 25 amps..

Figures 51, 54, and 57, showing the effect of 12.5 amps. at the various spacings, give results which are very similar in form to those obtained for copper. After deionization takes place, the dielectric strength of the air space should be directly proportional to the density; i.e., to the pressure; the temperature being assumed constant for all pressures. A significant fact to note is that for the 12.5 amp. arcs the initial breakdown voltage is about 100 volts higher on the average for similar spacings than that existing for the 50 or 25 amp. case. This lends weight to the theory that the air is partially replaced by vapor from the electrode material, which has a much lower recombination rate, thus lowering the initial breakdown voltage. The 50 amperage arc would, of course, produce a much greater evolution of vapor than an arc one-quarter its magnitude.

4. Effect of Arc Length - (Steel)

Figures 58 to 66 show the effect of arc length on reignition voltage versus time. Figures 58, 61, and 64, (at 50 amps., and 1, 1/2 and 1/4 atmos.), show that arc length has very little effect for this value of current either on initial restriking voltage or subsequent rate of rise which is very slow. As is expected, for later times the longer arcs show slightly higher breakdown strengths.

Examining the curves for 25 and 12.5 amps., the same type of voltage recovery takes place as was discussed for the copper electrodes. Here again we find that the short arc lengths have a higher dielectric strength for short times after current zero than do the longer arcs. This is clearly shown in Figures 60, 61, 62, 63, 64, and 66. Again a preferred arc length exists somewhere between 1 mm. and 2.05 mm. for the 12.5 amp. case at which short-time reignition voltage is a maximum. Again there is a remarkable similarity between Browne's Figure 40 for brass, Figure 60 for steel, and Figure 31 for copper. These curves show conclusively that the dielectric strength of short arcs is independent of boiling point.

C. Results - General

Although it is not the purpose of this thesis to correlate data obtained with that found for brass, still results are so analogous, especially for the case of copper electrodes, that

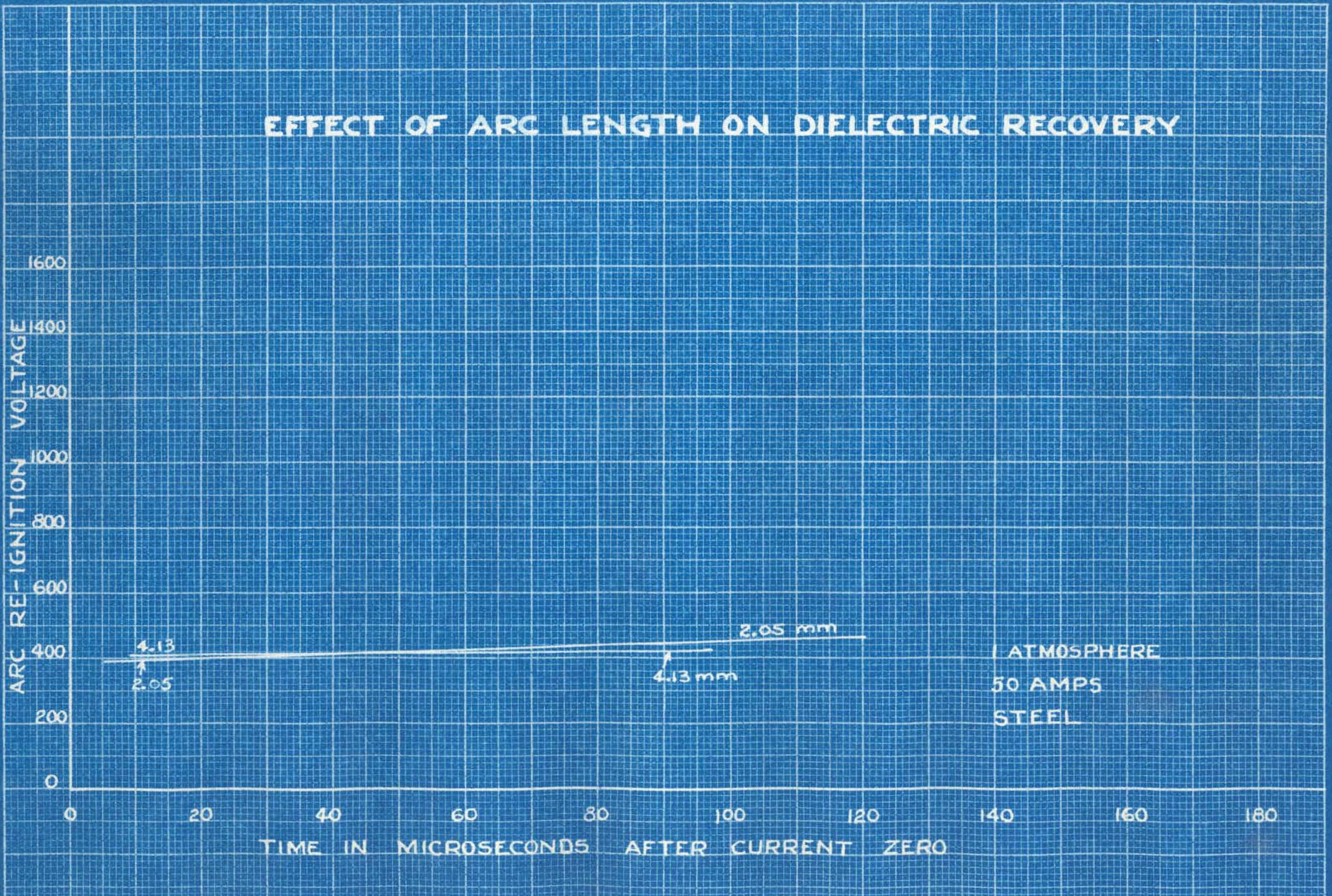

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
ARC RE-IGNITION VOLTAGE
1600
1400
1200
1000
800
600
400
200
0
4.13
2.05
2.05 mm
4.13 mm
1 ATMOSPHERE
50 AMPS
STEEL
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 58

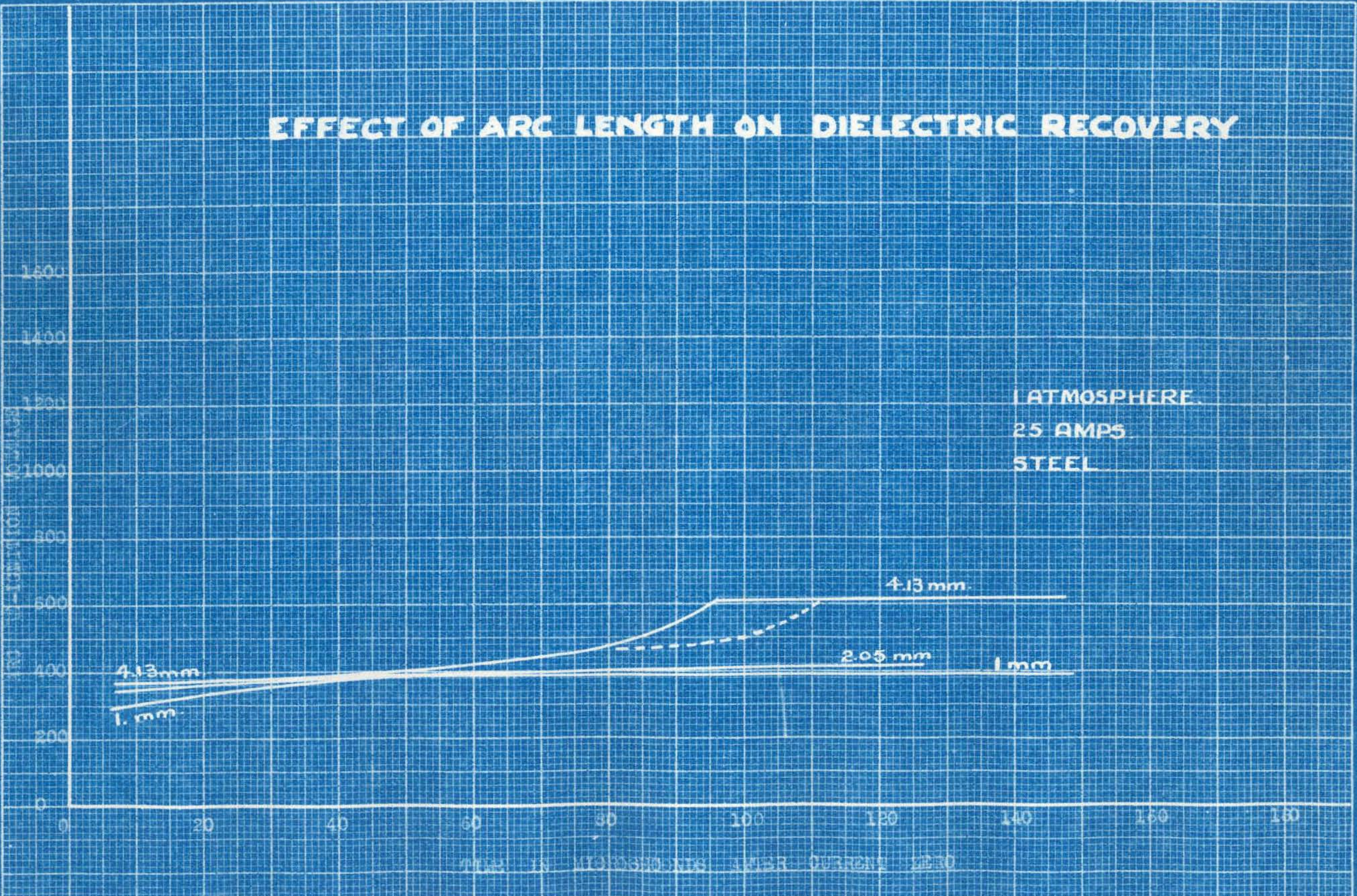

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
1 ATMOSPHERE.
25 AMPS.
STEEL.
4.13 mm.
2.05 mm
1 mm
4.13mm
1. mm.
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 59.

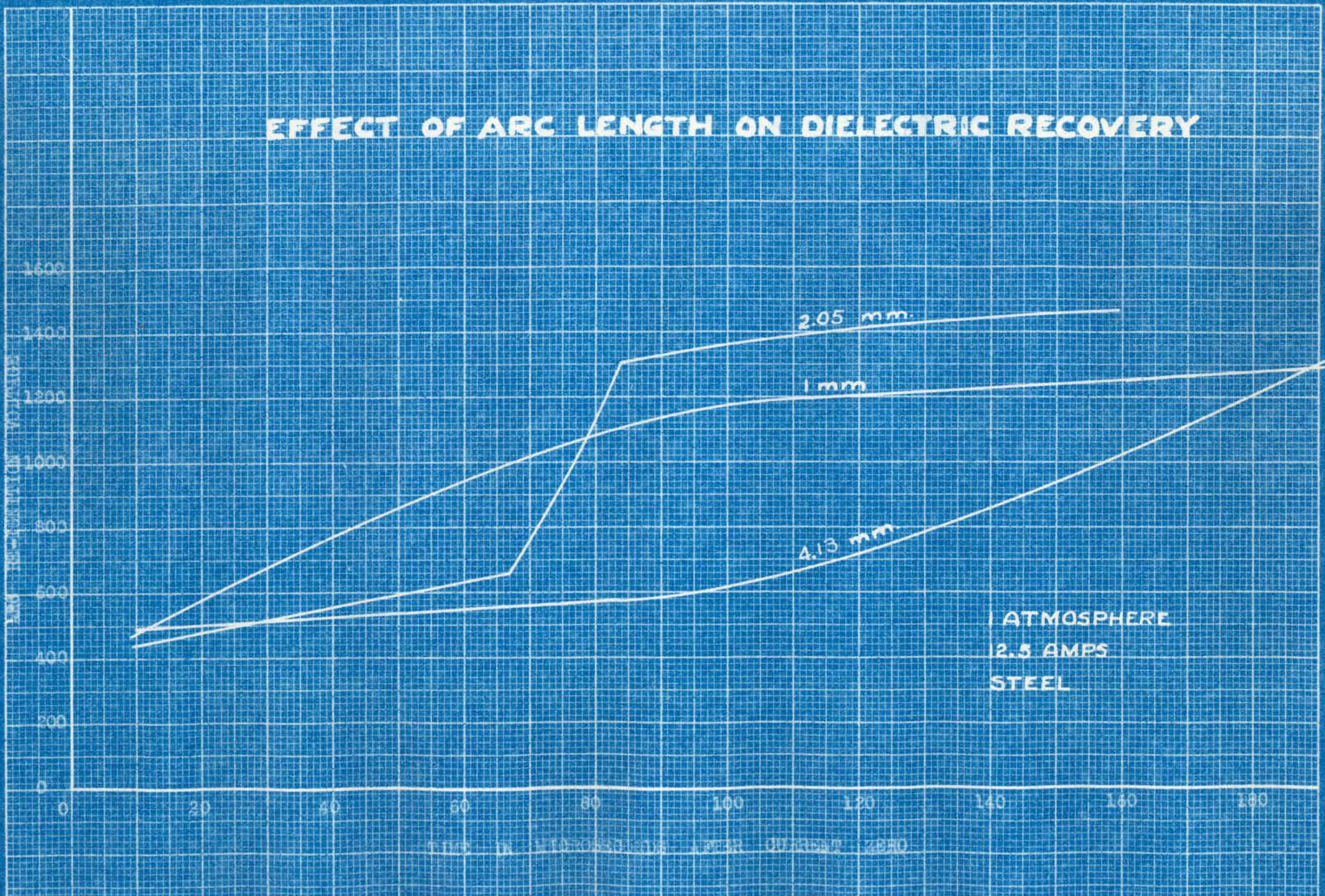

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
2.05 mm.
1 mm
4.13 mm
1 ATMOSPHERE
12.5 AMPS
STEEL
0
200
400
600
800
1000
1200
1400
1600
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 60

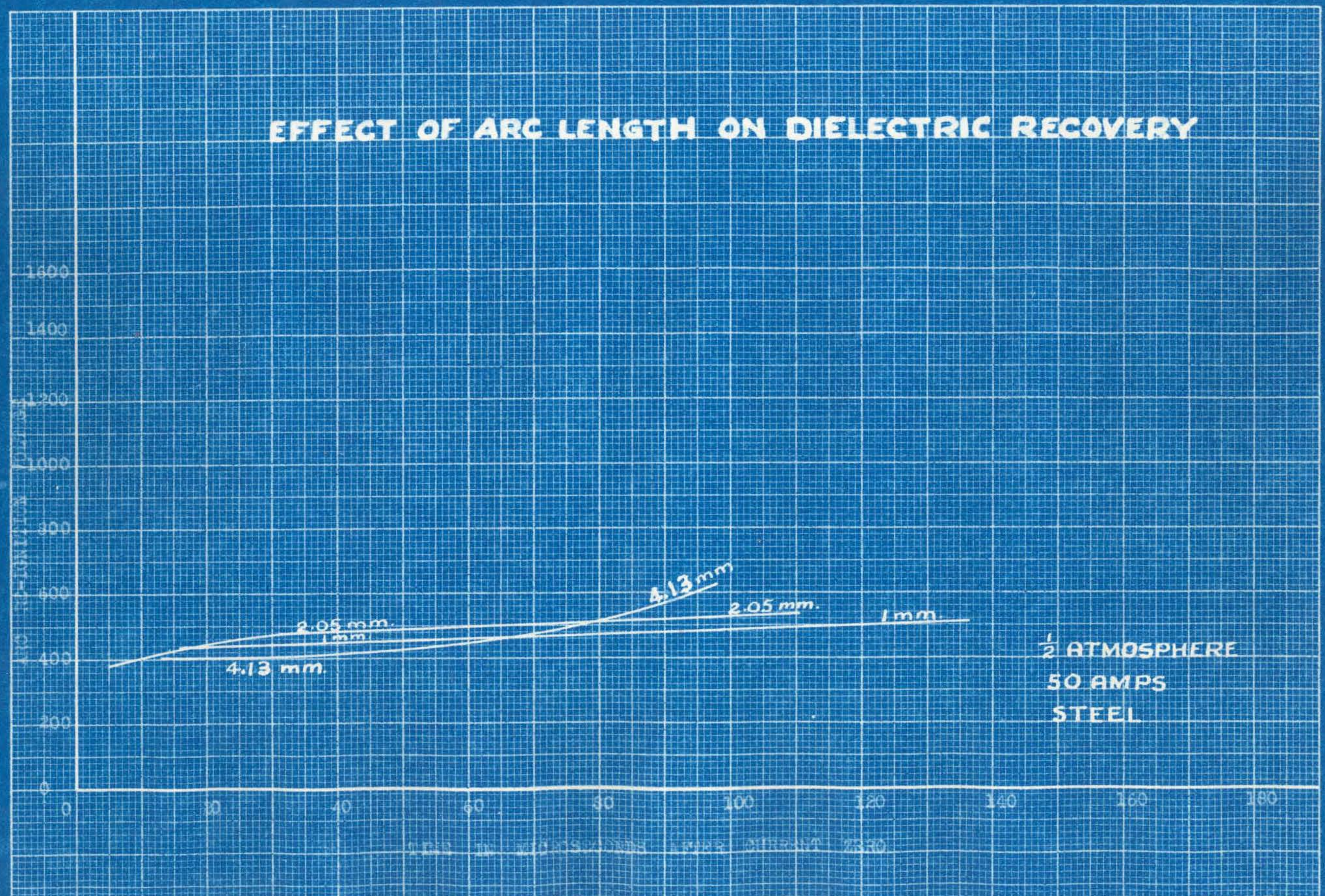

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
ARC RE-IGNITION VOLTS
TIME IN MICROSECONDS AFTER CURRENT ZERO
4.13 mm
2.05 mm.
1 mm.
2.05 mm.
1 mm.
4.13 mm.
½ ATMOSPHERE
50 AMPS
STEEL

FIG. 61.

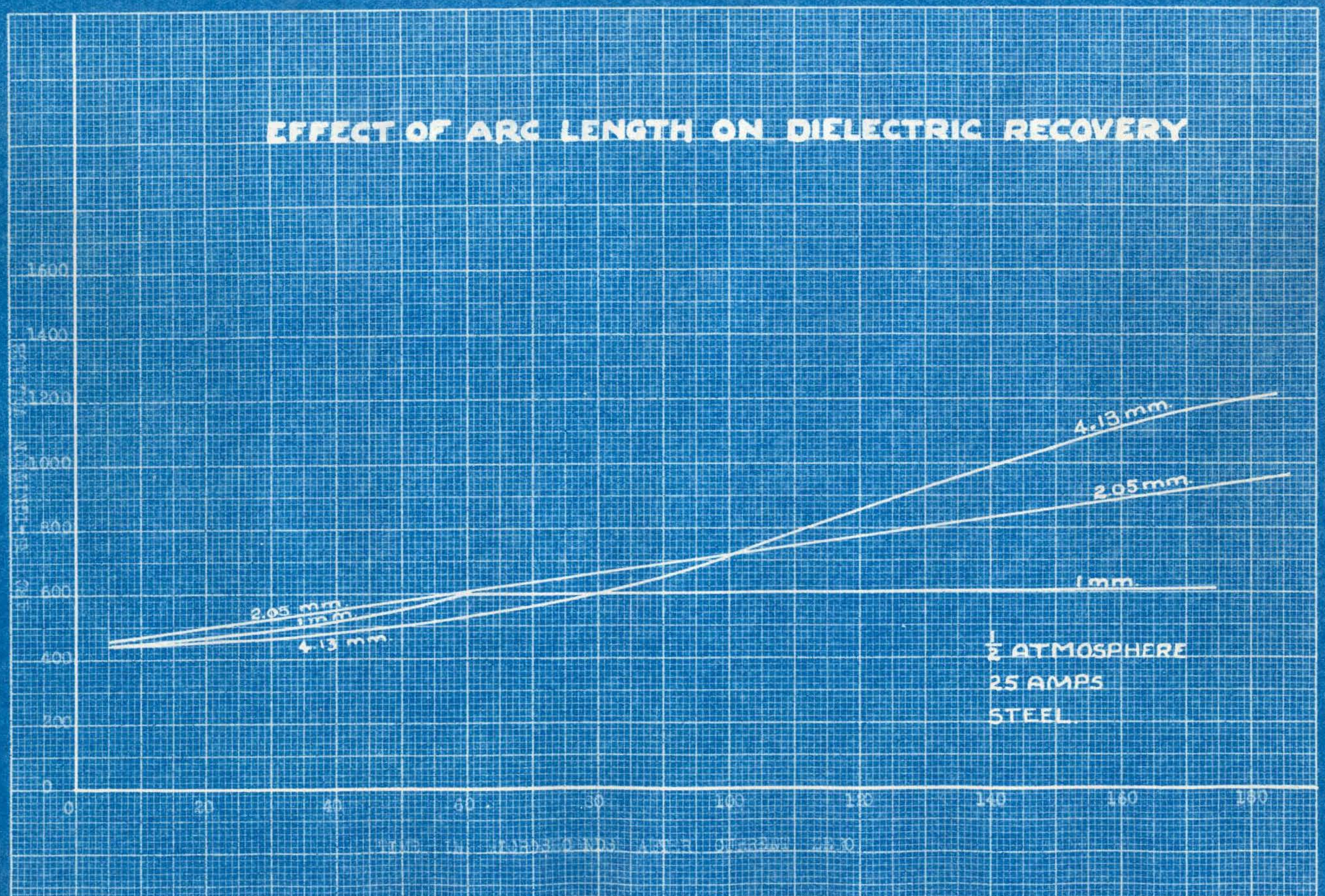

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180
4.13 mm.
2.05 mm.
1 mm.
2.05 mm.
1 mm.
4.13 mm
½ ATMOSPHERE
25 AMPS
STEEL.

FIG. 62.

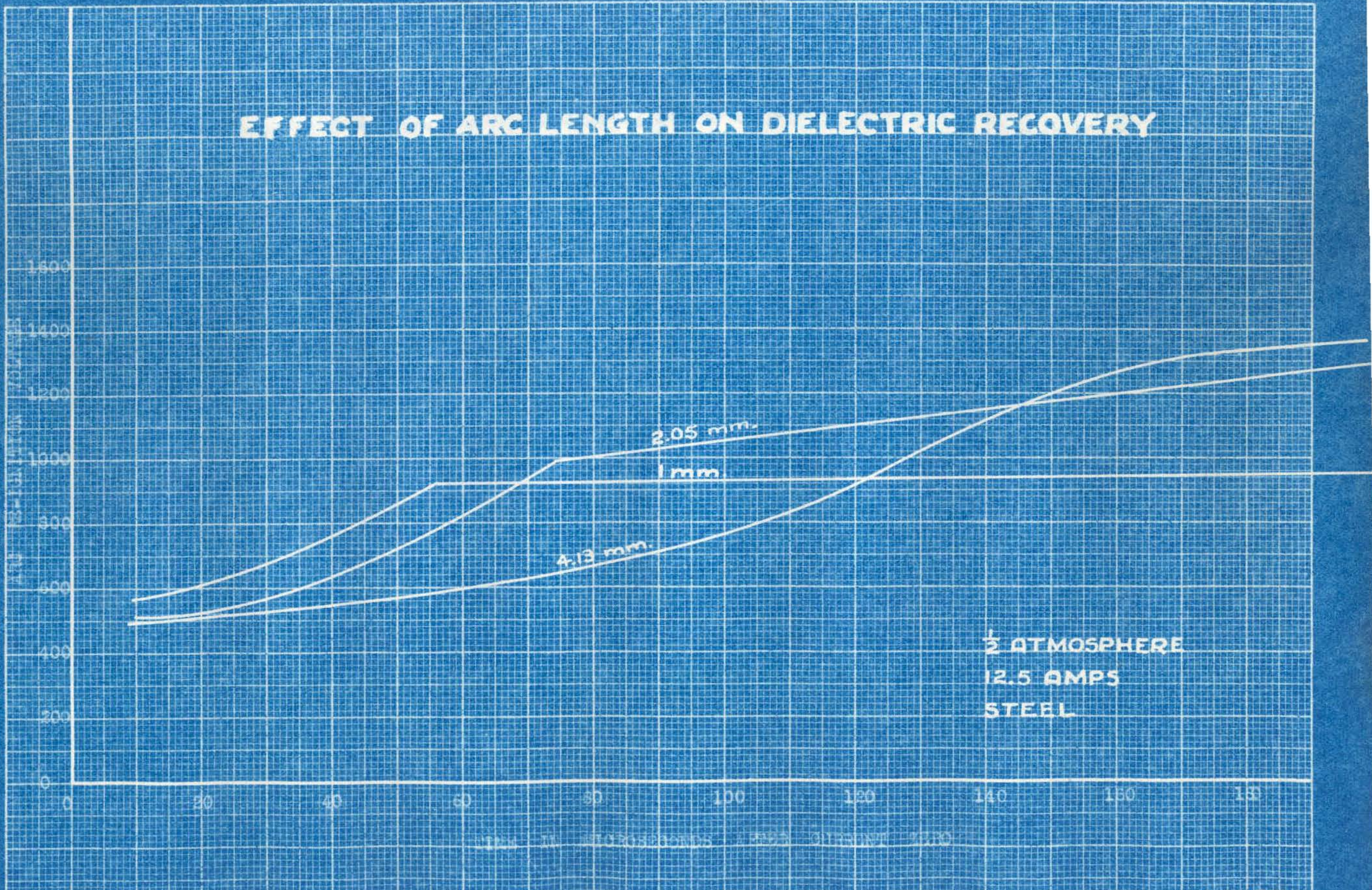

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
2.05 mm.
1 mm.
4.13 mm.
½ ATMOSPHERE
12.5 AMPS
STEEL
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160

FIG. 63.

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY

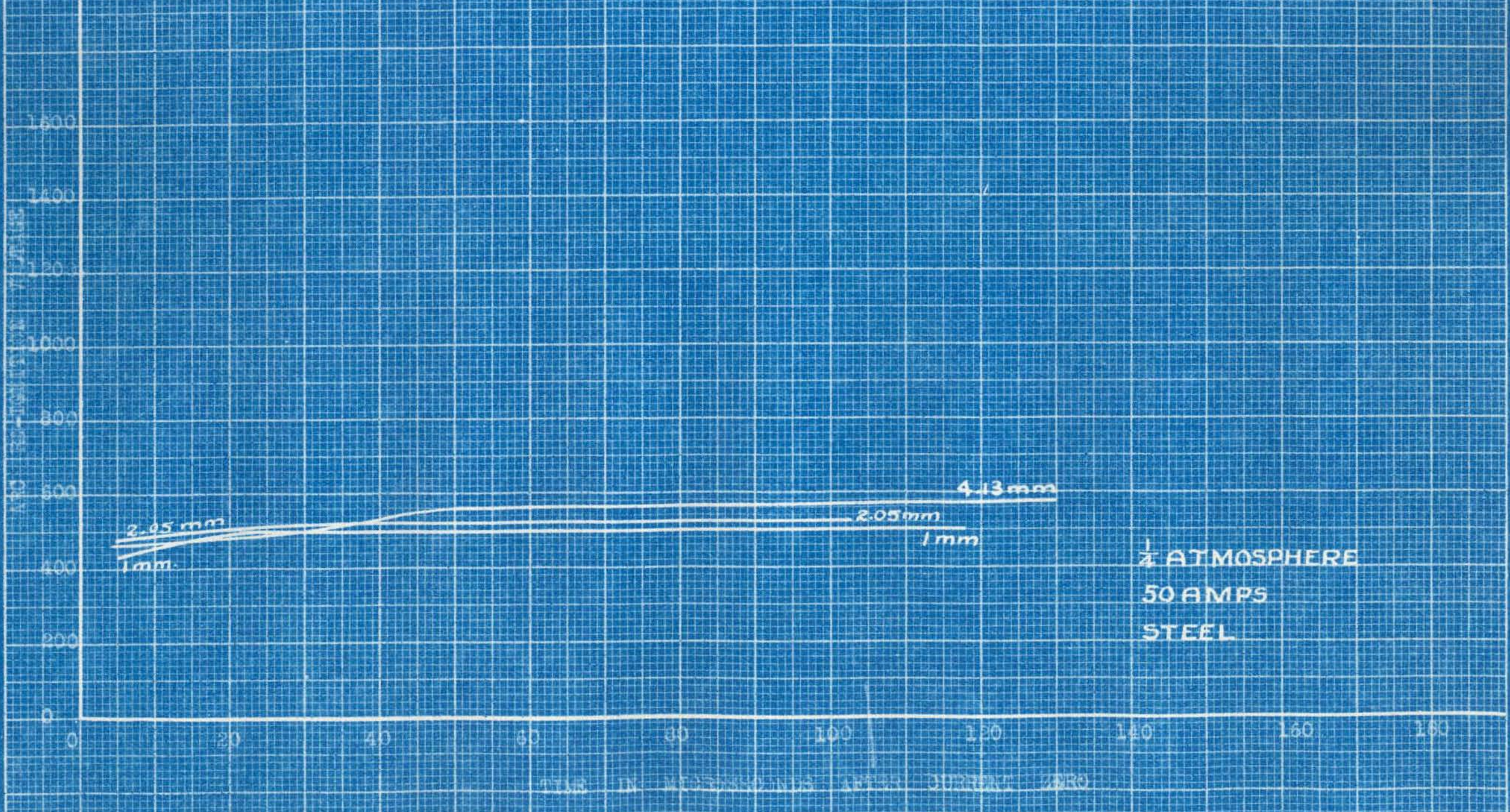


FIG. 64.

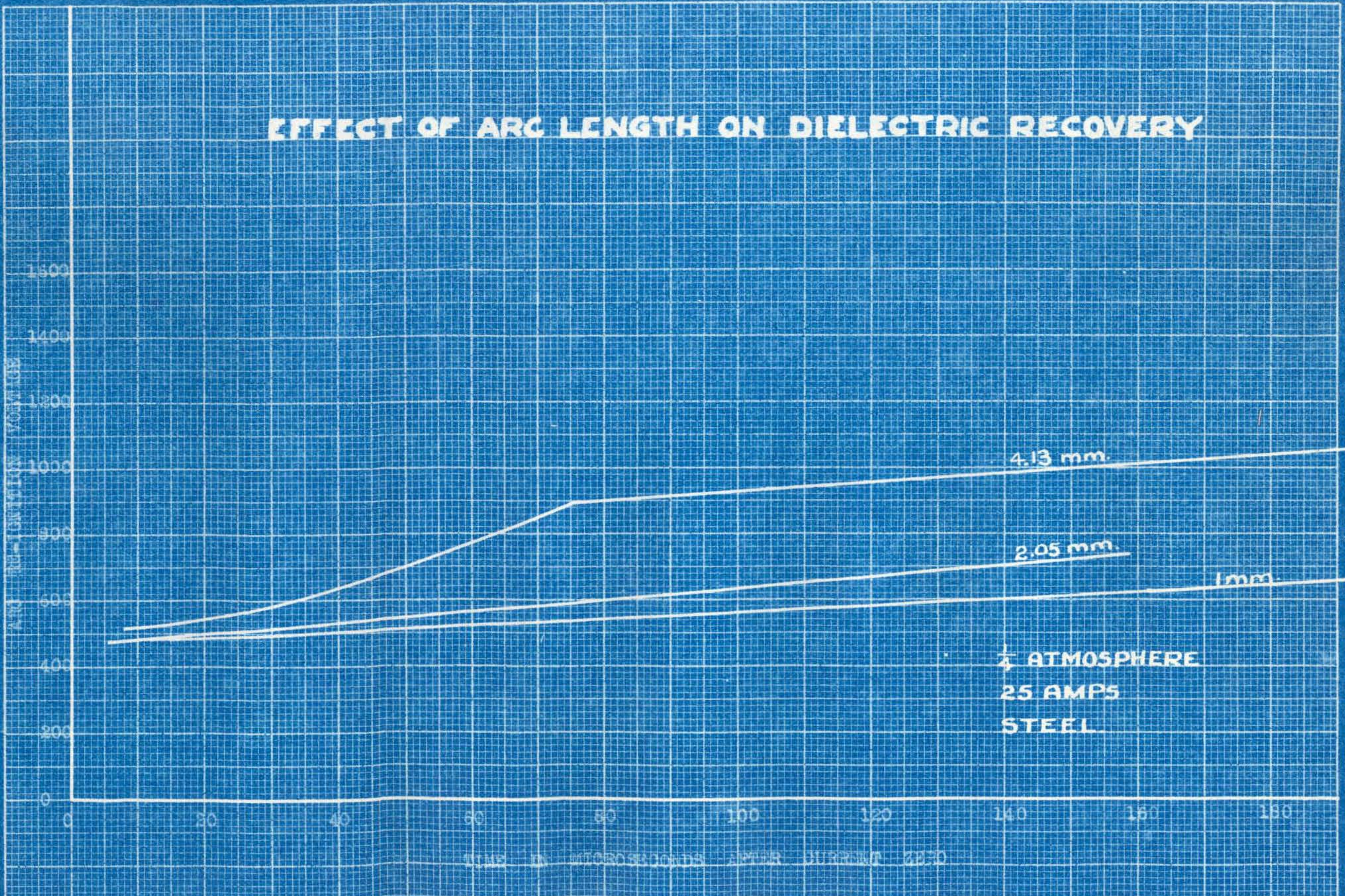

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
4.13 mm.
2.05 mm.
1mm.
¼ ATMOSPHERE
25 AMPS
STEEL
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
120
140
160
180
ARC RE-IGNITION VOLTAGE
TIME IN MICROSECONDS AFTER CURRENT ZERO

FIG. 65.

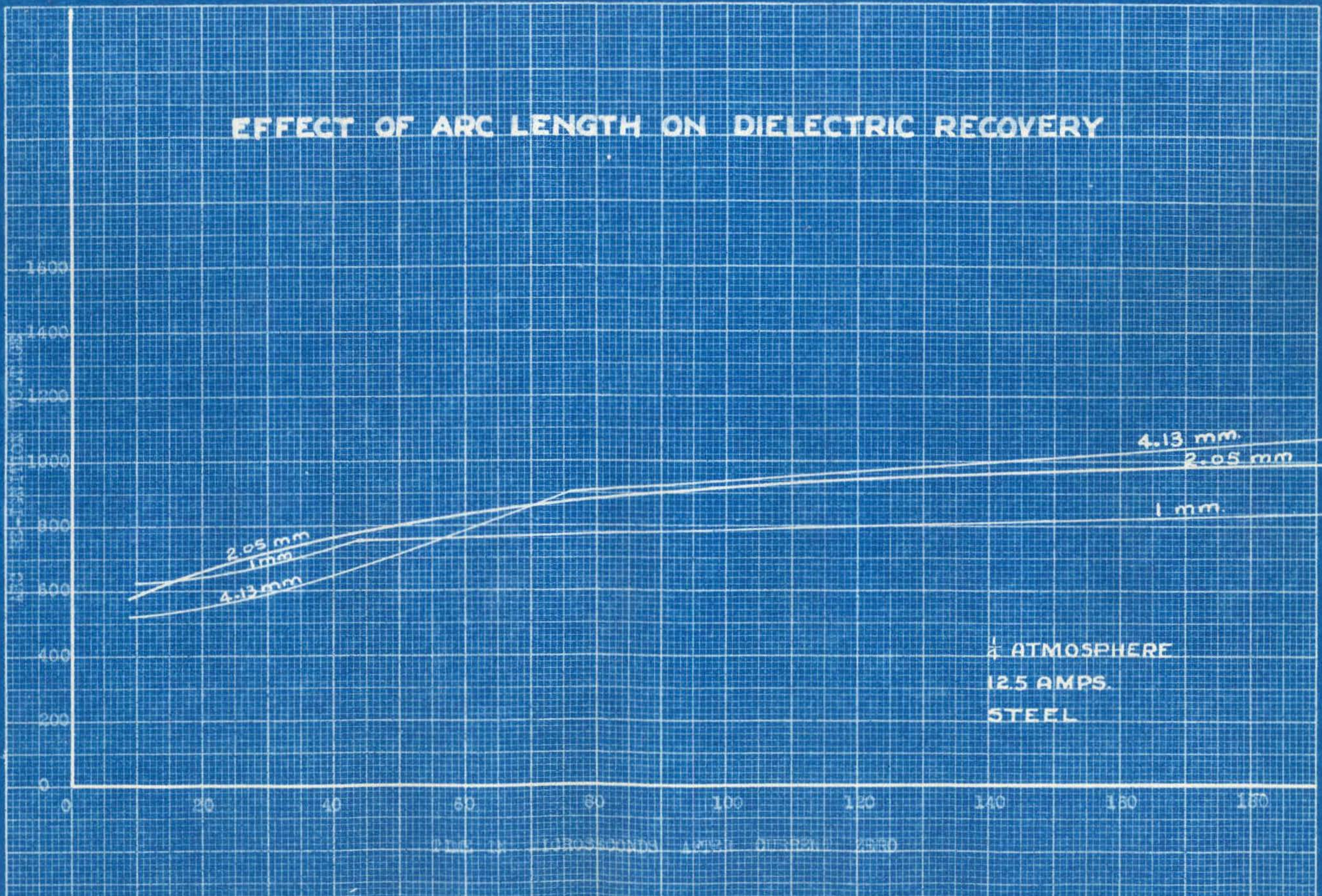

EFFECT OF ARC LENGTH ON DIELECTRIC RECOVERY
1600
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
140
160
180
2.05 mm
1mm
4.13 mm
4.13 mm.
2.05 mm
1 mm.
¼ ATMOSPHERE
12.5 AMPS.
STEEL

FIG. 66.

results obtained there can be applied directly to this case.

It will be noticed that the curves almost without exception show a definite transition point between two distinct regions: the first, a concave upward curve; and, the second, a nearly straight line. The first concave-upward portion represents dielectric recovery due to space charge growth associated with deionization, as given by Equation 5, Appendix E, and as discussed earlier under "Results". The second, usually a straight-line recovery, represents increase in dielectric strength due to the effect of cooling on the gas density. Assuming the latter to be true, the temperatures indicated by the striking voltage in air in this second region were calculated for three cases, (Appendix D). For steel at 1 atmosphere and 1 mm., the extrapolated temperature curve gives for the arc temperature a value of 2750° K.; for 2.05 mm., a value of 4500° K. is obtained. Both these values are for 12.5 amps.. A calculated point for copper at 1 mm., 1 atmos. and 50 amps. shows an arc temperature of 3500° K. Brass electrodes under the same conditions yielded 3800° K., - close enough agreement. For a D-C arc between copper electrodes, Suits obtained a value of temperature of 4050° K.

V. CONCLUSIONS

The following conclusions may be drawn:-

(1) Dielectric recovery by the arc space after current zero is due to the formation of a space charge sheath, as predicted by Slepian.

(2) The chief deionizing process for short arcs is not recombination, but is diffusion.

(3) The initial recovery voltage is lowered by increasing current.

(4) An optimum spacing exists between 1.0 and 2.05 mm. for copper electrodes at which the reignition voltage is highest for short times after current zero.

(5) Short arcs in copper have a higher dielectric strength than long arcs over the range shown by the curves; i.e., over the same range at which brass exhibits this property. This definitely disproves the theory that this property holds only for low boiling point electrodes.

(6) For steel electrodes the very short time breakdown voltage is about 100 volts higher for 12.5 amps. than for either 25 or 50 amps., supporting the theory that the air is partially replaced by electrode vapor.

(7) Short arcs in steel have a higher breakdown strength than the longer ones. This is very definitely shown for all currents and pressures used, except at 1 atmosphere and 25 and 50 amps., where the curves are too closely grouped for any analysis.

(8) A preferred arc length between 1.0 and 2.05 mm. exists for steel electrodes also, for which the breakdown voltage is a maximum.

(9) Temperatures are calculated which agree in order of magnitude (4000° - 6000° K.) with recent determinations.

There still remains considerable work to more thoroughly analyse the curves contained herein. It is hoped that further correlation can be made in the near future and the results published.

VI. ACKNOWLEDGMENT

The writer wishes to express his gratitude to the Electrical Engineering Faculty of the California Institute of Technology for their cooperation, to Dr. T. E. Browne for his excellent instruction and inspiration in this work; to Mr. T. Fahrner for aid in obtaining data; and to Miss Esther Gilbert for her invaluable help in preparing this thesis.

To the National Youth Administration a special acknowledgment is due, - for without the aid of the two assistants whom it supplied for six months, the very laborious and long machine work and calculations would have very much curtailed the scope of this investigation.

APPENDIX A.

APPARATUS

Figure 4 shows in more detail the actual circuit used. Three, single-phase, 1 K.V.A., transformers in parallel, together with a 7.5 K.V.A. transformer in series, provided the power supply at 690 volts. The reactors, air-core, three in number, were designed for minimum distributed capacitance and consisted of 19 layers, each of 19 turns of No. 7 wire. Each coil had a resistance of 0.63 ohms, an inductance of 0.0334 henry, and capacity of 18 micro-microfarads. The inductance of the circuit was varied by taps on the reactors and also by varying the coupling between the coils.

The electrodes were square blocks, 5 cm. per side initially 1.27 cm. thick. The lower electrode was drilled with a No. 59 hole (0.9 mm. diameter) through which a tungsten wire was projected by means of an extensible bellows (Silfon) seal to make contact with the upper electrode and then, falling back, to start the arc. The steel electrodes were shaped after each reading, polished smooth and plane with carborundum paste on a flat disc and then cleaned. With the copper electrodes it was possible to obtain clean surfaces by sandpapering; when they became at all pitted, they were reshaped also. The electrode supporting structure was mounted on a drilled glass base, ground to make good contact with a 12" belljar and the whole connected to a vacuum pump and a closed tube mercury manometer.

The voltage divider was composed of six identical resistor-capacitance sections in series. Each section consisted of a 600,000 ohm carbon resistor in parallel with a small, 50 to 100 micro-microfarad "trimming" condenser. The resistors were adjusted by filing to give equal D-C resistances, and the condensers by insertion into a tuned circuit to give equal voltage ratios at 50,000 cycles. For small displacements on the oscilloscope a voltage-divider ratio of one was used by connecting the leads directly across the arc, and for larger deflections a ratio of 2 or 3 was used. The divider was symmetrically arranged above ground to eliminate errors due to ground currents flowing through non-symmetrical capacitances to ground of other parts of the circuit. The rest of the circuit, as much as possible, was also balanced with respect to ground to eliminate distortion in the electrostatic deflecting field caused by high frequencies if one plate is closer to ground potential than the other.

The oscilloscope had only one pair of electro-static plates which was connected across the arc through the voltage divider. Deflection for the sweep was obtained by magnetic field coils connected through a phase-shifting transformer to the same supply as the arc. The coils were so designed that deflection of the spot across the tube screen took place only when the field current was near zero, and so a linear sweep was obtained. Condensers in series with the coils made the circuit a pure resistance. The reignition phenomena to be observed were centered on the screen by means of the phase shifting transformer. By applying a voltage of the same frequency as the arc supply, but displaced from it by 90°, the spot was cut off on its return path so that the reignition phenomena recurred for one polarity only.

The condensers used for shunting the arc were of two types: the smaller, mica insulated in molded composition; and the larger, ordinary "telephone" condensers of rolled paper. All were accurately measured at frequencies from 10 to 50 kilocycles, the smaller in a tuned circuit, and the larger with a condenser bridge.

The arc and all measuring equipment were about 15' from, and on a line perpendicular to the axis of the reactors, to avoid the latters'magnetic field.

The transformer voltage was read by means of a standard 20-1 potential transformer. A 200 volt D-C supply with voltmeter was also available for calibrating small deflections on the oscilloscope.

APPENDIX B.

EXPERIMENTAL TECHNIQUE

Data were taken in such a manner as to obtain curves of reignition volts versus time after current zero. The current pressure, and electrode separation were kept fixed for each set of readings and the arc shunt capacitance was varied to act as a parameter for the required curve.

The arc current was taken to be the short circuit current flowing when the system was shorted on itself. This current was checked regularly and its value altered by changing the taps or the coupling of the reactors. The pressure was adjusted and controlled by the vacuum pump and manometer. The separation was obtained by the use of gauges of the correct thickness. The lower electrode was first clamped into its supporting structure with the initiating tungsten wire near the bottom of the centrally drilled hole. The top electrode was then laid on the lower and its movable holder brought down to it and clamped. The top holder and electrode were then backed off and clamped firmly, using the gauges as separators. By this means it was unnecessary to do any complicated levelling to make sure the faces were parallel. The tungsten was then pushed through the lower electrode to make contact with the upper one, a quick return being obtained by a fairly strong spring.

Since the oscillograph sensitivity varied somewhat, depending on the width and intensity of line used, settings on the focusing or acceleration anodes, and line voltage, it was calibrated for every reading. All deflections were read by means of two glass slides which moved vertically across the whole face of the tube. A millimeter scale capable of small lateral adjustment was fastened horizontally below and above the screen so that positive and negative distances from the zero mark could be read. Before every reading the zero on the scale was adjusted to correspond to the position of the electron beam.

The line voltage was applied to the plates and the deflections measured in both positive and negative directions. The applied voltage was read through a standard 20-1 potential transformer and a voltmeter. This deflection was usually 33 mm. in the positive direction, and 35 mm. in the opposite direction, using a voltage divider ratio of 2 and peak applied voltage of 1000. A 200 volt D-C supply was used for reading directly the voltage corresponding to any deflection up to 15 mm. (V.D.R. = 1). Between these two points a constant mm. per volt sensitivity existed.

As soon as the arc was started, one slider was moved to read e_s, the average reignition voltage and the other to read average e_m. The arc circuit was broken and restarted several times to check these values and also to obtain a reading of E_1. Wherever possible, a voltage divider ratio of one was used. With steel electrodes at other than 1/4 atmosphere, the initiating hole was usually blocked with molten metal just after the arc was struck so that all three readings e_s, e_m, and E_1, had to be obtained while the arc was burning the first time. When it was felt that these readings were not sufficiently definite or reliable, a new set of electrode surfaces was used and the reading repeated under the same conditions.

Several precautions were observed. In some cases, particularly at the lower values of shunt capacitance, the arc did not move. In these cases, it was necessary to obtain the reading of e_s very quickly, before it fell as it invariably did when the arc stayed on burned metal. Often by extinguishing and restriking the arc several times, it was possible to make it move around on clean metal, in which case, the values on the screen were very uniform and well defined. For the higher values of capacity, the arc usually moved with great rapidity toward the edges where it bowed outwards. This condition of burning could be noticed on the oscilloscope screen and no readings were taken when this condition persisted.

The greatest variation in values appeared in $-e_m$, the negative maximum. Often two well-defined and consistently repeated values appeared simultaneously, either when two no glow traces appeared, or when the no glow and glow case appeared, which occurred near the point where the transition took place from no glow to glow. Readings were taken and recorded of all such consistently appearing values.

For each reading the following data were recorded:-

Open circuit volts.

Short circuit volts.

Deflection in mm. corresponding to open circuit volts in both directions.

S.C. amps.

Shunt capacity.

Separation in mm.

Pressure.

Reignition volts, e_s.

Negative maximum, e_m.

Initial voltage, E_1.

Glow frequency.

Behavior of arc, - kind of movement, etc.

APPENDIX C.

PROBABLE ACCURACY OF THE METHOD

A very complete and searching analysis of the accuracy of the experimental method followed, is given by Browne[5] and will only be summarized here.

Readings of deflections were probably accurate to within five percent on the large deflections and ten percent on the small deflections.

Errors due to non-linearity in oscilloscope deflection were eliminated by calibrating as much of the scale as possible for each set of readings, and then plotting a curve of voltage versus deflection for the screen. The maximum probable error was perhaps ten percent.

Voltmeters and ammeters were checked against standards and were accurate to within one percent. Inductance calculated from these readings $L = \dfrac{\mathcal{E}}{2 \pi f I}$ is thus accurate to at least two percent. The actual current in the arc was less than the measured short circuit current by about 5 percent, due to the neglect of the arc voltage.

The capacitance of the condensers used was measured to within two to five percent. The distributed capacitance of the circuit, found from the inductance and observed resonant frequencies of the circuit, was taken as the mean of several readings to be 150 micro-microfarads.

Measurement of electrode separation was easily accurate to five percent, and pressure to one percent.

Browne investigated fully the error occurring due to calculation of time by means of the simplified equations (X) and (Y), which neglect series resistance and conductance in parallel with the arc. Using the full equation, including series resistance:-

$$e = E - \varepsilon^{-\frac{R}{2L}t}\left\{(E - E_1)\cos wt + \frac{1}{\omega C}\left[-I_1 + \frac{RC}{2L}(E - E_1)\right]\sin wt\right\}$$

where $$w = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

and calculating with typical constants and R = 5 ohms, the effect of resistance of this magnitude was found to be quite negligible.

From an analysis of several oscillograms, Browne found that leakage conductance rose only when the arc voltage was above 600 or 800 volts. Since the greater portions of the normal voltage transients preceding reignition for the cases tested are below this figure, the evidence showed that leakage conductance could be entirely neglected without much error.

The total overall accuracy was estimated to be about five percent for voltage and ten percent in the calculated values of time.

APPENDIX D.

TEMPERATURE CALCULATION

Slepian and Mason give a curve of sparking voltage versus $p\ell$ for plane parallel electrodes in air, (Figure 70). Knowing a sparking voltage then, the corresponding value of $p\ell$ can be found.

The apparent pressure is then:-

$$p = \frac{p\ell}{\ell}$$

Then since

$$\frac{p}{p_o} = \frac{d}{d_o}$$

where d_o is gas density at pressure p_o and temperature T_o

Then since

$$T = T_o \frac{d_o}{d} = 273 \frac{p_o}{p} \text{ in } ^\circ K.$$

The assumptions included in this determination are:-

(1) That Slepian's and Mason's curve can be extrapolated back as shown dotted.

(2) That T_o can be taken as 273° K.

(3) That the perfect gas law holds even though the arc space was not in thermal equilibrium.

(4) That the gas temperature curves on Figures 67, 68, and 69 have been projected back with the correct slope.

APPENDIX E.

SPARKING IN IONIZED GAS

A commonly used value for sparking voltage in air at ordinary pressure and temperature is:-

$$V = 30{,}000\ d \text{ volts} \tag{1}$$

In more general form, applying Paschen's Law:-

$$V = 30{,}000\ d \cdot \frac{T_o}{T} \tag{2}$$

where $T_o = 273°$ K.

Now
$$d = A \frac{V^{2/3}}{n^{1/3}} \quad (7) \tag{3}$$

and
$$A = (136)\left(\frac{k}{\bar{c}}\right)^{1/3}$$

Eliminating d,

$$V = \frac{(6.8)(10^{19})\ k}{\bar{c}} \cdot \frac{1}{n} \cdot \left(\frac{T_o}{T}\right)^3 \tag{4}$$

Taking into account changes in pressure by the use of (2) above, instead of (1), then:-

$$V = \frac{(6.8)(10^{19})\ k_o}{\bar{c}_o} \frac{1}{n} \cdot \left(\frac{T_o}{T}\right)^3 p^{5/2} \text{ volts} \tag{5}$$

where k_o = mobility at 1 atmos. and 0° C.

$\bar{c}_o$ = average thermal velocity at 1 atmos. and 0° C.

p = pressure in atmospheres.

k = ionic mobility.

T = absolute temperature of arc gas.

d = thickness of space charge sheath.

n = density of ionization.

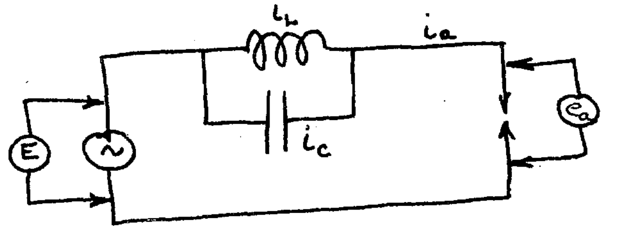
---

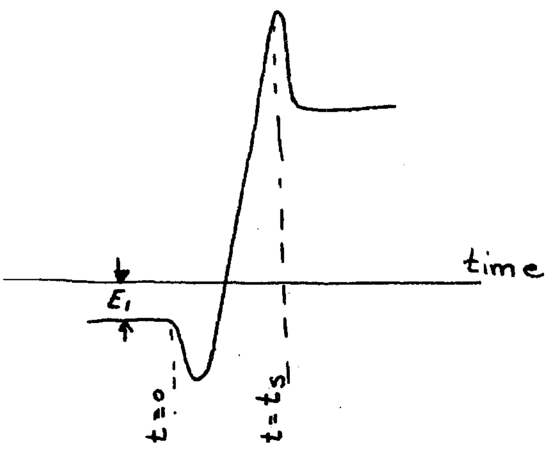
7. Slepian, "Electrical Properties of Gases", (a book) Westinghouse Elec. & Mfg. Co. (1933).

Appendix "F"

Reignition Voltage - Time Equations.

Arc Voltage During Current Zero





$$E = e_a + L\frac{di_L}{dt} = e_a + \frac{q}{C} \qquad (1)$$

at $i_a = 0$ $\quad i_L + i_c = i_a = 0$

$$\frac{di_L}{dt} = -\frac{di_c}{dt} = \frac{q}{LC} \qquad (2)$$

$$\therefore L\frac{di_L}{dt} - \frac{q}{C} = 0 = L\frac{di_c}{dt} + \frac{q}{C}$$

$$L\frac{d^2q}{dt^2} + \frac{q}{C} = 0$$

$$q = A\cos\omega t + B\sin\omega t \quad \text{where } \omega = \frac{1}{\sqrt{LC}} \qquad (3)$$

Initial Conditions

at $t=0$ $\quad e_a = -E_1$ and $i_L = I_1$ for E is practically constant and

$$\therefore \frac{q}{C} = L\frac{di_L}{dt} = \text{const.}$$

$$\therefore i_c = \frac{dq}{dt} = 0 \quad \text{or} \quad i_L \doteqdot I_1 = i_a$$

$$i_L = -\frac{dq}{dt} = -i_c = \omega A\sin\omega t - \omega B\cos\omega t$$

From (1) $\quad E = -E_1 + \frac{1}{C_L}A \qquad A = C_L(E - E_1)$

" (4) $\quad I_1 = -\omega B \qquad B = \frac{-I_1}{\omega}$

$$\therefore e_a = E - \frac{q}{C} = E - (E-E_1)\cos\omega t + \frac{I_1}{\omega C}\sin\omega t$$

Appendix "F" (Cont'd)

$$e_a = E - L\{\omega^2 C(E-E_1)\cos\omega t - \omega I_1 \sin\omega t\}$$

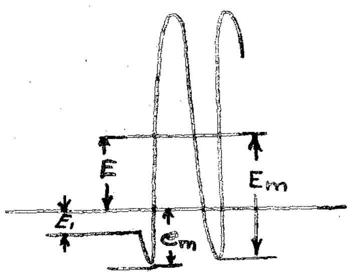
$$= E - \sqrt{(E-E_1)^2 + \left(\frac{I_1}{\omega C}\right)^2}\ \cos\left(\omega t + \tan^{-1}\frac{I_1}{\omega C(E-E_1)}\right)$$

$$= E - E_m \cos(\omega t + \theta)$$

where

$$\theta = \tan^{-1}\frac{I_1}{\omega C(E-E_1)} \qquad E_m = \sqrt{(E-E_1)^2 + \left(\frac{I_1}{\omega C}\right)^2}$$

$$I_1 = \omega C\sqrt{E_m^2 - (E-E_1)^2}$$



$$E_m = E - e_m$$

$$\therefore\ I_1 = \omega C\sqrt{(E-e_m)^2 - (E-E_1)^2}$$

$$e_a = E - (E-e_m)\cos(\omega t+\theta)$$

$$\doteq E\left[1 - \left(1 - \frac{e_m}{E}\right)\cos(\omega t+\theta)\right]$$

$$\cos(\omega t+\theta) = \frac{E-e_a}{E-e_m}$$

$$\omega t = \cos^{-1}\frac{E-e_a}{E-e_m} - \theta$$

$$t = \sqrt{LC}\left[\cos^{-1}\frac{E-e_a}{E-e_m} + \tan^{-1}\sqrt{\left(\frac{E-e_m}{E-E_1}\right)^2 - 1}\right]$$

$$f = \frac{1}{2\pi}\frac{1}{\sqrt{LC}} \qquad T = \frac{1}{f} = 2\pi\sqrt{LC}$$

APPENDIX G.

ARC BEHAVIOR

Due to the large variety of conditions under which the arc behavior was recorded, the data are given in note form below, with an explanatory summary following. In the notation used the first figure denotes current, the second separation, and the third the pressure.

COPPER

50 - 4.13 - 1	Rapid increase in gas pressure; violent flames when arc leaves the electrode edge.
50 - 1 - 1	For low shunting capacity, a soft sounding arc; as C increases, the arc becomes staccato, completely covering the electrode with a spotty trace; arc bowed out into length of 8 inches.
50 - .45 - 1	Arc self-starting.
50 - 2.05 - 1/2	Continuous spider-like trace to edge.
50 - 1 - 1/4	Large burnt spots, no depth of burning.
25 - 1 - 1/2	Arc goes out after 2-3 seconds.
25 - 4.13 - 1	Continuous trace up to 81 seconds, then goes into explosive movement.
25 - 2.05 - 1/2	e_s drops by 50% when the arc reaches the edge.
25 - 1 - 1	Hard to keep arc going when C is increased.
25 - 4.13 - 1/2	Great increase in pressure.

25 - 4.13 - 1/4	Arc travels to the side very quickly but with no preferred direction; e_s drops by 30% and e_m increases; no violent flames as with 1 atmosphere; soft fuzzy electrode traces.
25 - .45 - 1/4	Self-starting; after surface is covered, arc turns to purple glow.
12.5 - 4.13 - 1	Start of staccato trace at 138 sec.
12.5 - 2.05 - 1	Start of staccato trace at 75 sec.
12.5 - 1 - 1/2	At high C very diffuse arc; after electrode covered arc changes to diffuse purple glow; develops great heat.
12.5 - 1 - 1/2	Complete diffuse coverage of all electrode surface.
12.5 - 2.05 - 1/2	When oxidized around center hole, arc could not be restarted.
12.5 - .45 - 1/4	Arc changes to glow in 6-8 seconds.
12.5 - 1 - 1/4	Trace consisted of black spots mostly near edge.

STEEL

12.5 - .45 - 1	No readings could be taken at .45 mm. because arc was continuously shorted by thin spires of metal soon after arc started.
25 - 1 - 1	Two main craters; reading had to be taken quickly before characteristics changed.

25 - 4.13 - 1	Initiating hole welded over. Rapid movement only at high values of <u>C</u>.
12.5 - 1 - 1	Very rapid movement, maintained only for 2-3 cycles.
12.5 - 4.13 - 1	Difficult to maintain arc.
12.5 - 2.05 - 1	Difficult to maintain arc.
50 - 2.05 - 1/2	Dark, fine path; good movement. Arc sometimes shorted out by spire of metal.
50 - 1 - 1/4	Soft arc.
25 - 1 - 1/2	Good coverage - spotted trace.
25 - 1 - 1/4	Arc self-starting; electrode rough as though arc had passed but not stopped; some small molten spots also.
25 - 4.13 - 1/2	At low values of <u>C</u> total movement within 1/2" diameter circle. For higher values more movement.

<u>SUMMARY</u>

For low values of shunting capacity, the arc tended to burn near the center of the electrodes. As the capacity increased, the arc movement became more rapid. When it reached the edge for copper electrodes at 50 and 25 amps., the arc bowed out in violent flames. The manometer indicated a rapid increase in pressure, often great enough to send the mercury in the manometer tube surging from its position recording a 1/2 or 1/4 atmospheric difference, to striking the top of the tube with considerable violence. This effect is well known and has been described in early literature[8].

The different kinds of traces are shown in Figures 71 to 81. All the conditions holding at the time they were taken are noted under them.

Figure 81 shows an enlarged view of the center part of Figure 80. The hole shown is the initiating hole of diameter .9 mm. Measurements indicate a current density of approximately 10,000 amps. per square cm. for this case. Rougher calculations for Figure 79 show a current density of the same order of magnitude. This agrees with Langmuir's criteria for the high field theory of cathode spot.

In general e_s was much lower when the arc did not move, so that in such cases the circuit was broken and the arc restarted until it did move on new metal. It was also noticed (see 12.5 - 2.05 - 1/2) above, that it was harder to start the arc if the metal around the initiating hole had been previously burned, showing that the oxides and other products of burning when cold, support the arc with more difficulty than the parent metal.

Another point which is of interest is the fact that the arc ceased its continuous trace and broke into a fast spotty motion at roughly the same time when transition between the two kinds of dielectric recovery took place.

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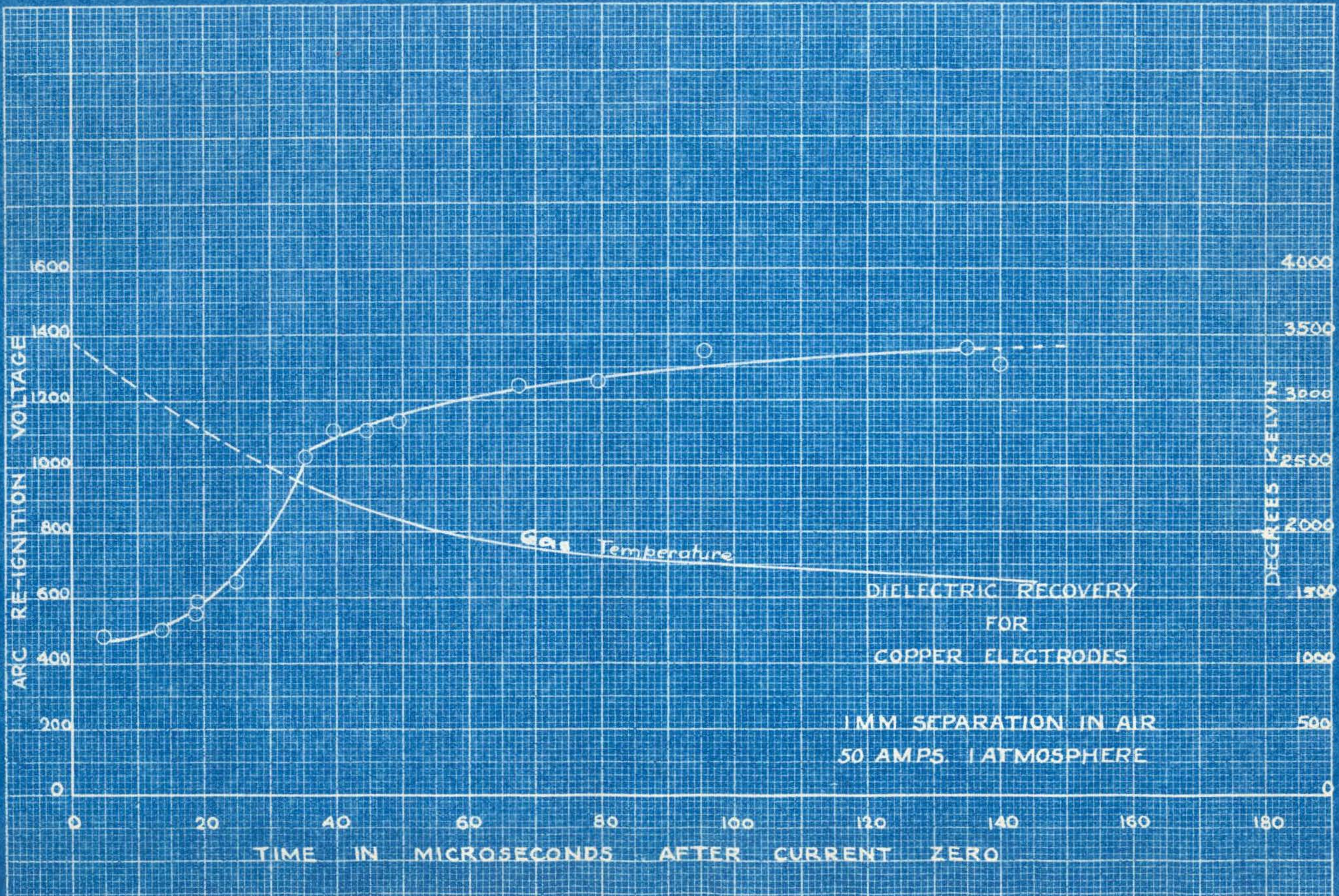
8. Thompson, J. J. and G. P., "Conduction of Electricity through Gases", (a book), Vol. II, page 566. Cambridge University Press, (1933).

The motion of the arc across the electrodes has been discussed in literature[8], and its cause is fairly obvious. The addition of 10^7 ergs of energy to 1 c.c. of gas would increase the pressure by 6.6 atmospheres. Consider this same energy applied to $\frac{1}{100}$ c.c., a very large over-estimate of the volume of a short arc, then the pressure rise of 660 atmospheres is experienced. This high pressure would spread as a wave giving the "bomb" effect described above, but would also cause the ionized gases in the core to move. The lowest dielectric path then usually occurs at a position slightly different from the previous arc position, and the arc then reignites at a new point.



ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
DEGREES KELVIN
0
500
1000
1500
2000
2500
3000
3500
4000
0
20
40
60
80
100
120
140
160
180
TIME IN MICROSECONDS AFTER CURRENT ZERO
Gas Temperature
DIELECTRIC RECOVERY
FOR
COPPER ELECTRODES
1MM SEPARATION IN AIR
50 AMPS. 1 ATMOSPHERE

FIG. 67

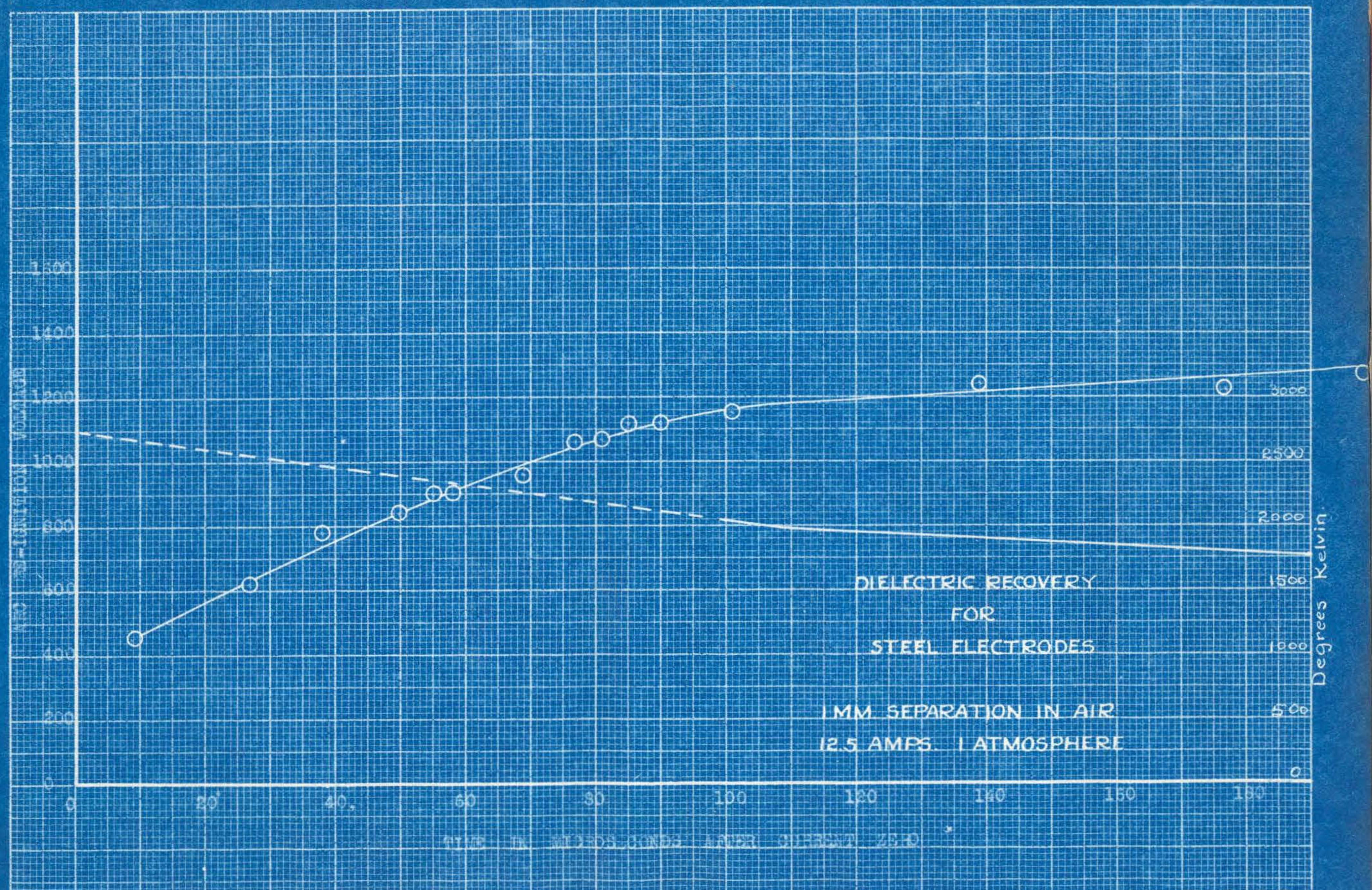

DIELECTRIC RECOVERY
FOR
STEEL ELECTRODES
1MM. SEPARATION IN AIR
12.5 AMPS. 1 ATMOSPHERE
Degrees Kelvin
0
500
1000
1500
2000
2500
3000
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
140
160
180

FIG. 68

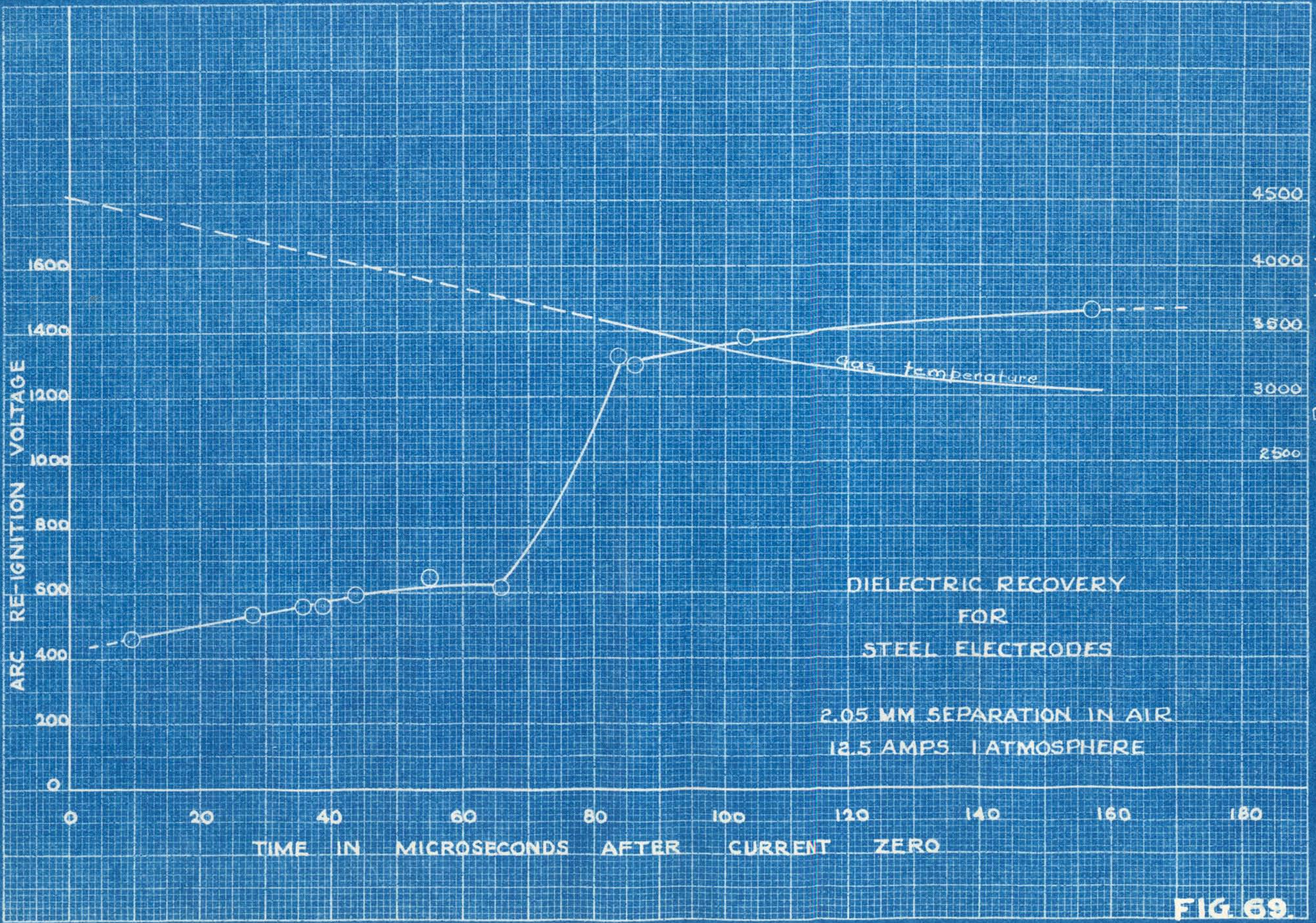

DIELECTRIC RECOVERY
FOR
STEEL ELECTRODES
2.05 MM SEPARATION IN AIR
12.5 AMPS. 1 ATMOSPHERE
ARC RE-IGNITION VOLTAGE
0
200
400
600
800
1000
1200
1400
1600
TIME IN MICROSECONDS AFTER CURRENT ZERO
0
20
40
60
80
100
120
140
160
180
Degrees Kelvin.
2500
3000
3500
4000
4500
Gas temperature

FIG. 69.

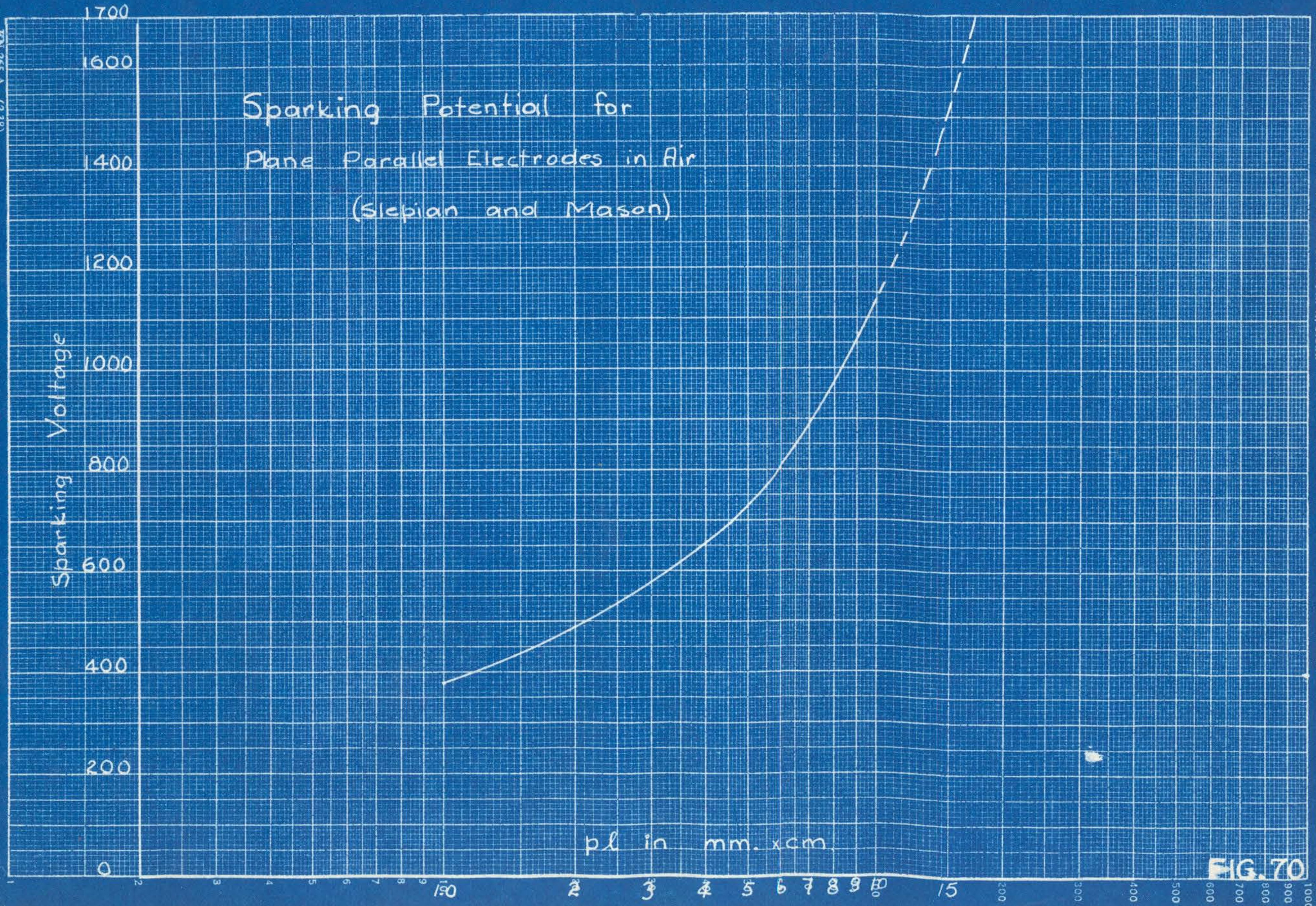
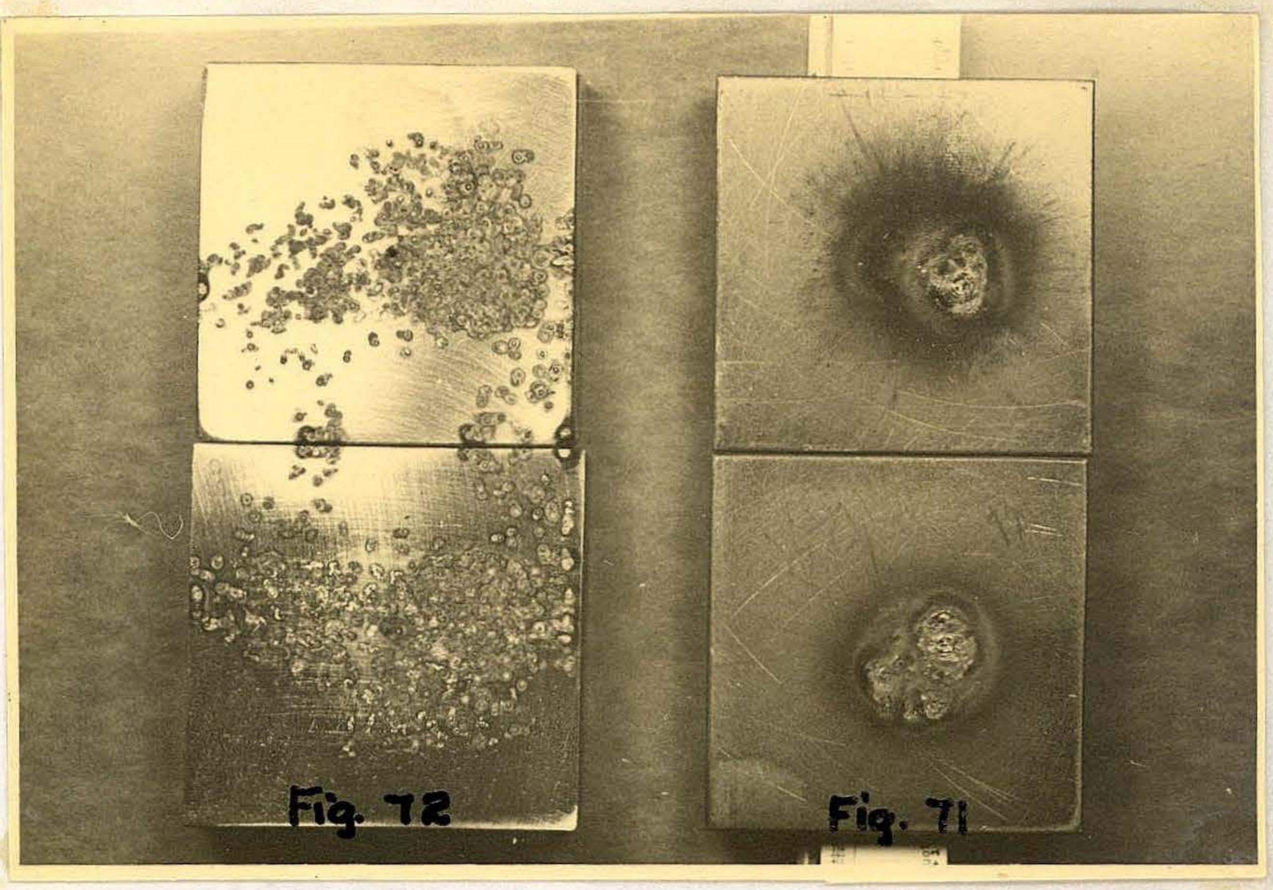
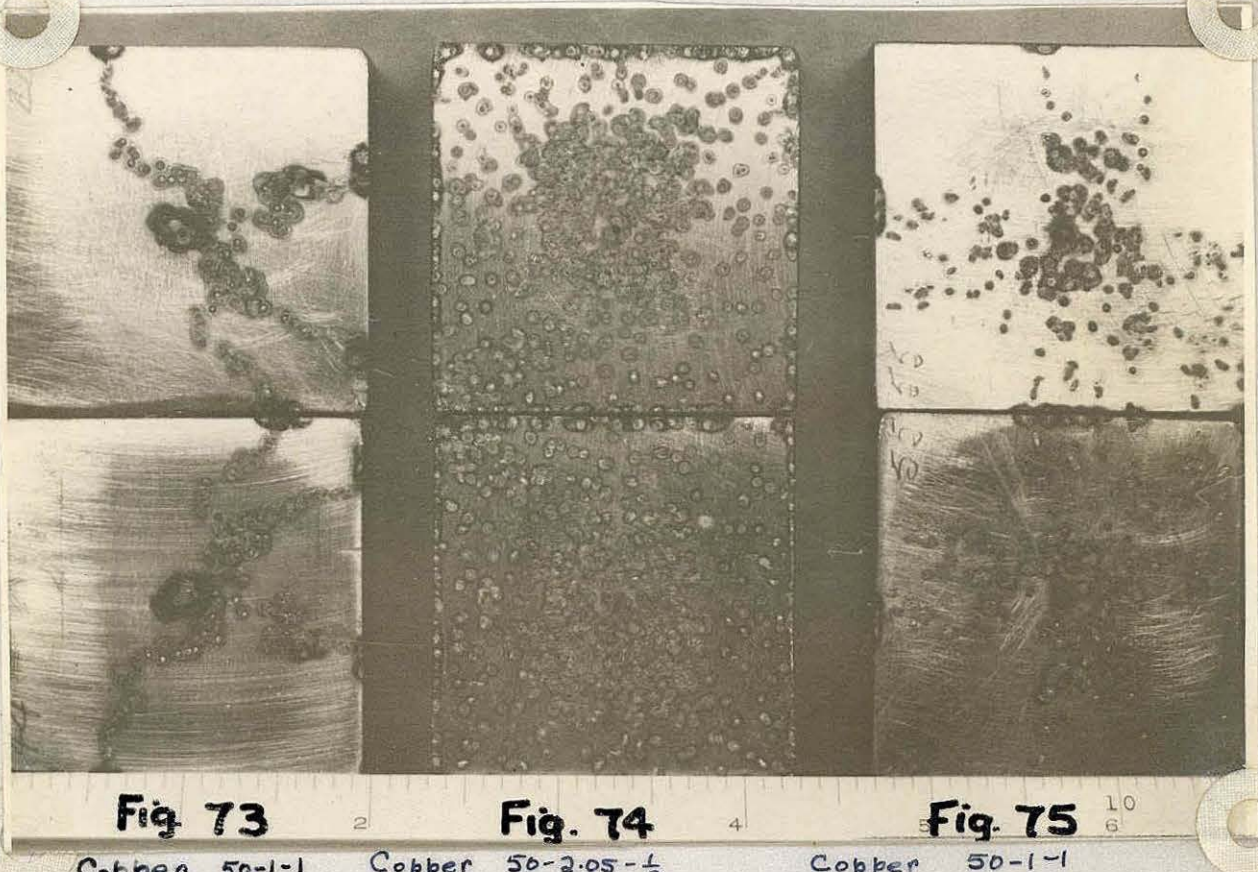

Sparking Potential for
Plane Parallel Electrodes in Air
(Slepian and Mason)
Sparking Voltage
1700
1600
1400
1200
1000
800
600
400
200
0
pl in mm. x cm.
1.0
2
3
4
5
6
7
8
9
10
15

FIG. 70



Copper 50-.45-1
e_s = 942 volts.
t_s = 13 μs

Steel 50-2.05-1
e_s = 394
t_s = 13 μs



Copper 50-1-1
e_s = 554
t_s = 18.6

Copper 50-2.05-$\frac{1}{2}$
e_s = 843
t_s = 41

Copper 50-1-1
e_s = 1310
t_s = 140

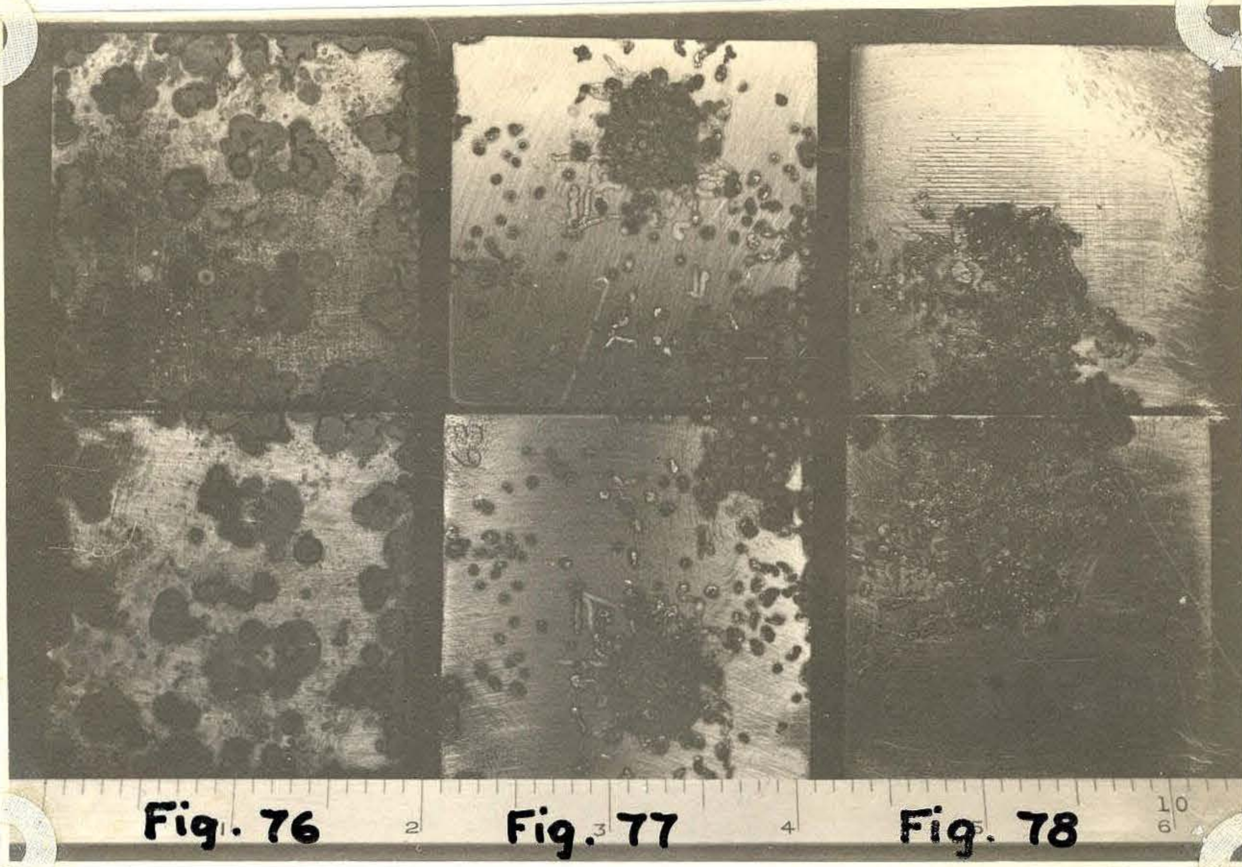


Fig. 76 Fig. 77 Fig. 78

Copper $50-1-\frac{1}{4}$
$e_s = 684$
$t_s = 21.5$

Copper $50-.45-1$
$e_s = 835$
$t_s = 36.1$

Copper $25-2.05-1$
$e_s = 655$
$t_s = 30$

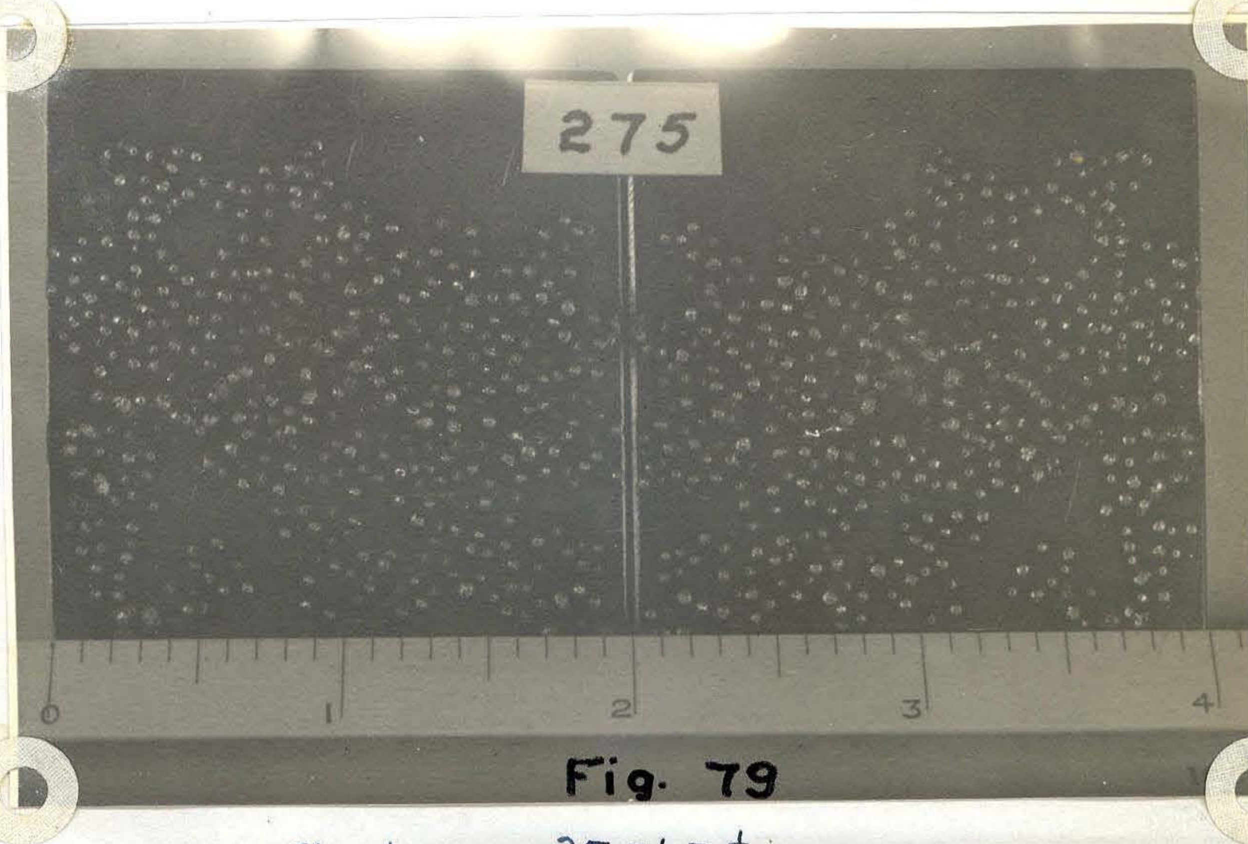


Fig. 79

Steel $25-1-\frac{1}{2}$
$e_s = 468$
$t_s = 6.5$

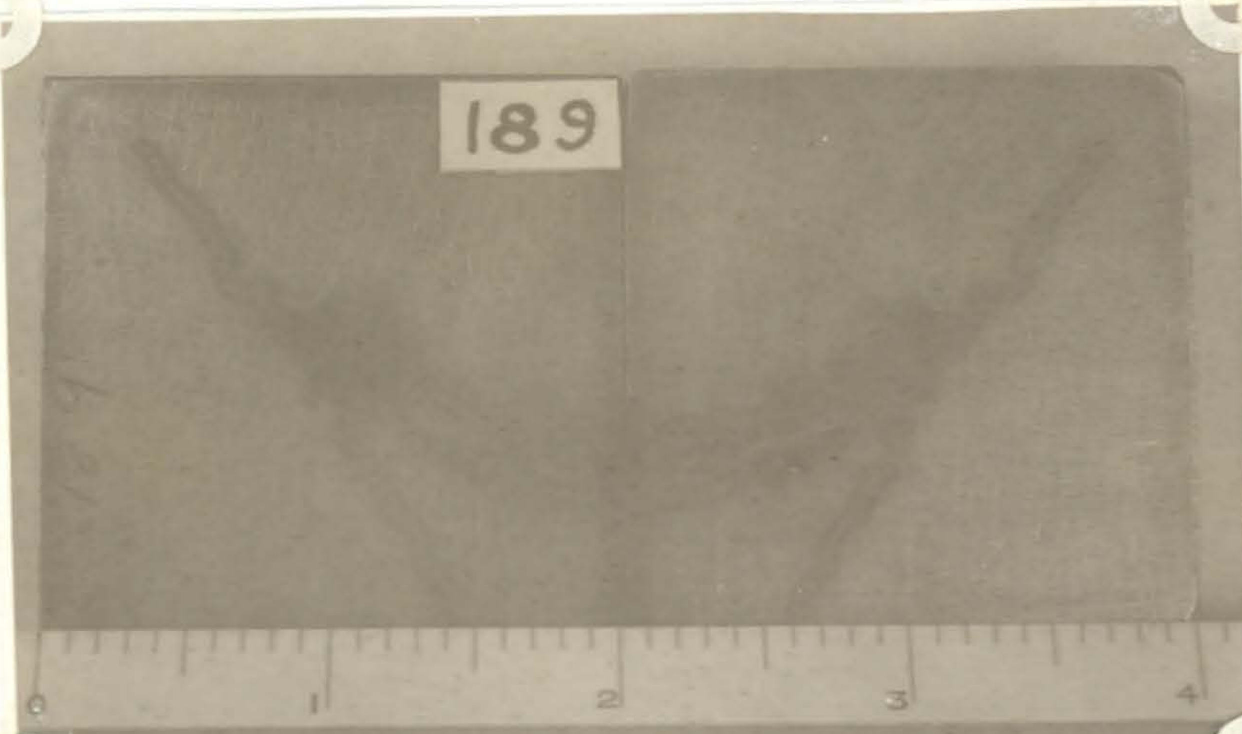


Fig. 80

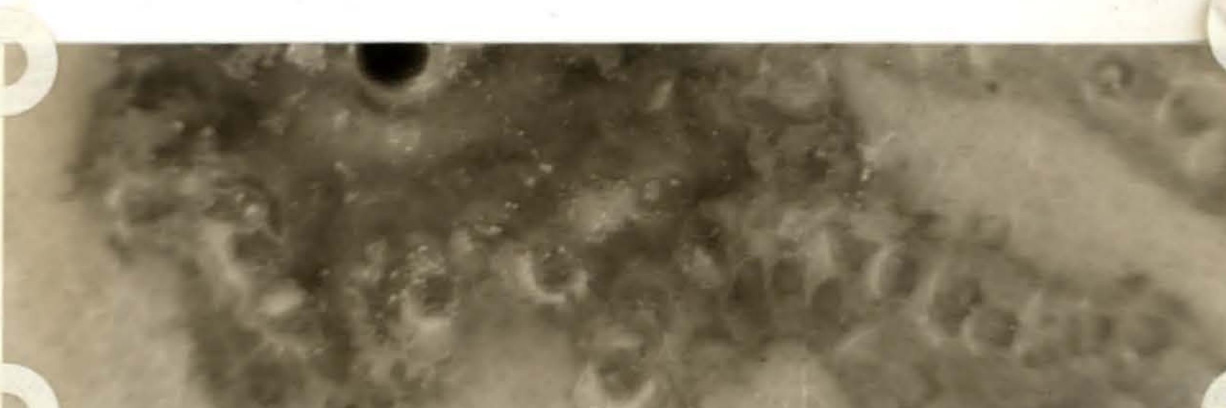


Fig. 81

Steel

$50-2.05-\frac{1}{2}$

$e_s = 439$

$t_s = 77.7$