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On the Behaviour of Fuse Wires

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Thesis

for

The Degree of

Bachelor of Science

in

Electrical Engineering

1907

Mendel Penco Weinbach

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Columbia, Mo.

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On the Behaviour of Fuse Wires

Introduction

The last few decades have witnessed the introduction of electricity as a factor of every day life in its use as a source of light, power and heat. The dangers of fire breaking out, or the damaging of machines or other apparatus by an unexpected rush of excessive current, have demanded the immediate use of protective means to interrupt the current before it becomes higher than the current capacity of the circuit.

The earlier forms of the so called "cut outs" were fuse wires, whose current carrying capacity was, or at least was supposed to be, equal to that of the circuit, but which would fuse and consequently open the circuit at the smallest excess of current above the normal load. Various other forms, like the magnetic circuit breaker, have subsequently come into use, but they are restricted mainly to guard against short circuits, while the ordinary fuse wire is still and will be used to open the circuit when the current exceeds the carrying capacity of the line.

Inadequacy of Preece's Formula

$$I^2 = ad^3$$

As far back as 1882 Prof. Forbes (Jour. Soc. Telegraph Engineers Vol. XIII. p. 238) ~~has undertaken a~~ undertook a

series of experiments on the overheating of wires by electric currents, and from his experiments he deduced the following relation between the maximum current and diameter of the wire $I^2 = ad^3$ where

I^2 = current in amperes

d = diameter of the wire

a = constant depending on the metal and units used.

This formula was subsequently used by W.H. Preece (Proc. Roy. Soc. Apr. 3, 1884 and Dec. 22-1887) to determine the fusing currents for various sizes of wires of metals and alloys, and since then it ~~is~~ has been known by his name.

To this formula, which is very much used in practice to determine the size of fuse wires to be used in a particular case, is due, at least in part, the fact that many a time a fuse wire fails to act exactly when it ought to. If we examine how Prof. Forbes obtained this formula, we will see that it cannot be used for what it was intended.

Let l = length of fuse wire in ~~cen.~~ c.m.

d = diameter in ~~cen.~~ c.m.

ρ = specific resistance of the metal

Then if R = resistance of the wire

$$R = \frac{4\ell}{\pi d^2}\rho$$

If W = watts supplied,

I = current in Amperes,

J = mechanical equivalent of heat

E_1 = supplied energy in thermal units per sec.

$$E_1 = \frac{4\ell}{\pi d^2 J}\rho\, I^2$$

He assumes that the heat dissipated by radiation, convection, etc. is proportional to the surface of the wire and to difference between fusing temperature and initial temperature of the wire, then

$E_2 = dleT$ where

E_2 = heat dissipated

e = heat dissipated per unit area per degree rise for the metal used.

T = difference in temperature. The next assumption he makes is that the total energy supplied to the wire is dissipated, then $E_1 = E_2$

$$\frac{4\ell\rho}{\pi d^2 J} I^2 = \pi d\ell eT$$

$$I^2 = \frac{J\pi^2 eT}{4\rho}\; d^3$$

T for any given metal may be considered for practical cases as constant (within a few degrees). Hence we may put $\frac{J\pi^2 eT}{4\rho}$ = constant (a) whence

$$I^2 = ad^3$$

According to this formula, as it is obtained on the assumption that the total heat generated in the wire is dissipated, the wire will never fuse! I have found in my experiments that currents, even smaller than those obtained by the above formula, will fuse a wire under ordinary conditions.

FACTORS THAT AFFECT THE FUSING TIME

There are a good many factors that affect the time of fusing a wire of a certain diameter, with a given current. These factors are:

1. The shape of the fuse; whether the fuse is cylindrical or in the form of a strip.
2. The position of the fuse; whether in a vertical or horizontal position.
3. The length of the fuse wire, which we have seen does not appear in Preece"s formula.
4. The temperature of the surrounding medium.
5. The coefficient of expansion of the metal of which the fuse wire is made.
6. The terminal effect; the amount of heat conducted through the wire to the terminal blocks.
7. The pressure or tension exerted by the terminal blocks.
8. Barometric pressure.

9. Whether the wire is insulated, enclosed in tubes, or imbedded in some non-conducting material, as many fuses on the market are.

10. Possibly also the Peltier effect: whether heat is absorbed or developed at the thermo-electric junction between the fuse wire and terminal blocks.

11. The formation of an oxide coating around the wire.

THE PHENOMENA OF FUSING FROM A PHYSICAL POINT OF VIEW.

If we regard the phenomena as a physical problem, it is evident that a fuse wire requires a definite amount of heat to raise it to the melting point, plus a definite amount of heat to melt it and possibly to vaporise part of it, and this amount of heat must be supplied by electrical energy. This is the case when the current is very high, the time it takes to fuse the wire is infinitesimal and the amount of heat dissipated is infinitesimal, and the problem is very simple.

But a fuse is not at all a protection against very high currents, but a protection against any excess of a certain rated current, which may be small or large as the case may be. In such a case the element of time and with it the surrounding conditions form an important factor. The question whether

the fuse will act depends now upon whether the heat generated in the wire exceeds the heat dissipated. If the rate of heat generated in the wire is not larger than the rate of cooling, it is evident that the fuse will never act. On the other hand, if the rate of cooling is smaller than the rate of heat generation, then after a certain time, the wire will reach its melting temperature and fuse. But the time that it takes the fuse wire to reach its melting point may be so large, that the excessive current flowing for that time may seriously injure some apparatus, then the sensitiveness to action of fuse wires comes in as another important factor.

RELATION BETWEEN FUSING CURRENT, LENGTH AND DIAMETER OF WIRE, AND FUSING TIME.

Apparently it seems, that as so many factors affect the phenomena of fusing, no formula could be developed to even approximate actual cases. But if a formula could be found in which the element of time should figure, the problem will be practically solved, for if the time element be made small, the total heat dissipated will be small, and also the other factors will have very little time to appreciably affect the fusing point.

Let

I = fusing current in Amperes

d = diameter of wire in cm.

l = length in cm.

ρ = specific resistance of the metal at $0^{o}C$.

T = difference between melting and initial (room) temperature of the wire.

α = average temperature coefficient of resistance of the metal between initial and melting temperatures.

t = time in seconds.

E_1 = supplied energy in Joules (watt-sec.)

then

$$E_1 = \frac{4l}{\pi d^2}\rho(1+\alpha T)\ I^2t$$

As the difference in temperature, T, for any given kind of wire may be considered for practical cases as a constant (within a few degrees) then

$$E_1 = K_1\frac{l}{d^2}\ I^2t \quad \text{where}$$

$$K_1 = \frac{4}{\pi}\rho(1+\alpha T)$$

Part of this supplied energy is dissipated by radiation and this is proportional to the surface of the wire and to some function of the difference in temperature T. If E_2 = energy lost by radiation

$$E_2 = \pi dleJf(T)t \quad \text{where}$$

e = average heat radiated per unit area (of the metal) per second per degree rise, between initial

and melting temperature.

J = Joule's equivalent (4.189).

But as stated above T is practically constant then $f(T)$ = constant, hence

$$E_2 = K_2 \ell dt \quad \text{where}$$

$$K_2 = \pi eJf(T)$$

Heat is also lost by conduction and convection through themedium surrounding the wire and this is proportional to the length of the wire and to some function of the difference in temperature.

$$E_3 = aJ\ell f(T)t$$

where E_3 = total energy lost by convection and conduction.

a = average heat lost per unit length, per unit degree rise, per second, then

$$E_3 = K_3 \ell t \quad \text{Where}$$

$$K_3 = aJf(T)$$

Loss of heat occurs also by conduction through the wire to the terminal blocks, and this is proportional to the cross sectional area of the wire, and to the difference in temperature, and inversely proportional to the length

$$E_4 = b\,\frac{\pi d^2}{4\ell}\,JTt$$

Where E_4 = heat lost by conduction.

b = average heat conducted per unit area,

per unit length, per $1^{\circ}C$, per second.

$$E_4 = K_4 \frac{d^2}{\ell} t \quad \text{Where}$$

$$K_4 = \frac{b\pi JT}{4}$$

In all the above expressions the heat is expressed in Joules.

The difference between the energy supplied and the energy dissipated is used to raise the wire to the melting temperature, and to melt the wire. If

E_5 = heat required to raise the wire to themelting point

$$E_5 = \frac{\pi d^2 \ell}{4} s \sigma JT \quad \text{Where}$$

s = specific gravity of the metal

σ = specific heat " " "

then
$$E_5 = K_5 d^2 \ell \quad \text{Where}$$

$$K_5 = \frac{\pi sJ}{4} \sigma T$$

The amount of heat required to melt the wire is

$$E_6 = \frac{\pi d^2 \ell}{4} sJL$$

Where L = latent heat of fusion of the metal. Then

$E_6 = K_6 d^2 \ell$ where $K_6 = \frac{\pi sJ}{4} L$

Equating the energy supplied to the energy consumed

we have $E_1 = E_2 + E_3 + E_4 + E_5 + E_6$

$$K_1 \frac{\ell}{d^2} I^2 t = K_2 \ell d t + K_3 \ell t + K_4 \frac{d^2}{\ell} t + (K_5 + K_6) d^2 \ell$$

$$\left[\frac{\ell}{d^2} I^2 - \frac{K_2}{K_1} \ell d - \frac{K_3}{K_1}\ell - \frac{K_4}{K_1} \frac{d^2}{\ell}\right] t = \frac{K_5 + K_6}{K_1} d^2 \ell$$

Putting $\frac{K_2}{K_1} = B$; $\frac{K_3}{K_1} = A$; $\frac{K_4}{K_1} = C$: $\frac{K_5 + K_6}{K_1} = D$

and factoring out $\frac{\ell}{d^2}$ we have

$$(I^2 - Ad^2 - Bd^3 - C\frac{d^4}{\ell^2})t = Dd^4$$

or $I^2 = Ad^2 + Bd^3 + (C\frac{1}{\ell^2} + D\frac{1}{t})d^4$

This equation gives us the relation between the fusing current, length and diameter of the fuse wire and the fusing time. It is seen that in Preece's formula, the first and last terms of the above equation do not appear at all.

This equation gives us means to work out a table of fusing currents for various size wires and metals having a specified length and that will fuse after a specified time.

It is important to note, that while the time (t) should be taken small, so as to give the fuse quick action, and admit very little heat dissipation, it should not however be taken two small for in that case the last term of the equation would be large and consequently the current would be two high. A fair value for (t) for practical cases would be the time corresponding to the <u>Knee</u> of the time--fusing current curve. (See PLATES 2 and 3), because the slope of the curve passes at this point through a critical value. Below this point large increments in current produce

small changes in time, while above this point small increments in current produce large changes in time. Thus (see PLATE 2) the fusing time for a non-insulated No. 27 copper wire of length 8 cm. should be taken 2 seconds the corresponding current is I = 24.75 Amp. Similarly (see PLATE 3) the fusing time for a non-insulated No 32 copper wire of length 8 cm. should be taken 1 second. The current I = 12.5

The equation obtained above brings forth an important point in relation to fuse wires.

If we put the equation in the form

$$I^2 - Ad^2 - Bd^3 - C\frac{d^4}{l^2} = D\,\frac{d^4}{t}$$

and let $t = \infty$ then

$$I = \sqrt{Ad^2 + Bd^3 + C\,\frac{d^4}{l^2}}$$

gives the minimum fusing current. No current smaller than this value of I will fuse a wire of the given dimentions.

It is beyond the scope of this dissertation to work out the fusing currents for every size wire of metals and alloys used in practice for fuse wires. The main object in view was to find out in what way ~~do~~ certain conditions affect the fusing time for a given current. Thus the effect of insulation;

Barometric pressure; how the fusing time is affected by having the wire enclosed in glass tubes with open and closed ends; the effect of length were succesively investigated and the results given below.

APPARATUS AND CONNECTIONS

PLATE 1.

The main laboratory D.C. 110 Volt leads were brought to the switch S. The current passed through an ammeter, which was carefully calibrated, and the current was controlled by means of lamp rack L. The switch s_1 was used to open the circuit when required, and the switch s_2 to short circuit the fuse, when the current had to be adjusted. The current was read when switched over the fuse.

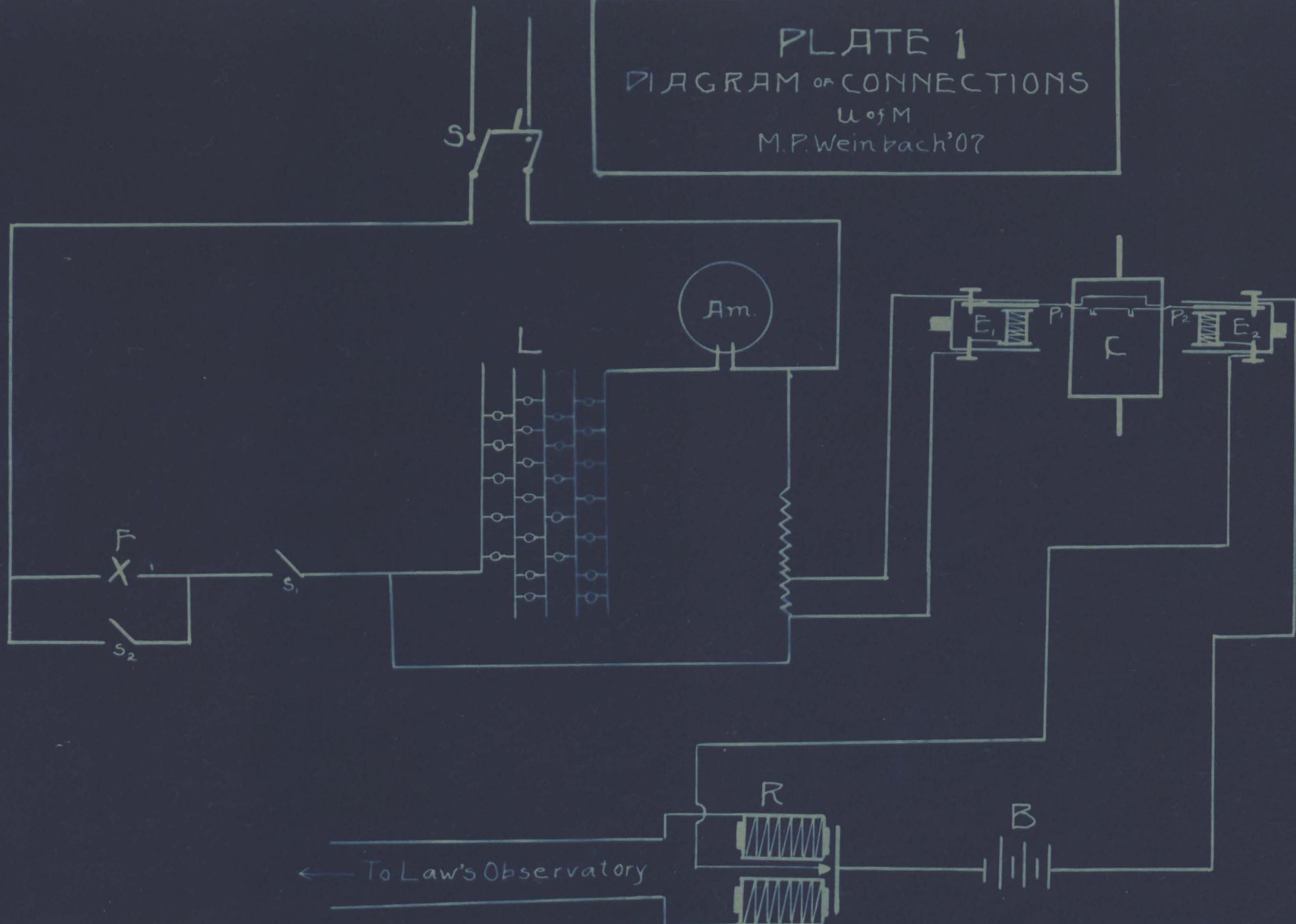
The time was measured cronographically. The cronograph C consisted of a drum revolved by clock work. Its speed could be properly adjusted by means of air vanes. The time record was made on a smoked paper fastened on the drum. E_2 was an electromagnet connected thru relay R and two Leclanché cells B to the observatory clock circuit. The pointer P_2 in its normal condition was in contact with the smoked paper, and was so connected to the electromagnet E_2 that it moved axially on the smoked paper

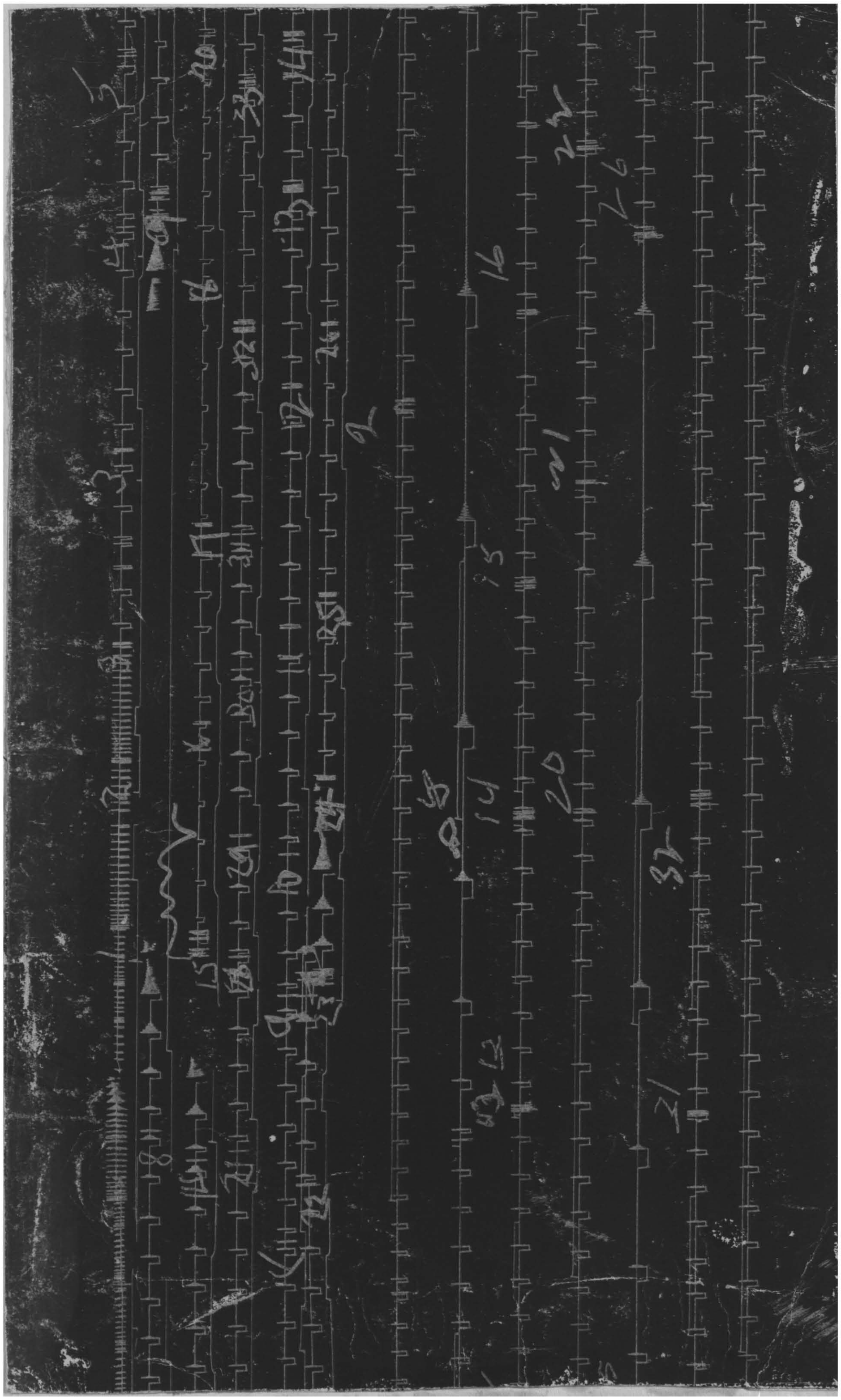
PLATE 1

DIAGRAM OF CONNECTIONS

U of M

M. P. Weinbach '07





whenever the circuit was broken, thus registering the beats of the observatory clock. E_1 is a similar electromagnet actuated by a fraction of the fusing current. When the current was switched over the fuse the pointer p_1 of this electromagnet made a vertical mark on the smoked paper. A similar mark was made when the circuit was broken i.e., when the fuse blew. The distance between the marks made by the electro-magnet E_2 connected to the clock circuit gave the distance corresponding to one second, while the distance between the marks made by the electro-magnet E_1 connected to the main circuit gave the fusing time measured to the same scale.

In order to fix the marks made by the two electromagnets, the smoked paper was immersed in a dilute solution of shellac in alcohol, which dried quickly. A sample of the time record is shown on the next page.

EFFECT OF INSULATION

The wires tested were No. 27 and No. 32 (B & S Gauge) copper wire of constant length = 8 cm. The diameter of the No. 27 non-insulated wire was .03605 cm. while the diameter over the double cotton insulation was = 0.05895 cm. The diameter of the non-insulated No.32 wire was 0.0219 cm. The fuse wire was connected to an ordinary fuse box with brass terminals. Current

were taken and

readings and measurements of time are given in the following tables.

TABLE I.

No. 27 Copper Wire length = 8cm.

out table

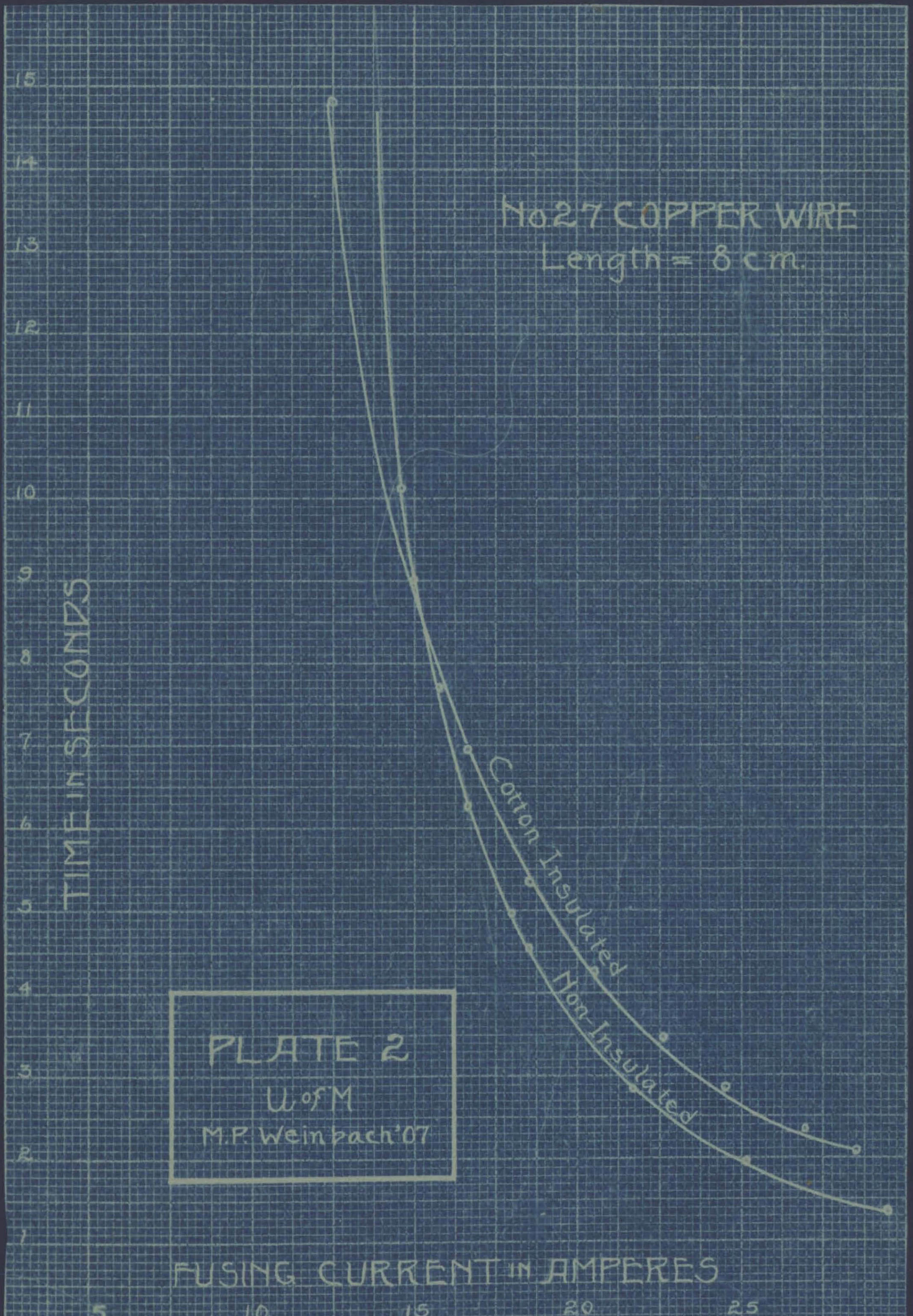
Non-Insulated			Insulated		
Obs.	I	t	Obs.	I	t
1	13.2	17.	1.	12.5	14.75
2	14.8	9.75	2	15.0	9.0
3	15.8	7.75	3.	16.7	7.0
4	16.8	5.18	4	18.5	5.2
5	18.0	5.0	5	20.5	4.0
6	18.5	4.15	6	22.6	3.66
7	21.7	2.81	7	24.5	3.12
8	25.2	1.96	8	27.0	2.46
9	29.5	1.57	9	28.5	1.46

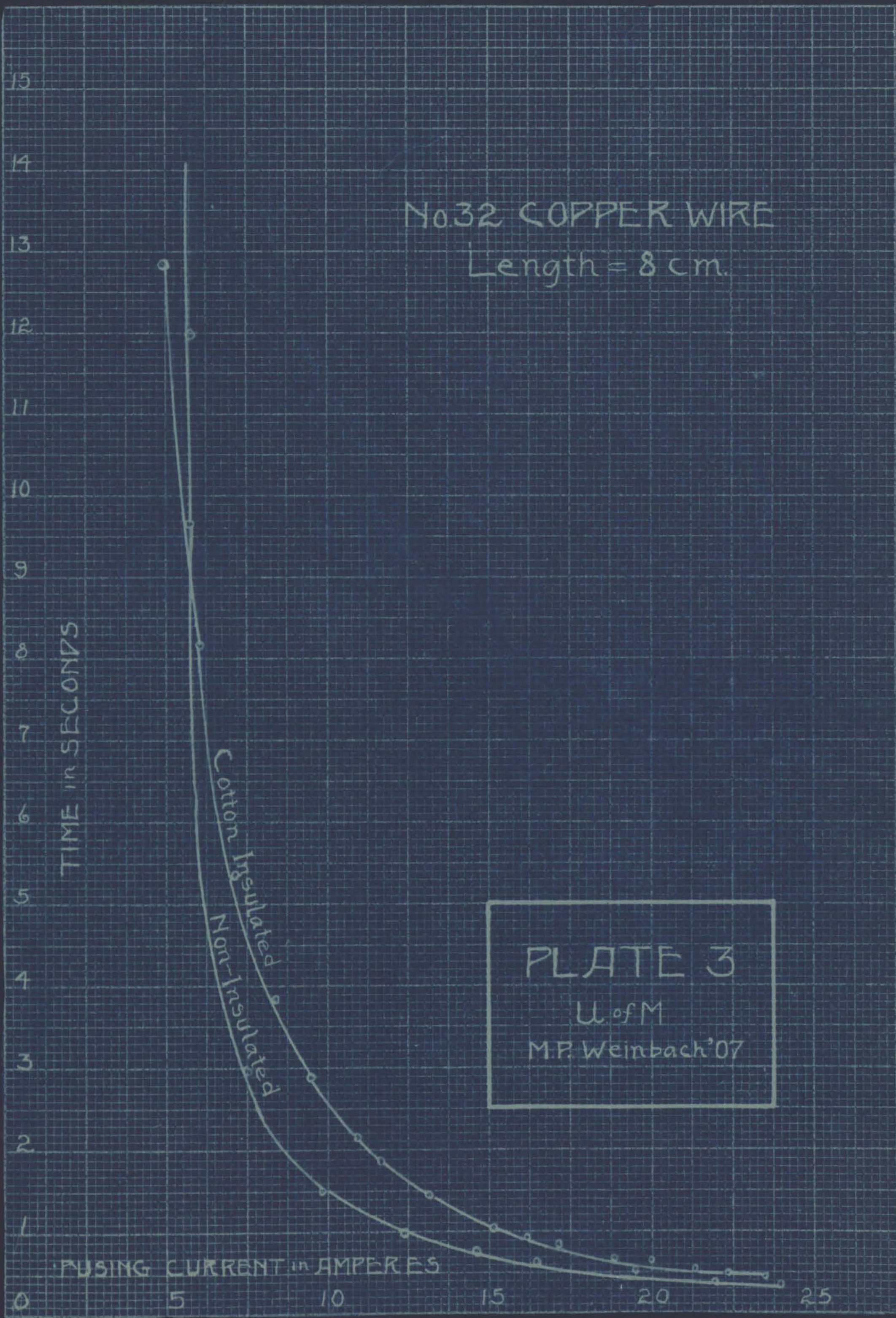
TABLE II.

No. 32 Copper Wire Length = 8cm

Non-Insulated Obs.	I	t	Insulated Obs.	I	t
1	6.4	18.5	1	5	13
2	7.5	3.0	2	6	6
3	9.8	1.5	3	7.2	5
4	12.4	.965	4	8.3	3.75
5	14.6	.797	5	9.5	2.80
6	16.5	.619	6	10.9	2.49
7	19.5	.509	7	11.6	2.27
8	22.0	.398	8	13.2	1.405
9	24.0	.367	9	15.2	1.34
10	26.0	.361	10	16.2	1.08
11	27.0	.291	11	17.2	.831
12	29.5	.333	12	18.8	.522
			13	20.9	.494
			14	21.3	.450
			15	22.3	.409
			16	23.5	.503

The graphical representation of these results is shown on PLATE 2 for the No. 27 wire, and in PLATE 3 for the No. 32 wire. The curves are plotted with the current (independent variable) as abscissa and time as ordinate. It is easily seen from these curves, that the insulation greatly affects the sensitiveness to


No 27 COPPER WIRE
Length = 8 cm.
TIME IN SECONDS
FUSING CURRENT IN AMPERES
Cotton Insulated
Non-Insulated
PLATE 2
U of M
M.P. Weinbach '07
5
10
15
20
25
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



No.32 COPPER WIRE
Length = 8 cm.
PLATE 3
U of M
M.P. Weinbach '07
TIME in SECONDS
FUSING CURRENT in AMPERES
Cotton Insulated
Non-Insulated
0
5
10
15
20
25
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

fusion of wires. For high currents the non-insulated is more sensitive than the insulated one. Thus from PLATE 2. we have seen that a current of 22.5 Amp. will fuse a No. 27 non-insulated wire of the same size in 3.4 seconds. On the other hand for low currents, the insulated wire is more sensitive to action. Thus 14.5 Amp. will fuse a No. 27 insulated wire in 9.5 seconds, and a non-insulated wire of the same size in 11 seconds. The point, where the two curves cross each other, shows where the two wires will fuse with the same current in the same time.

A comparison between the energies supplied to the two wires for any particular current, and also between the energies dissipated and consumed in the two wires, was thought to give some explanation to the above facts. In order to compute these energies recourse was made to the equation developed above, namely, $I^2 - (Ad^2 + Bd^3 + C\frac{d^4}{t})t = Dd^4$

As the same size and length of wire was used in the test, the term $Ad^2 + Bd^3 + C\frac{d^4}{t} =$ Constant $\frac{K_1}{R}$ and $Dd^4 = \frac{K_2}{R}$ Where R represents the average resistance of the wire between initial (room) and melting temperature. Hence the equation may be written

$$(RI^2 - K_1)t = K_2$$

and this equation must be the equation of the time-fusing current curve. The constants $\frac{K_1}{R}$ and $\frac{K_2}{R}$ were found from the curves on PLATE 2. Thus for the non-insulated wire $\frac{K_1}{R} = 119$ and $\frac{K_2}{R} = 1012$

The value of R was computed from the dimensions of the wire

$$R = \frac{4\ell}{\pi d^2} \rho \; (1 + \alpha T)$$

$$\ell = 8 \text{ cm.} \quad d = .03655$$

$$\rho = 1.594 \times 10^{-6}$$

$$T = 1086^\circ - 20^\circ$$ Where 1086° C

melting point of copper. Average value of $\alpha \equiv .00219$

Then R = .041615 ohms.

$$K_1 = R \times 119 = 4.95$$

$$K_2 = R \times 1012 = 42.114$$

Thus the final equation of the time-fusing current curve is $(.041615\ I^2 - 4.95)t = 42.114$

Where 4.95 is the average heat dissipated per second, and 42.114 Joules is the heat consumed in raising the wire to the melting temperature and to melt the wire.

This amount of energy can also be found from the physical constants of copper namely:

Specific heat of copper =	0.093
Latent heat of fusion =	43.0
Specific gravity =	8.89

then the Energy required to heat the wire to the melting temperature 1086° C is

$$\frac{\pi d^2 \ell}{4} \times 8.89 \times 0.093 \times (1086^\circ - 20^\circ)$$

$$= 7.197 \text{ Calories}$$

$$= 30.02 \text{ Joules.}$$

The energy required to melt the wire is

$$\frac{\pi d^2 \ell}{4} \times 8.89 \times 43 = 3.121 \text{ Calories}$$

$$= 12.96 \text{ Joules.}$$

The total energy consumed in the wire only is 30.02 + 12.96 = 42.98 Joules. The value obtained from the curve is 42.114 Joules. It is remarkable that the agreement should be so close. From the equation of the curve thus obtained, the energies supplied, and dissipated were computed and the results given in the following table where

t_1 = observed time,

t_2 = computed time from the equation,

W = Watts supplied,

J_1 = energy supplied in Joules

J_2 = " dissipated in Joules

J_3 = " consumed in the wire

TABLE III

No. 27 Non-insulated wire $l = 8$ cm. $R = .041615$

I	t_1	t_2	W	J_1	J_2	J_3
13.2	17.	18.4	7.26	133.21	91.10	42.114
14.8	9.75	10.12	9.12	92.5	50.10	"
15.8	7.75	7.75	10.38	80.68	38.57	"
16.8	5.18	6.22	11.75	72.98	30.87	"
18.	5.0	4.92	13.50	66.49	24.38	"
18.5	4.15	4.54	14.25	64.71	22.60	"
21.7	2.81	2.87	19.62	56.32	14.21	"
25.2	1.96	1.96	26.46	52.0	9.89	"
29.5	1.57	1.35	36.20	48.8	6.69	"

It should be noted that the computed time is in close agreement with the observed time. The equation of the time-fusing current curve for the No. 27 insulated wire was found in a similar way.

$\frac{K_1}{R} = 50$ and $\frac{K_2}{R} = 1575$

The final equation being $(0.041615\ I^2 - 2.0807)t = 65.54$.

As above the energies were computed and the results given in the following table:

TABLE IV.

No. 27 Insulated wire $l = 8$ cm $R = .041615$

I	t	t_1	W	J_1	J_2	J_3
12.5	14.75	14.85	6.5	96.40	30.86	65.54
15.0	9.0	9.0	9.375	84.28	18.74	"
16.7	7.0	6.95	11.61	80.95	14.41	"
18.5	5.2	5.2	14.24	76.60	11.16	"
20.5	4.0	4.25	17.50	74.40	8.86	"
22.6	3.66	3.42	21.62	72.70	7.14	"
24.5	3.12	2.86	24.98	71.50	5.96	"
27.0	2.46	2.32	30.35	70.40	4.86	"
28.5	1.96	2.07	33.81	70.00	4.46	"

As seen from the table, the amount of energy consumed in the wire and insulation only, is 65.54 Joules; this means that 23.426 Joules are consumed in the insulated wire in excess of the energy consumed in the non-insulated one. This excess of energy might have been consumed to raise the insulation to burning temperature.

The above results are represented graphically in PLATE 4, energy being plotted against current, and PLATE 5, where energy is plotted against time.

From PLATE 4, we see that for low fusing current, the total energy dissipated by the non-insulated wire is considerably larger than that dissipated

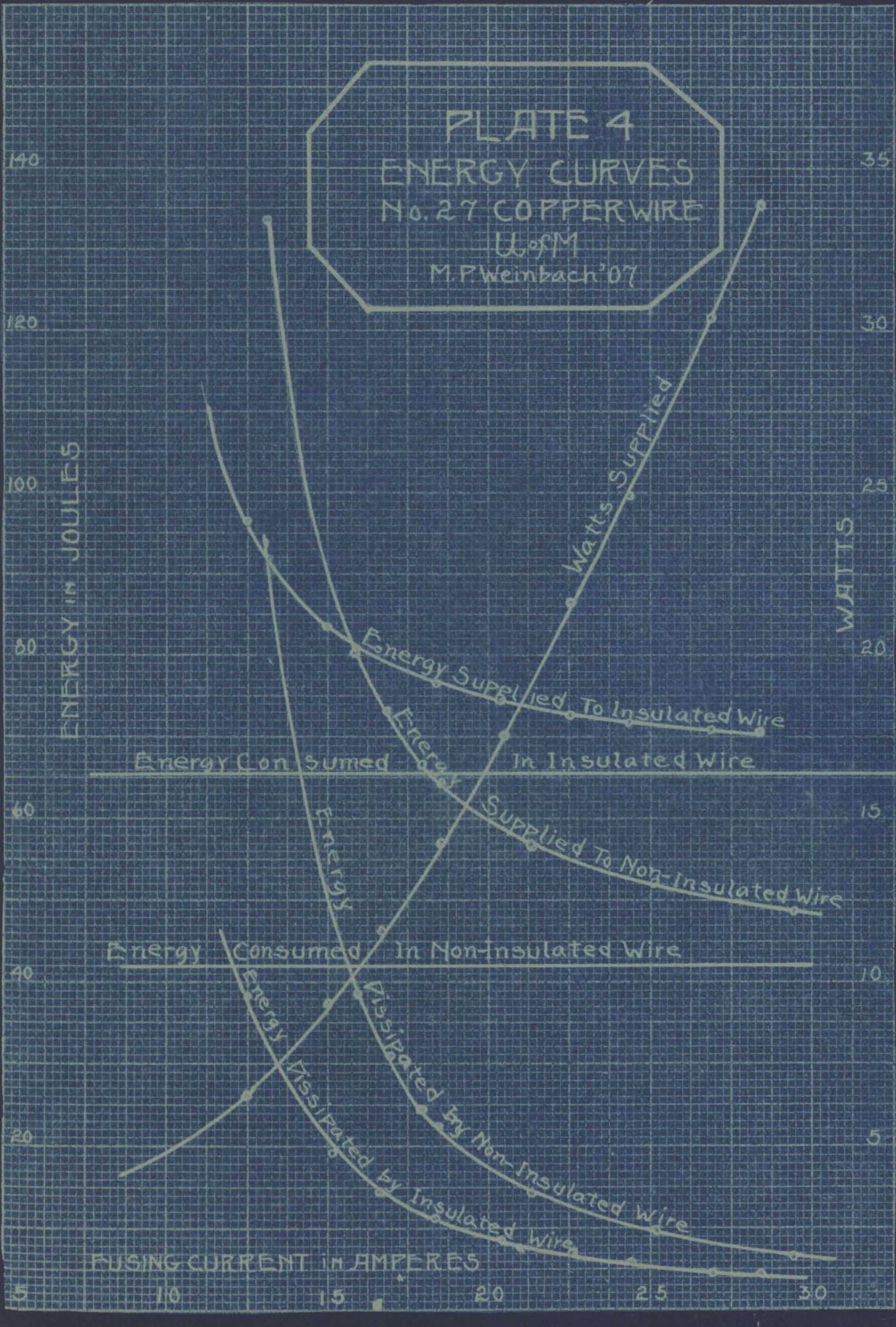


PLATE 4
ENERGY CURVES
No. 27 COPPER WIRE
U of M
M. P. Weinbach '07
ENERGY IN JOULES
WATTS
FUSING CURRENT IN AMPERES
Watts Supplied
Energy Supplied To Insulated Wire
Energy Consumed In Insulated Wire
Energy Supplied To Non-Insulated Wire
Energy Consumed In Non-Insulated Wire
Energy Dissipated By Non-Insulated Wire
Energy Dissipated By Insulated Wire
140
120
100
80
60
40
20
35
30
25
20
15
10
5
5
10
15
20
25
30

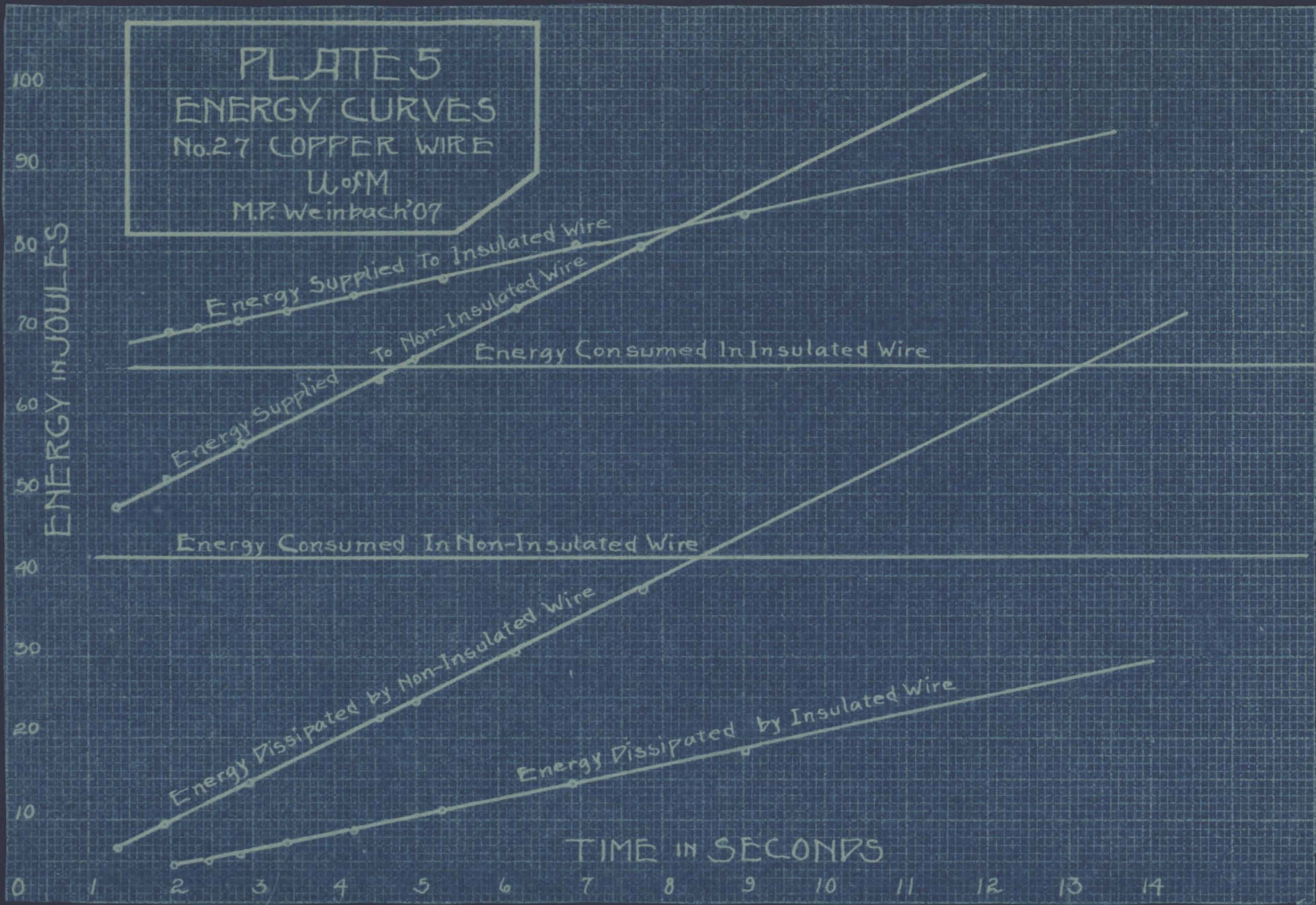


PLATE 5
ENERGY CURVES
No.27 COPPER WIRE
U of M
M.P. Weinbach '07
Energy Supplied To Insulated Wire
Energy Supplied To Non-Insulated Wire
Energy Consumed In Insulated Wire
Energy Consumed In Non-Insulated Wire
Energy Dissipated by Non-Insulated Wire
Energy Dissipated by Insulated Wire
ENERGY IN JOULES
TIME IN SECONDS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
10
20
30
40
50
60
70
80
90
100

by the insulated one, because of the very poor heat dissipating qualities of the cotton insulation. Thus for a current of 15 Amperes, the energy dissipated by the non-insulated wire is about 2.5 times more than that dissipated by the insulated one. This explains why for low currents the insulated wire fuses quicker. On the other hand, for high currents, the total energy dissipated by the non-insulated wire is small in comparison with the energy consumed by the cotton insulation only, and as a consequence the non-insulated wire will fuse quicker, Another reason why the insulated wire does not fuse as fast as the non-insulated one for high currents is that the burned up cotton insulation may form a coating around the wire, holding in it the molten metal of the wire, thus keeping the current flowing for quite an appreciable length of time.

In view of this reasoning at the point where the two curves (PLATE2) cross each other, as the two wires fuse with the same current in the same time, the same amount of energy must be supplied to both of them. Consequently the two supplied energy curves on PLATE 4 must cross each other for that current. Furthermore, as the energy required to raise the two wires to the melting temperature and to melt them is

the same, then the same amount of energy dissipated by the uninsulated wire must be equal to the energy dissipated by the insulated wire plus the energy consumed in the cotton insulation. From PLATE 4, at the point of intersection of the supplied energy curves, we obtain:

Energy dissipated by the non-insulated wire = 41 Joules. Energy dissipated by the insulated wire = 18 Joules. Difference between the energies dissipated by the two wires = 41 - 18 = 23 Joules which agrees fairly well with the value otherwise obtained for the energy consumed in the cotton insulation namely 23.426 Joules.

EFFECT OF BAROMETRIC PRESSURE

The object in view in this test was to find what effect ~~does~~ the barometric pressure has have upon fusing time for a given current.

The apparatus and connections used in the previous test were also used in the present one, except the terminals were changed. The terminals TT(see PLATE 6) to which the fuse wire was connected, were heavy copper wires, passing thru sealed glass tube a, a and rubber stopper into the glass jar JJ, resting on the ground glass plate G. By means of the glass tube b and rubber tube r, the jar was put in

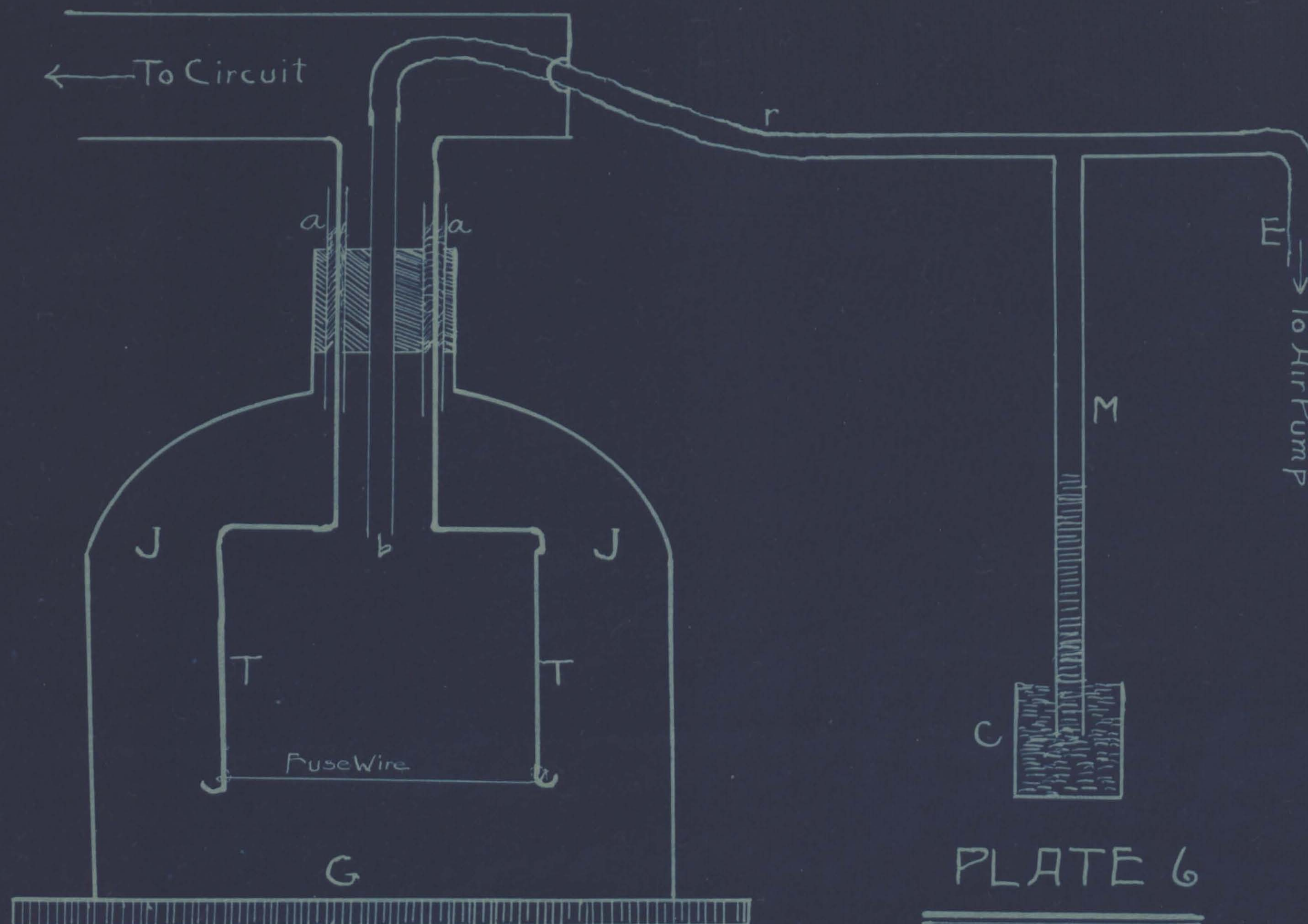


PLATE 6

communication with the manometer tube M, dipping into mercury at C. The manometer was connected at E to the air pump. The pressure was measured by subtracting the height of the mercury column in M from the barometer reading.

On account of the limited space in the glass jar J, the length of the wire tested had to be taken only 6 cm. The wire tested was No. 27 (B & S Gauge) non-insulated copper wire. Readings of fusing current, and measurements of the fusing time, were made, having the wire enclosed in the jar at atmospheric pressure (73.9 cm), at 50 cm. of mercury, 40 cm. 28 cm, 19 cm and .90 cm of mercury. The results obtained for 50 and 40 cm of mercury, were practically the same as those obtained for atmospheric pressure.

TABLE V.

No. 27 Non-insulated Copper wire. l = 6 cm.

Atmospheric pressure 73.9 cm.		Pressure 29.0 cm.		Pressure 19. cm		Pressure 0.90 cm.	
I	t	I	t	I	t	I	t
15.0	8.0	14.6	8.15	14.2	8.9	14.1	8.5
15.75	5.7	16.0	5.1	15.3	6.0	15.0	6.8
16.4	4.85	17.0	4.0	16.4	4.9	16.75	5.0
17.4	4.0	18.2	3.3	17.4	4.2	18.8	3.8
19.2	3.1	19.2	2.9	19.0	3.4	20.0	3.3
20.0	2.7	21.0	2.3	21.5	2.5	21.6	2.8
22.3	1.9	22.8	1.9	23.1	2.0	23.0	2.4
23.9	1.5	23.5	1.7	24.3	1.8	25.0	1.8

These results are represented graphically on PLATE 7. The portion where the curves intersect one another is replotted to a larger scale on PLATE 8. Comparing these curves, we see that for low currents, the sensitiveness to fusion of the wire increases as the pressure decreases. Thus for a constant time of fusion equal to 9 seconds, the fusing current required is 14.8 Amp. when p= 73.9 cm; 14.45 Amp. when p = 29 cm.; 14.1 Amp. when p =19 cm and 13.95 Amp. when p=0.90cm.

On the other hand for high currents the sensitiveness to fusion of the wire decreases with the decrease of pressure. Thus comparing the curves for

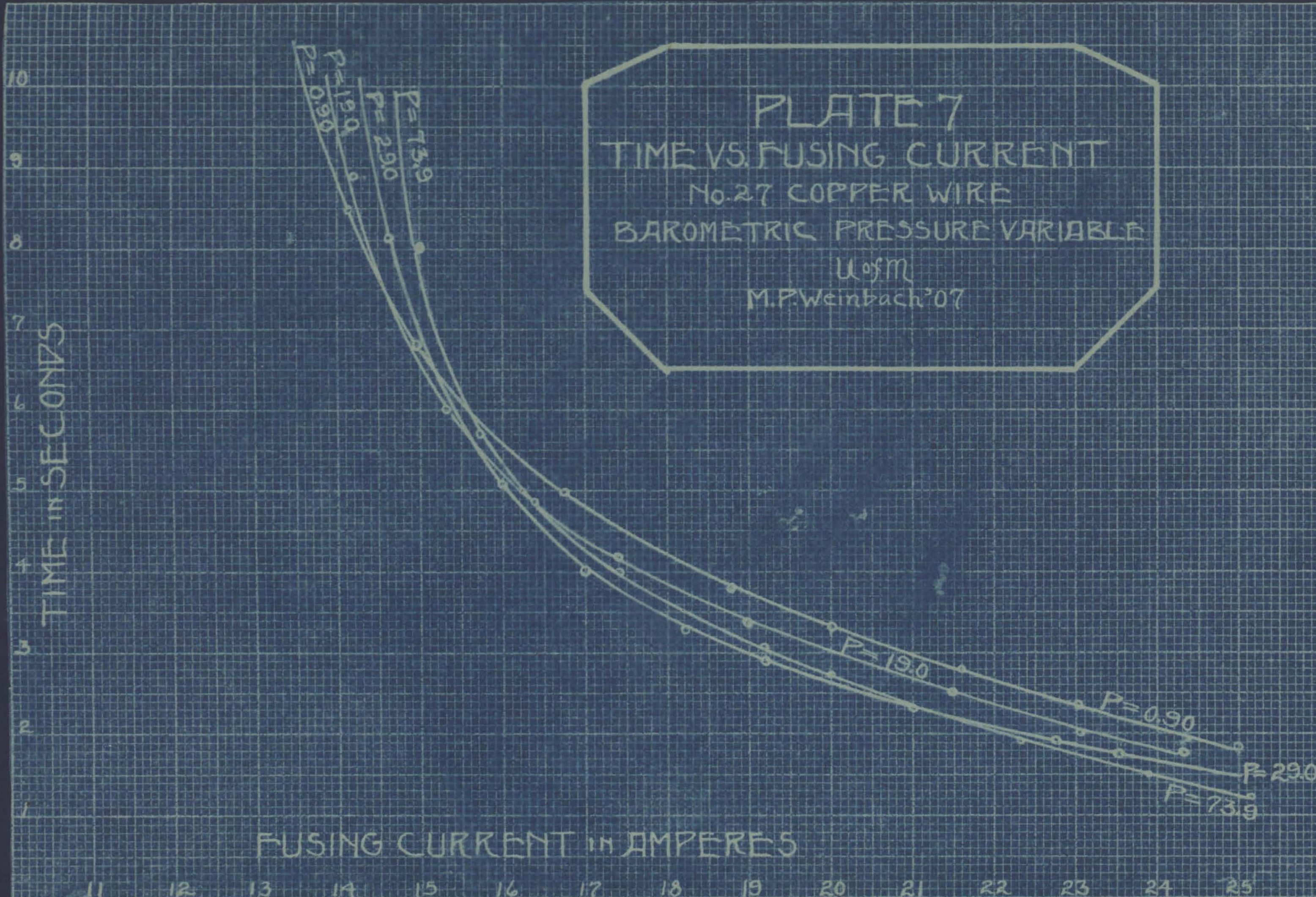


PLATE 7
TIME VS. FUSING CURRENT
No. 27 COPPER WIRE
BAROMETRIC PRESSURE VARIABLE
U of M
M. P. Weinbach '07
TIME IN SECONDS
FUSING CURRENT IN AMPERES
P = 0.90
P = 19.0
P = 29.0
P = 73.9
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

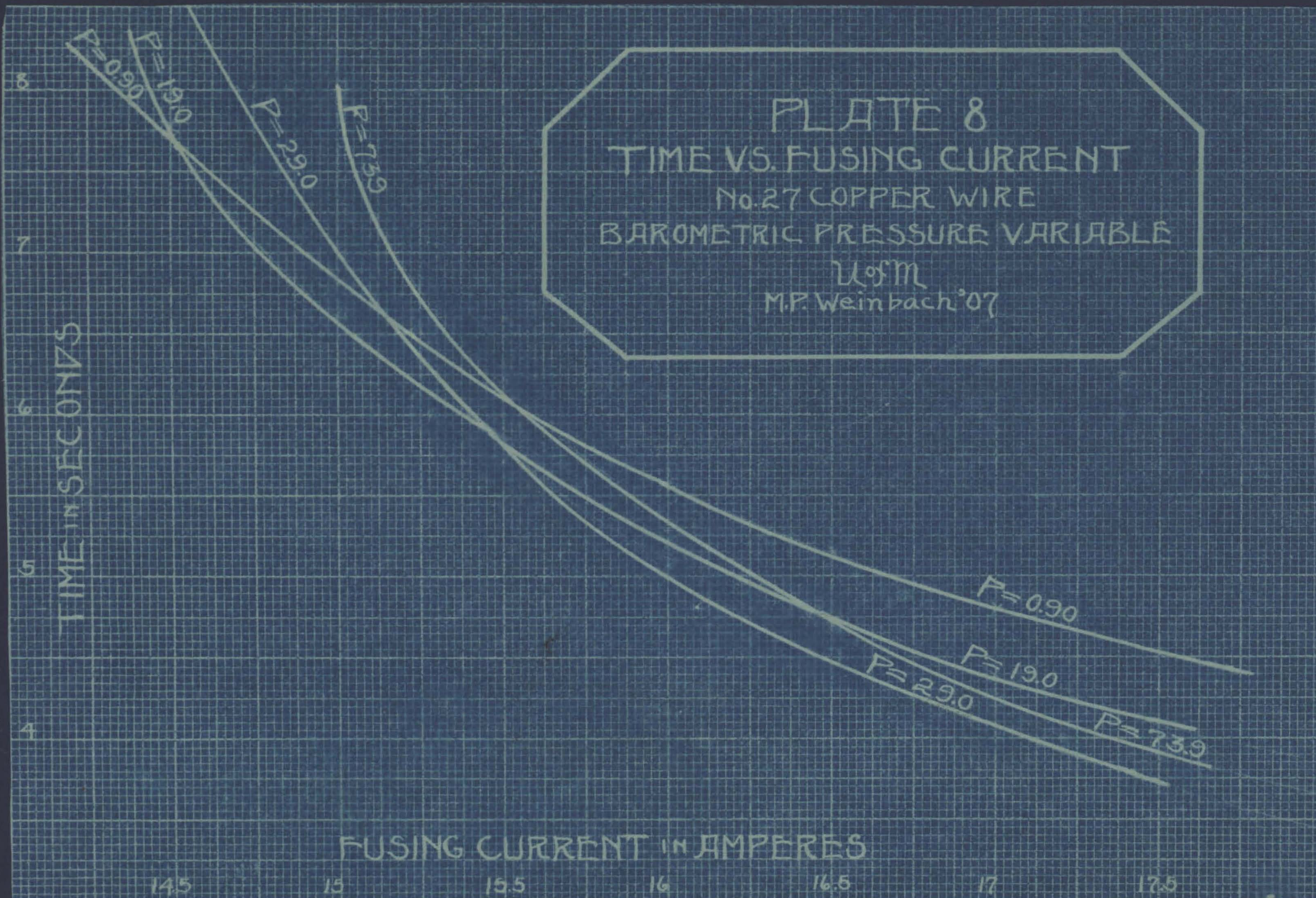


PLATE 8
TIME VS. FUSING CURRENT
No. 27 COPPER WIRE
BAROMETRIC PRESSURE VARIABLE
U of M
M.P. Weinbach '07
P=0.90
P=19.0
P=29.0
P=73.9
TIME IN SECONDS
FUSING CURRENT IN AMPERES
8
7
6
5
4
14.5
15
15.5
16
16.5
17
17.5

p = 73.9 and p = 29 cm. we find that up to a current of 21.4 Amp. the wire fuses quicker for the lower pressure, while above this current, the wire will fuse quicker for the higher pressure. The current corresponding to the point where the two curves intersect each other may be considered as a critical current, for with this current, the wire will fuse in the same time under both pressures. For any two different pressures there seems to be a critical fusing current, corresponding to the intersection of the time-current curves for these two pressures.

The curves on plate 7 also show that the critical current for atmospheric pressure decreases with the decrease of pressure. Thus the critical current for p = 73.9 and p = 29 is 21.4 Amperes. For p = 73.9 and p = 19, I = 16.4 Amperes; for p = 73.9 and p = 0.9, I = 15.6. Amperes.

It was observed that for high currents and for pressures below 30 cm. of mercury, the wire became incandescent. This may be the ~~cause~~ reason why for high currents, the time it takes to fuse the wire is larger for lower pressure; the heat radiated from the wire being larger than the heat radiated for higher pressures.

On the other hand, the fact that for low currents the wire fuses quicker for lower pressures, may be due to the decrease in the heat dissipated by convection through the air for low pressures. According to this explanation, at the point of intersection of two curves, the increase in radiation equals the decrease in the heat by convection.

EFFECT OF GLASS TUBES.

A series of experiments were carried out with non-insulated No. 27 copper wire of constant length of 7 cm. Readings of fusing current, and measurements of fusing time were taken for

1. Wire in free air.
2. Wire extended along the axis of a glass tube 7 cm long, 2 cm. in diameter, ends open.
3. Wire along axis of same tube ends closed.
4. Wire along axis of glass tube, 7 cm. long, 1 cm. in diameter, ends open.
5. Wire along axis of the same tube, ends closed.

The terminals used in this experiment were heavy copper wires: the reason for using such terminals was to facilitate passing them through the stoppers in the closed tube test. (The following table gives the data obtained.)

TABLE VI.

No. 27 Non-insulated Copper Wire 1 = 7 cm.

In Air		Tube 2 cm diam.				Tube 1 cm. diameter.			
		ends op.		ends cls.		Ends op.		ends closed.	
I	t	I	t	I	t	I	t	I	t
15.7	7.8	15.1	6.2	14.3	6.4	13.7	6.3	13.5	5.8
17.0	5.3	16.4	4.7	16.1	4.5	14.3	5.4	14.4	4.9
18.4	4.0	17.6	3.9	18.3	3.3	15.5	4.3	16.1	3.4
20.3	3.25	20.7	2.8	20.7	2.4	16.5	3.3	18.0	2.2
22.0	2.7	22.0	2.4	22.0	2.1	19.	2.2	20.	1.7
23.5	2.4	23.4	2.2	22.6	2.0	21.0	1.9	21.4	1.6
25.0	2.2	27.6	2.0	24.0	1.9	23.	1.7	22.7	1.5

These results are represented graphically in PLATE 9 where time is plotted against fusing current.

From these curves we see that the fusing current for the same time decreases with the size of the tube. Thus for the open end tubes we find that, for t = 4 seconds, the current for the wire enclosed in the 2 cm tube is decreased by 15.65%.

For the closed end tubes, we find that for t = 4 seconds, the fusing current is decreased by 9.71% for the 2 cm tube, and by 18.01% for the 1 cm tube.

Attempts were made to use smaller size tubes, but the experiments could not be carried out on account of the fact that the wire as soon as it got hot, ex-

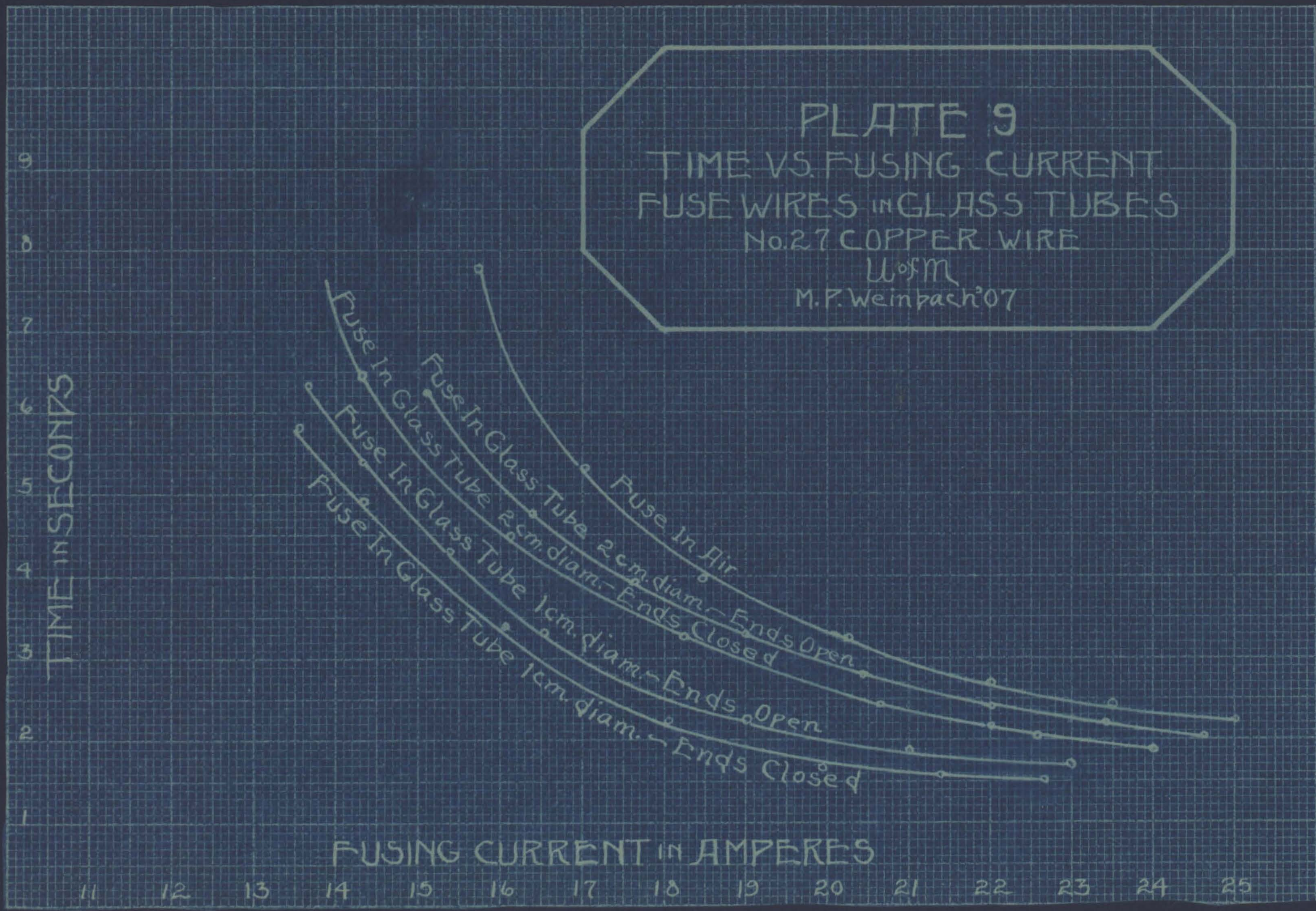


PLATE 9
TIME VS. FUSING CURRENT
FUSE WIRES IN GLASS TUBES
No. 27 COPPER WIRE
U of M
M. P. Weinbach '07
Fuse In Air
Fuse In Glass Tube 2 cm. diam. – Ends Open
Fuse In Glass Tube 2 cm. diam. – Ends Closed
Fuse In Glass Tube 1 cm. diam. – Ends Open
Fuse In Glass Tube 1 cm. diam. – Ends Closed
TIME IN SECONDS
FUSING CURRENT IN AMPERES
1 2 3 4 5 6 7 8 9
11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

panded and touched the walls of the tube thus transmitting heat directly to the tube. This may explain the peculiar results obtained by Prof. A. Schwartz and W.H.James of Manchester, England. (See London Electrician Apr. 5--1905) Experimenting with fuses enclosed in glass tubes, with open ends, they found that there is a certain size tube for which the fusing current is a minimum' For tubes smaller than this size (about 1 cm in diameter) the fusing current increases. This may easily be explained from the fact that for small size tubes, the wire is more or less directly connected to the tube, transmitting heat to it, and as a consequence requiring a larger fusing current.

The fact that the fusing time, for the same current, decreases with the size of tube, may be due to the decrease in the heat dissipated by convection currents.

This results show that from a practical standpoint, the enclosed fuse is of greater value because the sensitiveness to fusion is greater, and also because the danger of fire from scattered particles of molten metal is eliminated.

EFFECT OF LENGTH

The terminals used in this test were brass screws, screwed in a board. The distance between the terminals could be adjusted to suit the length of the fuse wire to be tested. Readings of fusing current and measurements of time were made for a No. 27 non-insulated copper wire of various lengths. The data obtained is given in the following tables:

TABLE VII.

No. 27 Non-insulated Copper Wire.

l = 3 cm		l = 4 cm		l = 5 cm		l = 6 cm.	
I	t	I	t	I	t	I	t
20.5	7.0	17.8	7.85	17.1	6.9	16.2	7.3
20.9	6.15	18.3	6.95	17.8	5.85	16.8	6.25
21.7	5.0	18.7	6.5	18.5	5.0	17.7	5.3
22.6	4.0	19.9	4.85	19.4	4.4	18.6	4.3
23.6	3.2	20.9	3.8	20.4	3.35	19.7	3.3
25.0	2.4	21.8	3.15	21.3	2.6	21.0	2.5
		22.7	2.5	22.8	2.0	22.2	2.0
		24.0	2.0	23.7	1.8	23.2	1.8
		25.0	1.6	25.0	1.6	24.4	1.6

TABLE VIII.

No. 27 Non-insulated Copper wire.

l = 7 cm		l = 8 cm		l = 9 cm		l = 10 cm.	
I	t	I	t	I	t	I	t
16.0	6.8	16.0	6.5	16.1	6.05	15.5	6.6
16.5	6.0	16.6	5.6	17.0	5.0	16.3	3.6
17.2	5.2	17.4	4.75	17.9	4.15	17.1	4.75
18.1	4.35	18.3	4.0	19.	3.3	18.3	3.7
19.1	3.5	19.3	3.2	20.0	2.6	19.3	3.0
20.3	2.7	20.0	2.75	22.0	1.9	21.1	2.1
21.6	2.15	21.4	2.2	24.0	1.55	23.0	1.65
22.8	1.8	22.1	1.9			25.0	1.4
		23.2	1.7				

The graphical representation of these results is shown on PLATE 10, where time is plotted against fusing current for various lengths of fuse wire. From these curves we see that the sensitiveness to fusion of a wire increases with the length of the wire. The reason for this is that the longer the wire the less heat is lost by conduction through the wire to the terminal blocks. It was observed during these tests that for longer wires, the rupture occurs at the middle of the wire.

The curves on PLATE 11, showing the variation of the fusing current with the length of the fuse

wire, were obtained from the curves on PLATE 10 by plotting the fusing current as a function of the length of the wire, considering the fusing time constant.

These curves show plainly how the fusing current decreases as the length of the wire is increased.

To find the law of variation of fusing current with the length of fuse wire, recourse was made to the equation developed in the preceding pages namely:

$$\left\{I^2 - \left(Ad^2 + Bd^3 + C\frac{d^4}{l^2}\right)\right\} t = Dd^4$$

As the same size wire was used in these tests, we may put $Ad^2 + Bd^3 = K$ (constant) and

$$Cd^4 = K_2 \text{ (constant)}$$

If we consider the fusing time also constant then

$$\frac{Dd^4}{t} = K_3 \text{ (constant)}$$

Consequently the equation may be written

$$I^2 = K + \frac{K_2}{l^2} + K_3$$

Letting $K + K_3 = K_1$ then

$$I^2 = K_1 + \frac{K_2}{l^2}$$

This equation showing the law of variation of the fusing current and length of wire, must then be

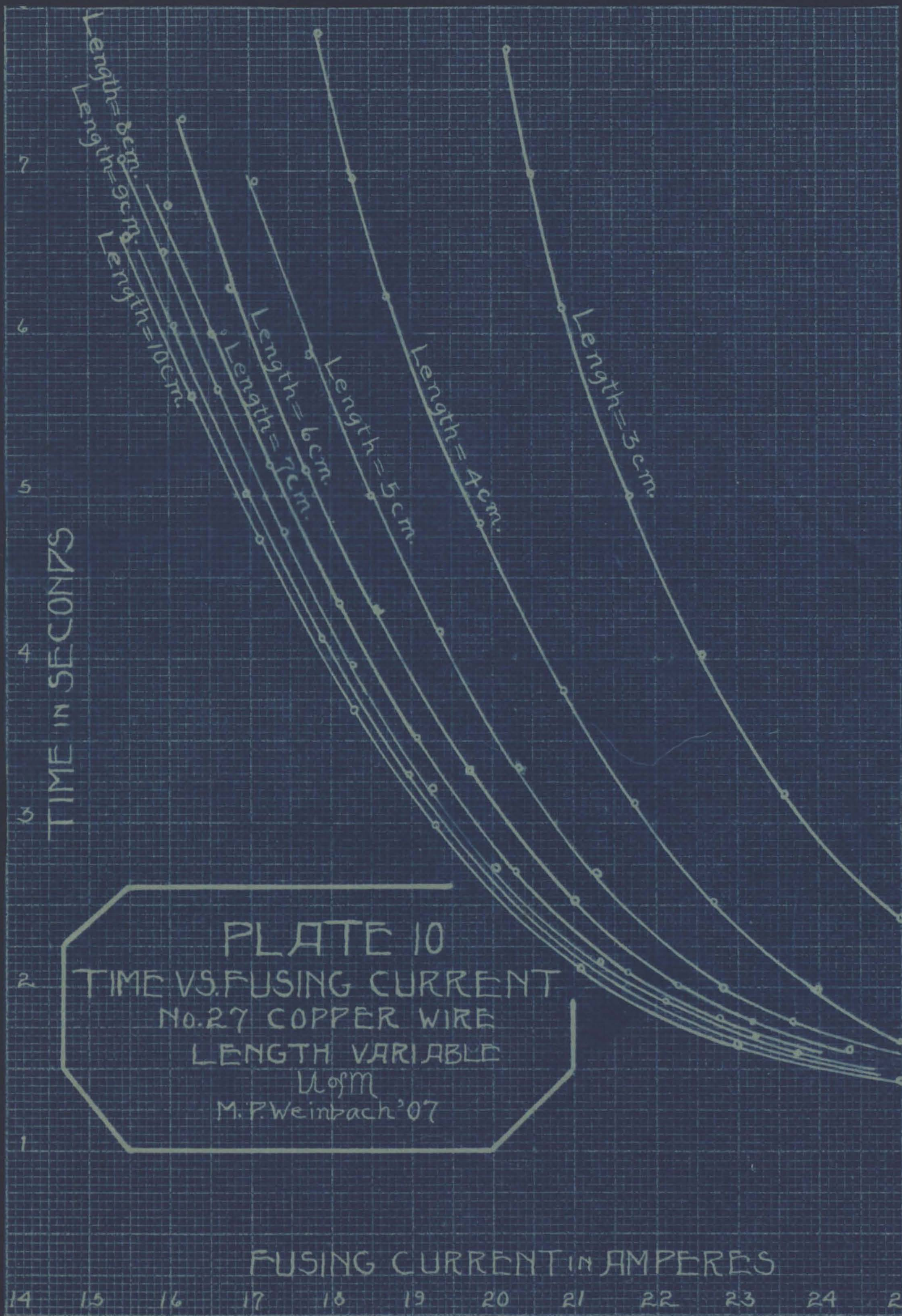


PLATE 10
TIME VS. FUSING CURRENT
No. 27 COPPER WIRE
LENGTH VARIABLE
U of M
M. P. Weinbach '07
TIME IN SECONDS
FUSING CURRENT IN AMPERES
Length = 3 cm.
Length = 4 cm.
Length = 5 cm.
Length = 6 cm.
Length = 7 cm.
Length = 8 cm.
Length = 9 cm.
Length = 10 cm.
1
2
3
4
5
6
7
14
15
16
17
18
19
20
21
22
23
24

the equation of the curves on PLATE 11. The constants K_1 and K_2 have been determined from the curve I vs. ℓ for a constant time of 6 seconds and also for t = 3 seconds. For t = 6 seconds, the equation is

$$I^2 = 238 + \frac{1800}{\ell^2}$$

and for t = 3 seconds

$$I^2 = 353 + \frac{1950}{\ell^2}$$

From these two equations, the current has been calculated for the length of fuse wire used. The observed and computed values are given in the following table:

TABLE IX.
No. 27 Non-insulated Copper Wire.

t = 6 seconds			t = 3 seconds.		
ℓ	obs I	comp I	ℓ	obs I	comp I
3 cm	21.0	21.0	3 cm	23.8	23.8
4 "	18.9	18.75	4 "	21.9	21.8
5 "	17.7	17.6	5 "	20.75	20.8
6 "	16.9	16.98	6 "	20.2	20.2
7 "	16.5	16.55	7 "	19.8	19.8
8 "	16.3	16.3	8 "	19.5	19.6
9 "	16.15	16.15	9 "	19.45	19.4
10 "	15.9	16.0	10 "	19.3	19.3

As the computed values do agree so close with the observed values of the fusing current, it is evident that the variation of the fusing current and

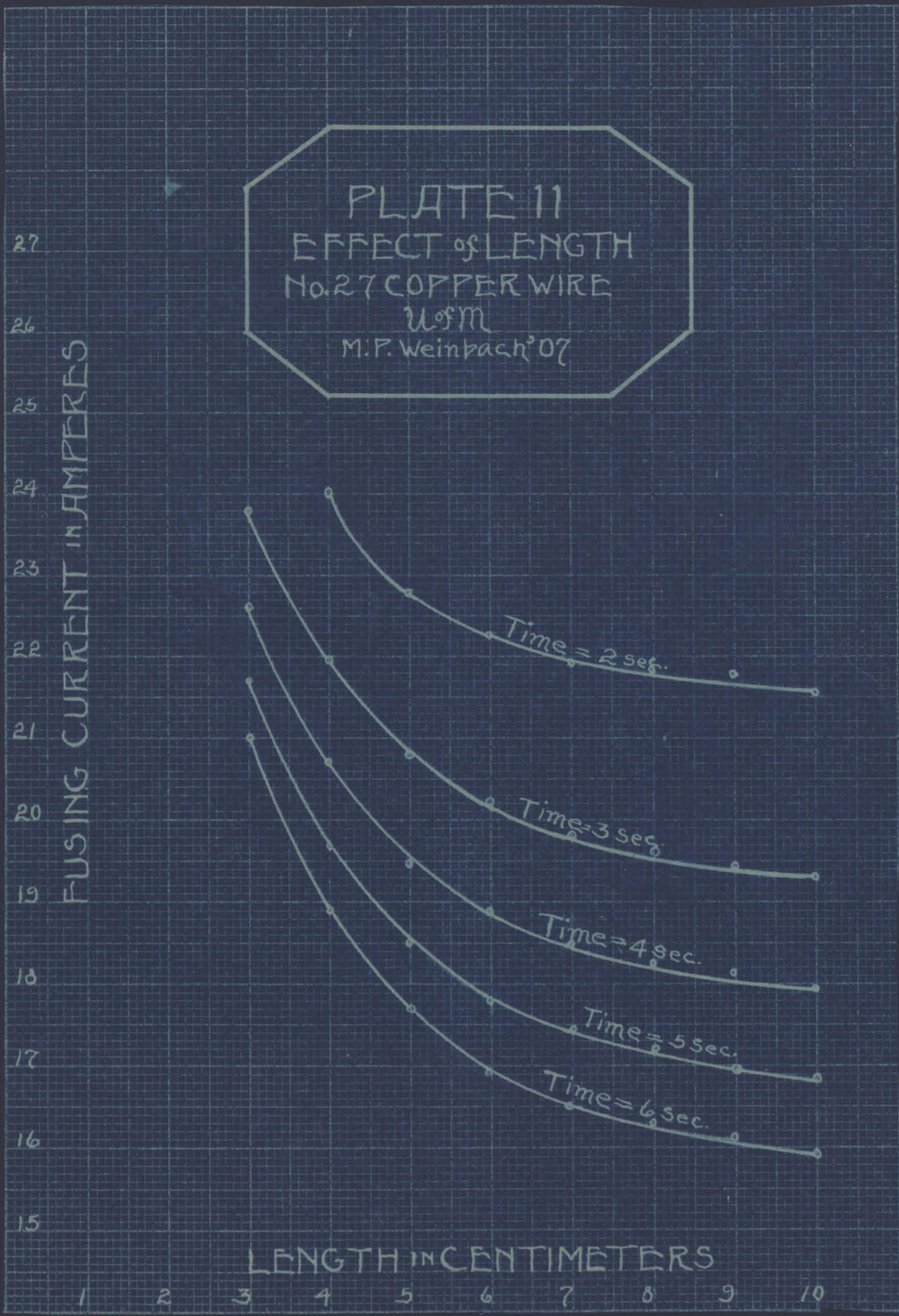


PLATE 11
EFFECT of LENGTH
No. 27 COPPER WIRE
U of M
M.P. Weinbach '07
FUSING CURRENT IN AMPERES
LENGTH IN CENTIMETERS
Time = 2 sec.
Time = 3 sec.
Time = 4 sec.
Time = 5 sec.
Time = 6 sec.
27
26
25
24
23
22
21
20
19
18
17
16
15
1
2
3
4
5
6
7
8
9
10

length, is according to the law: $I^2 = K_1 + \frac{K_2}{l^2}$ and this is also an evidence of the correctness of the formula $I^2 = Ad^2 + Bd^3 + (C\frac{1}{l^2} + \frac{1}{t})d^4$

Conclusion

The results of the experiments outlined in the previous pages clearly show how the sensitiveness to fusion of a wire is dependent on the surrounding conditions. Thus, we have seen that the effect of insulation is to increase the sensitiveness for low currents and decrease it for high currents. The effect of barometric pressure is to increase the sensitiveness to fusion of a wire for low currents and low pressures, and to decrease it for high currents and low pressures. Inclosing fuse wires in tubes increases their sensitiveness to fusion: as the size of the tube diminishes, the sensitiveness increases, The sensitiveness getting larger as the size of the tube is diminished. PLATES 10 and 11 clearly show the effect of length on the fusing time. The longer the wire, the less time it takes a wire to fuse with a given current.

The close agreement between the observed and computed values of time from the equations of the time-fusing current curves, and also between the observed and computed values of current in the

test on length variation, prove the accuracy of the formula

$$I^2 = Ad^2 + Bd^3 + \left(C\frac{1}{\ell^2} + D\frac{1}{t}\right)d^4$$

The writer hopes that if opportunities will present themselves in the near future, to work out a table of fusing curremts based on this formula, for sizes of wire of metals and alloys used in practice for fuse wires.

DUE	RETURNED

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