AN INVESTIGATION OF THE
IMPEDANCE OF AN ALTERNATING
CURRENT ARC IN AIR

THESIS FOR THE DEGREE OF M. S.

Webster Lazell Bowler

1934

Inter-Department Correspondence

MEMORANDUM Date Sep't. 5/34

To Dean of the Graduate School

From L. S. Foltz, Dep't. of E.E.

Subject Approval of thesis for M.S. degree in E.E.

The thesis of Mr. W. L. Bowler, "An Investegation of the Impedance of an Alternating Current Arc in A Air" is approved.

....

Signed ______________________

AN INVESTIGATION OF THE IMPEDANCE

OF

AN ALTERNATING CURRENT ARC IN AIR

A Thesis

Submitted to the Faculty

OF

Michigan State College

of

Agriculture and Applied Science

by

Webster Lazell Bowler

Candidate for the Degree

Master of Science

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This Thesis is submitted to

the Faculty of the Graduate School

of Michigan State College as partial

fulfillment of the requirements for

the Degree of Master of Science in

Electrical Engineering.

ACKNOWLEDGMENT

For their willing and helpful advice and assistance I wish to thank Professor Foltz and the other members of the Electrical Engineering Department.

The solution of this problem was made possible through the kindness of the City of Lansing Board of Water and Light in the loan of the transformers and due to the cooperation of Mr. F. H. Mitchell, college electrician, in loaning to me the necessary switching equipment.

W. B.

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***

INTRODUCTION

Dry air under ordinary conditions is said to be a dielectric. If the molecules of this same air be sufficiently excited, the air becomes ionized or conductive. Heat is the most common source of energy for ionization. Ionization of air may be produced by an electrostatic field, and the passing through it of X-rays or ultra-violet rays.

If two conductors, having a difference of potential between them, are allowed to come in contact with each other, a current will flow, tending to neutralize the difference of potential. If these conductors are separated, a small spark may be visible at the point of separation. This spark produces heat which, in turn, produces ionization of the surrounding air. If the spark continues as an arc, the electrodes may become heated to their fusing temperature.

If the air alone were the source of ionized particles, the discharge between electrodes would be short lived since all of the particles (ionized air) would be swept away rapidly by the electrostatic field. At the fusing temperature of a metal the molecules become agitated to such a degree that some of them at the surface are removed from their neighbors and away from the surface to such distances that they become more susceptible to the action of the electrostatic field than to the force holding them in the metal. The impelling field then causes the charged particles to form a part of the arc stream.

At a given condition of temperature and pressure the

number of molecules in unit volume of the conducting vapor is fixed. Since the surrounding air cools the arc plasma, the conducting vapor is confined to a stream, the area of which is proportional to the current. It is assumed that the current density of an arc is constant.

As the plazma of the arc is cooled, energy is given up in the form of heat. If more heat is supplied, the arc will continue. If a sufficient amount of heat is not supplied to the arc plasma as it cools, recombination will take place more rapidly than ionization and the arc will be extinguished (3).

Consider now a transmission line whose wires may be swinging to and fro. Suppose an arc be struck between the swinging wires. As this arc pulls out or decreases in length, the voltage across it may vary between wide limits. It has been determined that the effective current values do not vary a considerable amount under such conditions.

Since, in an arc, the impedance is wholly resistance, power is the product of the voltage and current of the arc. It is this power in which we are here interested.

3. For this and succeeding references see Bibliography

THE PROBLEM

Since an arc may exist on a transmission line and may be pulled out into great lengths, it is evident that the power starts from zero and varies with the current and the length. The absolute value of the power at any instant is a function of the voltage and current.

We know that the voltage and current of any system are functions of the circuit constants of that system. We know further that the arc impedance pulsates at twice the frequency of the impressed voltage wave.

The object of this thesis is to determine the relationship between the impedance of the arc and the impedance of the line over which it is fed. An expression for the arc power can then be found.

Note here Thevinin's theorem, which states that maximum power will be absorbed from a net when the impedance of the external circuit is the conjugate of the net impedance. If the external circuit be composed of pure resistance, maximum power will be absorbed from the net when the magnitude of the resistance is equal to the absolute value of the net impedance.

HISTORY

Periodical history of the electric arc dates back as far as 1892, at which time we find articles dealing with the back electromotive force of an electric arc. At that time it was the popular belief that the potential of an arc was composed of constant and variable components. The constant component was known as the counter electromotive force. It was believed that the constant component was due to the fact that the resistance, or a part of it, proportioned itself to the current.

Sylvanius Thompson (60) reasoned that this phenomenon of voltage, which is independent of current strength and arc length, could exist only if there were at any one surface of an arc a something equivalent to a transition resistance which varied inversely with the area over which it takes place, and if the area over which it takes place is proportional to the current.

These facts as set forth by logical deduction are, in crude form, facts which were later proved by laboratory methods.

In The Electrician (66), 1897, an editorial states that few physical phenomenon have ever more successfully and persistently baffled experimental research than the secret of electric arc phenomenon. One party advanced the somewhat metaphysical idea of negative resistance as a basis of explanation.

More recent experiments dealt with the arc as a source of light, and it was in this stage that an immense amount of research was undertaken. With the coming of the incandescent lamp the arc was to become a thing of the past as far as illumination was concerned. It became evident that the arc was to continue as a factor in transmission and distribution of power.

The pranks of arcs today offer to engineers and scientists problems which are overcome only with an expensive outlay of materials and comprehensive analysis.

An interesting study of the effects of arcs upon reactance relays (63) has shown that an arc, being mostly resistance, has a negligible effect. The distance measurement of a reactance relay is based upon the impedance of the line between the fault and the impedance of the fault. The effect upon the relay, therefore, is to cause it to function as if the fault were more distant than it really is. This tendency, of course, depends upon the arc impedance as a ratio of the line impedance to the fault location. In the same article it is pointed out that an impedance relay which should operate in an intermediate time for a fault at the end of a protected section may operate in less than intermediate time or may even fail to operate on faults involving long arcs, particularly on short lines or in the presence of wind. In general, reactance relays give the same indication for arcs at the end of long lines as they do for metallic faults at the same location.

Engineers of today have contributed much to the knowledge of arcs. Mr. J. Slepian* of the Westinghouse Electric

* See Bibliography

& Manufacturing Company is probably our foremost scientist in this field. His articles on arc extinction have aided much in the design of circuit breakers and other protective equipment.

A most interesting study of arc ignition characteristics (3) has been carried out by Messrs Dow, Attwood, and Krausnick, at the University of Michigan. In their analytical investigations they used the cathode ray oscillograph and applied the probe measurement scheme as set forth by Langmuir.

Actual conditions of arc over were carried out on lines owned by Consumers Power Company (43). Results of these experiments show that the apparent power factor of an arc varies, with line constants, over wide limits. Values were found as low as 75 per cent in each type of circuit. It was found further that a high value of apparent power factor occurs at the start of the arc and decreases to a lower value near the point of extinction.

PROCEDURE

The nature of the problem of determining the true power of an arc is such that consideration must be given to the equipment procurable.

When a transmission line arcs, an enormous amount of power is apt to be consumed depending, of course, upon the Kv. A. available. It was considered advisable to attack the problem on a small scale and attempt to predict phenomena which might occur on a larger scale.

Arc electrods that would be well insulated from ground and that would allow of drawing out the arc and adjustment of spacing required little material, and the construction was simple.

Two fiber tubes 1 1/4 inches outside and 5/8 inch inside diameter and 4 3/16 inches long were tapped 3/4-16 at each end. They were then mounted perpendicularly on an asbestos board base with 15 inch spacing. A brass plug was screwed into the top of each tube and secured in place by a fiber lock nut. The plugs are drilled to accommodate the electrode holders, which are 7/16 round, brass rods each 6 inches in length and tapped at one end to accommodate a fiber handle, threaded 5/16-18. The opposite end of the holder was drilled along its center line to allow the electrods, which are .201 inches in diameter, to slip freely but without looseness into the holder. A connector was made to slip over the electrode holder, and a flexible wire connected the collar to a binding post pedestal placed 5 inches from the foot of each tube and in line with them. A set screw was provided in the top of each plug to assure a good connection between plug and holder. Set screws were also provided for holding the electrodes accurately in place and for securing the connectors to the holders. The pedestals referred to are constructed of 3/4 inch red fiber, each 4 3/16 inches long. They were bolted to the base, as were the tubes, and a binding post with a rubber top was secured to the top of the pedestal. The purpose of the rubber top is to prevent corona loss that might otherwise occur. The space between the base of the binding posts and the bolt projecting up from the base was filled with sealing wax. The entire apparatus was placed upon a slab of the asbestos material to prevent any loss which might otherwise occur through the reinforced concrete shelving.

For adjustment of arc length a taper scale was made of tool steel and graduated in millimeters from one to twenty. Very accurate measurements were possible since the ratio of length to thickness of the scale was about fifteen to one.

The electrodes proper were made from # 4 DCC wire. The cotton was removed and the wire carefully straightened with a minimum of bending to prevent altering the resistivity of the wire. Horn gaps, six and twelve inches in length, and straight electrodes were experimented with. It was evident that a much steadier arc could be obtained between straight electrodes and the distance between them could be more accurately determined. The electrodes used finally were 2-1/2 inches in length, and the faces were very slightly curved. It was found that with slightly curved faces the arc length could be measured just as accurately and that the arc tended to hold itself between the rounded tips of the electrodes with less fringing and consequently less error in actual length of the arc stream.

A 5 Kv-A, 4400-440 volt transformer was chosen for preliminary tests. The campus 440 volt power circuit was used as supply. It was found that an arc could be struck and drawn out to a length of two to three inches before extinguishing itself due to air currents. At this point the transformer was found to be defective.

In the first test two ~~230~~ 2300-115 volt potential transformers were connected in series across the arc to obtain oscillograph recordings. The wave form of voltage being so distorted the method seemed impractical. For volt meter readings, however, a potential transformer was connected across the primary (low voltage) side. This was carried out because in actual conditions the volt meter readings of voltage of that magnitude would be taken only through potential transformers.

For oscillograph recording it was necessary to construct a potential divider which would consume negligible power and which would not break down under the strain of high potentials. It was possible to secure suitable wire wound resistors having 300,000 ohms when in series.

The power consumed by this resistor at 4400, volts was approximately $\frac{(4400)^2}{(300,000)}$ x 300,000 or E^2/R = 80.7 watt. This power was consumed at open circuit only. At the reduced voltage during arc discharge the power was reduced to a negligible value. A switch with a long insulated handle was placed in the side of the resistor adjacent to the high potential side of the arc. This served as a protection to instruments as well as to the operator. The secondary was tapped from the end of the resistor nearest ground potential.

The secondary of this potential divider must have a very high resistance and must produce a minimum of 20 milliamperes for operation of a super-sensitive oscillograph element. The only possible way of obtaining such conditions is to use the potential divider as a control circuit of an amplifier and the best type is that of a vacuum tube. Thus a 45 tube was connected with a grid bias suitable for class A amplification. A bypass condenser of 20 micro-forads is placed across the grid bias resistor to allow the desired voltage wave to pass through the grid filament circuit of the vacuum tube. The grid circuit of this tube requires but micro amperes and thus no appreciable disturbance is set up. A key is wired across the filament grid circuit which provides for short circuiting the amplifier except at the instant the oscillogram is taken. This is a needed protection against damage to the tube as the ratio of reduction of voltage is 143-1 across the potential divider.

In operation the amplifier was found not to give a proper recording of the voltage on both sides of the voltage zero. This trouble was remedied by altering the bias of the tube so as to obtain an unattenuated wave on one side of the axis with an attenuated wave on the other. It was so adjusted, however, that the lowest portions of both curves were correctly reproduced, and it could thus be observed whether or not rectification was taking place. Note that the indication of rectification would be a displacement of the waves to one side of the voltage zero. By reversing the polarity of the amplifier with respect to the oscillograph, the voltage wave can be made to fall on either side of the axis. In the second set of films this was done so that the oscillograms could be more easily analyzed, i. e., the voltage and current waves were made to record 180 degrees out of phase, which is not the normal respective position. The plate or oscillograph current was furnished by a power pack.

Before taking data the oscillograph was calibrated by determining the millimeters deflection per volt applied to the arc. This was done by inserting a slide wire resistor, capable of carrying the exciting current of the transformer, in series with the transformer primary and adjusting the open circuit voltage, as recorded by a potential transformer and calibrated meter, through a range of values from 20 to 6000 volts. The deflection was read by a scale from the ground glass plate of the revolving mirror attachment.

The wave form of the arc current was determined by placing an oscillograph element across a 0.1 ohm shunt in the grounded side of the arc circuit.

The oscillograph series resistance element in the current circuit was set at zero, and the corresponding element in the voltage circuit was adjusted to give 30 milliamps plate current as read by the plate current milliameter.

For the second set up there was obtained from the City of Lansing Board of Water and Light two G. E. 5 Kv-A., 220-2200 volt transformers. It was necessary to know with all accuracy practicable the constants of the circuits employed. Hence, resort was made to a laboratory generator as a source of power.

Open circuit and short circuit tests were made on the two transformers and the equivalent circuits computed in terms of the high side. The leakage was small and could have been disregarded. However, it was carried through for sake of completeness.

A saturation run and zero and unity power factor load tests were made upon the generator and its synchronous impedance curve plotted for the zero power factor loading.

To obtain as stable conditions as possible the fields of the generator and synchronous driving motor were excited by laboratory storage batteries. The line connecting the generator with the transformer consisted of two # 6 rubber covered, copper wires tightly taped together.

From the data it was possible to estimate the total impedance of the line, transformers, and generator. For protection of the transformers and generator a current limiting reactance was inserted in the line. This reactance served also as the line impedance of the test conditions. The generator was rated at 7.5 Kv-A and the transformers at 5 Kv-A each, ~~giving~~ enough reactance was inserted to prevent the generator current exceeding its normal value with the transformer primaries short circuited.

In construction, the reactors were identical. Each consisted of 450 turns of # 8 DCC copper wire wound on a bobbin 2.75 ~~in.~~ inside diameter, 12 inches outside diameter, and winding space 3.3 inches in width. The bobbins were secured together by eight brass bolts and were wrapped with unvarnished cambric. Each coil had an inside, a center, and an outside terminal. The center terminal permitted either the outside or inside portion of the winding to be used. After some preliminary experimenting it was found that certain combinations of these inside and outside coils gave a range of impedance values suitable for these tests. Single pole, single throw knife switches were attached to the coils, three to two of the units and two to the remaining. These switches were so arranged that they could be easily and rapidly manipulated.

The connections made possible by means of switching were outside and center coil, center coil only, outside and center coils short circuited.

In operation the coils were so placed on the floor that their mutual effect was small.

As a safety precaution a magnetic switch was installed with the control buttons on the table directly before the operator. When the switch was closed, two 220 volt lamps (red) were in parallel ~~line~~ across the live circuit. It may here be said that the lamps served their purpose well. As a further precaution a single pole mechanical circuit breaker in series with the high potential side of the line was so placed that it was easily opened before adjusting the apparatus.

For safety and for the protection of material, it was necessary to place all meters in the side of the secondary nearest ground potential and to make certain by inspection that the ground circuit could not be opened by opening oscillograph switches. THIS CONDITION WAS MAINTAINED. This was facilitated by grounding both primary and secondary windings of the transformer to a water pipe.

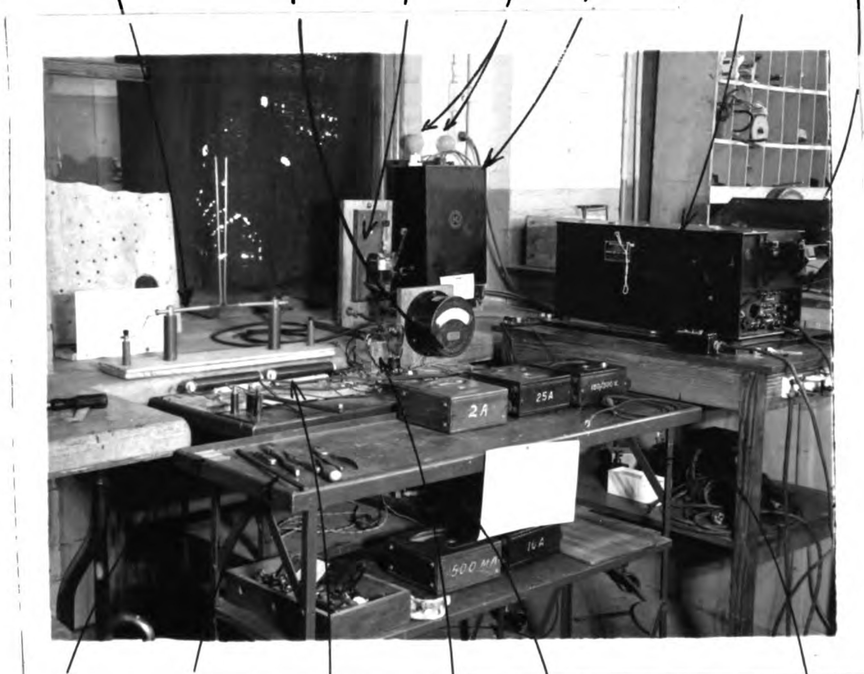
The meters used are of the vane type and are described on the data sheets following. Each meter used was calibrated, simultaneous readings being taken of standard and of meter on test. The circuit diagram shows the locations of the various instruments.

Starting the arc by fuse wire and by # 30 copper was attempted but without satisfaction. It seemed that a more rapid means should be available. Due to the relatively short arc lengths used it was possible to start the arc by bridging the gap with the charred end of a bakelite rod. This method proved safe, simple, and rapid.

In taking readings the proper line impedance was set, the mechanical circuit breaker closed, the generated voltage checked, the oscillograph shutter adjusted for automatic operation, the magnetic switch closed, the arc started, if necessary, by the rod, the switch connecting the potential divider closed, and the oscillograph motor started. Immodiately before taking readings the short circuiting lever of the key was released and the key depressed, the slide camera shutter opened, the key released, and the control switch of the oscillograph turned to the suitable stop determined by the condition of film speed. At the instant the shutter opened, which was accompanied by the characteristic click, meter readings were taken. Again the key was closed, the camera shutter closed, the magnetic switch opened, and the potential divider also disconnected.

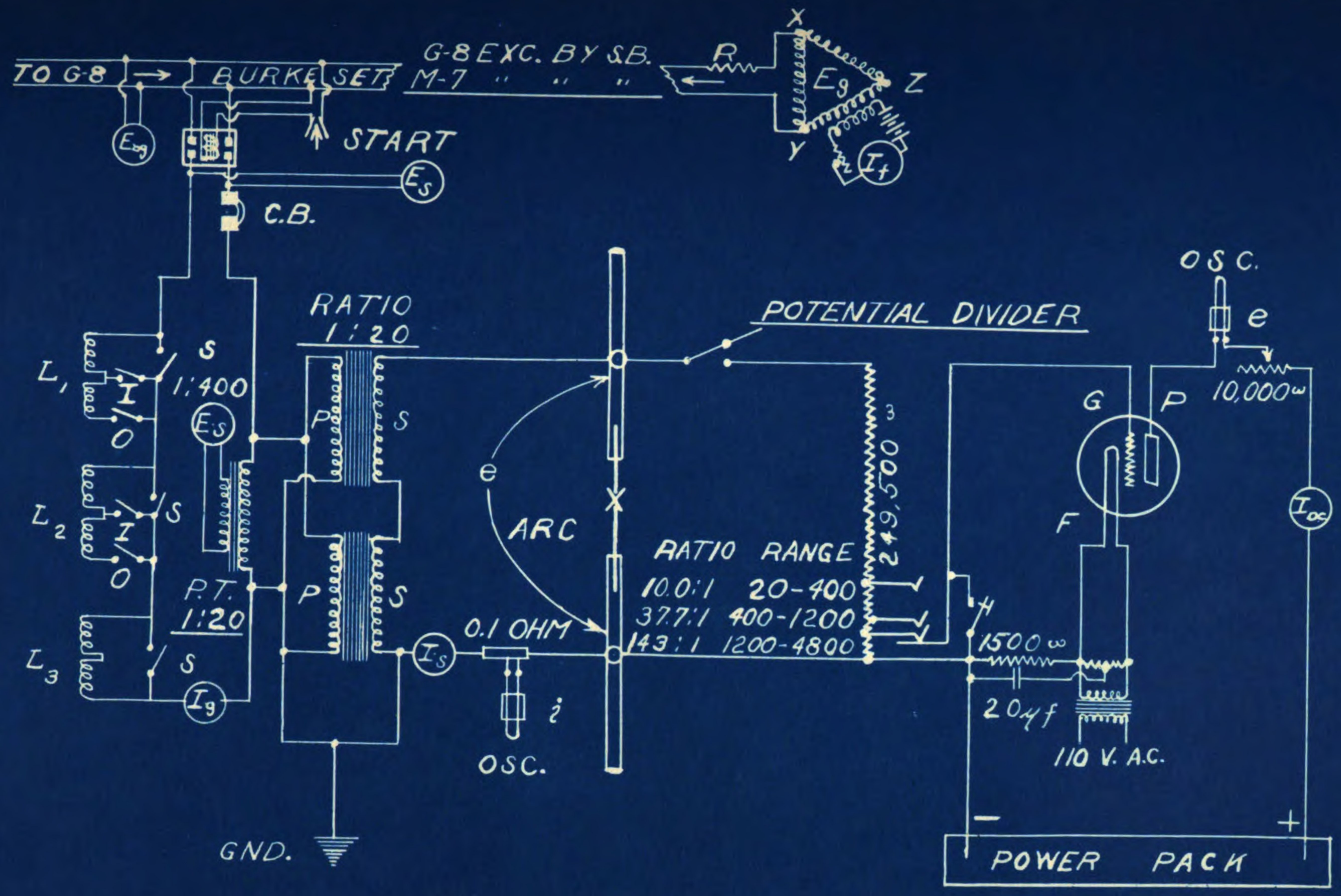
In the first test arc lengths from 1 to 10 mm. were used at intervals of one millimeter with the exception of the 9 millimeter length. (Seven values of line impedance were used at each arc length.) Oscillograms were taken at the same value of line impedance for each length of arc. In addition, so that the arc characteristics could be determined, a voltage reading, E_S, was taken as described above. The reading obviously does not give the correct value of r.m.s. voltage across the arc due to the distorted wave form. These readings are referred to in the discussion as apparent voltage readings and the impedance thus computed as the apparent impedance.

For obtaining the second set of data a higher film speed was used so that the oscillograph records could be more accurately analyzed. This time the potential transformer was eliminated from the circuit to avoid any possibility of error from that unit. Three arc lengths were used and five impedance values for each length. Oscillograms were taken at each reading, but it was found later that the oscillograph failed to record voltage after oscillogram # 11 had been taken. The reason for this was discovered later as being the fault of the element but not of a nature that previous pictures had been affected.



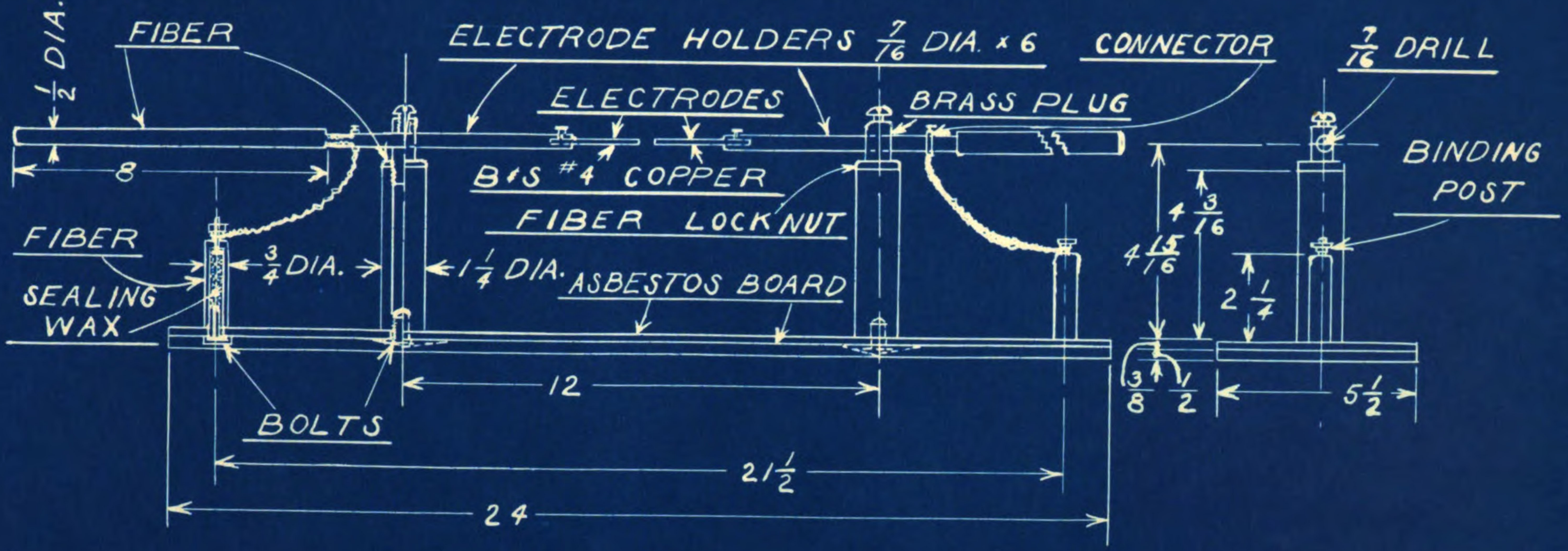
Transformers (under ledge in rear of apparatus) and capacitor not visible in photograph.

PHOTOGRAPH OF APPARATUS



SCHEMATIC DIAGRAM OF APPARATUS

ALL DIMENSIONS IN INCHES



SCALE 1" = 4"

W. L. Bowler.

DIMENSIONED DIAGRAM OF ARC

TEST DATA

REGULATION DATA OF G-8

Field of G-8 Excited by S. R. Storage battery

Field of M-7 Excited by M. M. Storage battery

Resistance Load Test Resistor-Heater Element Bank		Inductive Load Test Inductor - Banks A & B Series	
Igen.	Egen.	Igen.	Egen.
0	220	0	220
5.0	214	2.95	205
6.6	212	5.3	191
10.0	206	7.4	179
11.7	202	9.25	169
14.2	196	12.2	152
15.8	191	13.5	145
17.9	185	14.7	138
19.4	179	16.6	125
20.8	173	19.2	110
22.1	168	21.8	96
23.5	162	22.8	91
24.4	156	23.8	86

Field Current of G-8, 2.0 Amperes

Rating of G-8, 5 Kv-A, 220 v., 60 cycles

LINE DATA

Data taken after three hours operation

Amperes I_L	Volts E_L	Ohms R_L
3	2.9	.967
9	8.4	.934
15	13.9	.926

Average resistance 0.942 ohm.

TRANSFORMER DATA

Low Side Parallel - High Side Series

Ratio 20:1

O. C. Data:

E_L	I..	W_L	$\|Y_L\|$	$\dot{Y}$ G	- jb
171	.615	60	.00359	.00205	.00294
180	.67	65	.00372	.00200	.00313
200	.81	78	.00405	.00200	.00352
210	.895	86	.00426	.00195	.00379
220	1.05	96	.00477	.00198	.00434
230	1.65	104	.00718	.00197	.00690

S. C. Data:

I_L	E_H	I_H	W_H	$\|Z_H\|$	$\dot{Z}$ r	+ jx
2.5	14.2	.3	3.5	47.4	38.9	27
11.0	26.2	.48	11.5	54.1	49.5	21.8
15.0	38.6	.82	25.5	46.4	36.6	28.4
20.0	52.0	1.09	45.2	47.7	38.1	27.7
25.0	65.0	1.28	66.0	50.8	40.4	30.8

Rating of Transformers

5 Kv-A - 220.440 - 1100 - 2200 volts

60 cycles

INDUCTANCE COIL DATA

Position	Coil No.	R (Ω)	L (h)	r	X	Average Amperes
1	I II III	.651 .660 .658	.0375 .0375 .0372	1.969	43.0	5.05
2	I II III	.418 .660 .658	.0173 .0375 .0372	1.736	35.25	5.97
3	I II III	.418 .415 .658	.0173 .0171 .0372	1.491	27.45	7.49
4	I II III	.418 .660 0	.0173 .0375 0	1.078	21.0	9.2
5	I II III	.418 .415 0	.0173 .0171 0	.833	13.19	13.86
6	I II III	.651 0 0	.0375 0 0	.651	14.38	12.53
7	I II III	.418 0 0	.0173 0 0	.418	6.63	20.37

r ohms = Ω

h henries

CALIBRATION DATA

of

Westinghouse Portable Oscillograph.

Supersensitive Element - Position No. II.

Element series resistance	3000 ohms
I_{DC}	26 M. A.
I_{oDC} Reading	5.6 Cm.
I_{26DC} Reading	8.0 Cm.

Open Circuit Arc Voltage E_{max}	Millimeters Deflection D
368	8.5
566	13.0
850	19.0
1130	27.0
1414	32.0
1698	35.0
1980	37.0
2260	40.0
2540	42.0
2840	43.0

1 Mm. deflection represents 43 volts.

STANDARD MONOTRONE HARDNESS OF ELECTRODES BEFORE AND AFTER TESTS

Average hardness before tests

10.0 Monotrone

Average hardness after tests

7.5 Monotrone

Data taken at tip of electrodes with Monotrone diamond point instrument

Depth of impression 0.0006 inches

DATA - V. A. CHARACTERISTICS, No. 1

Impedance Set. / Arc Lgth	Rdg	1	2	3	4*	5	6	7
1	Eg	202	217	210	196	179	184	142
	Ig	5.05	6.0	7.45	9.60	13.4	12.1	19.4
	Is	250	297	369	460	670	610	970
	Es	320	340	320	300	320	200	120
2	Eg	222	217	210	200	178	183	140
	Ig	5.05	5.9	7.7	9.4	13.4	12.25	20.1
	Is	245	294	380	460	665	620	1200
	Es	402	380	440	440	160	160	120
3	Eg	221	217	209	199	178	182	139
	Ig	5.05	5.9	7.4	9.4	13.4	12.5	20.1
	Is	245	290	365	465	670	620	1100
	Es	400	320	284	240	180	200	160
4	Eg	223	221	182	209	182	186	143
	Ig	5.1	6.1	13.6	9.7	13.8	12.8	20.6
	Is	250	300	680	480	680	630	1400
	Es	320	280	208	244	204	200	160
5	Eg	226	221	214	212	221	186	141
	Ig	5.1	6.0	7.51	7.50	6.0	12.8	26
	Is	245	296	370	380	310	635	1400
	Es	200	368	320	324	480	240	160
6	Eg	226	321	213	203	182	186	142
	Ig	5.07	6.05	7.50	9.7	13.6	12.7	20.4
	Is	253	302	370	475	690	640	1020
	Es	380	340	320	280	220	240	200
7	Eg	225	221	213	202	181	186	143
	Ig	5.05	5.90	7.50	9.70	13.40	12.7	20.5
	Is	250	287	361	480	680	640	1020
	Es	560	512	340	300	260	260	220
8	Eg	225	220	214	202	182	186	142
	Ig	5.05	6.00	7.50	9.70	13.4	12.6	20.5
	Is	250	300	368	480	670	630	1025
	Es	500	440	400	340	300	292	216
10	Eg	226	221	214	203	182**	188	142
	Ig	5.03	5.9	7.35	9.3	13.1	12.4	20.4
	Is	245	295	363	455	660	620	1020
	Es	600	620	560	500	360	360	248

Key to table on next page.

* Reactance value at which oscillograms 1 - 10, inc., were taken.

** Oscillogram 10-b taken at this point.

E_g = voltage at transformer primary.

E_{og} = 249 volts = generated e.m.f.

I_s = arc current in milliamperes.

I_g = generator current.

f = 60 cycles

DATA—VOLT-AMPERE CHARACTERISTICS

Test No. II.

Impedance Setting		2	3	4	6	7
Arc Length	Reading					
	Osc. Nos.	1	2	3	4	5
	E_g	213	205	201	189	160
4	I_g	6.00	7.35	8.2	10.27	15.7
	I_s	.296	.358	.402	.535	.785
	Osc. Nos.	10	9	8	7	6
	E_g	212	216	202	190	160
6	I_g	5.85	7.6	8.48	10.4	15.6
	I_s	.290	.356	.408	.530	.780
	Osc. Nos.	11*	12*	13	14	15
	E_g	244	236	201	190	161
8	I_g	6.9	8.5	8.18	10.3	15.5
	I_s	.341	.423	.405	.530	.775

Note:

$E_{0}g$, generated e.m.f., 245 volts.

E_g, generator terminal voltage, volts.

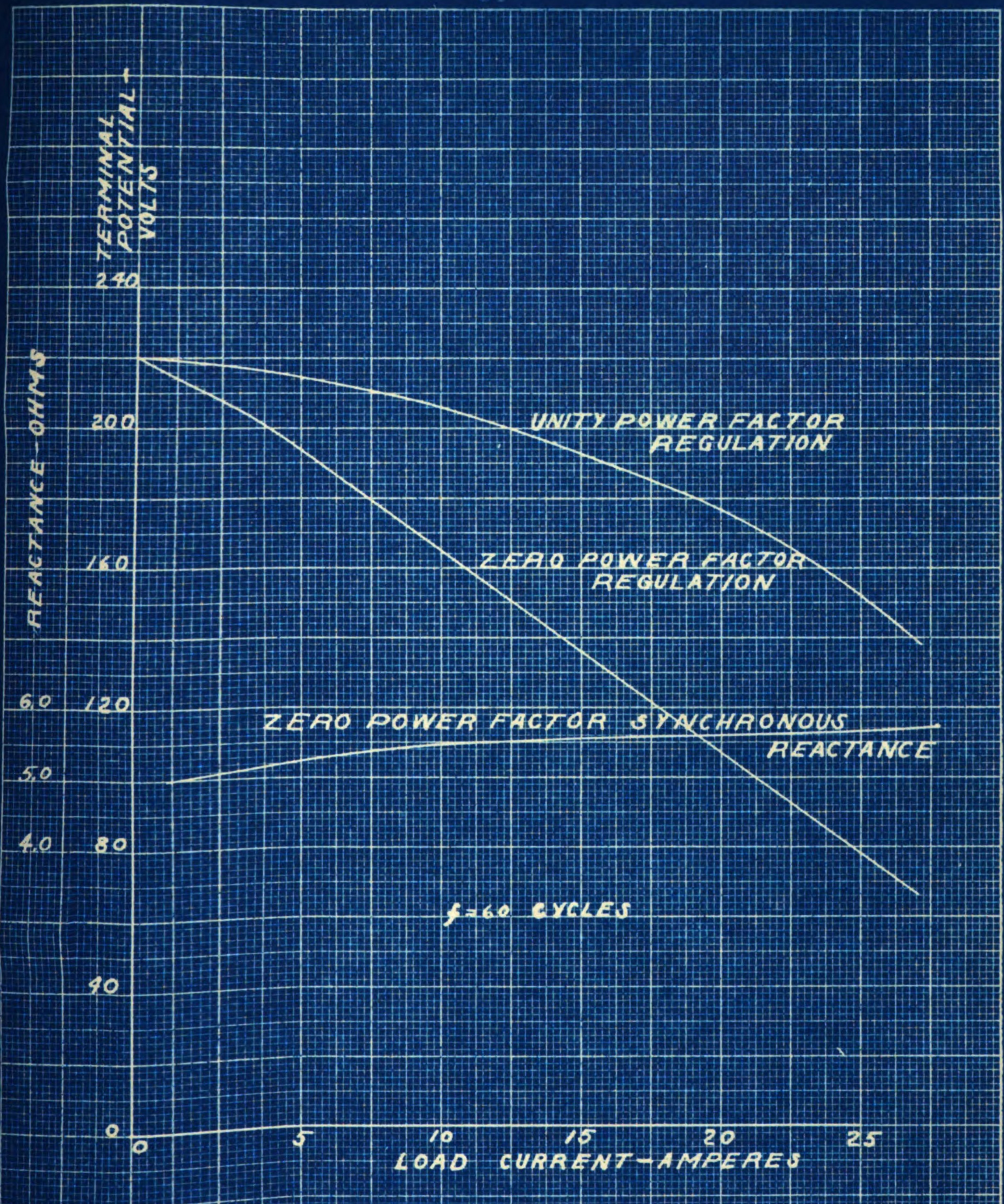
I_g, generator current, amperes.

I_s, arc current, milliamperes.

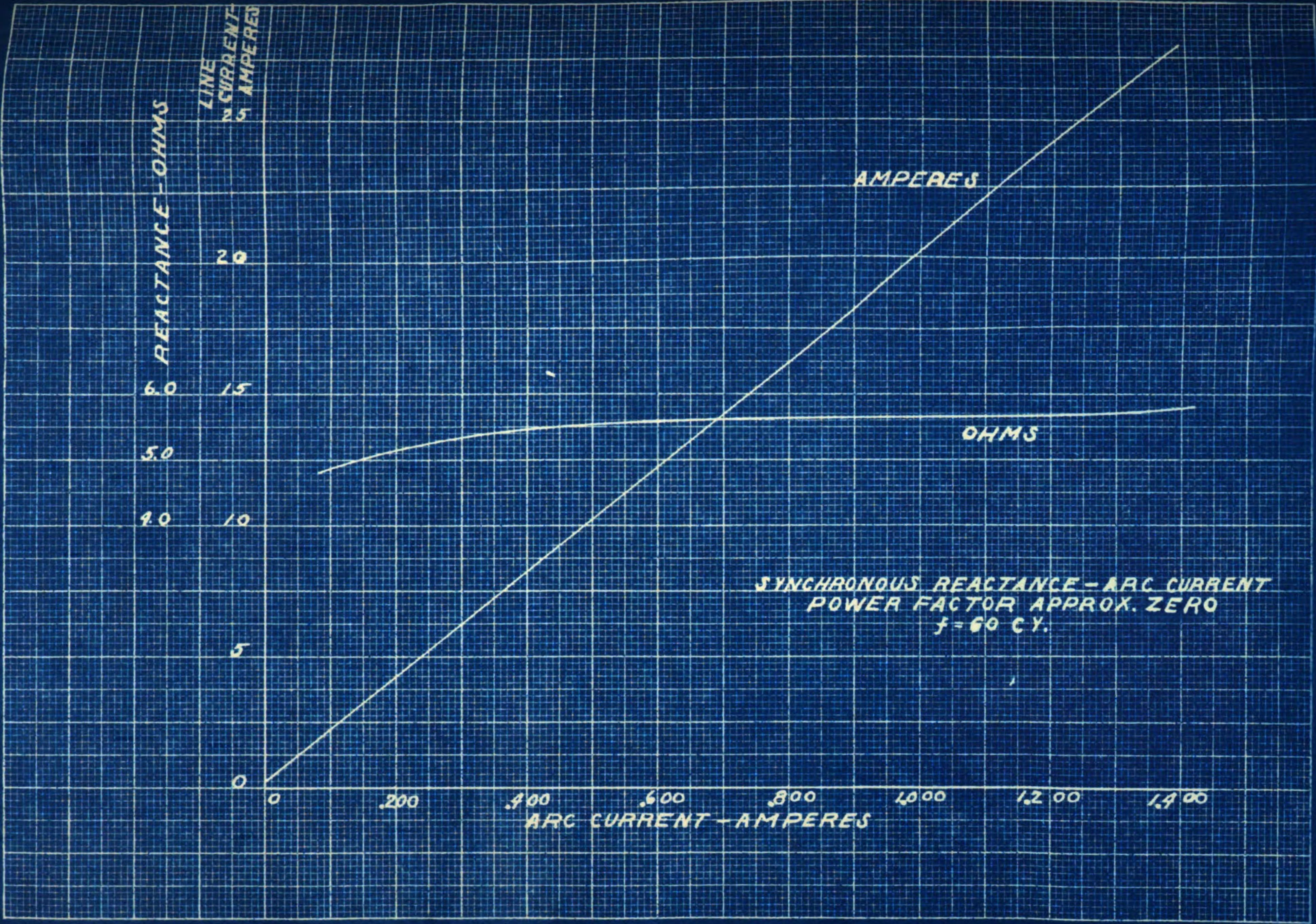
f, frequency, 60 cycles .

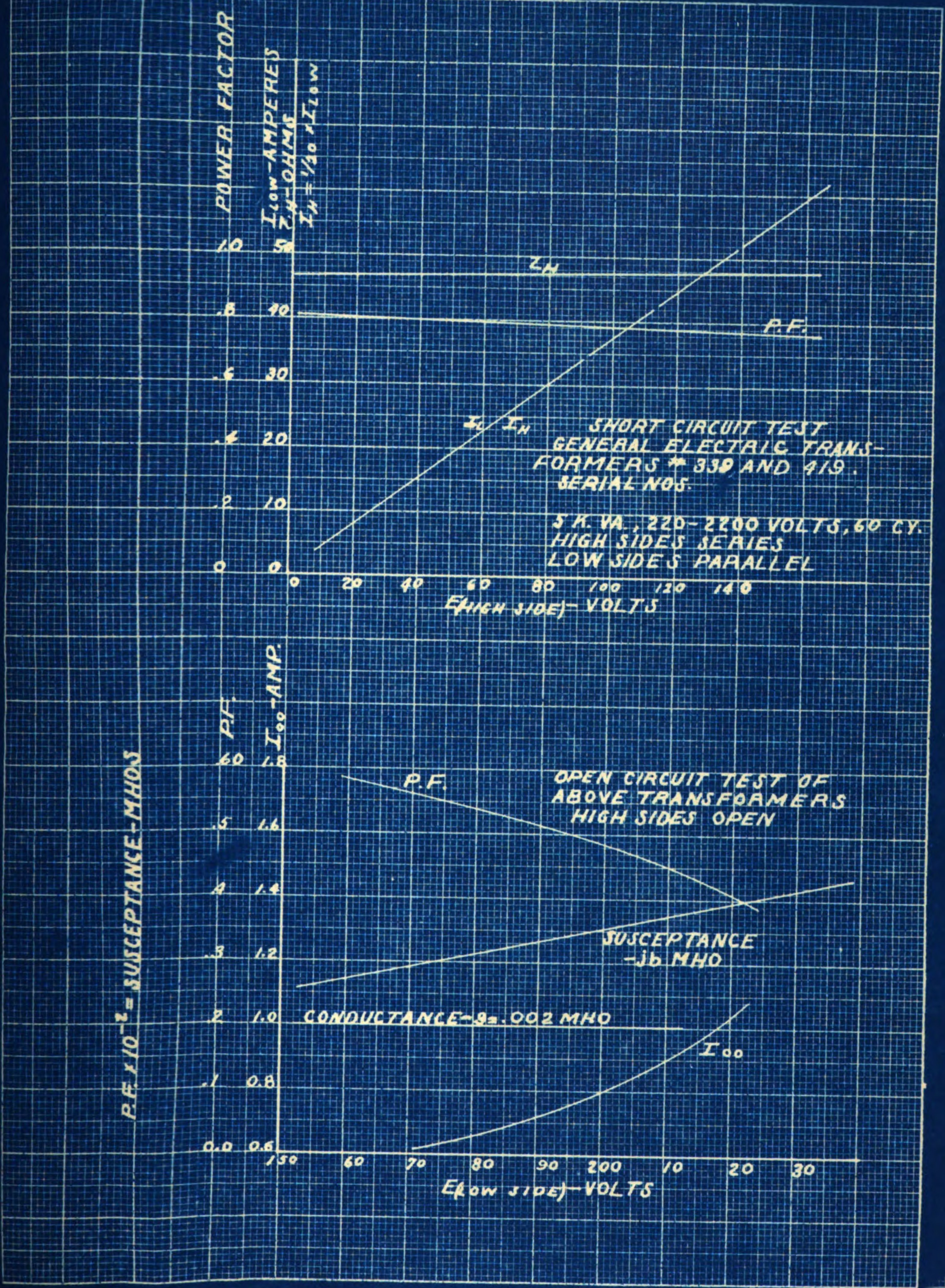
* E_{og} increased to 275 volts to hold arc.

COMPUTED DATA



REGULATION AND REACTANCE OF
GENERATOR - G B
220-240 VOLTS 7.5 K.V.A. 60 CY. 1800 R.P.M.


SYNCHRONOUS REACTANCE - ARC CURRENT
POWER FACTOR APPROX. ZERO
f = 60 CY.
REACTANCE - OHMS
LINE CURRENT - AMPERES
AMPERES
OHMS
6.0
5.0
4.0
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
ARC CURRENT - AMPERES


POWER FACTOR
I_{LOW}-AMPERES
Z_H-OHMS
$I_H = 1/10 \times I_{LOW}$
1.0
.8
.6
.4
.2
0
50
40
30
20
10
0
Z_H
P.F.
I_L I_H
SHORT CIRCUIT TEST
GENERAL ELECTRIC TRANS-
FORMERS # 339 AND 419.
SERIAL NOS.
5 K.VA., 220-2200 VOLTS, 60 CY.
HIGH SIDES SERIES
LOW SIDES PARALLEL
0
20
40
60
80
100
120
140
E(HIGH SIDE)-VOLTS
P.F. $\times 10^{-2}$ = SUSCEPTANCE-MHOS
P.F.
I_{00}-AMP.
.60
.5
.4
.3
.2
.1
0.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
P.F.
OPEN CIRCUIT TEST OF
ABOVE TRANSFORMERS
HIGH SIDES OPEN
SUSCEPTANCE
-jb MHO
CONDUCTANCE-g=.002 MHO
I_{00}
150
60
70
80
90
200
10
20
30
E(LOW SIDE)-VOLTS

COMPUTED TRANSFORMER DATA

Equivalent Circuit Data

$f = 60$ n

Low Sides Parallel

High Sides Series

Open Circuit Data:

$E = 220$v.

$I_{..} = 1.1$ amperes

$P.F. = .415$

$g = 0.002$ mho

$b = 0.004$ mho

Short Circuit Data:

$E = 122$ volts

$I = 45.4$ amperes

$P.F. = .78$ sme $= .625$

$Z = 47$ ohm $= (36.7 + j29.4)$

Reduced to Low Side

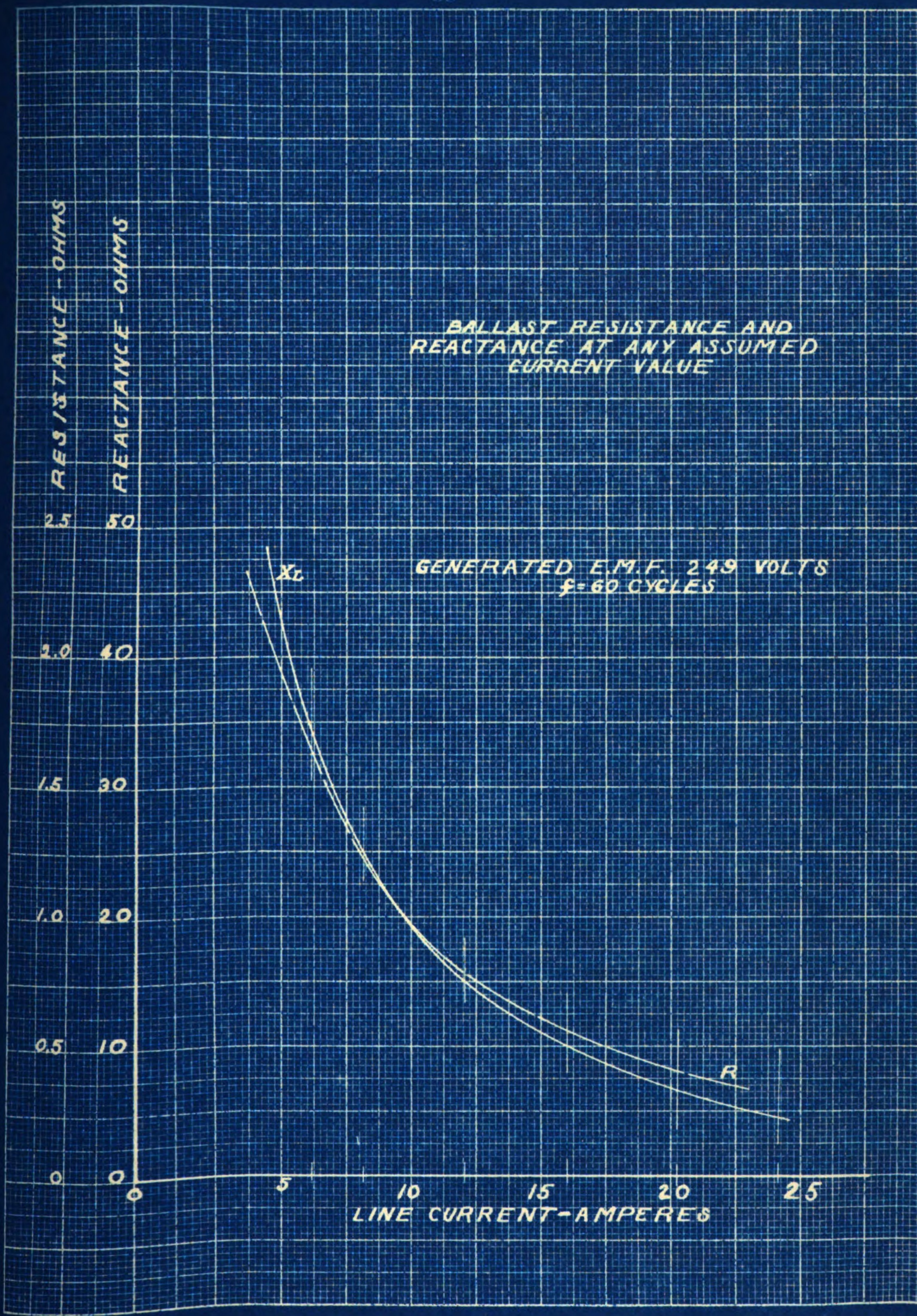
$Y = (0.002 - j0.004)$ mho

$Z = (0.0917 + j0.0734)$ ohms

Reduced to High Side

$Y = (0.000005 - j.00001)$ mho

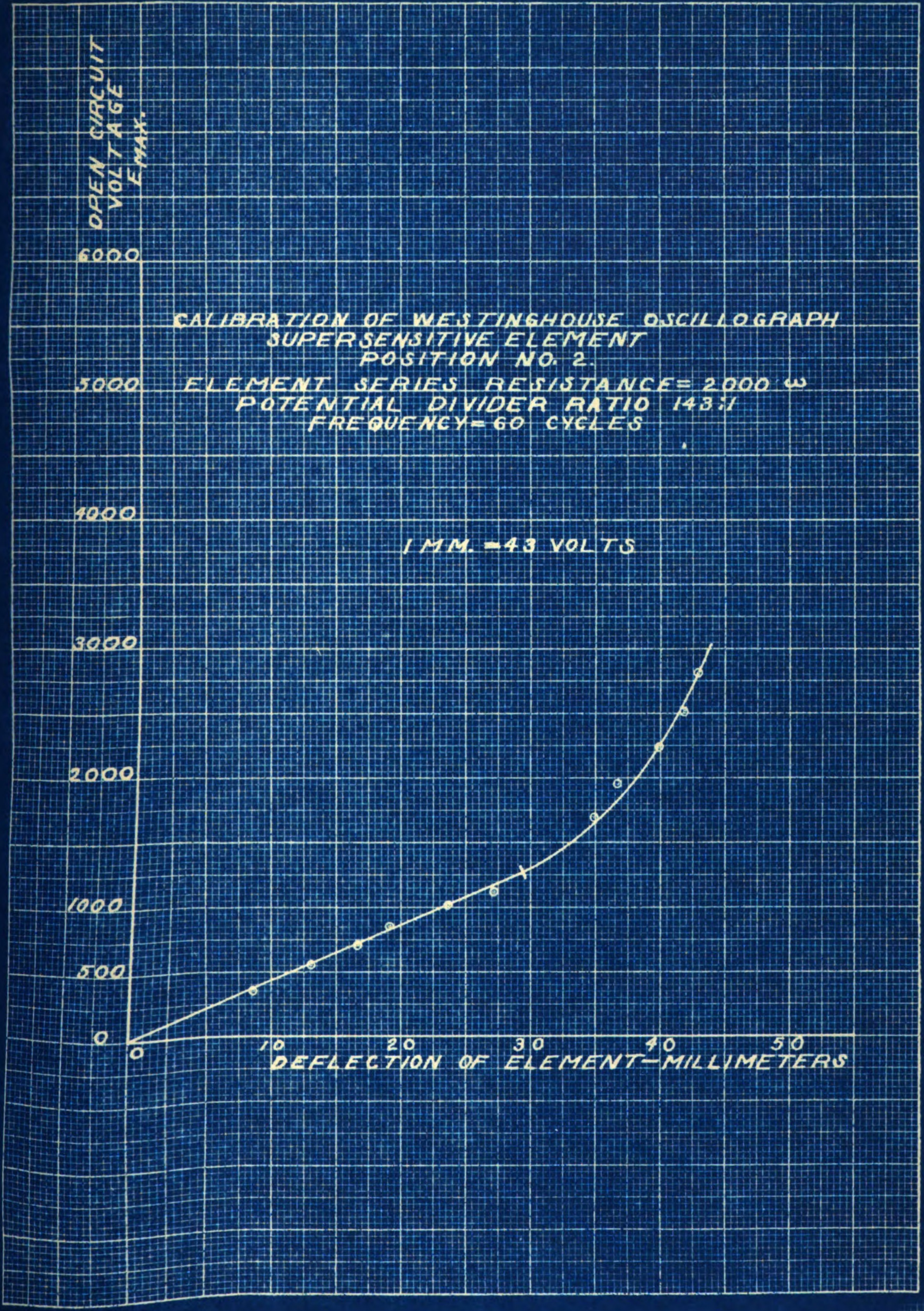
$Z = (36.7 + j29.4)$ ohms


BALLAST RESISTANCE AND
REACTANCE AT ANY ASSUMED
CURRENT VALUE
GENERATED E.M.F. 249 VOLTS
f=60 CYCLES
RESISTANCE - OHMS
REACTANCE - OHMS
2.5 50
2.0 40
1.5 30
1.0 20
0.5 10
0 0
X_L
R
0
5
10
15
20
25
LINE CURRENT-AMPERES

GENERATOR SYNCHRONOUS REACTANCE

AT CHOSEN CURRENT INTERVALS

Arc Current Milliamperes	300	400	600	800	1000	1200
Generator Current Amperes	6.2	8.2	12.2	16.2	20.2	24.2
Generator Synchronous Reactance Ohms	5.32	5.41	5.56	5.58	5.62	5.63
Synchronous Reactance Reduced to High Side Ohms	2,128	2,164	2,224	2,232	2,248	2,252


OPEN CIRCUIT VOLTAGE E MAX.
CALIBRATION OF WESTINGHOUSE OSCILLOGRAPH
SUPERSENSITIVE ELEMENT
POSITION NO. 2.
ELEMENT SERIES RESISTANCE = 2000 ω
POTENTIAL DIVIDER RATIO 143:1
FREQUENCY = 60 CYCLES
1 MM. = 43 VOLTS
6000
5000
4000
3000
2000
1000
500
0
0
10
20
30
40
50
DEFLECTION OF ELEMENT—MILLIMETERS

TOTAL EXTERNAL IMPEDANCE AND ADMITTANCE

Arc Current		r	+j	x	Total Z	Absolute Z
300 Ma.	Zr	36.7	+j	29.4		
	Z_L	376.8		0		
	Zg	220		2,128.0		
	Zc	660		15,520	1,293 +j 17,677	17,700/85°+
400 Ma.	Zr	36.7	+j	29.4		
	Z	376.8		0		
	Zg	220		2164.0		
	Zc	520		9200.0	1,153 +j 12,409	12,470/84°+
600 Ma.	Zr	36.7	+j	29.4		
	Z_L	376.8		0		
	Zg	220		2224		
	Zc	340		6000	973 +j 8,253.4	8,300/83°+
800 Ma.	Zr	36.7		29.4		
	Z_L	376.8		0		
	Zg	220		2232		
	Zc	232		4080	865.5 +j 6,341.4	6,400/82°+
1000 Ma.	Zr	36.7	+j	29.4		
	Z_L	376.8		0		
	Zg	220		2248.0		
	Zc	168		2720.0	801.5 +j 4,997.4	5,060/80°+
1200 Ma.	Zr	36.7	+j	29.4		
	Z_L	376.8		0		
	Zg	220		2252.0		
	Zc	120		1840.0	753.5 +j 4,121.4	4,120/79°+

Note:

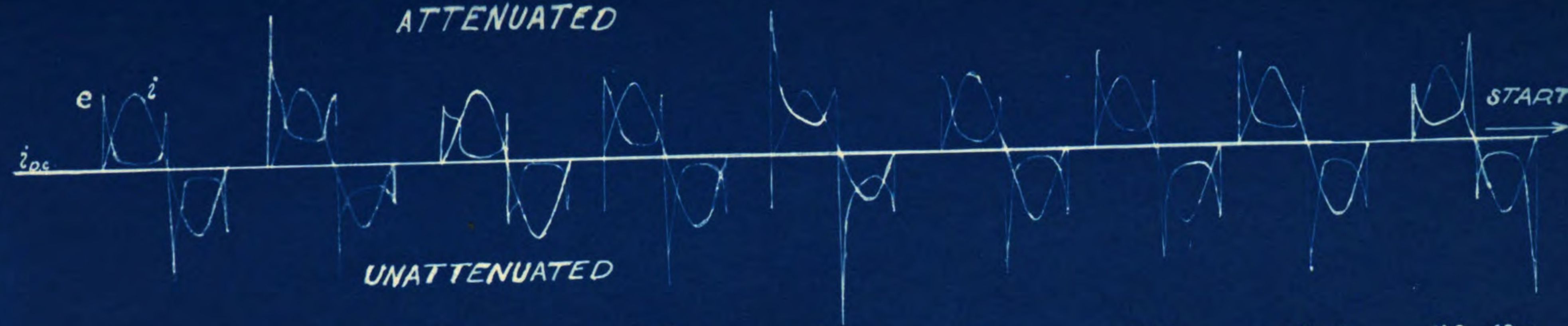
Zr = transformer impedance

Z_L = line impedance

Zg = generator synchronous impedance

Zc = reactor coil impedance

F = 60 cycles.



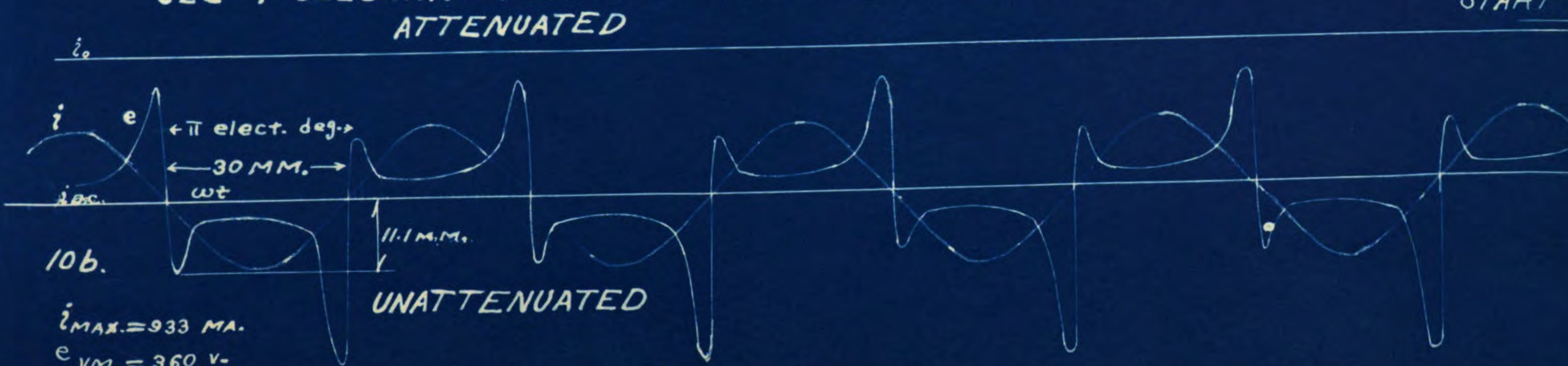
	NO. 1.	NO. 2.	NO. 3.	NO. 4.	NO. 5.	NO. 6.	NO. 7.	NO. 8.	NO. 10a.
i_{MAX}	=650 MA.	650	658	679	535	672	680	600	643
e_{VM}	=440 V.	440	240	244	324	280	130	340	500

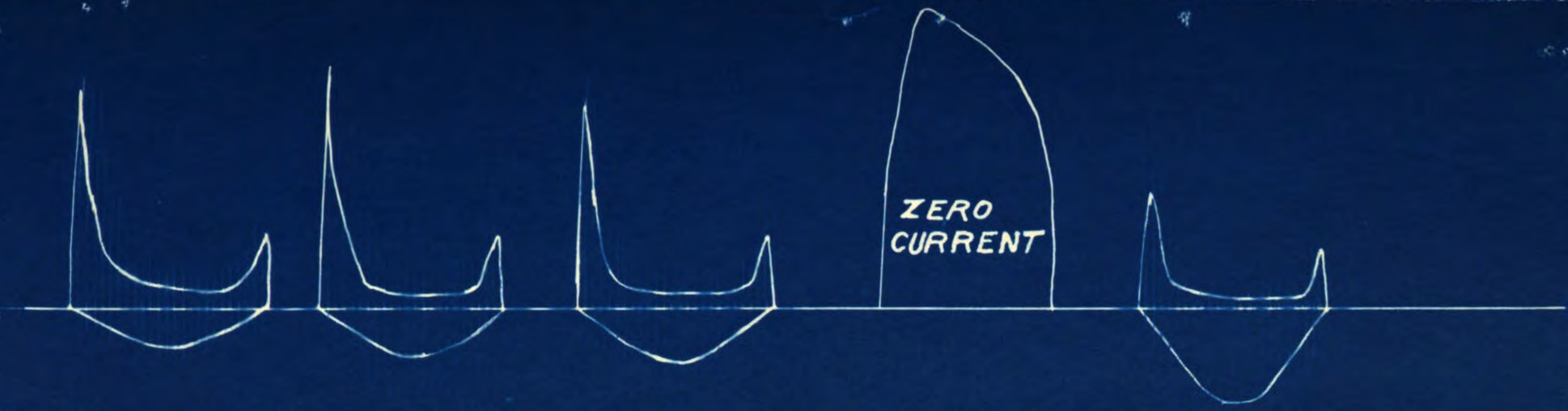
OSCILLOGRAM WAVES—TEST NO. I.

TOP — REPRESENTATIVE WAVES OF CORRESPONDING OSCILLOGRAMS NOS. 1-10a.

BOTTOM — OSCILLOGRAM NO. 10b TAKEN AT HIGHER FILM SPEED THAN NO. 10a.

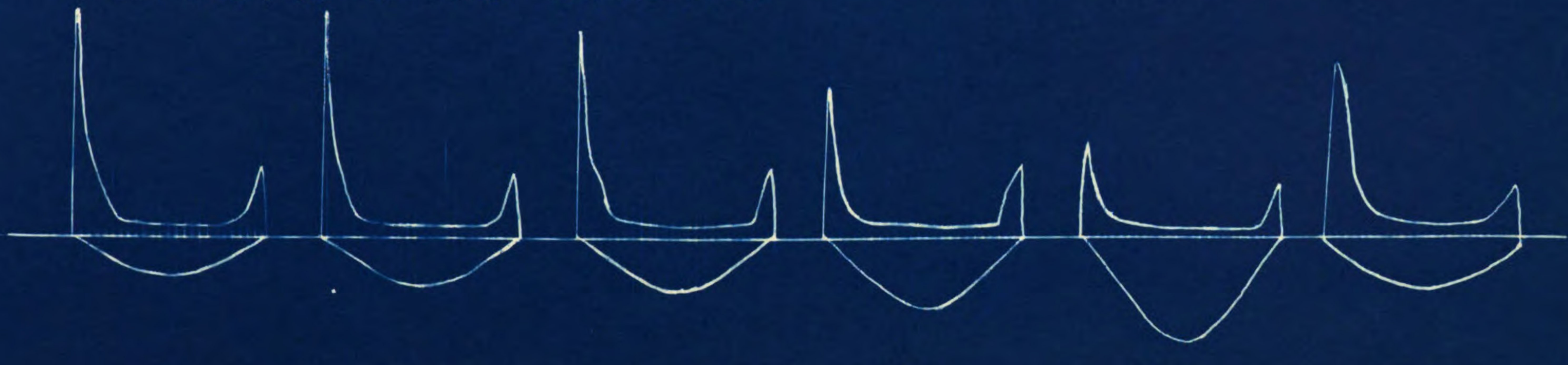
SEE FOLLOWING PAGE FOR OSCILLOGRAMS OF TEST NO. II.





NO. 10a NO. 9 NO. 8 NO. 7 NO. 6

FIGURES 1 TO 11 ARE REPRESENTATIVE WAVES FROM THE CORRESPONDING **NUMBERED** OSCILLOGRAMS OF TEST **NUMBER II**. FOR EXPLANATION, **SEE PROCEDURE**. SEE ALSO, **PRECEDING** PAGE FOR **NOS.** 1-10 **OF** TEST NUMBER **I**.



NO. 1 NO. 2 NO. 3 NO. 4 NO. 5 NO. 11

PLANIMETER OSCILLOGRAM DATA - Test No. 1

Oscillogram No.	1	2	3	4	5	6	7	8	10a
Area Sq. in.	0.064	0.065	0.050	0.063	0.105	0.062	0.0081	0.105	0.087
Base - b inches	.38	.38	.40	.40	.36	.42	.40	.40	.39
Ave. Ord. inches	.1684	.171	.125	.157	.269	.1478	.2025	.2625	.2231
Effective Ordinate	.2325	.236	.1725	.217	.372	.204	.285	.362	.308
Effective Volts	249.5	253.5	185	233	399	306	306	388	330

Volts per inch ordinate = 1072 - from Osc. calibration.

Average height x 1.38 = effective ordinate (See data from Test 2, page 47.)

CIRCUIT IMPEDANCE - Test No. 2

Position	2		3		4		6		7	
Ave. Gen. I	6.25		7.84		8.25		10.38		12.26	
Syn. Rect. G.	5.22		5.38		5.41		5.48		5.55	
All Impedances Reduced to High Side										
	r	jx	r	jx	r	jx	r	jx	r	jx
Generator	220	2,090	220	2,150	220	2,165	220	2,195	220	2,220
Line Reactors	695	14,100	596	11,100	431	8,400	260	5,750	167	2,650
Transformer and Line	413.5	29.4	413.5	29.4	413.5	29.4	413.5	29.4	413.5	29.4
Z total	1,328 +j	16,219	1,229 +j	13,279	1,064 +j	10,594	893 +j	7,974	800.5	4,899
Z absolute	16,300	/89°+	13,320	/89°+	10,630	/89°+	9,030	/89°+	4/970	/88°+
Effective Arc Resistance (Computed). See page 47										
Arc Length										
4 mm.	1100		785		667		438		210	
6 mm.	1330		922		950		Arc went out		99	
8 mm.	* 1120		- - - - -		Voltage Element Failed		- - - - -		- - - - -	

* Generated e.m.f. increased 11.2 per cent to hold arc.

PLANIMETER DATA - Test No. 2

Osc. No.	1	2	3	4	5	6	8	9	10	11
Voltage wave										
Area Sq. in.	.246	.225	.215	.206	.161	.201	.284	.304	.339	.299
Ave. Ord.	.271	.264	.227	.167	.205	.180	.172	.165	.0657	.183
Base - b	1.2	1.25	1.25	1.25	1.25	1.2	1.25	1.15	1.25	1.25
Current wave										
Area Sq. in.	.185	.247	.250	.340	.485	.587	.248	.206	.179	.274
I Max. inches	.25	.316	.34	.44	.66	.60	.333	.30	.25	.33
Ave. Ord.	.153	.197	.200	.272	.386	.489	.198	.179	.143	.219
Ave. Max.	.612	.624	.589	.617	.585	.815	.595	.596	.572	.663
Ave. $\frac{e}{i}$	1.34	.914	.86	.606	.1702	.342	1.142	1.472	1.893	.835

COMPUTED CURRENT DATA

Oscillogram Number	1	2	3	4	5	6	8	9	10	11	Units
Average Current	.153	.194	.197	.273	.389	.370	.199	.172	.145	.217	Inches
Effective Current	.170	.217	.221	.314	.441	.415	.225	.199	.166	.237	Inches
Maximum Current	.25	.316	.34	.44	.66	.60	.33	.30	.25	.33	Inches
Meter rdg. Eff. amperes	.296	.358	.402	.535	.785	.780	.408	.356	.290	.341	Amp./cycle
Eff./Ave. Current	1.11	1.12	1.12	1.15	1.14	1.12	1.13	1.16	1.14	1.09	Form factor
Maximum/Effective	1.47	1.45	1.54	1.40	1.49	1.44	1.47	1.51	1.51	1.39	Ratio
Average/Maximum	.612	.608	.580	.620	.590	.616	.604	.573	.580	.657	I ave./I max.
Plan. Ave./Computed Ave.	1.0	1.01	1.01	.995	.995	1.32	.995	1.04	.986	1.06	Ratio of accuracy
Eff. Comp./Ave. plan	1.11	1.10	1.10	1.15	1.14	85	1.13	1.11	1.16	1.08	Form * factor

Average ≠ 1.13

* Indicates accuracy of planimeter determinations

*COMPUTED VOLTAGE DATA

Oscillogram Number	1	2	3	4	5	6	8	9	10	11	Unit
Average Ordinate	.194	.159	.152	.141	.102	.153	.207	.196	.252	.197	Inches
Effective Ordinate	.301	.257	.245	.214	.151	.707	.355	.30	.354	.348	Inches
Effective** / Average	1.55	1.61	1.61	1.52	1.48	.462	1.72	1.53	1.41	1.72	Form factor
Plan. Ave. / Comp. Ave.	1.06	1.13	1.13	1.17	.65	1.09	1.10	1.35	1.08	.929	Ratio of accuracy
Eff. Comp. Ord. / Ave. Plan. Ord.	1.46	1.43	1.42	1.3	2.3	.423	1.56	1.135	1.35	1.90	
Effective Volts per cycle	329	281	268	234	165	77.2	388	328	387	380	Volts
Eff. amperes (Meter reading)	.296	.358	.402	.535	.785	.780	.408	.356	.290	.341	Amperes
Effective Power	111	100.8	107.8	125	129.5	60.1	158	117	112	130	Watts
Effective Resistance	1.110	785	667		210	990	950	922	1,330	1,120	Ohms

* The term "computed" is understood to mean the data obtained from ordinate analysis.

** Average of readings gives 1.58.

PROCEDURE FOR PLOTTING CHARACTERISTICS

1. Plot volt ampere characteristics from data of Test No. 1.
2. From curves of (1) determine voltage at equal increments of arc current.
3. From data of (2) compute impedance at chosen current intervals.
4. From (2) and (3) plot:

   A. Arc impedance - arc length.

   B. Arc impedance - arc current.

   C. Arc voltage - arc length.

   D. Arc voltage - reciprocal of arc current.
5. From (4-D) obtain E_o and C' for each arc length.
6. From (5) plot E_o - arc length to obtain g and α.
7. From (5) plot C' - arc length to obtain r and δ.
8. From (5, 6, and 7) write the equation for the arc characteristics.
9. From generator and transformer data compute equivalent circuits reduced to the high side of the system.
10. From the coil data determine resistance and reactance at various positions of test.
11. From (10) plot reactance and resistance of coils against corresponding line currents.
12. Plot line current - arc current.
13. From (11) and (12) plot arc current against values of reactor impedance (X_L and R) as in (11).

14.

15.

16

17

14. From (13) determine r and X_L of coils at values of arc current corresponding to those chosen in (2).

15. From data on line determine line constants.

16. From (9, 14, and 15) determine the resultant line impedance at chosen values of arc current.

17. From (4-B and 16) record and plot arc impedance values against corresponding line impedance values.

18. Compute power consumed by arc from (2) and plot against total external impedance.

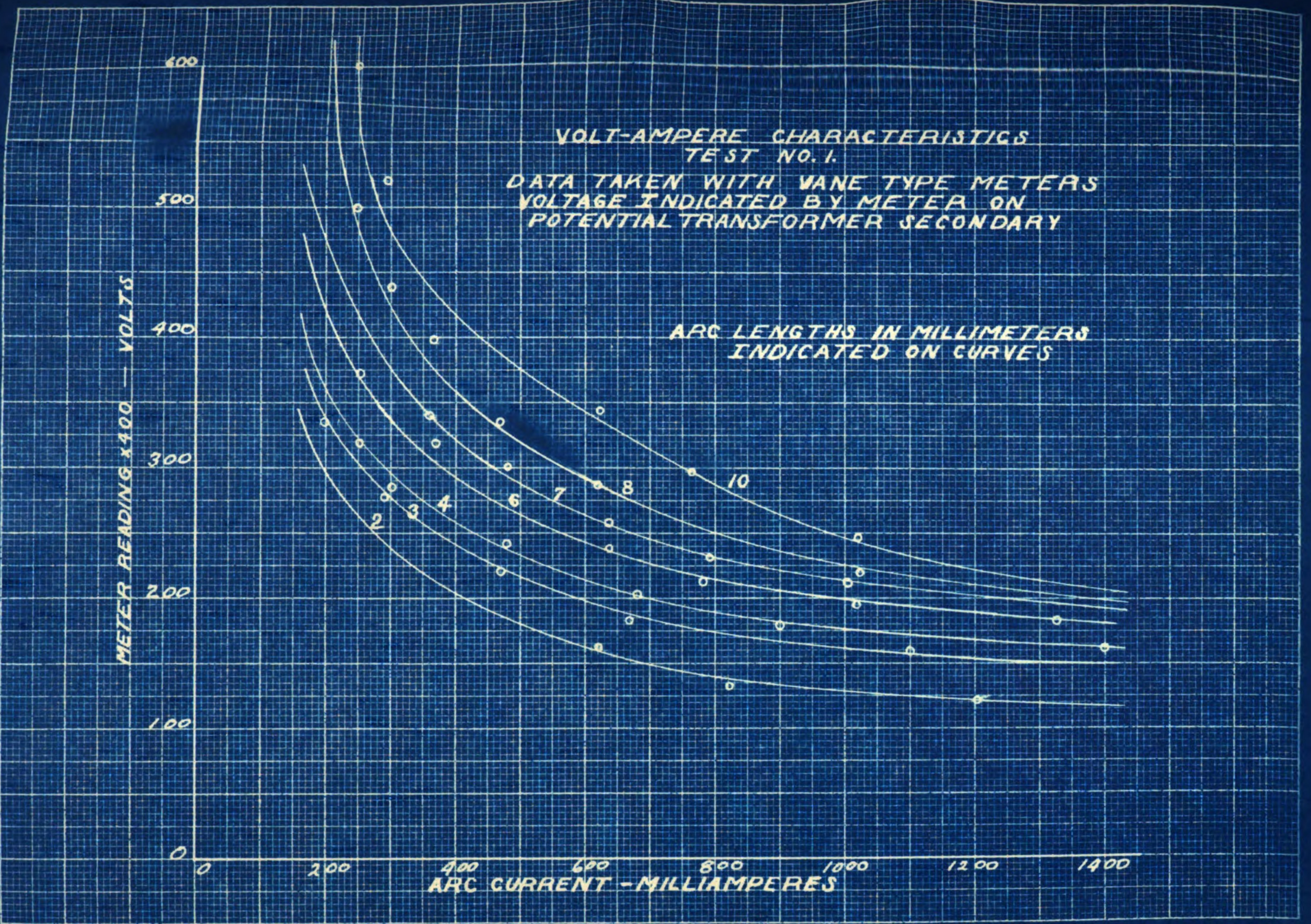
19. Plot power consumed by arc against the resistance component of the external line impedance.

20. From the oscillogram data of Test No. 2, plot the volt-ampere characteristics at the 4 mm. arc length.

21. On same sheet plot volts - reciprocal of arc current.

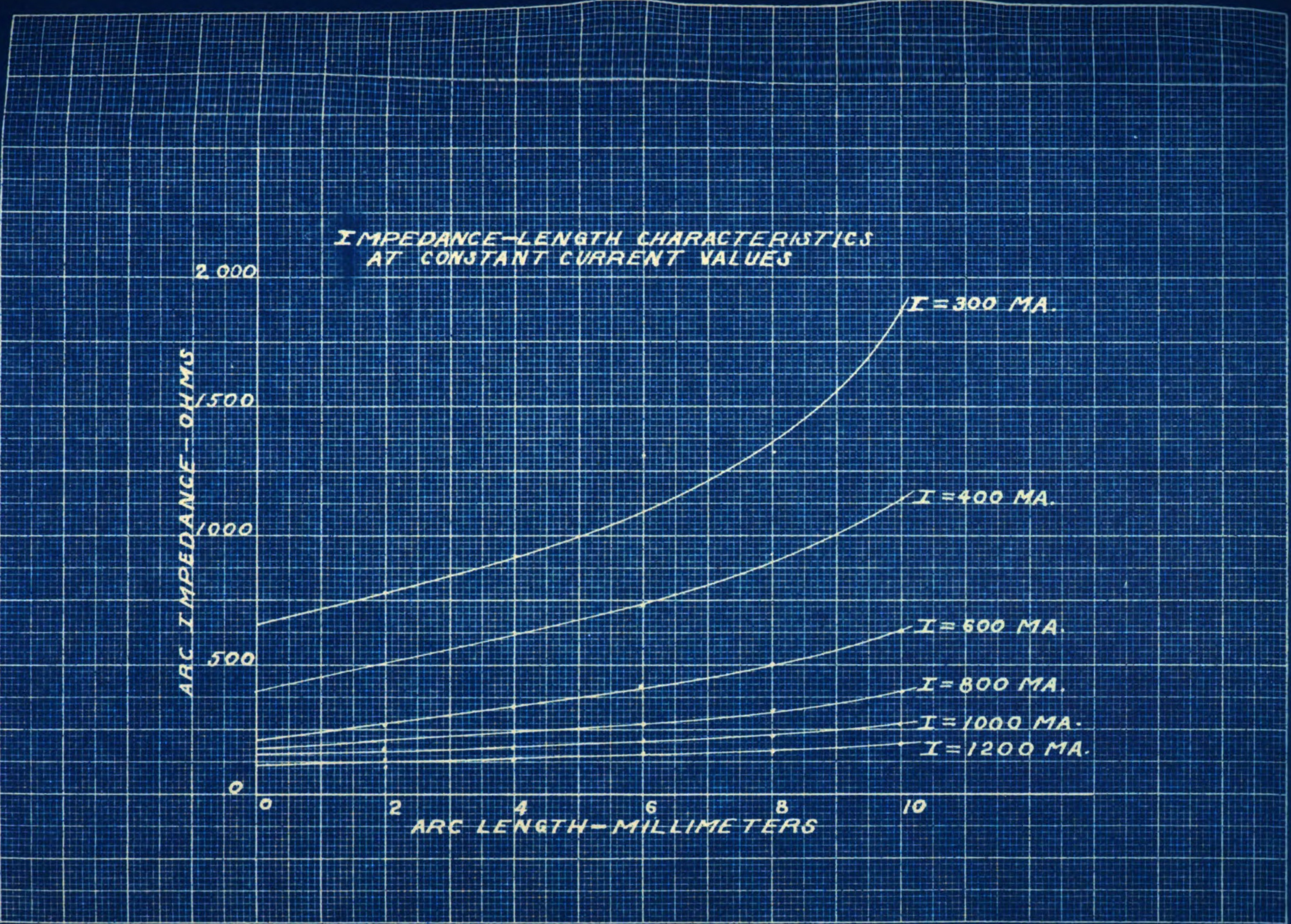
22. Plot arc resistance against corresponding circuit impedance at the 4 mm. arc length.

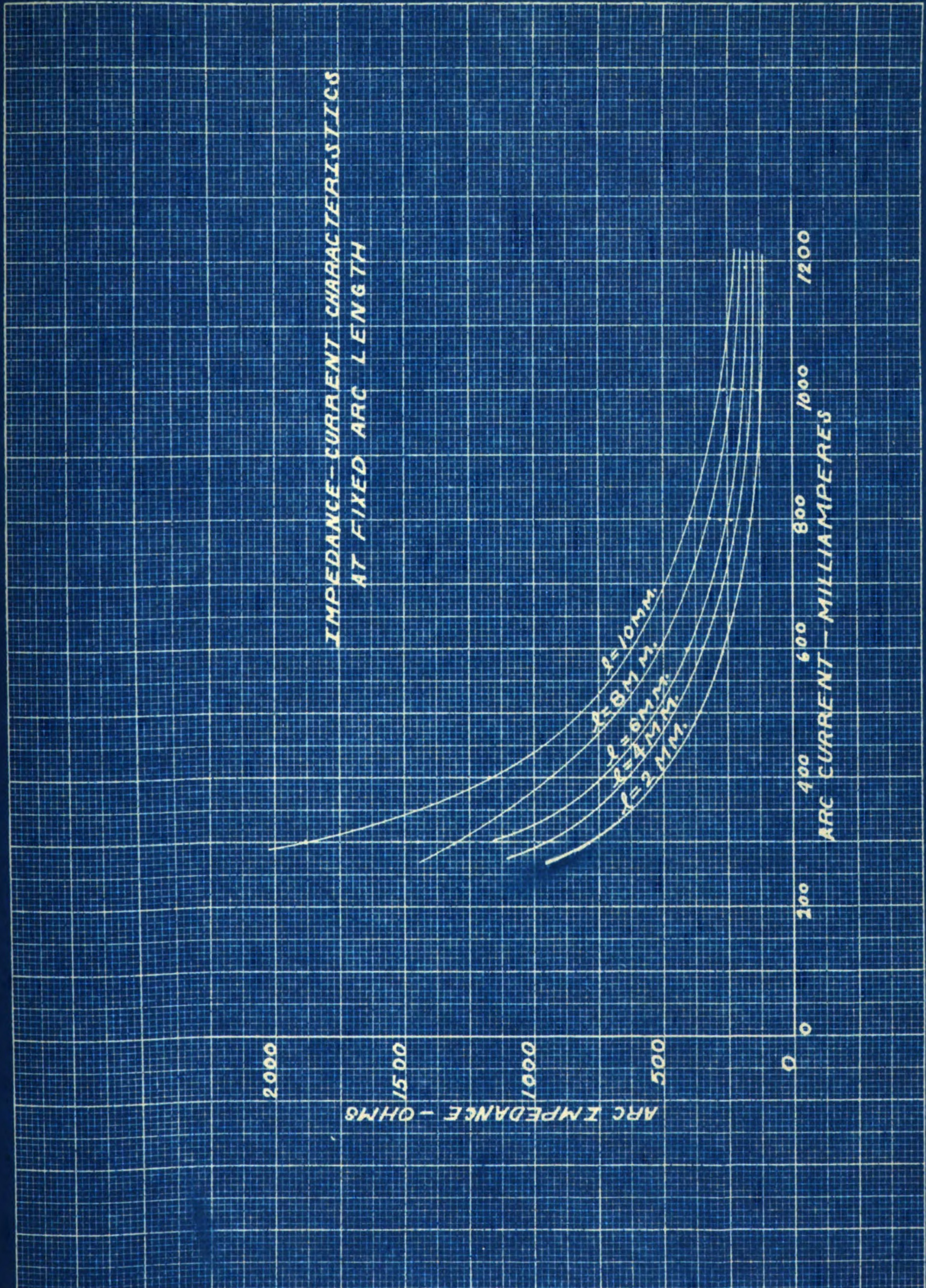
23. The plot of power against absolute line impedance is made on the same sheet.

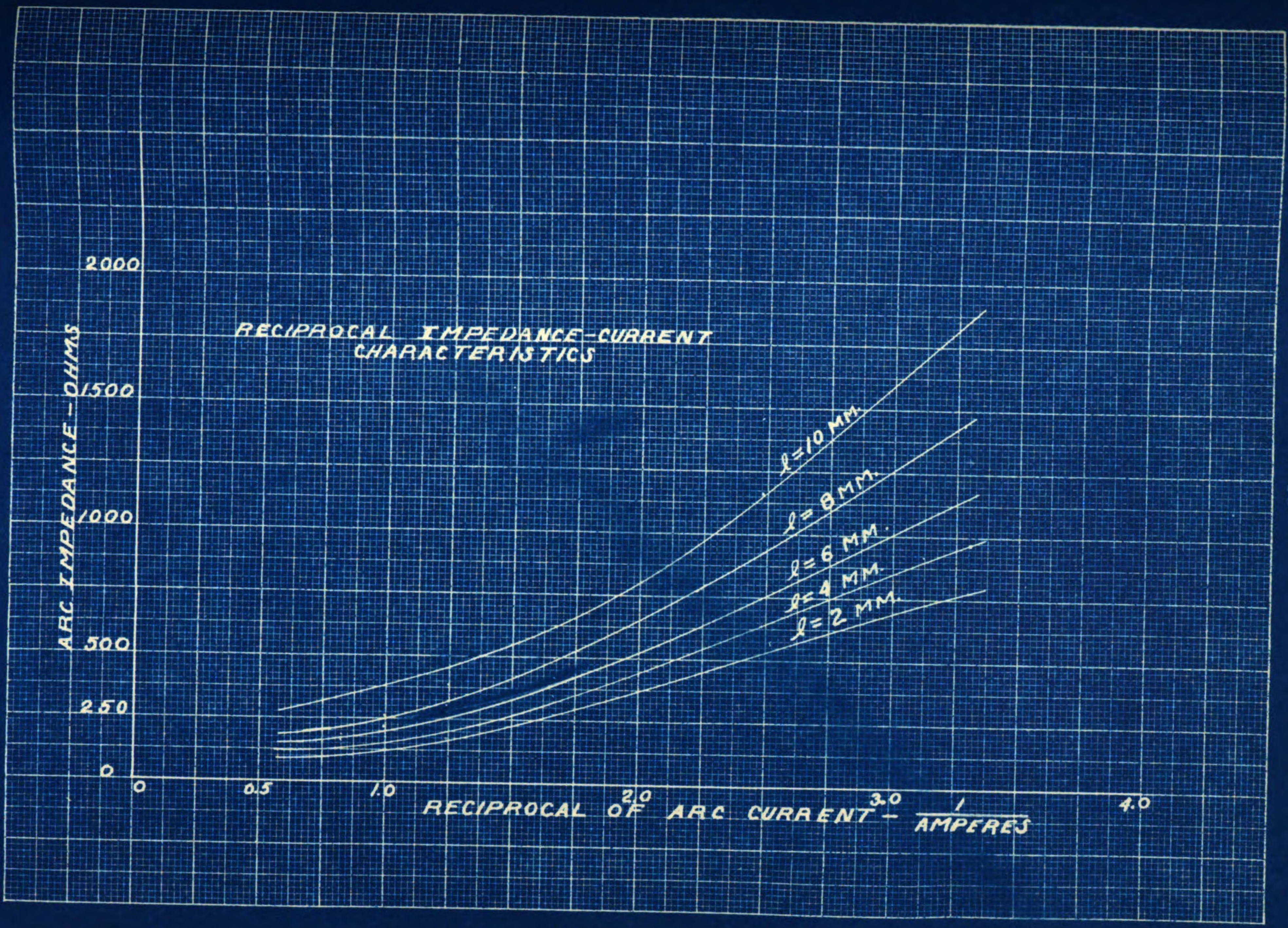

VOLT-AMPERE CHARACTERISTICS
TEST NO. 1.
DATA TAKEN WITH VANE TYPE METERS
VOLTAGE INDICATED BY METER ON
POTENTIAL TRANSFORMER SECONDARY
ARC LENGTHS IN MILLIMETERS
INDICATED ON CURVES
2
3
4
6
7
8
10
METER READING x 400 — VOLTS
0
100
200
300
400
500
600
ARC CURRENT - MILLIAMPERES
0
200
400
600
800
1000
1200
1400

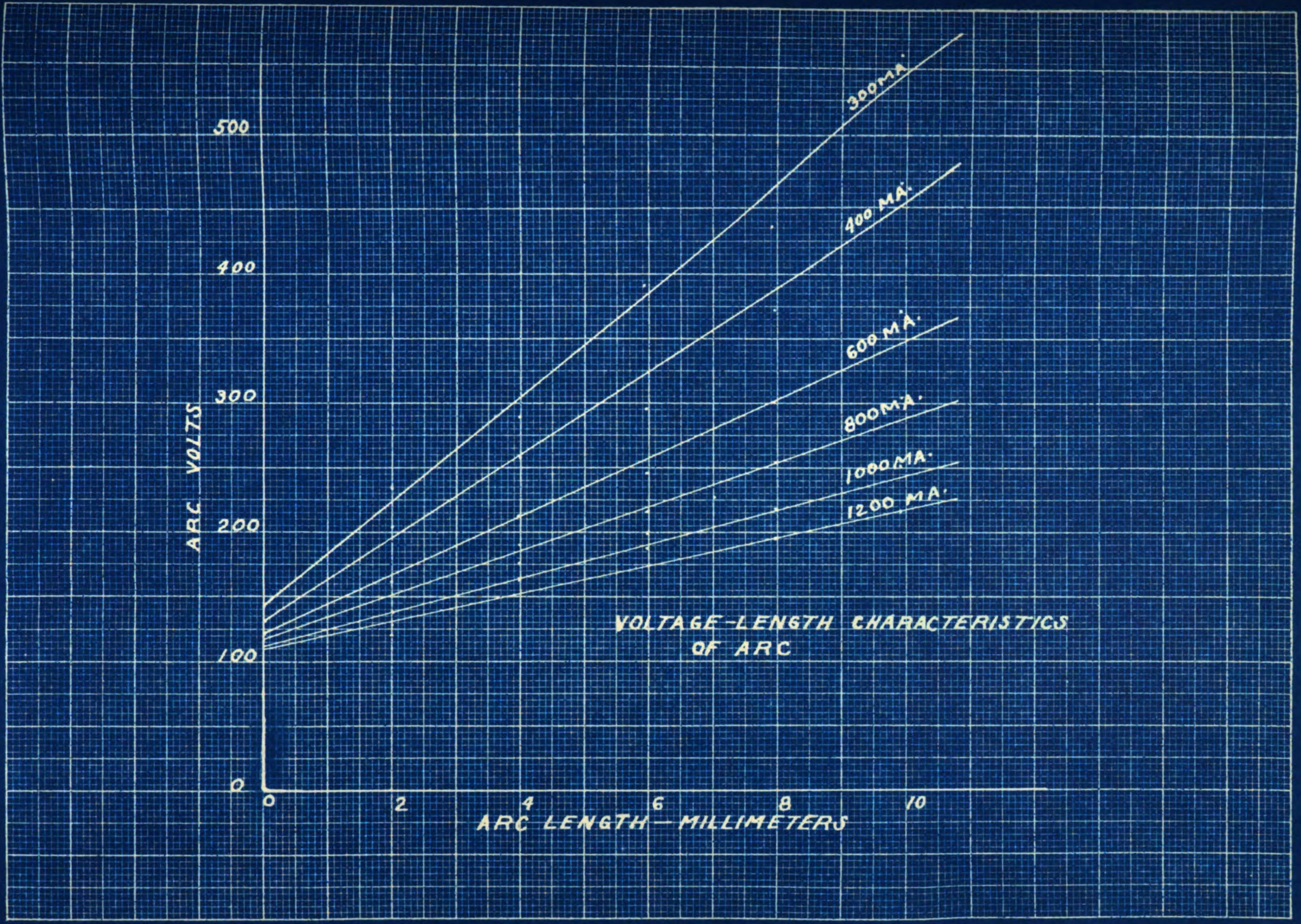
DATA TAKEN FROM V-A CHARACTERISTICS, Test No. 1

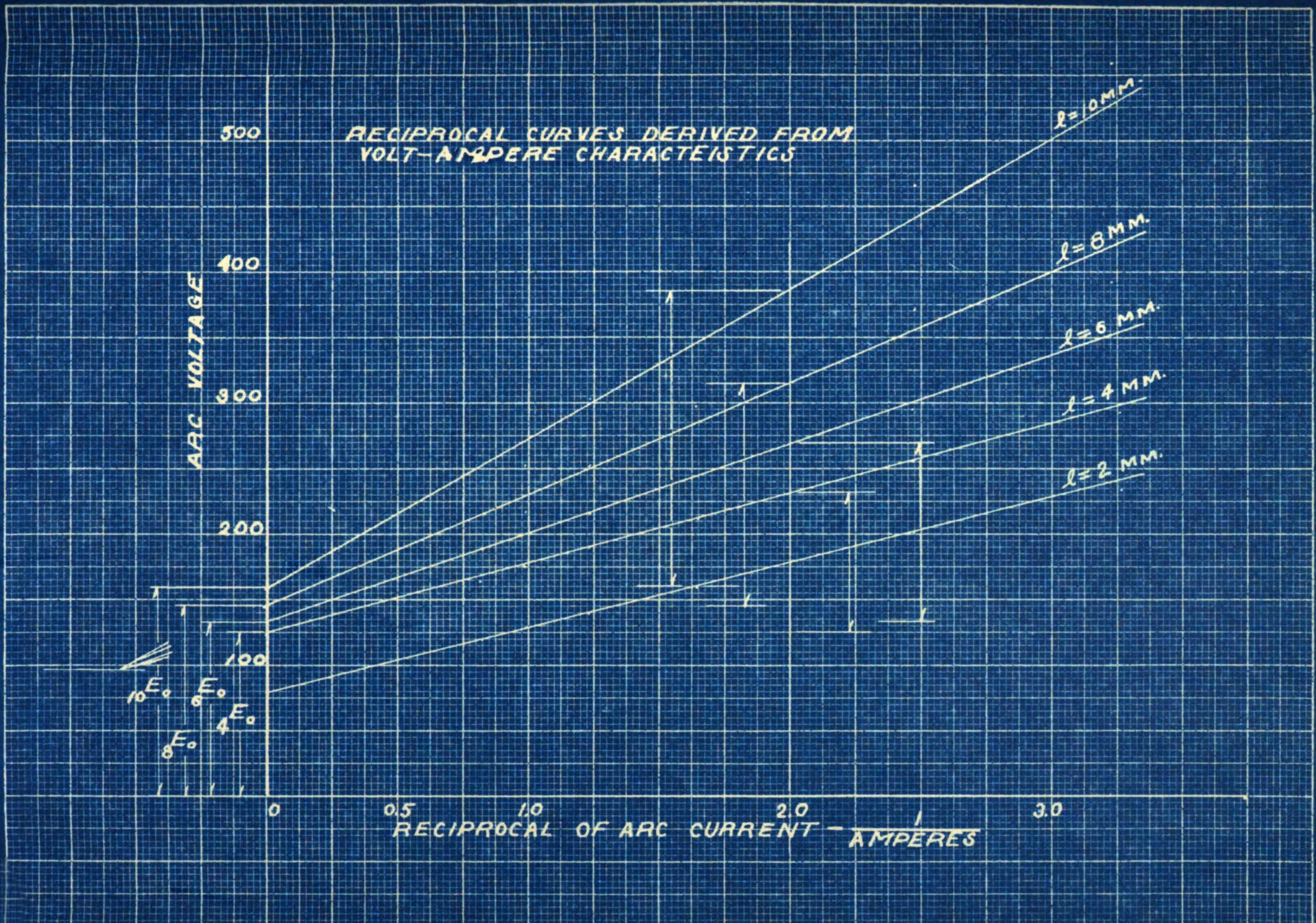
φ	I M.A.	Unit		2	3	4	5	6	7	8	10	External Impedance
		E	Arc volts	237	318	293	355	395	405	440	566	
3.3	300	Z	Arc ohms.	790	1060	976	1180	1320	1350	1460	1890	17,700
		P	Arc watts	71.1	95.4	87.8	106	118	121	132	170	
		E	Arc volts	205	258	258	305	298	325	375	470	
2.5	400	Z	Arc ohms.	512	645	645	762	745	812	937	1.175	12,470
		P	Arc watts	82	103	103	122	119	130	150	188	
		E	Arc volts	162	203	215	248	248	268	302	375	
1.25	600	Z	Arc ohms.	270	338	341	413	413	446	503	625	8,300
		P	Arc watts	97.1	122	129	148	148	161	181	225	
		E	Arc volts	139	175	192	214	218	236	255	307	
1.66	800	Z	Arc ohms.	173	219	240	267	272	295	319	384	6,400
		P	Arc watts	111	140	154	171	174	189	204	247	
		E	Arc volts	128	163	176	190	201	217	220	255	
1.0	1000	Z	Arc ohms.	128	163	176	190	201	217	220	255	5,060
		P	Arc watts	128	163	176	190	201	217	220	255	
		E	Arc volts	120	160	165	173	190	205	195	218	
.833	1200	Z	Arc ohms.	100	133	137	144	158	171	162	182	4,190
		P	Arc watts	144	192	198	208	228	246	234	262	


IMPEDANCE—LENGTH CHARACTERISTICS
AT CONSTANT CURRENT VALUES
2000
1500
1000
500
0
ARC IMPEDANCE—OHMS
0
2
4
6
8
10
ARC LENGTH—MILLIMETERS
I=300 MA.
I=400 MA.
I=600 MA.
I=800 MA.
I=1000 MA.
I=1200 MA.


IMPEDANCE-CURRENT CHARACTERISTICS
AT FIXED ARC LENGTH
ℓ=10MM.
ℓ=8M M.
ℓ=6MM.
ℓ=4MM.
ℓ=2 MM.
ARC IMPEDANCE - OHMS
0
500
1000
1500
2000
ARC CURRENT—MILLIAMPERES
0
200
400
600
800
1000
1200


RECIPROCAL IMPEDANCE-CURRENT CHARACTERISTICS
ARC IMPEDANCE - OHMS
2000
1500
1000
500
250
0
0
0.5
1.0
2.0
3.0
4.0
RECIPROCAL OF ARC CURRENT - 1/AMPERES
l=10 MM.
l=8 MM.
l=6 MM.
l=4 MM.
l=2 MM.


300 MA.
400 MA.
600 MA.
800 MA.
1000 MA.
1200 MA.
500
400
300
200
100
0
ARC VOLTS
0
2
4
6
8
10
ARC LENGTH — MILLIMETERS
VOLTAGE-LENGTH CHARACTERISTICS
OF ARC


RECIPROCAL CURVES DERIVED FROM
VOLT-AMPERE CHARACTEISTICS
ARC VOLTAGE
500
400
300
200
100
l=10 MM.
l=8 MM.
l=6 MM.
l=4 MM.
l=2 MM.
$_{10}E_0$
$_8E_0$
$_6E_0$
$_4E_0$
0
0.5
1.0
2.0
3.0
RECIPROCAL OF ARC CURRENT - 1/AMPERES

DATA FOR WRITING CHARACTERISTIC EQUATIONS

General form of equation:

$$E = g + \alpha 1 + \frac{\gamma + \delta 1}{I}$$

Determination of constants:

$C = \frac{\Delta E}{\Delta (1/I)}$	1	$E_o = (g + \alpha 1)$
54	4	125
63.5	6	133
86.5	8	144
113.5	10	158

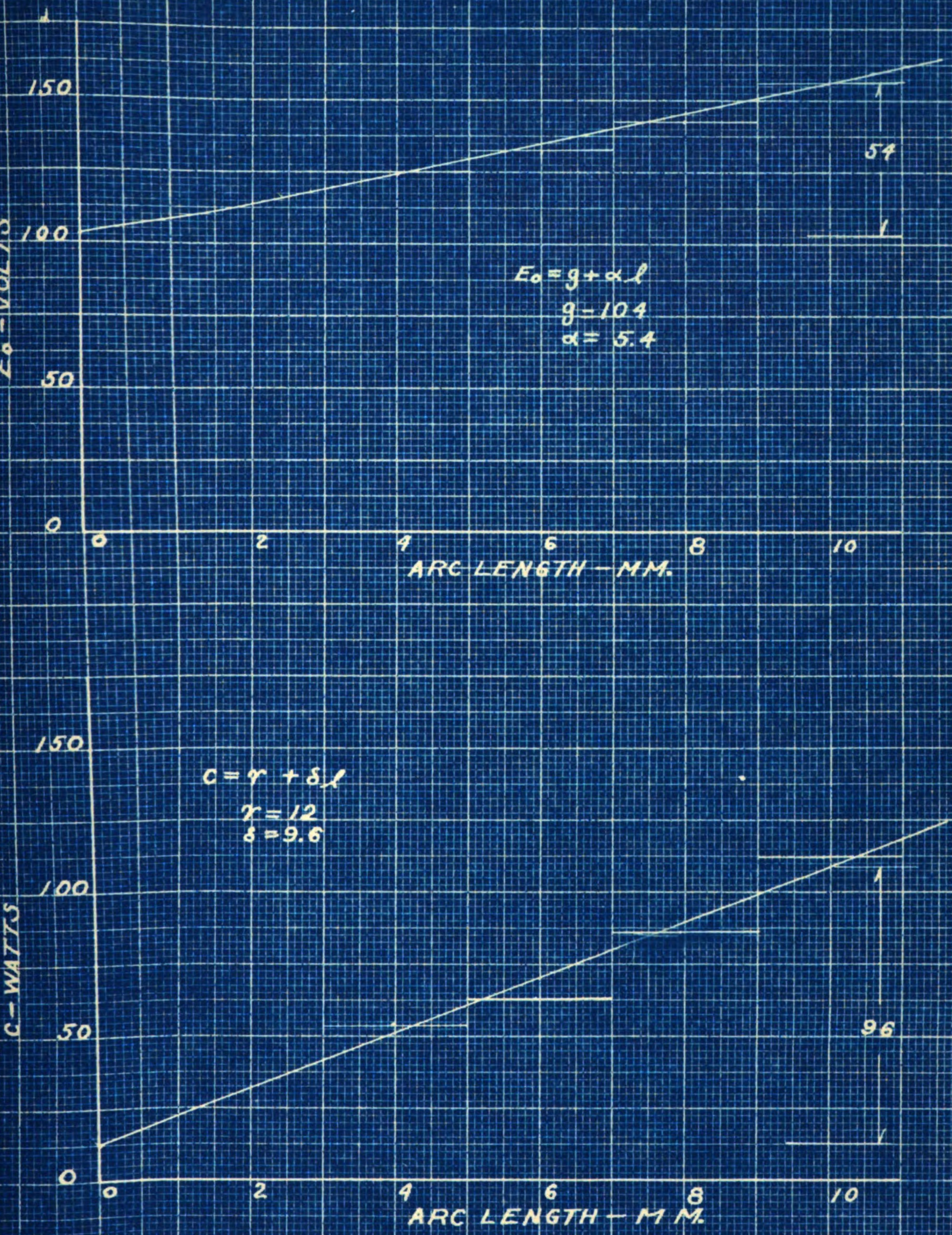
$$E = E_o + C/I$$

1	E_o	+ C/I
4	125	54/I
6	133	63,5/I
8	144	86.5/I
10	158	113.5/I

where

$$E_o = g + \alpha 1$$

and $$C = \gamma + \delta 1$$



DETERMINATION OF CONSTANTS OF EQUATION OF VOLT-AMPERE CHARACTERISTICS

CONSTANTS OF DIRECT CURRENT ARC CHARACTERISTICS FOR COPPER ELECTRODES*

$g = 21.38$ Arc voltage for $I = 1$

$\alpha = 3.03$ $\ell = 1$

$\delta = 15.24$ $e = 50.3$ V.

$\gamma = 10.96$

Electrodes 16 mm. diameter, flat tips, parallel surfaces.

MY VALUES FOR THE ALTERNATING CURRENT ARC FOR COPPER ELECTRODES

$g = 104$

$\alpha = 5.4$

$\gamma = 12$

δ 9.6

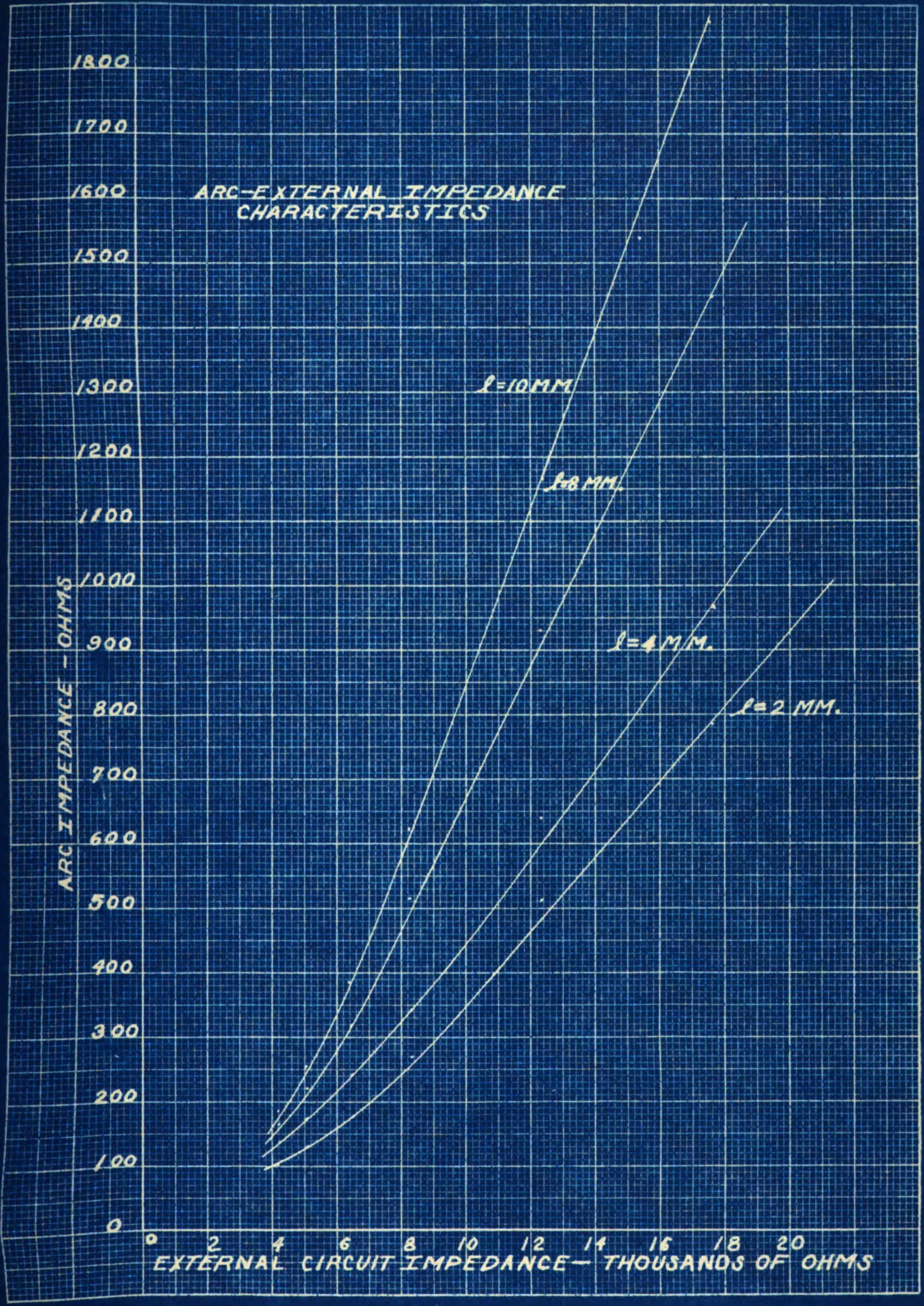
Electrodes 0.201 inches diameter (5.10 mm.), slightly rounded faces.

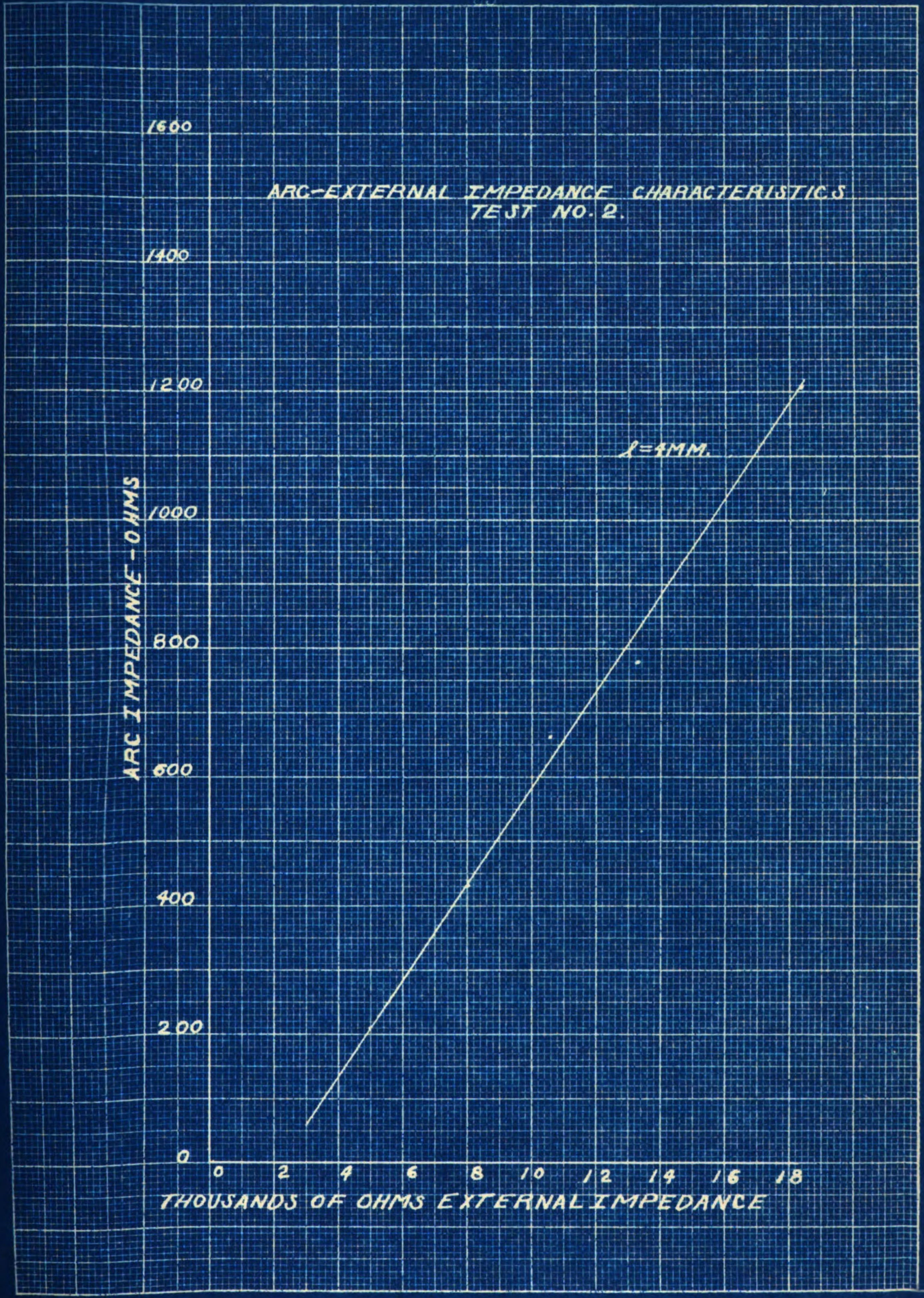
The equation is

$$E = 104 + 5.4\ell \quad \frac{12 + 9.6\ell}{I} \text{ volts.}$$

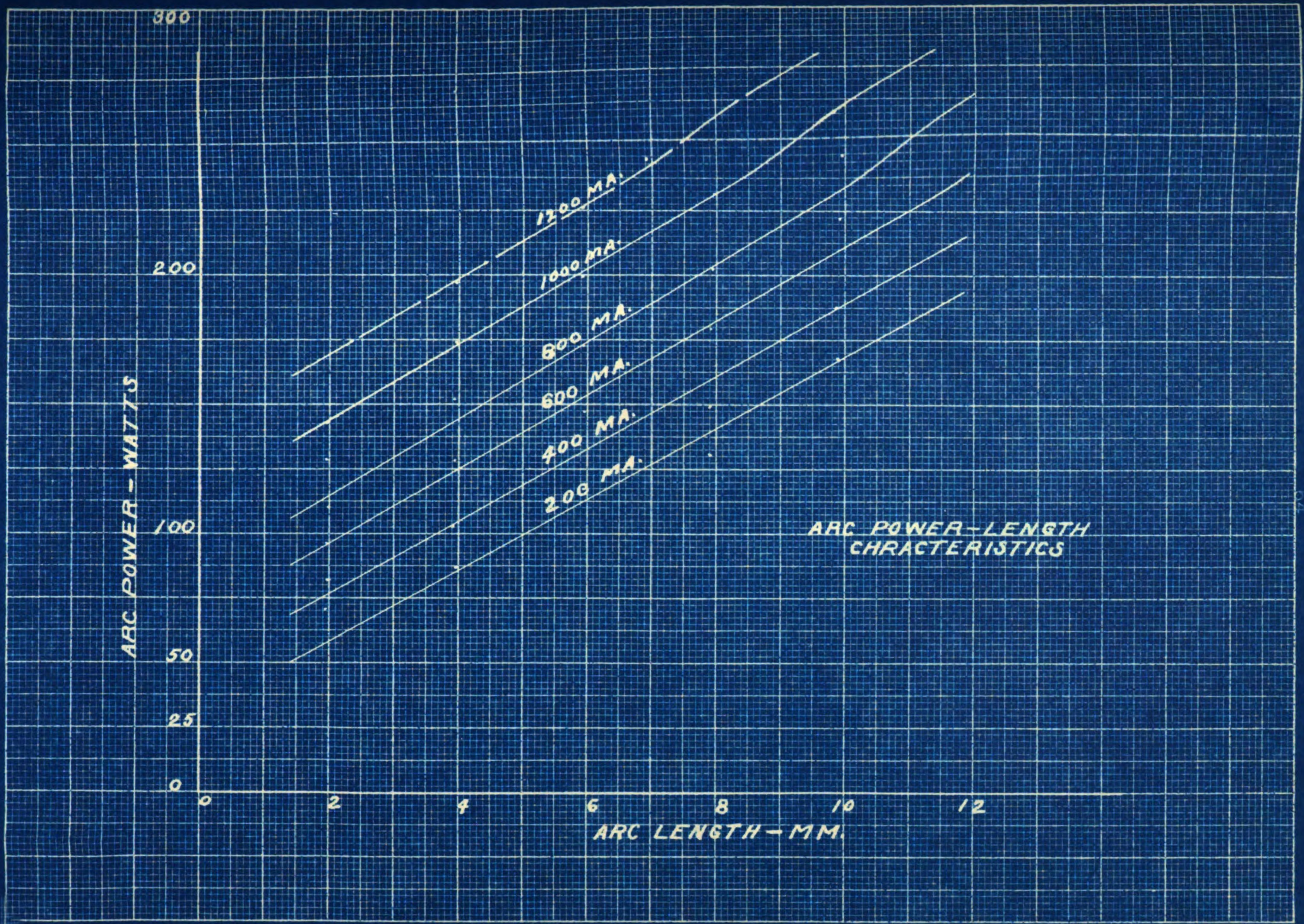
* Page 79, table 15, Ewald Rasch, 'Electric Arc Phenomenon'. by C. E. Guye and L. Zebrikoff

ARC-LINE CHARACTERISTICS

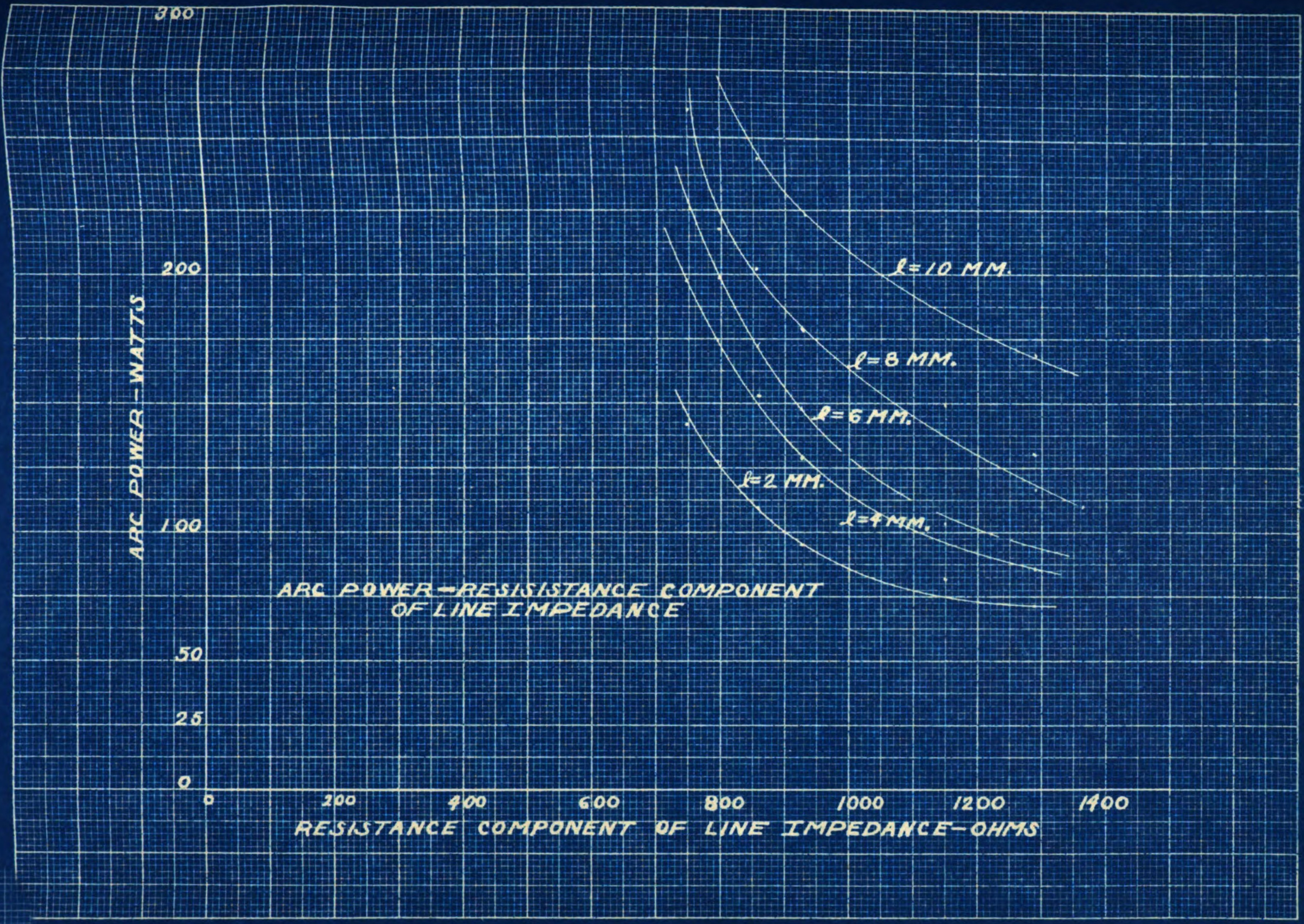

ARC-EXTERNAL IMPEDANCE
CHARACTERISTICS
ARC IMPEDANCE - OHMS
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
l=10 MM
l=8 MM.
l=4 MM.
l=2 MM.
0
2
4
6
8
10
12
14
16
18
20
EXTERNAL CIRCUIT IMPEDANCE— THOUSANDS OF OHMS

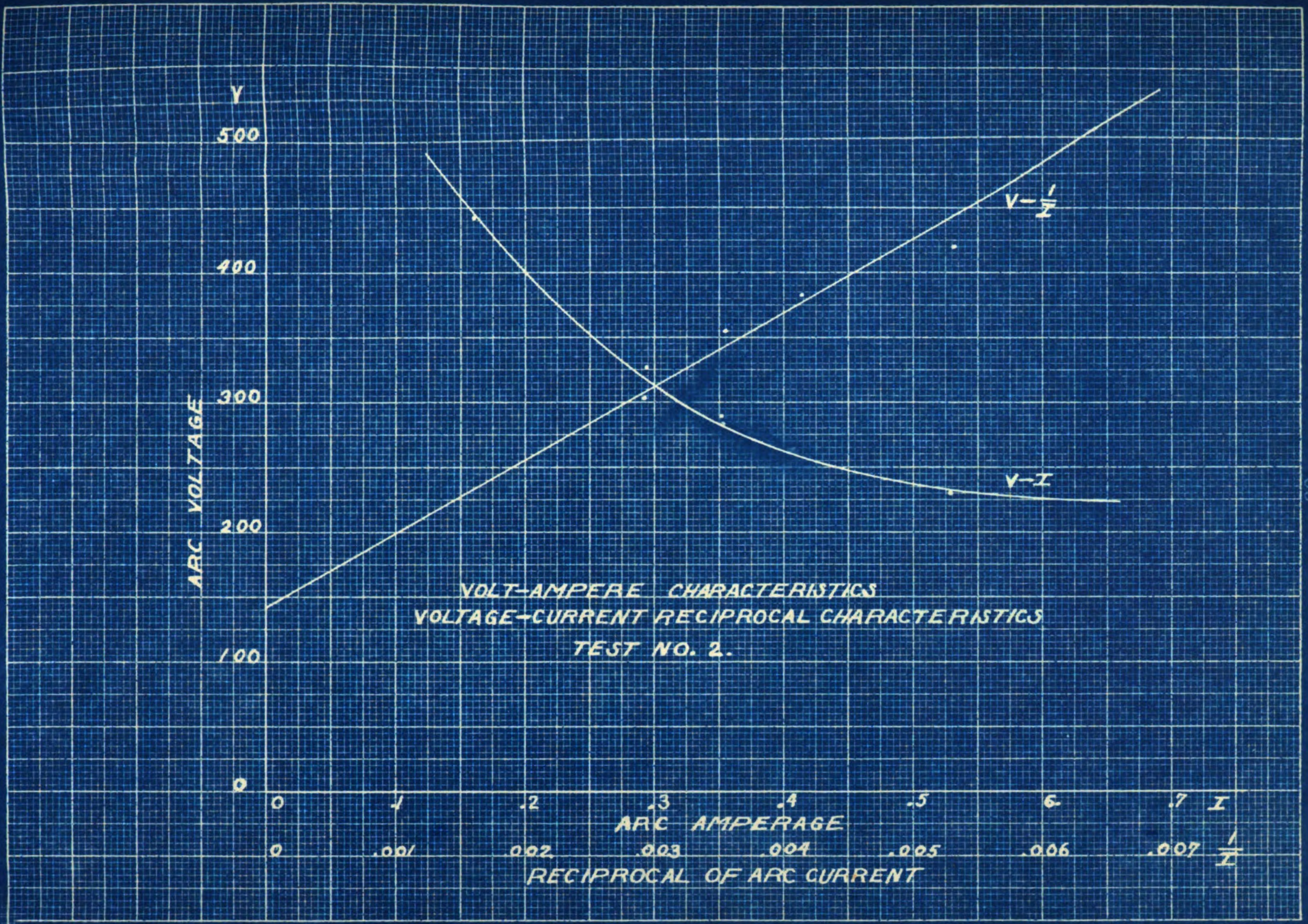


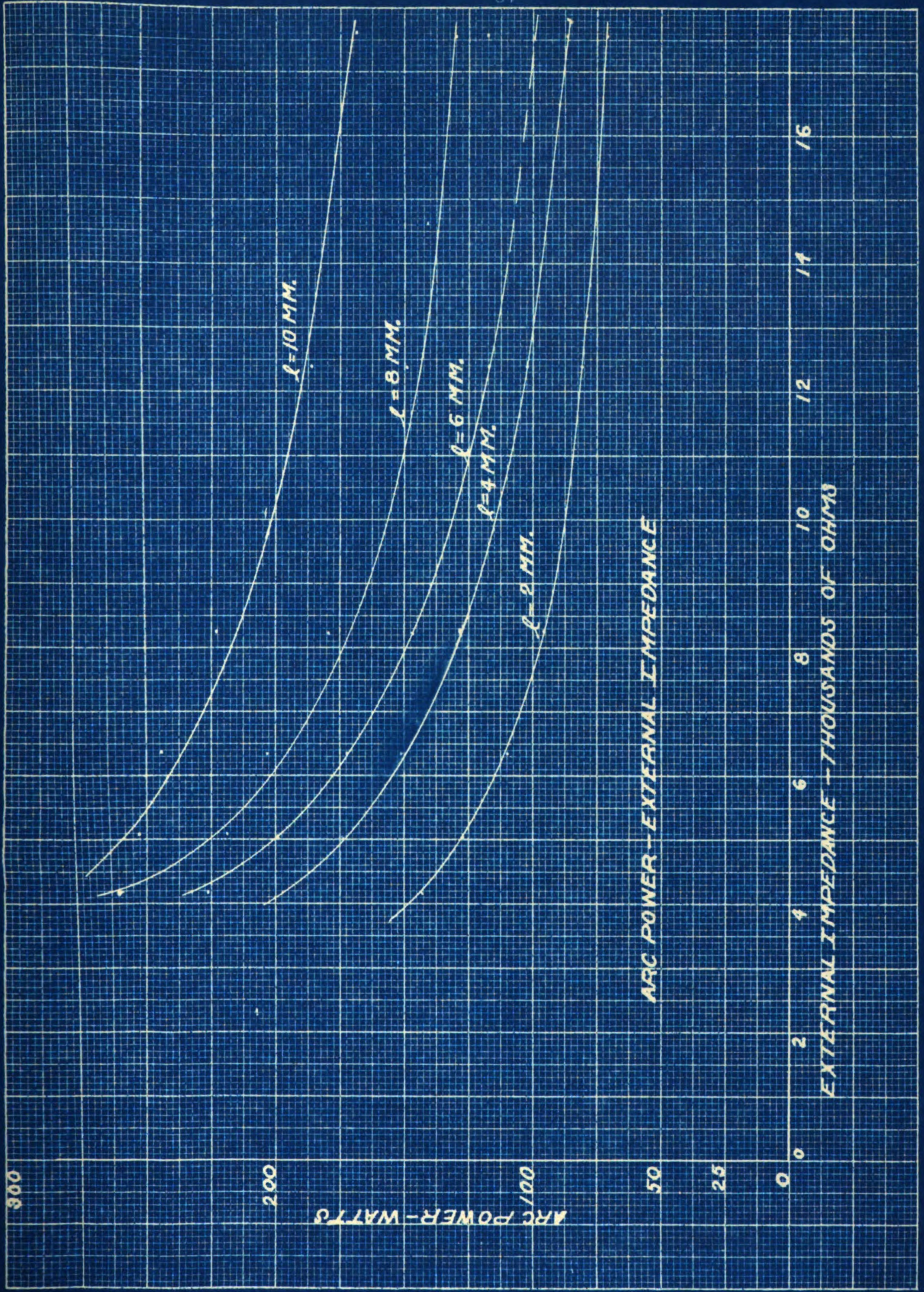
ARC-EXTERNAL IMPEDANCE CHARACTERISTICS
TEST NO. 2.
l=4MM.
ARC IMPEDANCE - OHMS
1600
1400
1200
1000
800
600
400
200
0
0 2 4 6 8 10 12 14 16 18
THOUSANDS OF OHMS EXTERNAL IMPEDANCE



ARC POWER-LENGTH
CHARACTERISTICS
1200 MA.
1000 MA.
800 MA.
600 MA.
400 MA.
200 MA.
ARC POWER - WATTS
300
200
100
50
25
0
0
2
4
6
8
10
12
ARC LENGTH - MM.


300
200
100
50
25
0
ARC POWER-WATTS
0
200
400
600
800
1000
1200
1400
RESISTANCE COMPONENT OF LINE IMPEDANCE-OHMS
l=10 MM.
l=8 MM.
l=6 MM.
l=2 MM.
l=4 MM.
ARC POWER—RESISISTANCE COMPONENT
OF LINE IMPEDANCE


VOLT-AMPERE CHARACTERISTICS
VOLTAGE-CURRENT RECIPROCAL CHARACTERISTICS
TEST NO. 2.
V
500
400
300
200
100
0
ARC VOLTAGE
V-1/I
V-I
0 .1 .2 .3 .4 .5 .6 .7 I
ARC AMPERAGE
0 .001 .002 .003 .004 .005 .006 .007 1/I
RECIPROCAL OF ARC CURRENT


ARC POWER–EXTERNAL IMPEDANCE
l=10 MM.
l=8 MM.
l=6 MM.
l=4 MM.
l=2 MM.
EXTERNAL IMPEDANCE – THOUSANDS OF OHMS
0
2
4
6
8
10
12
14
16
ARC POWER–WATTS
0
25
50
100
200
300

DISCUSSION

By graphical methods (49)* it is shown that in general the voltage - current characteristics of an Alternating Current Arc in air between copper electrodes have the following equation**:

$$E = E_0 + \frac{C}{I} = (g + \alpha l) + \frac{(\gamma + \delta l)}{I} \text{ volts}$$

where

g = 104 volts, is the voltage required to maintain an arc at the theoretical infinitely short length.

α = 5.4, is a constant and represents the rate of change of E_0 with a change of arc length, l.

E_0 is the voltage across the arc which is independent of current but a function of length.

γ = 12, is a constant which represents the power in watts dissipated at the electrodes.

δ = 9.6, is a constant and represents the rate of change of C with a change of arc length.

C is the power consumed by the arc in watts.

I is the current through the arc in amperes.

Characteristics of arc impedance show that the impedance increases with an increase in arc length at a given current value. It increases more rapidly as current decreases. (See page 53)

* The method followed has been used by other experimenters in determining characteristics of arcs between carbon electrodes.

** The values here presented are based upon the apparent voltage as recorded with a vane type voltmeter, using a potential transformer. (See procedure, page 16)

Arc impedance decreases with an increase of current at a given arc length.

For a constant length of path and increasing current the area of the arc stream increases with current, thereby increasing the area of the conducting path and decreasing the resistance. For a periodic current wave, then, it is reasonable to assume that the resistance of the path pulsates at twice the frequency of the current wave.

A decrease in external impedance allows the current to increase in the arc circuit, and consequently the voltage across the arc will fall. Thus a falling arc impedance exists with a corresponding decrease of circuit impedance. The rate at which arc impedance decreases is greater for longer arcs since the impedance in general of a long arc is greater than that of a shorter one at similar current values, and for any arc length the limiting impedance is a constant.

The product E x I of an arc decreases as line impedance increases. That is, since arc impedance increases with line impedance, the current squared of the arc decreases faster than the impedance increases and the power consequently must decrease, giving a falling characteristic.

For any given arc length, within the limits examined, the falling impedance - power characteristic seems to approach a limiting value which must be in the minimum power necessary to sustain an arc under these conditions. That is, if the external line impedance be increased enough, the arc current will fall and the voltage will rise, but the power will also fall until a point is reached at which the power given up by the arc (in the nature of recombination in the arc plasma) is equal to the power consumed by it, and the arc extinguishes.

It may be noted here that as the length of an arc increases, the power consumed also increases as practically a straight line function of length. (See page 64) Also, the recombination and cooling increase since the area of the plasma has been increased in the operation. In this manner also, a point of equilibrium is approached beyond which stability is impossible.

Below a certain length an arc may be blown out and it will re-ignite by itself due to the breakdown of the air. This phenomenon makes possible the arc which travels up the horns of a stationary horn gap of suitable spacing and again strikes itself, repeating this process continually.

The oscillograms of Test No. 2 were analyzed for average and effective values of both voltage and current by drawing 25 ordinates per half cycle and analyzing the representative half cycle of each oscillogram. By representative half cycle is meant the curve which most nearly fits all of the waves recorded during an exposure. A pencil tracing was made of each wave, and the average of these tracings was inked.

For comparison and check, planimeter average values were also computed. The fact that these averages check is proof that the selected ordinates are representative of the complete half cycle and are satisfactory for the computation of effective values.

It is suggested that this method may be used more in the future for determining effective values of this type of wave since a very close check is noted.

From computations it was determined that the current was very near sinusoidal since the form factor is close to 1.11. The voltage wave, it is interesting to note, gives an average form factor of 1.38 for the waves photographed after discarding two unreasonable figures. It may be pointed out that a value of .75 to 1.0 for the ratio of effective power to apparent power has been observed (48) under actual field test conditions. This reciprocal ratio would be from 1.33 to 1.0.

The effective volt - ampere characteristic of these computations is similar to that of the previous set of data. From the volts - reciprocal of current curve (See page 63) there is obtained an intercept of E_o = 140 volts for the 4 mm. length. The corresponding value from the other test is 125 volts. This result is valid since computations have shown that actual effective values are higher than apparent values (meter readings).

To explain mathematically the relationship between arc power or arc impedance and line impedance from the standpoint of per cent of maximum values is a difficult task due to the discontinuous nature of the voltage characteristics, and can be undertaken only through the medium of complex mathematics. This fact has been brought out by Dr. C. P. Steinmetz (57) and is presented in his work entitled, Alternating Current Phenomenon. Further, it has been pointed out by him that a Fourier's analysis does not apply.

It has been shown in the paper by Messrs Attwood, Dow, and Timoshenko (3) that, except for the first few microseconds after current zero, the voltage builds up according to the law

$$\text{volts} = e = 992 - 1{,}131\varepsilon^{-0.0147t} + 64\varepsilon^{-1.64t} .$$

This equation applies, as pointed out by the authors, only during the re-ignition period, that is, while the voltage is building up to its maximum value. For the particular circuit under consideration the equation applied after about five microseconds after current zero, and re-ignition lasted for about 37 microseconds. After this a glow took place during which period the voltage rose slightly and at a slower rate for about 24 microseconds. This period was followed by the arc discharge and the accompanying fall of voltage.

It seems reasonable to assume that after the arc is struck, the current will build up according to a law governed by the impedance and resistance of the external circuit, and further by the resistance of the ionized and conducting column of ionized vapor which is a differential function of the current flowing and the potential impressed at any instant.

CONCLUSIONS

In conclusion, within the limits examined, the power consumed by an alternating current arc increases linearly with an increase of arc length with given circuit values of r and l.

At a given arc length the power consumed by the arc diminishes as the impedance of the external circuit is increased. Power is not a linear function of the external impedance, but the characteristic becomes more nearly linear as the arc length is increased. The power consumed by the arc appears to approach a constant minimum value for each arc length as the circuit impedance is increased. This minimum value is probably the minimum power required to sustain an arc of the corresponding length.

Arc impedance increases as a straight line function of line impedance for large line impedance values. At smaller values of line impedance the rate of increase of arc impedance becomes less.

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Section II. Theory of the Arc, Mathematical and Physical.

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