PRINCE

Laws of Corona

Electrical Engineering

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LAWS OF CORONA

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

David Chandler Prince

ENTITLED Laws of Corona

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Electrical Engineering

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Part I.

Theoretical Investigation of the Laws of Corona.

I. Introduction.

It is exceedingly difficult to isolate the fundamental laws of corona because of the multitude of variables which affect the loss. Until recently two lines of approach have been open to the investigator. He might attack the problem either by means of high potential alternating voltages at any pressure or by comparatively low direct current potentials in gas at much reduced pressure. These two methods of attack have led to two different sets of investigations which, apparently, bear no relation to one another.

Peek, Whitehead, Steinmetz, and numerous others have studied corona with high alternating potentials. They have produced more or less empirical equations for losses between cylindrical conductors under different conditions. These formulae are valuable in commercial work and often pass as laws governing corona loss but their empirical nature renders them valueless in determining the nature of phenomena under extraordinary circumstances. For instance, they throw very little light on the kind of phenomena which occur with distorted waves, abnormal frequencies, odd conductor sections, severe weather conditions

and numerous other variables which undoubtedly bear on the question.

Various physicists, of whom J.J.Thomson and J.S.Townsend are examples, have studied the conductivity of gases under artificial conditions with constant current potentials under one thousand volts. Their theories are much more definately and closely defined than those of the engineering group. They have formulated mathematical relations which cover the leakage phenomena rather well under the conditions with which they worked. It seems to the writer that the best mode of finding the fundamental laws of corona should be by methods similar to those used by these physicists. We shall, then, explain their theories briefly.

II. Townsend's Equation and the Collision Theory of Ionization.

According to the generally accepted kinetic molecular theory, a gas is composed of numerous electrically neutral molecules which move rapidly to and fro colliding with each other and rebounding. These collisions are responsible for the pressure of the gas but do not produce any changes in the molecules

themselves. Among these neutral molecules there are,from natural causes,a small number of charged particles or ions. These ions migrate aimlessly like the molecules,until acted upon by an electric field when they proceed toward the electrodes producing the field. Upon striking the electrodes these ions give up their charges and a certain minute current is observed to flow from one electrode to the other through the gas. This current is increased by increasing the number of ions in the field. This may be done by natural changes such as splashing of water,decay or eminations from the earth,or,artifically,by Roentgen rays,flames and the like,or by a strong electric field. In corona phenomena,the electric field is the source of ionic formation. Prof.J.S.Townsend has developed his "Collision Theory"to account for ionization by an electric field.

He supposes that,when an ion,after reaching a certain velocity,collides with a neutral molecule, the molecule is ionized and becomes a pair of ions, one positive and one negative. Consider a pair of parallel plates perfectly insulated from each other except for the intervening air. The plates are very large as compared with their separation so

that a column of unit cross section may be used as representative.

Let α = the number of positive or negative ions which one negative ion will generate in moving one centimeter through the gas.

X = the potential gradient in volts per centimeter.

N_0 = the original number of ions per cubic centimeter. These are produced by natural processes of unknown origin, or, as in Townsend's experiments, artificially by Roentgen rays.

N = the number of negative ions at any place after N_0 ions have traveled through a distance x.

l = the distance between the plates in centimeters.

$\alpha N dx$ = the number of ions of either kind formed in a distance dx

Then

$$dN = \alpha N dx \qquad \frac{dN}{N} = \alpha\, dx$$

$$N = A\epsilon^{\alpha x} \qquad x = 0,\ N = N_0$$

$$N = N_0 \epsilon^{\alpha x}$$

Let C be the number of ions arriving at the positive plate.

Then

$$C = \int_0^l N_0 \epsilon^{\alpha x} dx = \frac{N_0}{\alpha}(\epsilon^{\alpha l} - 1)$$

is, of course, the current in proper units.

In deriving the foregoing equation only the negative ions are supposed to be ionizing agents and α is assumed to be a constant whose value is determined by the potential gradient and other factors.

The energy possessed by a negative ion upon collision is proportional to the length of free path traversed by the ion and to a function of its velocity;these,in turn,depend upon X, p, & t potential gradient,pressure,and temperature. Both tests and theoretical calculations indicate that the velocity of an ion in an electric field is extremely high as compared with the velocities of molecules in a gas. This being so,an ion may,with out serious error,be assumed to travel in a stationary field.

Let βp = the number of collisions made by an ion in moving one centimeter.

Then $\frac{1}{\beta p}$ = the mean free path.

Out of y paths the chance of the ions traveling one of length $x+$ is $y\epsilon^{-\frac{x}{c}}$ where c is the mean length of path. Then the chance in our gas is $\beta p \epsilon^{-\beta p x}$. The chance of the occurrence of a path between the length x_1 and x_2 is

$$\beta p(\epsilon^{-\beta p x_1} - \epsilon^{-\beta p x_2})$$

The number of ions that will be formed by collisions terminating paths of this length is b_1 .

Let $x_1 = \frac{P}{X}$ and $x_2 = \frac{Q}{X}$ then the number of ions formed by collisions resulting from a drop of from P to Q volts is

$$\beta p\left(\epsilon^{-\frac{\beta p P}{X}} - \epsilon^{-\frac{\beta p Q}{X}}\right)$$

Then
$$\alpha = p\sum_{P=0}^{P=\infty} \beta_P\left(\epsilon^{-\frac{\beta p P}{X}} - \epsilon^{-\frac{\beta p (P+1)}{X}}\right)$$

From this equation it follows that

$$\frac{\alpha}{p} = f\left(\frac{X}{p}\right)$$

This is a purely theoretical relation but it has been proven by Prof. Townsend by plotting the values of $\frac{\alpha}{p}$ found from experimental curves given elsewhere in this thesis.

Townsend expands the equation for α in the form of a series

$$\alpha = b_1\left(\epsilon^{-\frac{\beta}{X}} - \epsilon^{-\frac{5\beta}{X}}\right) + b_2\left(\epsilon^{-\frac{5\beta}{X}} - \epsilon^{-\frac{10\beta}{X}}\right) + \text{-----}$$

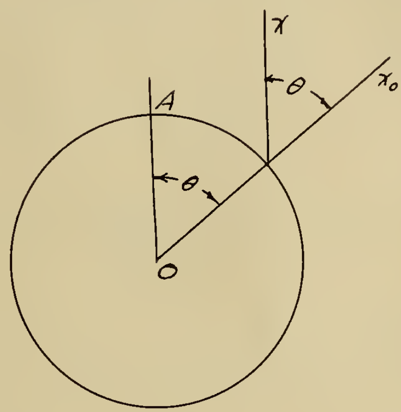
At 760 mm. pressure β = 21 while b_1, b_2,--- have been calculated in the following table.

b_1 = .03	b_4 = 9.0	b_7 = 20
b_2 = .75	b_5 =13.0	
b_3 = 2.70	b_6 =16.0	

The curve using these values for the constants checks nearly with the curve for $\frac{\alpha}{p} = f\left(\frac{X}{p}\right)$ obtained experimentally by Townsend.

A much simpler relation than this has been worked up by the writer which, while perhaps less rigidly mathematical, covers the experimental curve rather

well. It seems reasonable to suppose that an ion impinging with a certain minimum velocity upon a molecule will ionize it by virtue of the kinetic energy given up in the collision. The energy is proportional to the length of path so that we may say that the ion must complete a path x_0 long and normal to the molecule's sphere of action to produce ionization.



If x is the length of path completed by an ion in the direction shown in the figure and is barely sufficient to produce ionization then $x \cos\theta = x_0$ where θ is the angle between x and the normal x_0. x_0 is the minimum path normal to the sphere that will be traversed to produce ionization. If the ion had hit within the area bounded by the cone which is swept out by the revolution of θ about OA, ionization would have resulted, if out side no effect would have been produced. The probability of a collision within this angle is $\frac{\text{Projected area inside}}{\text{Great circle of sphere of action}}$

That is $\frac{\pi r^2 \sin^2\theta}{\pi r^2} = \sin^2\theta = 1 - \cos^2\theta$

But $\cos\theta = \frac{x_0}{x}$ $\therefore$ Probability $= 1 - \left(\frac{x_0}{x}\right)^2$

Then α may be said to equal the product of these two probabilities.

$$\alpha = \left(1 - \left(\frac{x_0}{x}\right)^2\right) \beta p \epsilon^{-\beta p x}$$

The energy relation for an ion is $f(m,v) = eXx$

Transposing and multipling by βp, $\beta p x = \frac{f(m,v)\beta}{2e} \frac{p}{X} = r\frac{p}{X}$

Also average $x = \frac{K}{\beta p}$ $\quad x_0 = \frac{K}{\beta p_0}$

Therefore $\alpha = \left[1 - \left(\frac{X_0}{P_0}\right)^2 \left(\frac{p}{X}\right)^2\right] \beta \epsilon^{-r\frac{p}{X}}$

It may be objected that this equation is little better than empirical but it is certainly far simpler than Townsend's equation and follows the experimental data very well. These equations could readily be extended to cover the case of a round conductor but experiments have shown that corona does not follow this law close enough to make such deductions of value.

It is obvious that any factor which would increase the value of the quantity N_0 would cause a relatively large increase in the gaseous conductivity. If, then, positive ions should become effective as ionizing agents, the conductivity would be increased. Moreover such an effect would be cumulative and break down of the dielectric would result. This is a

general proposition where continuous potentials are used. It is possible that a time element is involved so that 'two sign' ionization can occur in alternating current circuits with out a disruptive discharge resulting.

III. Energy Theory of Ionization.

It is not the purpose of this thesis to show that the foregoing theory is incorrect, but rather to show the difficulty of applying theoretical formulae to the conductivity of gases at atmospheric pressure. The energy theory of ionization seems to throw much light on corona but, like the collision theory, it is not easily applied. According to this theory the breaking up of a molecule into cation and anion requires a fixed amount of energy. The amount of energy expended when N ions travel through space is

$$\frac{dE}{dx} = NeX$$

where N_0 = the number of - ions supplied to the field.

e = the charge on an ion.

X = the electric field intensity.

dx = the distance moved.

Some of this energy will be dissipated and hence not available. If E is the energy at any place, the rate

of dissipation should be proportional to it, or

$$\frac{dE}{dt} = -K_2 E$$

Tests have shown that the velocity of ions is proportional to the first power of the gradient therefore

$$V = \frac{dx}{dt} = \frac{K_1 X t}{p} \qquad dx = \frac{K_1 X t}{p} dt$$

then $$dE = \frac{K_1 N e X^2 t}{p} dt - K_2 E dt$$

This energy will be available for ionization. If the energy to ionize a molecule is E_o then

$\frac{dE}{dt} = -NE_o$ gives the rate at which energy is used up in ionizing molecules.

Then $$NE_o + K_2 E = K_1 N \overset{r}{\left(\frac{et}{p}\right)} X^2$$

If the field is undergoing continuous discharge the amount of energy at any place is constant. Then equals and the above equation may be written

$$(N + K_3) E_o = K_1 N r X^2$$

Since $K_3 E_o$ is a perfectly definate value there will be a certain value for the product $K_1 N r X^2$ below which ionization will not take place. This relation gives the "critical" gradient so often met in engineering works on corona. According to this theory, the critical gradient depends upon the number of ions present and upon the temperature, pressure and degradation constant as well. If the positive ions cause ionization the value of N speedily passes beyond the control of out side conditions and disruptive discharge takes place.

The last equation above applies to any point.

Take the particular case of a point between two plates which are parallel to each other.

Let N = the number of ions passing any section per second.

Using the other terms as before we have

(1.) $$dN = (KrNX^2 - C)\,dx$$

(2.) $$dX = \frac{N_+ - N_-}{X}\,dx = \frac{(2N - \int_0^l N\,dx)\,dx}{X}$$

(3.) $$X\,dX = (2N - \int_0^l N\,dx)\,dx$$

Integrating (3)

(4.) $$\tfrac{1}{2}X^2 = \int (2N - \int_0^l N\,dx)\,dx + D$$

Substituting in(1).

(5.) $$dN = \left[KrN\left\{\int (2N - \int_0^l N\,dx)\,dx + D\right\} - C\right]dx$$

A solution of these equations should give the laws of corona between parallel plates. Equation (3.) gives the change of potential gradient with distance. The basis of this relation is as follows: The potential gradient between parallel plates is constant except as disturbed by ions in the field. Any distortion of this value will be due to the difference in the number of ions of positive and negative sign. The ionic stream density will be directly proportional to the number of ions passing any point per second and inversely proportional to the velocity of the ions. Since it has already been stated that the velocity is proportional to the electric

field strength,the variation of field strength with a movment dx is expressed by the relation

$$dX = C\frac{N_+ - N_-}{X}\,dx \qquad \text{where } N_+ = N - \int_0^1 N\,dx \quad N_- = N$$

This same relation could have been applied to the equations given with the collision theory as the inadaptability of those equations to the phenomena of leakage at atmospheric pressure is probably due to the forces of ions in the field. This was not done because of the complicated nature of the equations found in dealing with the energy theory.

IV. Some Corona Phenomena Explained by These Theories.

With the simplest possible conditions,as obtained in leakage between parallel plates,the theoretical loss equations are quite complicated. Without solving them,however,to explain many of the corona phenomena is possible.

In all the equations deduced by the physicists there is one point in common. Ions are assumed to exist naturally in the gas under test or ions are supplied artificially by Roentgen rays or their equivalent. It seems entirely likely that the number of ions existing in the air shall largely

influence the phenomena at corona. Many men, particularly of the engineering group, have sought to connect critical voltage and quantity of discharge with atmospheric factors such as barometric pressure, humidity and temperature. For instance, Mr. Mershon gives the variation of corona loss as a function of a "vapor product". This product is found by multiplying relative and absolute humidities together and is used as a coefficient to reduce all tests to standard conditions. Again, Whitehead has, artificially varied humidity in his tests and has concluded that no such relation exists. Wilson, an English physicist, has found that a charge of electricity has a strong tendency to form clouds. These observations may look irrelevant and contradictory but there is a thread of theory connecting them. The outside humidity conditions may be created by the electric state of the air. Humidity and corona may depend upon the same factor for their value and not upon each other.

No one seems, yet, to have made a direct study of this relation. The writer, some time ago conceived a method for testing the relation between ions present in the air and atmospheric conditions. Suppose a gold leaf electrometer were sharged at regular intervals and the time for a partial dis-

charge carefully noted with the attendant weather conditions. It would then be an easy matter to observe any connection between the two. The electrometer discharge time should be inversely proportional to the number of ions present.

In the event that no set relation between free ions and temperature, pressure and humidity exists, it might be necessary to add an electric coefficient to the observations of the weather bureau. Such an observation might well be useful in forecasting storms once its vagaries became well understood.

Another phenomenon in connection with small wires has troubled corona investigators. It has been observed that, at critical voltage, the dielectric at the surface of a small conductor seemed to be stressed much more highly than that surrounding a larger conductor. It has been suggested that the air around a small wire is different from that around a larger one. It seems to the writer that the collision and energy theories furnish a better explaination. Consider an ion traversing its last free path to the electrode. A small part of the distance is traversed but once the rest many times. The condition is analogous to that of the frog who hops two feet up the bank and then slides down one. He covers each foot three times excepting the last one which he crosses but once. Similarly the ionic

concentration is much less near the surface of any conductor. The force very near the surface of the conductor is, then, less efficient in ionization than the same force farther away. Potential gradient is very large near a small conductor hence a large amount of potential is lost in a zone where few ions can be acted upon. It has been observed that a conductor from which a discharge procedes is surrounded by a thin dark tube. This must be the zone where the ions make their last paths before striking the wire.

V. Conclusion.

The investigations, both theoretical and experimental, which have been carried on in connection with this thesis have been for the purpose of determining a simple relation governing corona loss as a function of the variables involved. Toward this end the conditions of test were simplified as much as possible. The difficulties due to wave shape and transients were eliminated by the use of direct current of high potential. Difficulties due to unequal potential gradient before the start of corona were eliminated by the use of flat parallel plates one of which was equipped with a guard ring. Complete sets of tests

were made at one time to avoid changes in atmospheric conditions during test. The energies of the investigators were concentrated upon one end,vs,finding the relation between conductivity of air and potential gradient. The conclusions to which the investigations have lead are briefly:

(a) That while equations are easily obtained which explain leakage phenomena at low pressures,these equations do not hold at pressures ordinarily found even though the electrodes used be flat plates.

(b) That equations can be derived which will explain the nature of leakage between flat plates at atmospberic pressure allowing for distortion of the force field by the presence of ions but that such a relation is too complicated to compare favorably with existing emperical formulae.

(c) That an extension of the equations to cover loss from round conductors would not be of much value unless a short cut should be discovered in the mathematics.

(d) That the collision and energy theories lead directly to valuable qualitative conclusions as follows:-

(1) Critical voltage is a function of ions in the air as well as of pressure and temperature.

(2) Sizes of conductor at which abnormal surface dielectric strengths are found will depend upon the pressure of the gas.

The amount of qualitative data could be greatly extended by continued research with that end in view. The object of this thesis was more restricted and so does not contain all possible information of this kind. This work is principally important in suggesting further investigation along promising lines.

Part II.

Experimental Investigation of the Laws of Corona.

I. Description of Apparatus and Tests.

The point of most interest about the apparatus is the source of E.M.F. To secure the ten thousand volts potential,which was used in the experiments, twenty small direct current machines of five hundred volts each were connected in series. The set up was so arranged that the series connection was never broken. This removed the danger in switching the full voltage induced. The machines were operated in two groups of ten each. The original ten are individually belt driven from a counter shaft. The wiring of these machines is so arranged that the units can be cut in in succession and the voltage brought up gradually by the use of one single pole double throw switch per machine. But one rheostat is used for the whole ten. As this set up is of some interest a schematic diagram of the wiring is included.

In as much as the voltage could be varied by small steps over a range of five thousand volts with the first machines it was not deemed necessary to have any rheostats in the circuits of the second set. Instead,these machines are individually self-excited and have one single pole field switch each. This second set is connected mechanically in two groups of five machines each by insulating flexible

couplings. The groups of five are belt driven from a motor.

Several types of air gap were used in preliminary tests. Measurement of leakage from a needle point was first attempted. The dielectric broke down very readily with the result that the needle was completely consumed. Fine parallel wires were tried and burned up. For the safety of the instruments a resistance was then constructed. It consisted of a glass tube about a meter long having an electrode in each end. The tube,when filled with distilled water,showed a resistance of about half a megohm. This resistance was used in series with the air test gaps in all regular tests;the drop through it was,however,too small to require a correction. A similar water tube was used as a voltmeter multiplier. This showed some tendency to heat and so was calibrated before and after every test. The change between succeding calibrations was not great.

In measuring the loss from flat plates a special piece of apparatus was constructed. It consisted of two parallel disks mounted upon threaded shafts so that their spacing was adjustable. The high potential disk was solid and was connected through the safety resistance to the ungrounded side of the machines. The other plate was surrounded by a guard ring in the same plane which was grounded.

The center plate was grounded through the galvanometer used as an ammeter. By this system of plates the current was measured from an area to which all leakage was reduced to a minimum.

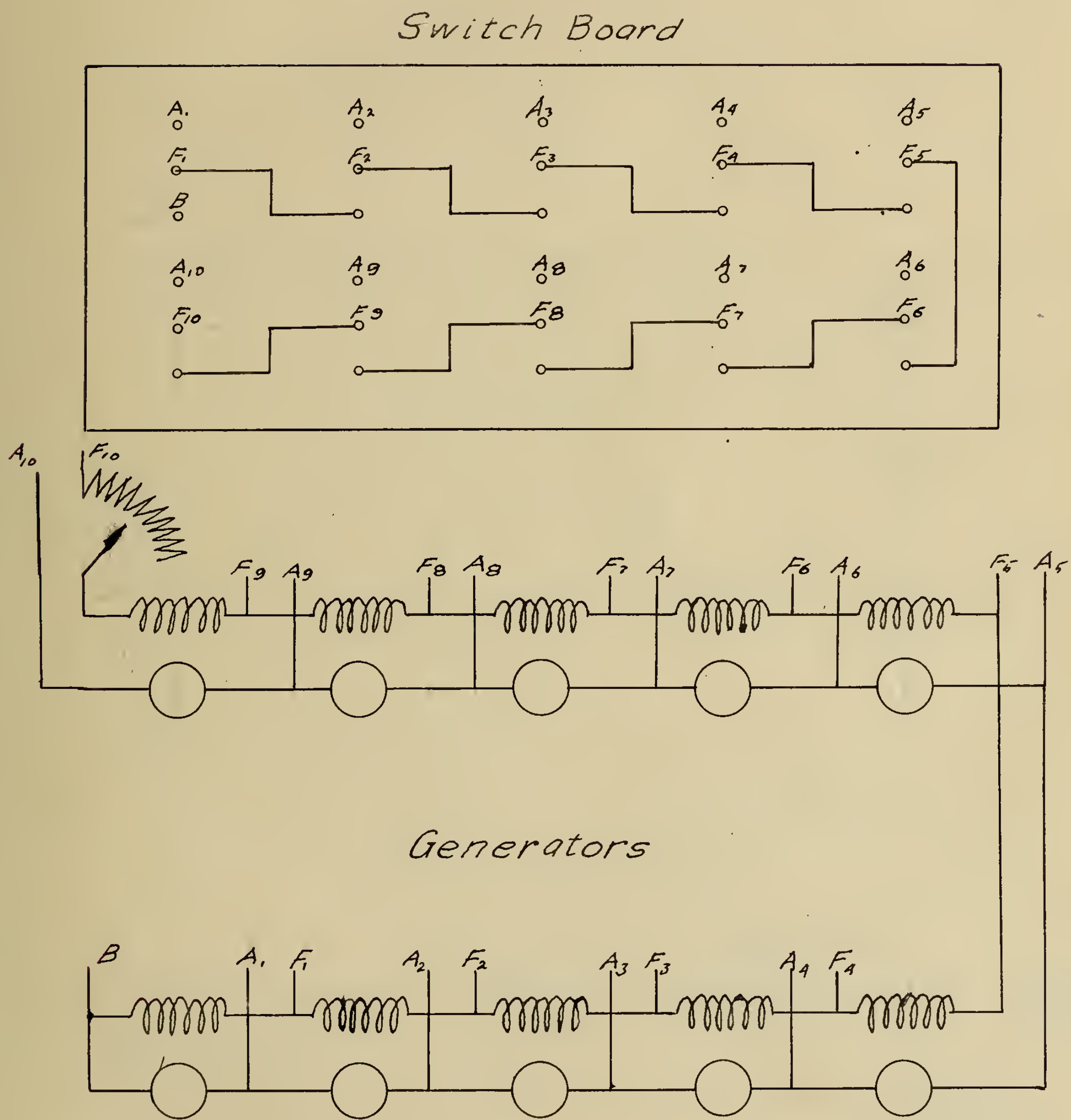
In making the tests various potentials were impressed upon the gap and the resulting currents measured. The voltmeter was calibrated for small potentials by a 1500 volt voltmeter in parallel with it. When the potential exceded 1500 volts the low reading instrument was disconnected.

II. Discussion of Test Data.

On pages 24 and 25 will be found data and curves derived by Prof.Townsend for current between parallel plates. The corresponding values for α are also given. It will be noted that the values of α vary but little and with no apparent law as l varies. On pages 26 to 30 are the curves and data obtained from the tests made in connection with this thesis. The general form of the curves between X and I are the same. At a glance they appear to come from similar equations but they do not. The values of α show a decided falling off for the greater values of l. The conclusion drawn by the writer from this fact is that some polarization must take place near

the electrodes. Such an hypothesis brings in great complications as was seen in the part of this paper devoted to theory. Similar phenomena occur in other cases of gaseous and liquid conduction. The mercury vapor arc has a voltage drop almost independent of its length. Polarization is a familiar bugbear in the primary battery. It seems very probable, then, that polarization occures in all cases of gaseous conduction except those at very pow pressures when the numbers of ions present would not be sufficient to disturb the field.

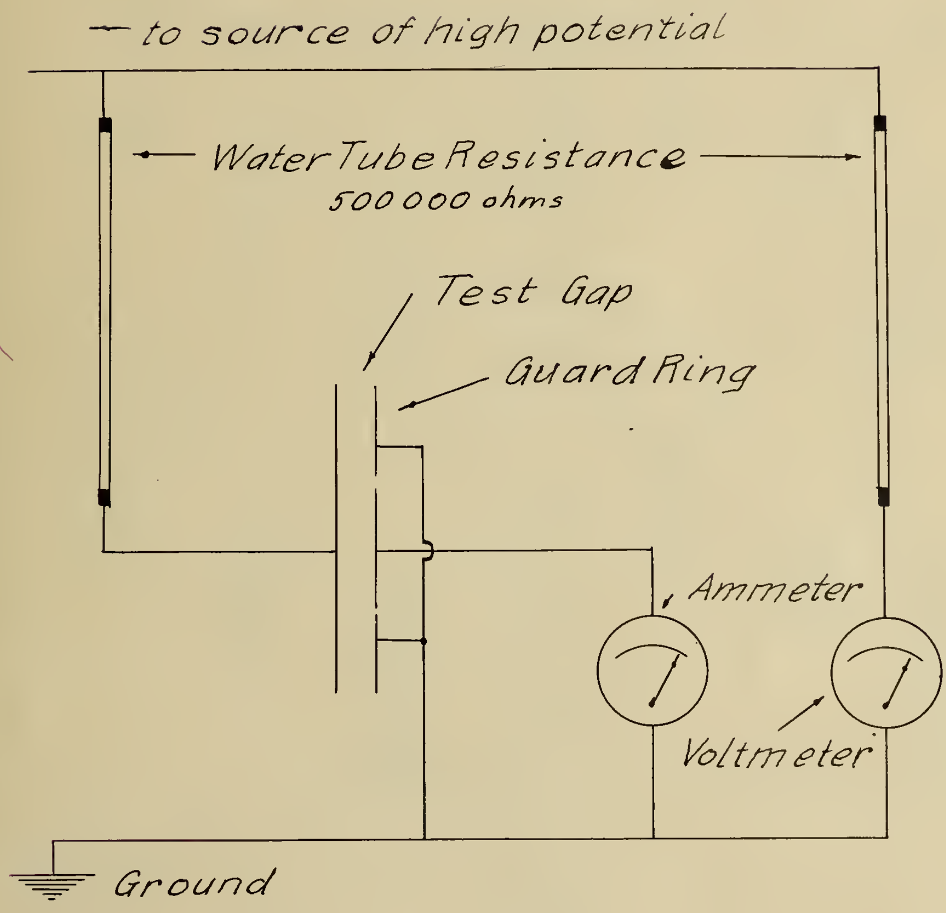
Diagram of Connections for Generators.



A_{10} and B are terminals.

Diagram of Connections

for Leakage Test.



Data Sheet.

The following are values of α calculated from the experimental curves (Page 25.) by the use of the relation $C = \frac{N_0}{\alpha} \times (\epsilon^{\alpha l} - 1)$. Curves and calculations are from Townsend.

X = the potential gradient in volts per cm.
p = the pressure in m.m. of mercury.
l = the distance between plates in cm.
α = the number of ions formed by one negative ion in moving one cm.

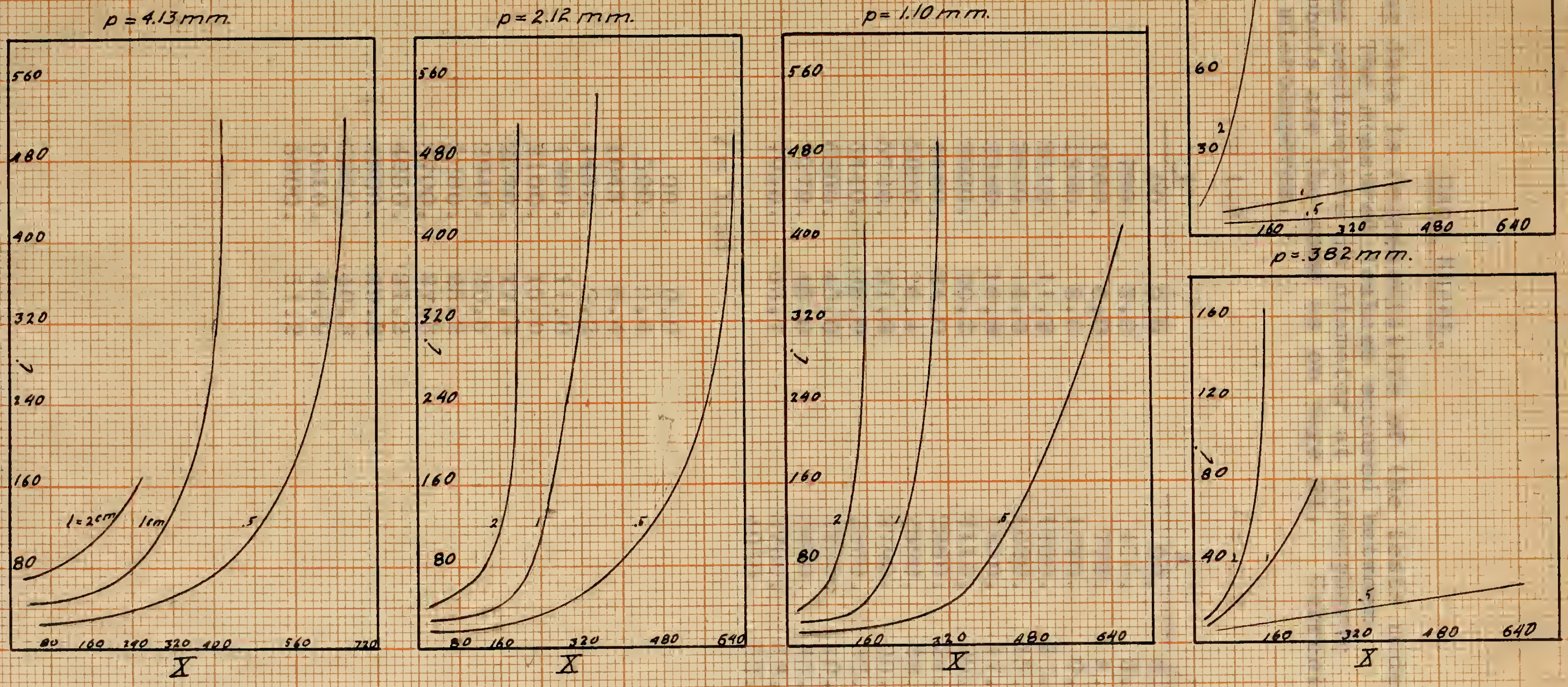
X	p = 4.13				p = 2.12			
	l = 2	l = 1	l = .5	Ave.	l = 2	l = 1	l = .5	Ave.
80					.13			.14
120	.13			.135	.42	.40		.44
160	.28	.30		.31	.90	.90		.91
200	.50	.51				1.60		
240		.99		.95		2.35	2.35	2.4
320		2.1	2.2	1.95		4.10	4.00	4.2
400		3.6	3.6				6.00	
480			5.3	5.00			7.80	8.0
560			7.1				9.40	
640			8.9	8.70			10.80	11.3

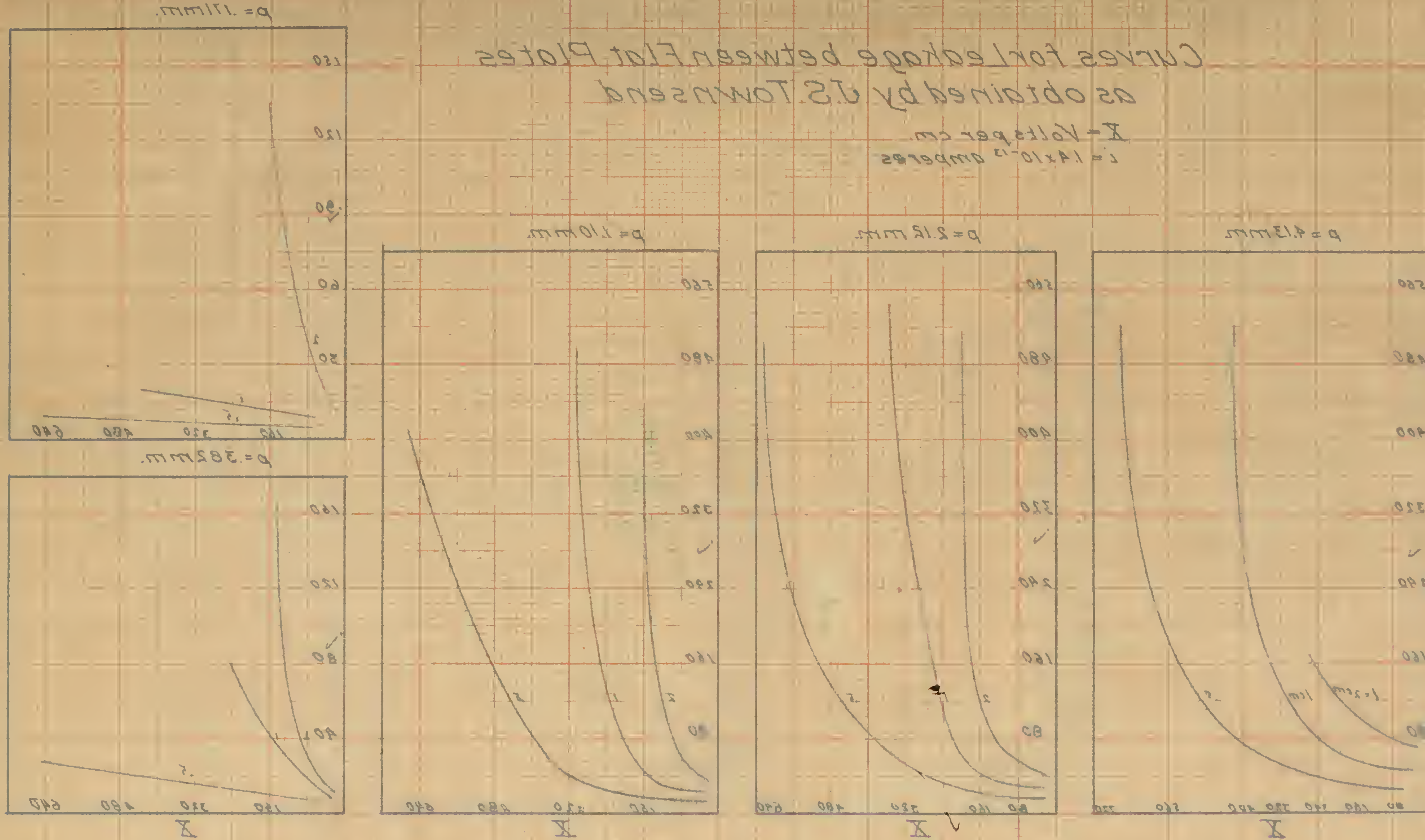
X	p = 1.10				p = .335			
40					.34			.35
80	.45			.44	1.30			1.3
120	1.11	1.09		1.20	2.00			2.1
160	2.02	1.98		2.05	2.80	2.90	2.90	2.8
200		2.8				3.40	3.40	
240		3.7	4.00	4.00		3.80	3.80	3.9
320		5.4	5.5	5.70			4.50	4.5
400			6.8				5.00	
480			8.0	8.50			5.40	5.3
560			9.3				5.80	
640			10.6	10.5			6.20	5.8

X	p = .171			
20	.24			
40	.65			.66
80	1.35	1.36		1.37
120	1.80			
160	2.25	2.1	2.1	2.1
240		2.45		2.4
320		2.65	2.70	2.6
480			3.15	2.8
640			3.25	3.0

Curves for Leakage between Flat Plates as obtained by J.S. Townsend

X = Volts per cm.
$i = 1.4 \times 10^{-13}$ amperes




Curves for Leakage between Flat Plates
as obtained by J.S. Townsend
X = Volts per cm.
i = 1.4×10⁻¹³ amperes
p = .171 mm.
p = .382 mm.
p = 1.10 mm.
p = 2.12 mm.
p = 4.13 mm.
X

Data Sheet.

The following data is representative of the tests made by the writer. The measured leakage occured between plates about ten centimeters in diameter at atmospheric pressure. Symbols are the same as on page 24. Current is measured in microamperes.

ℓ = .6

X	I
00.	0.0
1580.	3.2
2680.	6.0
3770.	8.4
4830.	11.6
5730.	14.4
6760.	16.0
7800.	18.0
8840.	21.6
9950.	25.2
10800.	27.6

ℓ = .95

00.	0.0
980.	3.2
1670.	4.8
2420.	8.0
3030.	11.2
3640.	13.2
4140.	16.8
4740.	20.0
5420.	23.2
6050.	25.6
6600.	29.2
6900.	30.4
7950.	34.5
8950.	38.8
10000.	48.0
11050.	51.7

ℓ = 1.2

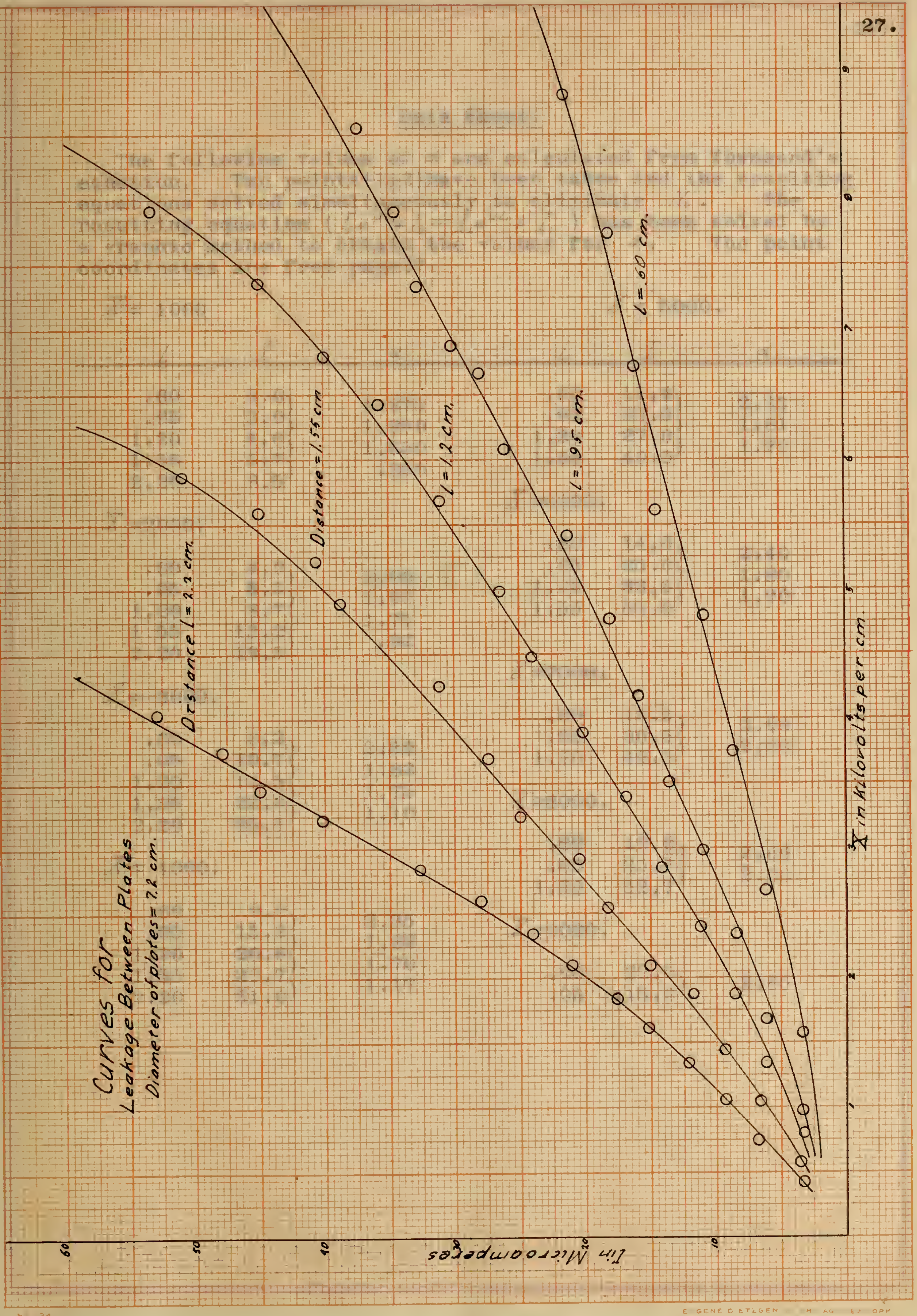
X	I
00.	0.0
790.	3.2
1360.	6.0
1880.	8.6
2410.	11.2
2830.	14.0
3380.	16.8
3920.	20.2
4480.	24.0
5030.	26.4
5720.	31.2
6440.	36.0
6800.	40.0
7370.	45.0
7950.	53.7

ℓ = 1.55

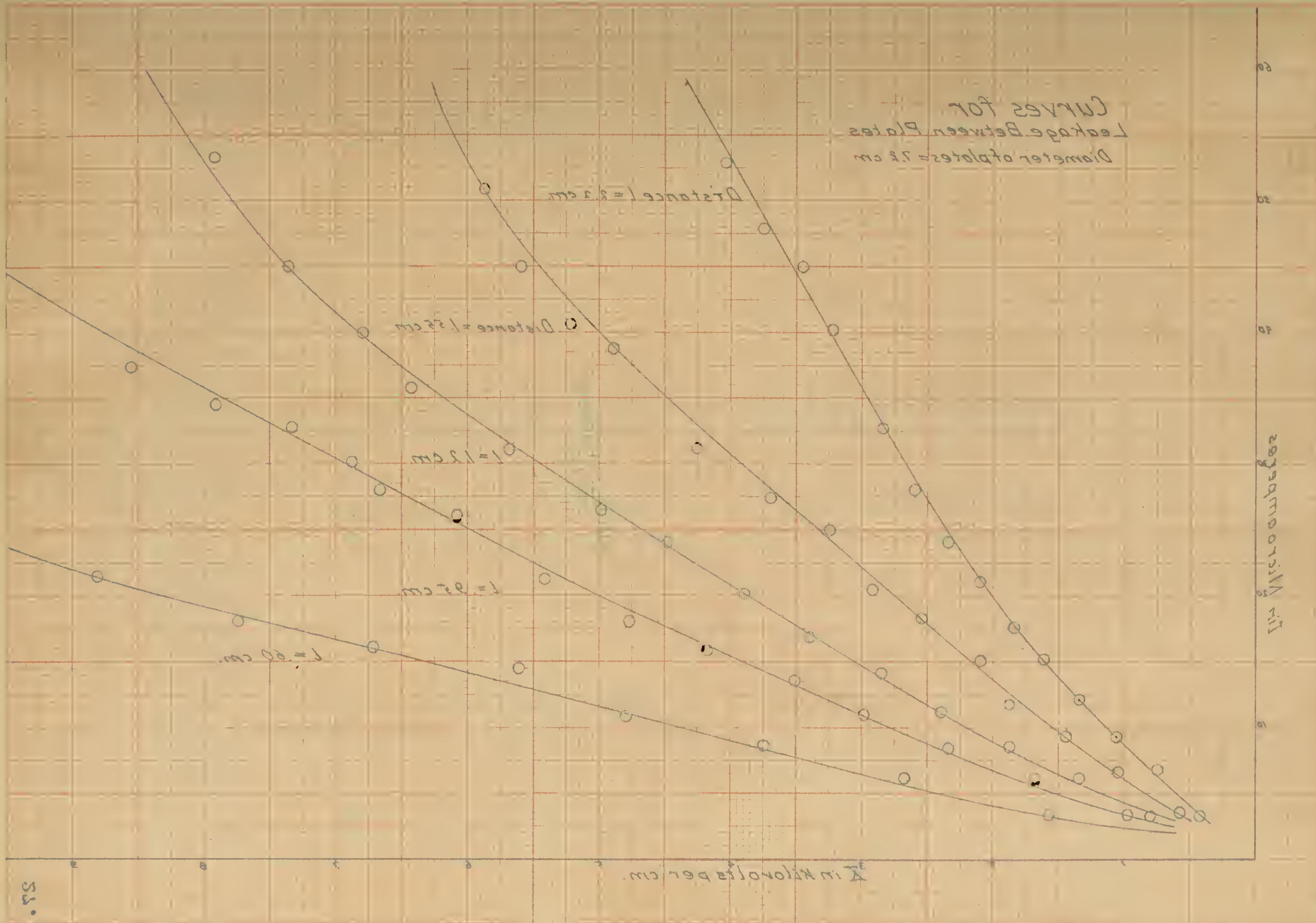
00.	0.0
590.	3.4
1045.	6.4
1450.	9.2
1890.	11.6
2100.	15.0
2570.	17.8
2940.	20.5
3260.	25.2
3700.	27.6
4250.	31.2
4900.	39.2
5250.	40.8
5610.	44.9
5900.	51.2

ℓ = 2.2

X	I
00.	0.0
450.	3.4
776.	6.4
1070.	9.0
1350.	12.0
1620.	15.2
1850.	17.6
2110.	20.8
2360.	24.0
2590.	28.0
2790.	30.0
2860.	32.8
3200.	40.0
3450.	45.6
3760.	48.0
4050.	53.0



Curves for
Leakage Between Plates
Diameter of plates = 7.2 cm.
Distance l = 2.2 cm.
Distance = 1.55 cm
l = 1.2 cm.
l = .95 cm.
l = .60 cm.
X in kilovolts per cm.
i in Microamperes
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60


Curves for
Leakage Between Plates
Diameter of plates = 22 cm
Distance l = 2.2 cm
Distance = l 5.5 cm
l = 12 cm
l = 25 cm
l = 60 cm.
X in Kilovolts per cm.
i in Microamperes

Data Sheet.

The following values of α are calculated from Townsend's equation. Two points(1&2)have been taken and the resulting equations solved simultaneously to eliminate N_0. The resulting equation ($I_1\epsilon^{\alpha l_2}+I_2=I_2\epsilon^{\alpha l_1}+I_1$) has been solved by a graphic method to obtain the values for α. The point coordinates are from page27.

X = 1000

l	I	α
.60	2.0	1.875
.95	3.0	1.950
1.20	4.0	1.650
1.55	5.7	.850
2.20	8.5	

X =2000.

l	I	α
.60	4.0	2.00
.95	6.5	1.90
1.20	8.7	1.75
1.55	13.2	.92
2.20	19.5	

X = 3000.

l	I	α
.60	6.2	2.30
.95	10.7	1.82
1.20	14.5	1.75
1.55	22.0	1.10
2.20	35.5	

X = 4000.

l	I	α
.60	9.0	2.35
.95	15.2	1.82
1.20	20.6	1.70
1.55	30.7	1.17
2.20	51.0	

X = 5000.

l	I	α
.60	11.4	2.35
.95	20.0	1.81
1.20	27.0	1.70
1.55	40.0	

X=6000.

l	I	α
.60	14.0	2.40
.95	25.0	1.80
1.20	33.5	1.90
1.55	53.0	

X=7000.

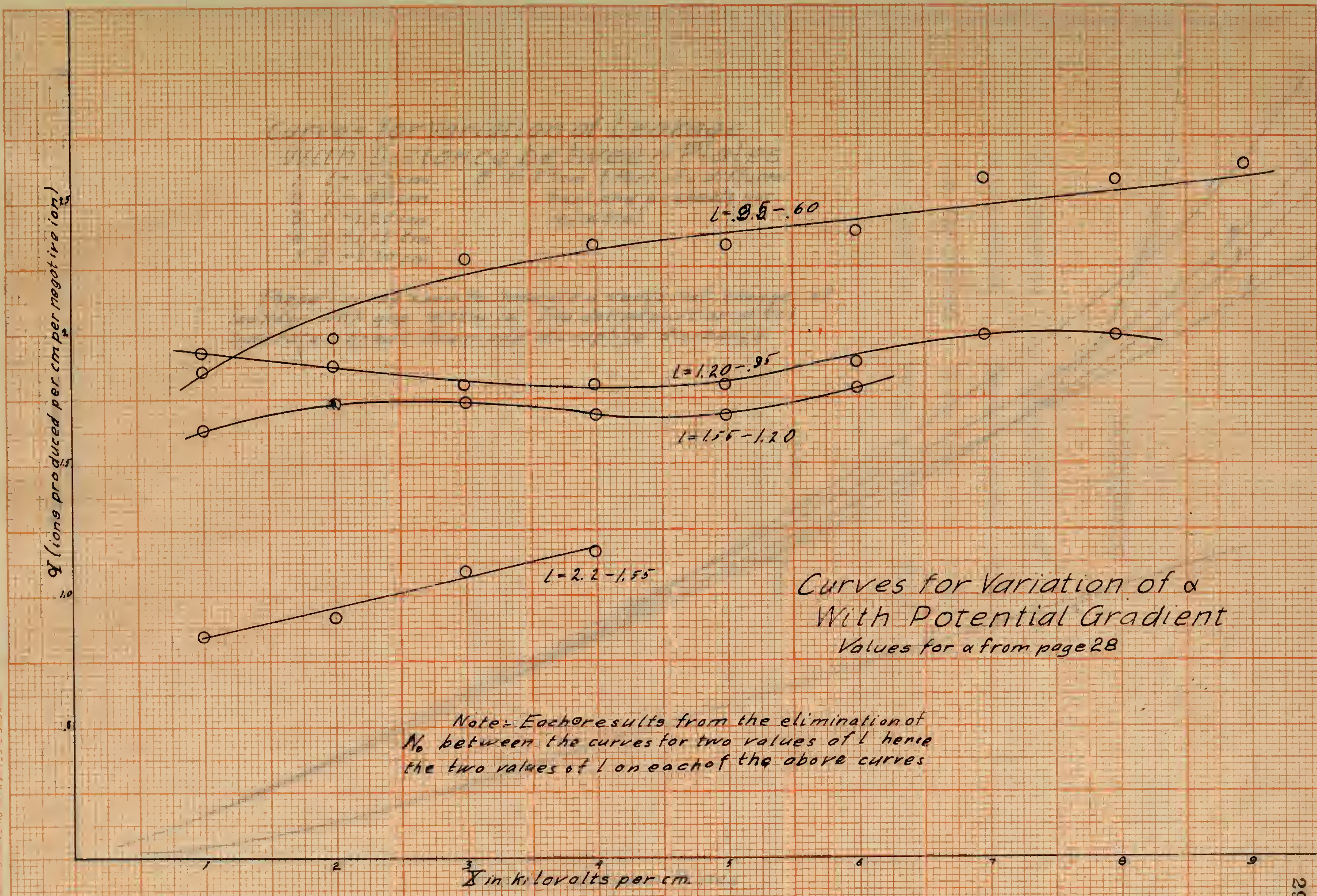
l	I	α
.60	16.5	2.60
.95	30.5	2.00
1.20	42.5	

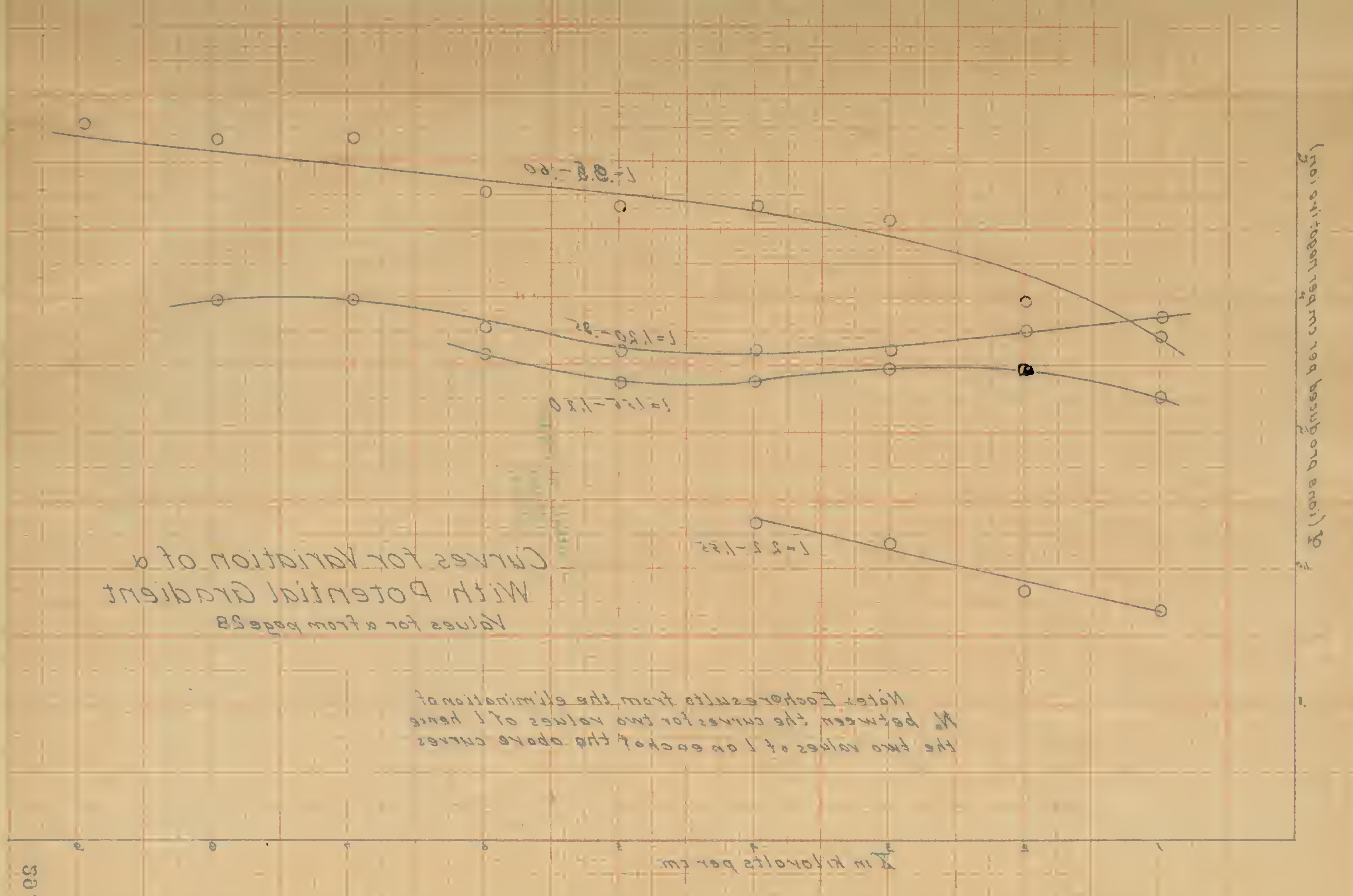
X=8000.

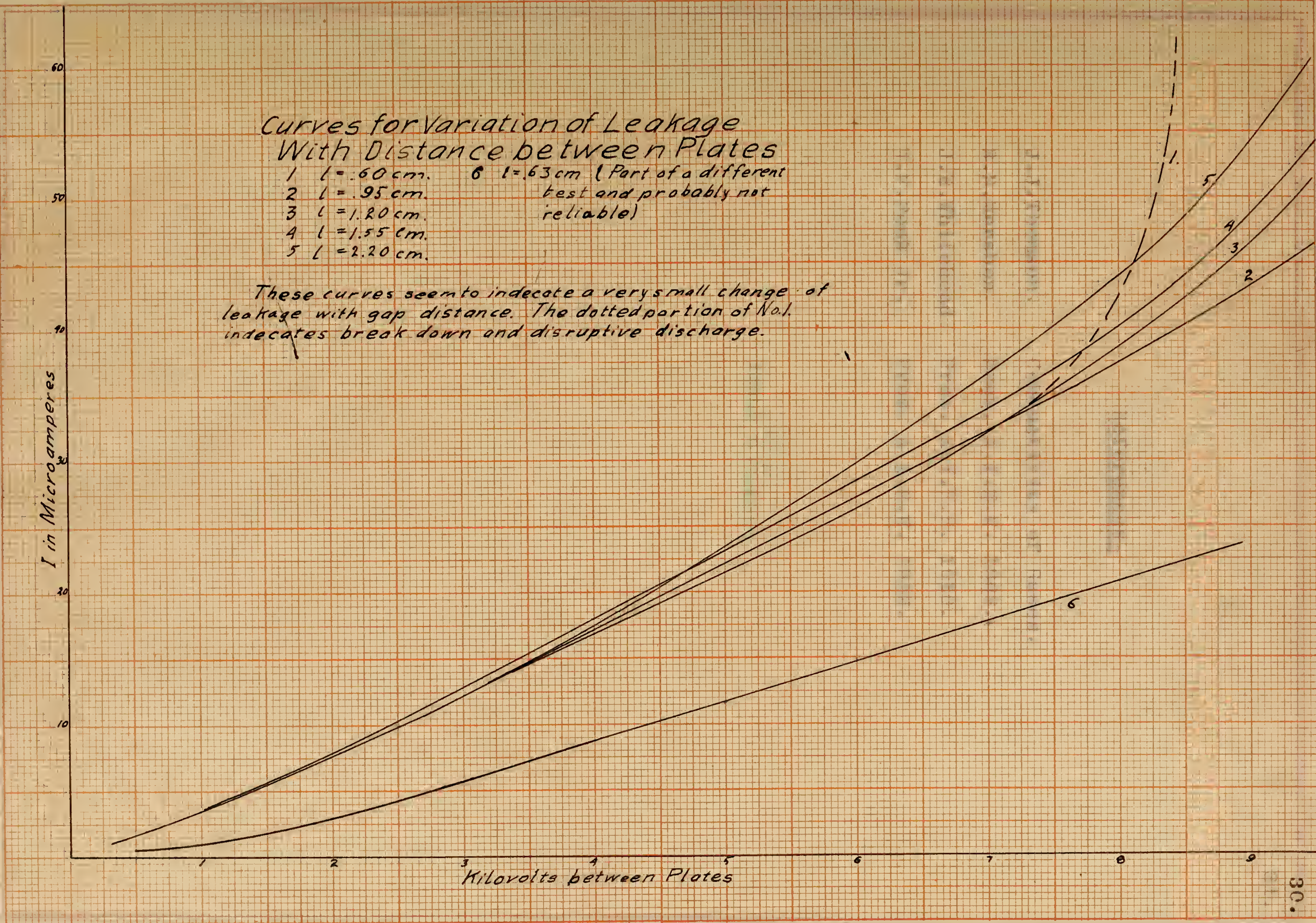
l	I	α
.60	19.0	2.60
.95	35.7	2.00
1.20	52.7	

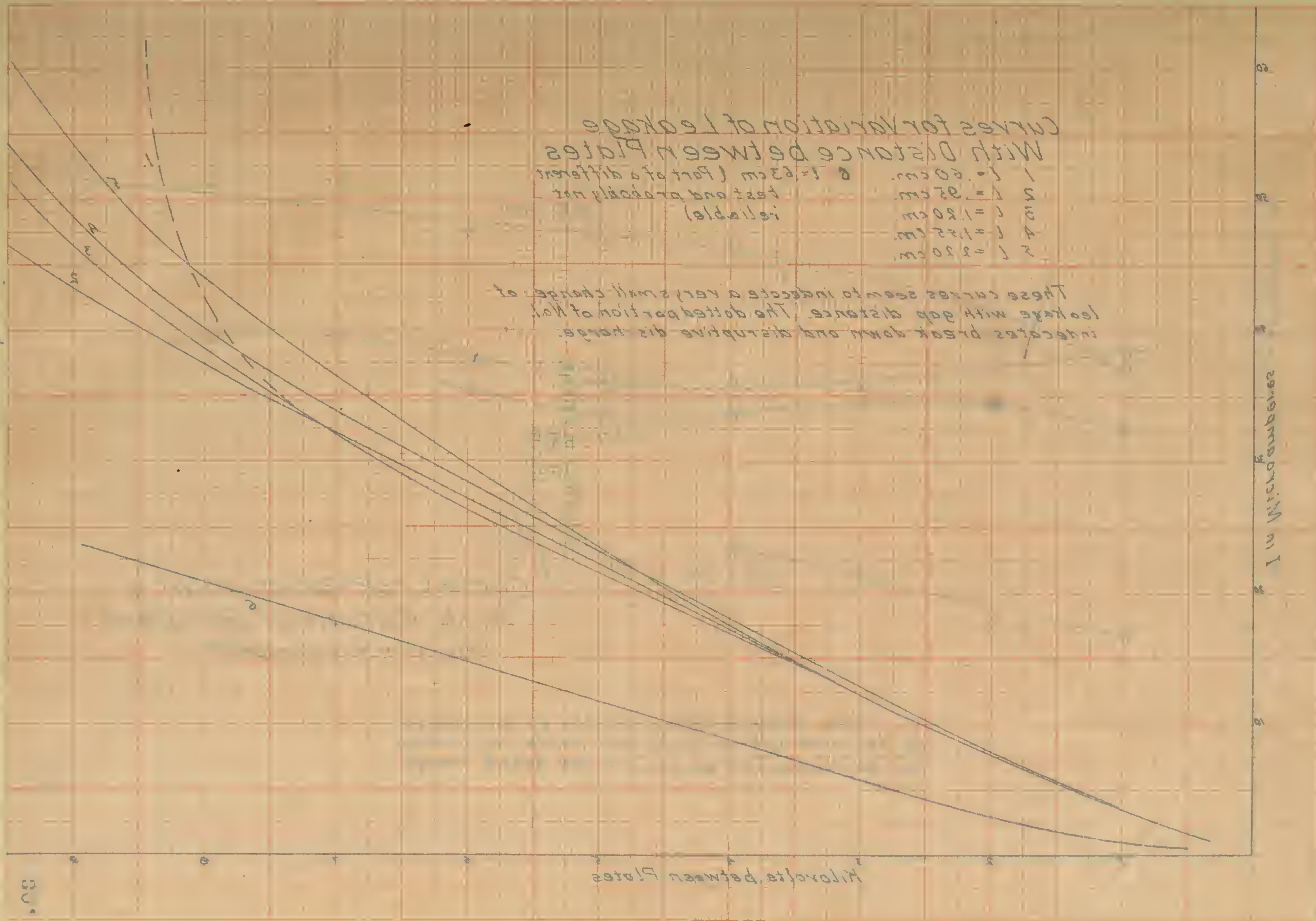
X=9000.

l	I	α
.60	22.0	2.65
.95	415.0	


α (ions produced per cm per negative ion)
2.5
2
1.5
1.0
.5
1
2
3
4
5
6
7
8
9
X in kilovolts per cm.
l=.95-.60
l=1.20-.95
l=1.55-1.20
l=2.2-1.55
Curves for Variation of α
With Potential Gradient
Values for α from page 28
Note:- Each o results from the elimination of
N_0 between the curves for two values of l hence
the two values of l on each of the above curves


Curves for Variation of α
With Potential Gradient
Values for α from page 28
Note: Each result from the elimination of N between the curves for two values of l hence the two values of l on each of the above curves
l=3.5-.160
l=1.20-.35
l=1.56-1.20
l=2.2-1.55
X in kilovolts per cm.
q (ions produced per cm per second)


Curves for Variation of Leakage
With Distance between Plates
1 l = .60 cm.
2 l = .95 cm.
3 l = 1.20 cm.
4 l = 1.55 cm.
5 l = 2.20 cm.
6 l = .63 cm (Part of a different test and probably not reliable)
These curves seem to indecate a very small change of leakage with gap distance. The dotted portion of No. 1 indecates break down and disruptive discharge.
I in Microamperes
Kilovolts between Plates
10
20
30
40
50
60
1
2
3
4
5
6
7
8
9



Curves for Variation of Leakage
With Distance between Plates
1 l = .60 cm.
2 l = .95 cm.
3 l = 1.20 cm.
4 l = 1.55 cm.
5 l = 2.20 cm.
6 l = .63 cm (Part of a different test and probably not reliable)
These curves seem to indicate a very small change of leakage with gap distance. The dotted portion of No. 1 indicates break down and disruptive discharge.
I in Microamperes
Kilovolts between Plates

References.

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