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THESIS

THREE MECHANISMS
OF
BREAKDOWN OF PYREX GLASS

by

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and
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Electrical Engineering Department
of
Massachusetts Institute of Technology

June, 1929

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Approved 5/23/29

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167497

Cambridge, Massachusetts
May 23, 1929.

Professor A. L. Merrill,
Secretary of the Faculty,
Massachusetts Institute of Technology

Dear Sir:

We respectfully submit a thesis entitled "Three Mechanisms of Breakdowns of Pyrex Glass" as a partial fulfillment of the requirements for degree of Bachelor of Science in Electrical Engineering.

Respectfully submitted,

ACKNOWLEDGMENTS

The authors of this thesis wish to take this opportunity to express their sincere appreciation for the guidance and cooperation of Mr. P. H. Moon, and to acknowledge their indebtedness to Mr. A. S. Norcross for his valuable suggestions.

INTRODUCTION

In the past electrical engineers had many other investigations than those of dielectrics with which to concern themselves. The insulation at hand was good enough to meet their requirements; therefore, little was done toward investigating the phenomena of dielectric breakdown.

Today the limited knowledge of insulation strength is hindering the transmission of power over any great distance. The highest commercial voltage to date (1929) is 220 k.v. which limits a transmission line to about 220 miles, that is, a line that is economically possible.

The subject of dielectric strength is apparently a complex one due to the fact that dielectric breakdown is influenced by so many variables, some of which, at present, seem to be unknown. Some of the variables that at present are known to affect the breakdown voltage are thickness of dielectric, temperature, and at high temperature the application of voltage, resistivity, and thermal conductivity. It is also quite possible the mechanical stress set up in glass after the spheres have been blown, affect the breakdown. It was also formally believed that the area of the electrode had an effect but recent investigations tend to disprove this if edge effect is eliminated.

Previous experiments have been performed with flat electrodes and flat dielectrics but the results were inconsistent and worthless due to the fact that the breakdown always occurred near the edge of the electrodes where the electrostatic field was the strongest and not where the dielectric was the weakest.

In order to arrive at the fundamental laws governing dielectric breakdown it has been found desirable to select a homogeneous material for the tests so that the breakdown does not occur at some weak spot. Paper, fiber, cloth and like materials are not desirable dielectrics to work with because of the non-homogeneity. Glass, on the other hand, presents an ideal material in this respect.

In 1904 Mościcki, in an effort to eliminate edge effect breakdown by obtaining a uniform field, performed tests on glass tubing that he sealed at the end and drew out so that the side walls were thin. In this way he obtained a much higher breakdown gradient than previously determined by investigators using flat plates. This value was 1900 k.v. (max.) alternating potential at 50 cycles, per centimeter of thickness.

In 1928 two other investigators, Inge and Walther, eliminated edge effect by the use of thin glass spheres and also by placing the electrodes and flat specimens in a semi-conducting bath. They thus greatly increased the gradient. Their value was 3100 kilovolts per centimeter for both alternating and direct potentials.

More recently, Inge and Walther, after eliminating edge effect by blowing spheres, made some experiments with thin glass at low temperatures and found the breakdown gradient independent of the thickness.

In 1922 Wagner made public his thermal theory of breakdown of solid dielectrics. While conducting tests Wagner noticed that just prior to the rupture the speciments would be heated in some spots and comparatively cool in others. Interrupting a test before breakdown he observed that the electrical qualities of the hot and cold spots were practically the same. According to Wagner, for a given temperature, breakdown voltage is proportional to the thickness.

Inge and Walther, during their experiments, found that this was true and also that, for a given thickness of specimen, with a decrease in temperature a point is finally reached where a continued decrease in temperature no longer lowers the breakdown voltage. This last region is known as the disruptive region.

In between these two regions they found a smooth curve connecting the two mechanism. This disruptive region was first theoretically determined by Rogawski who in a report worked out from the structure of the molecule of a simple polarized lattice of sodium chloride, mathematical relations which showed the breakdown gradient independent of thickness. This value was 100 - 200 million volts/cm. He believed breakdowns of this type were caused by the rupture of the molecule and called it the disruptive region.

Just prior to Rogawski's work, Joffé presented his ionization theory of breakdown. He set forth that ionization of the dielectric,caused by the potential gradient, finally lead to the breakdown. Inge and Walther at the time of their work believed they had experimentally found this ionization region but now it is believed that their breakdowns occurred in the disruptive region and the region they set forth as indefinite was really the ionization one.

To return to the thermal breakdown of Wagner, all insulating materials have a negative temperature coefficient, that is, as the temperature increases the resistance decreases so that at high temperatures normally good insulators become good conductors. Wagner then stated that due to the non-homogeneity, the conductivity of one section will differ from that of another. The point of highest conductivity will heat up, thereby decreasing the resistance, allowing more current to flow and the process repeats itself. This accumulative effect causes the rupture when the hottest spot burns through.

In 1928, Moon and Norcross of the Electrical Engineering Department of the Massachusetts Institute of Technology attempted to verify the results of Inge and Walther and to study the intermediate region in more detail by varying the temperature through a wider range. Their results tend to show three definite regions as outlined above; disruptive, ionization and thermal. They used lime glass, G-1 (lead) glass, and mica and both known means of eliminating edge breakdown, (spheres and flat specimens in a semi-conducting bath). They found that their curves for G-1 glass fitted the five points of Inge and Walther as well as those the latter drew.

The thermal region has been most successfully studied. It seems that the value of voltage obtained in this region depends on the resistivity of the specimen. Moon and Norcross give the following formula for this region for G-1 glass:

V = breakdown voltage in K.V. $V = K_3 d^{n_3} (10)^{-\frac{b_3}{T}}$

$K_3 = 1.22 \times 10^{-3}$

d = thickness of specimen in microns

$n_3 = .25$

T = absolute temperature (C)

$b_3 = b/2 - T/2.3$

Where b is the slope of the resistivity line plotted against temperature.

After having carefully studied the previous endeavors along these lines, the authors attempted to obtain three definite regions of breakdown using Pyrex glass blown into spheres.

PURPOSE OF THESIS

The object of this thesis is to determine, if possible, the three mechanisms of breakdown of Pyrex glass and to verify the theory of dielectric breakdown as applied by Moon and Norcross to lime and lead glass.

MATERIAL USED

Pyrex glass was used to obtain similar data to those obtained on lime and lead glass by Messrs. Moon and Norcross in order to verify their theory.

This material was readily obtained in tube form from which we were able to blow spheres, thereby apparently eliminating edge effect completely.

Pyrex glass is homogeneous, which is a necessary quality in order to eliminate the possibility of weak spot breakdown.

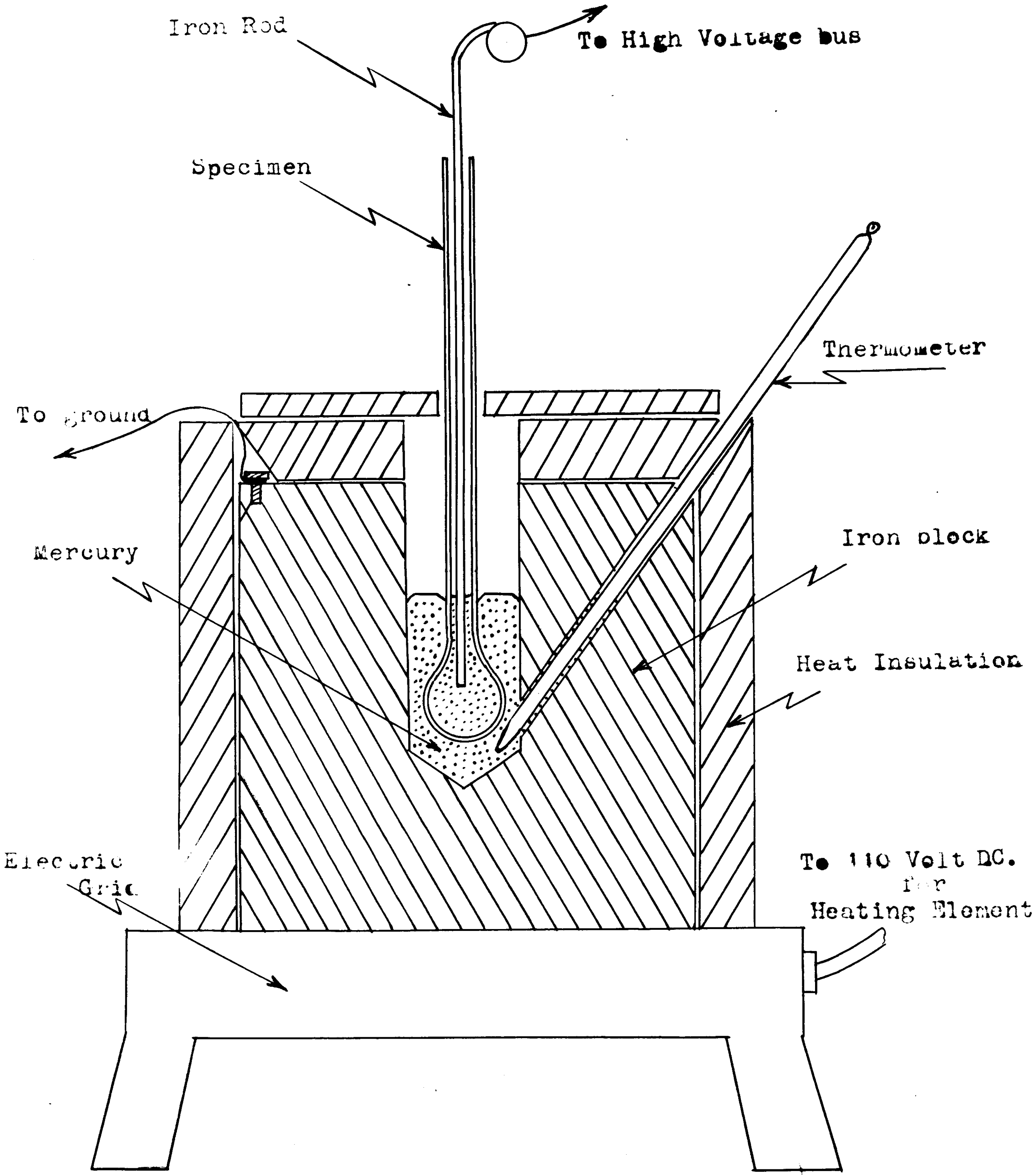
One undesirable feature is that the effect of blowing spheres on the chemical and physical structure of the glass is unknown.

APPARATUS

A 100-kilovolt kenetron rectifying set in the Electrical Engineering Research Laboratory of the Massachusetts Institute of Technology, was used for the major part of the tests. At high temperatures, where lower breakdown voltages were obtained, a 4000-volt D.C. motor-generator set was used. The Pyrex glass spheres were placed in a well in a thermally-insulated iron block heated electrically, and the electrode material filled this well and the specimen.

The temperatures were ready by means of a thermometer that had a range from 0°C - 400°C. Several lower range thermometers were used to check this one at lower temperatures and the higher range was calibrated against the boiling point of water and the melting point of tin and it was found to be correct within ± 2°C. This was as accurate as the temperature could be held constant.

The heating block consisted of a piece of six inch steel shafting with a well for the specimen. There was also a hole for the thermometer so that it was immersed in the electrode material. The illustration (Figure 1) shows clearly the layout of the heating apparatus with the specimen in place. The block it-



Heating Equipment

Figure [illegible].

3

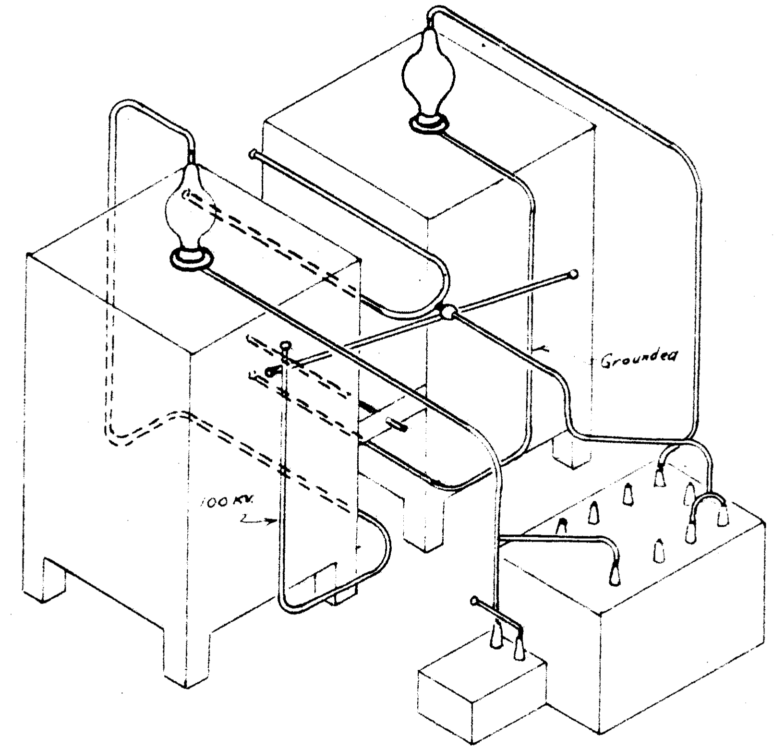
self was the ground connection while the iron rod was the negative terminal on the Kenetron set and the positive one on the motor generator set.

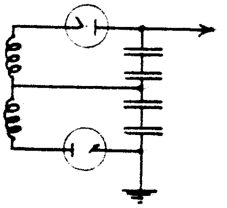
The Kenetron set consists of a high-voltage transformer, two kenetrons, and a condenser bank. These could be connected to give 50 k.v. full-wave rectification or 100 K.V. half-wave rectification. (See Figure 2). The primary voltage was controlled by an induction regulator and a motor driven rheostat. The high and low voltage connections are given in Figures 2 and 3. Tabulated data on the parts will be found in the Appendix.

A voltmeter and ammeter in the primary gave the operator an idea of the conditions on the low voltage side but were not used in recording data.

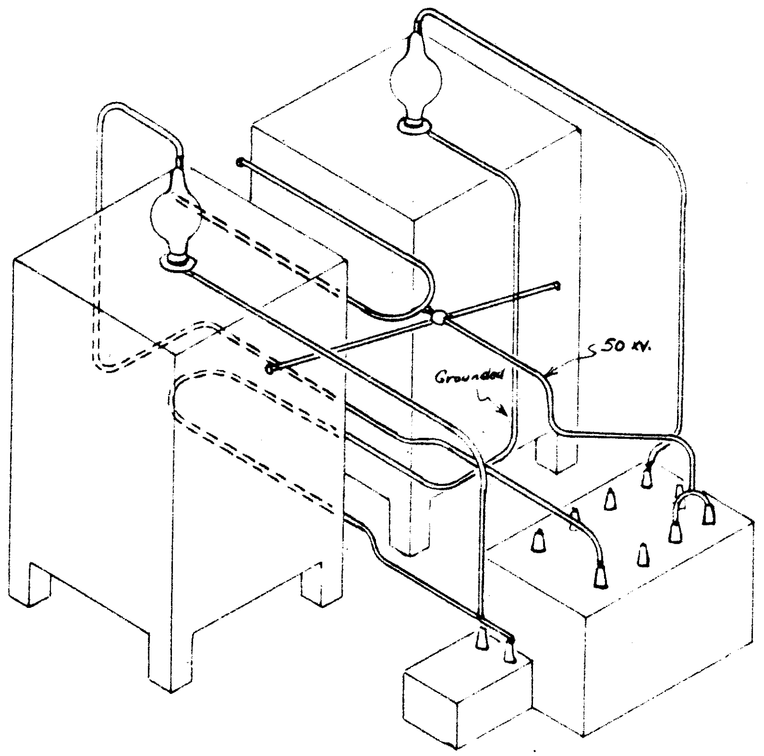
The secondary voltage was read by an electrostatic voltmeter constructed by P. H. Moon. (See Bibliography). This voltmeter was used above 20 k.v. Below 20 k.v. a Weston D. C. voltmeter with a specially-constructed multiplier was used. Both meters were read by telescopes outside the high tension cage.

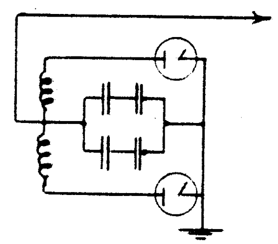
When the motor-generator set was used, the high potential was controlled by a hand operated drop wire rheostat in the generator field and by a field rheostat that varied the speed of the driving motor.





100 KV.
HALF-WAVE



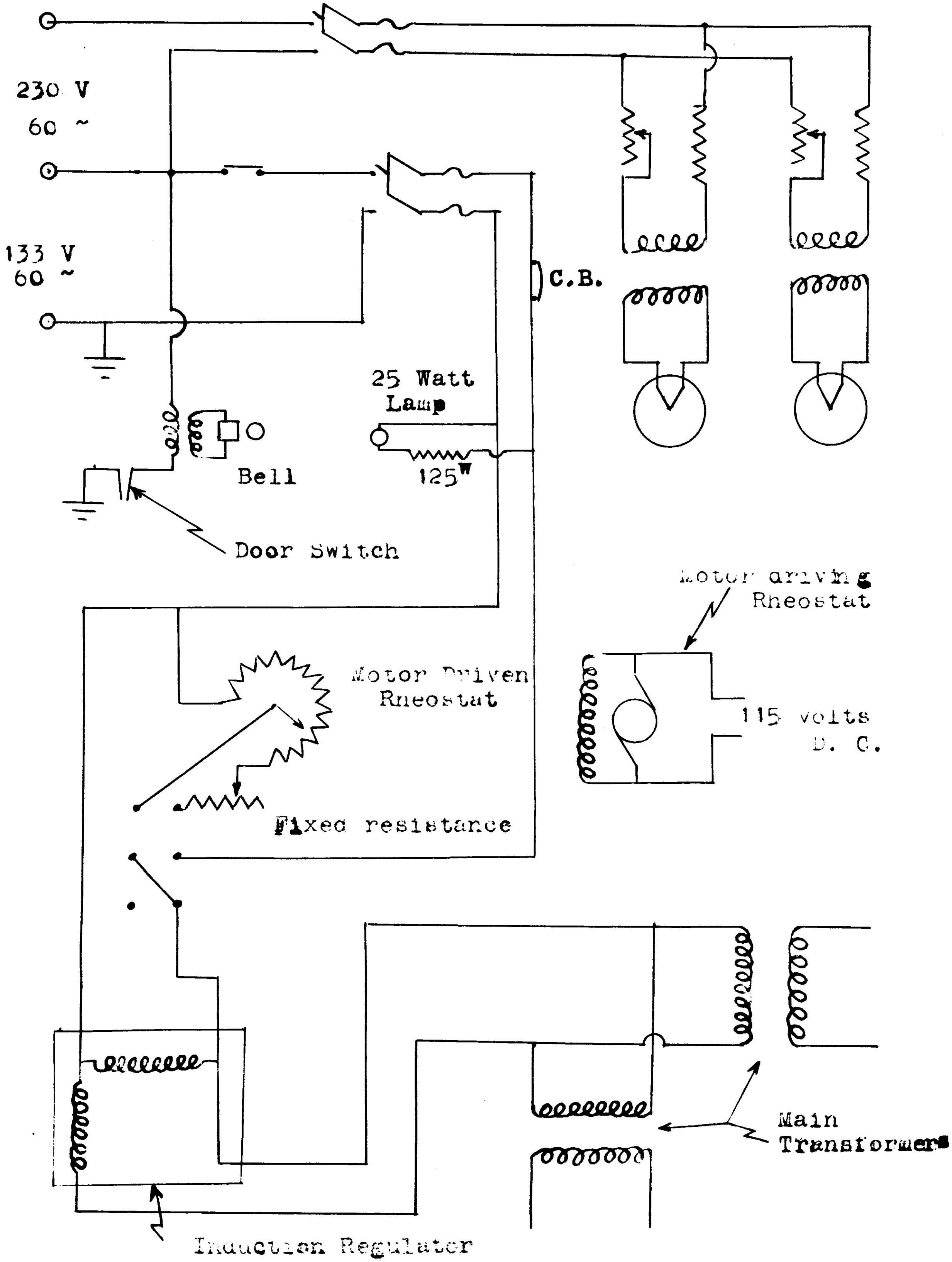


50 KV.
FULL-WAVE

HIGH-TENSION CONNECTIONS

D.C TESTING OUTFIT

P.H.M. 6/21/26.



Low Voltage Connections

Figure .

When either set was used a water tube was placed in series with the high potential lead in order to limit the current when rupture occurred, to prevent injury to the apparatus, and also to prevent shattering of the specimen, if possible.

The following safety devices were used. All high potential apparatus were inside a large metal fence, each section of which was grounded to a heavy copper ground wire which, in turn, was connected to two radiators and to the neutral of the D.C. supply. The case of the induction regulator was also grounded. A knife switch on the door made it impossible to complete the circuit without the door being closed and just before the door was closed, a contact was made which rang a bell as a warning to anyone who might have been inside the fence.

There is also a device that discharges the condensers immediately when the cage door is opened, thus doing away with the possibility of trouble with residual charges.

When using the motor-generator set, the operator sat at the driving motor and generator field controls and read the voltmeter directly. This meter was never more than 500 volts above ground because of the multipliers. The frame of the generator was grounded for safety.

DESCRIPTION OF TEST

It was first necessary to heat the glass tubing and seal up the end which was then blown into a sphere. To vary the thickness of the spheres they were blown different sizes and 8 mm. - 10 mm. tubing was used. The thickness of the spheres varied from 15 microns (.015 mm.) to 400 microns (.4 mm.).

Mercury electrodes were used the greater part of the time. The block was filled with mercury and heated to the desired temperature, and then the sphere also was filled with mercury and placed in the well in the block. The wire from the high-tension bus was then placed inside the glass tube, sinking into the Hg. The iron block was grounded. The voltage was then increased slowly until the specimen was punctured, the voltage being recorded.

The specimen was then removed carefully, inserted into a dilute solution of nitric acid to remove the mercury. Pieces of glass around the hole were then measured, with micrometers. This was done very carefully because a small error here had a great effect on the results. About six measurements were made of each specimen and the smallest reading was taken as the thickness of the specimen where the puncture occurred.

At room temperature (25°C) and at 50°C water, slightly acidic, was used as an alternate electrode. For the higher temperatures mercury was used most of the time. Mercury boils at 357.2°C; and at 300° C considerable mercury vapor, which is very poisonous, was given off. At the lower temperature, a dilute solution of hydrochloric acid was also used and at the higher temperature Wood's metal. In both cases the results checked those taken with mercury electrodes (See table below).

TABLE I

Voltage	Thickness	Electrode
250°C		
1300	.025	Cu
2320	.025	Hg
3650	.045	Hg
3450	.045	Wood's Metal
300°C		
1200	.105	Cu
2800	.100	Hg
25°C		
6600	.015	Hg
4440	.014	HCl

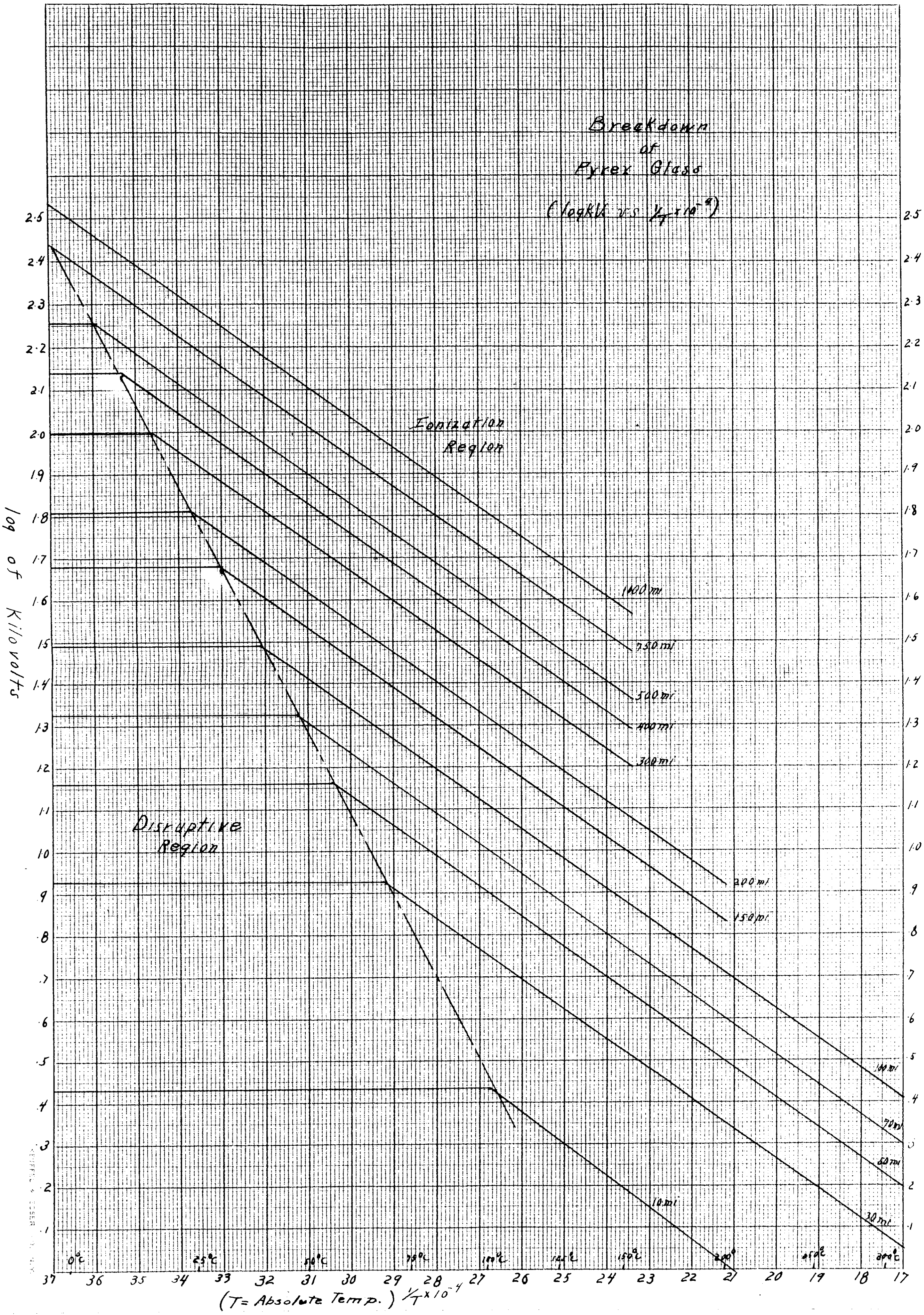
However, when copper dust was used, the specimen always broke at a much lower voltage than that obtained with any of the other electrodes. (See previous table).

The results are tabulated in the Appendix. From this data curves were drawn up of log of voltage vs. log of thickness, and log of voltage vs. the reciprocal of the absolute temperature.

DISCUSSION OF RESULTS

The curves for the disruptive and ionization regions (See Fig. 4) were easily obtained and compare favorably with those of Moon and Norcross. The slope obtained in the ionization region showed that the voltage varied as the .71 power of the thickness in centimeters for Pyrex. G-1 glass gave an exponent of .66 while lime glass gave .63. In the disruptive region a gradient of 3100 K.V. per cm. was obtained. This exactly checks the value obtained with G-1 and lime glasses. Although the slopes are nearly the same, Pyrex gives a slightly higher breakdown voltage throughout the ionization region than lime glass. At 100° C and 100 microns, in the ionization region, a value of breakdown voltage of 8000 volts higher than that of lime glass was obtained.

In trying to obtain the thermal region considerable difficulty was encountered. In Figure 5, the 200° and 250° curves were successfully drawn giving the thermal region but they came unexpectedly close together. The 300° curve was not definitely enough defined to be of any value. When Figure 4 was plotted, it was seen that these curves did not fit in with the thermal theory as it was impossible to draw a straight line through these points.


Breakdown
of
Pyrex Glass
(log KV vs 1/T × 10^-4)
Ionization
Region
Disruptive
Region
1400 mi
750 mi
500 mi
400 mi
300 mi
200 mi
150 mi
100 mi
70 mi
50 mi
30 mi
10 mi
log of Kilovolts
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0°C
25°C
50°C
75°C
100°C
125°C
150°C
200°
250°C
300°C
37
36
35
34
33
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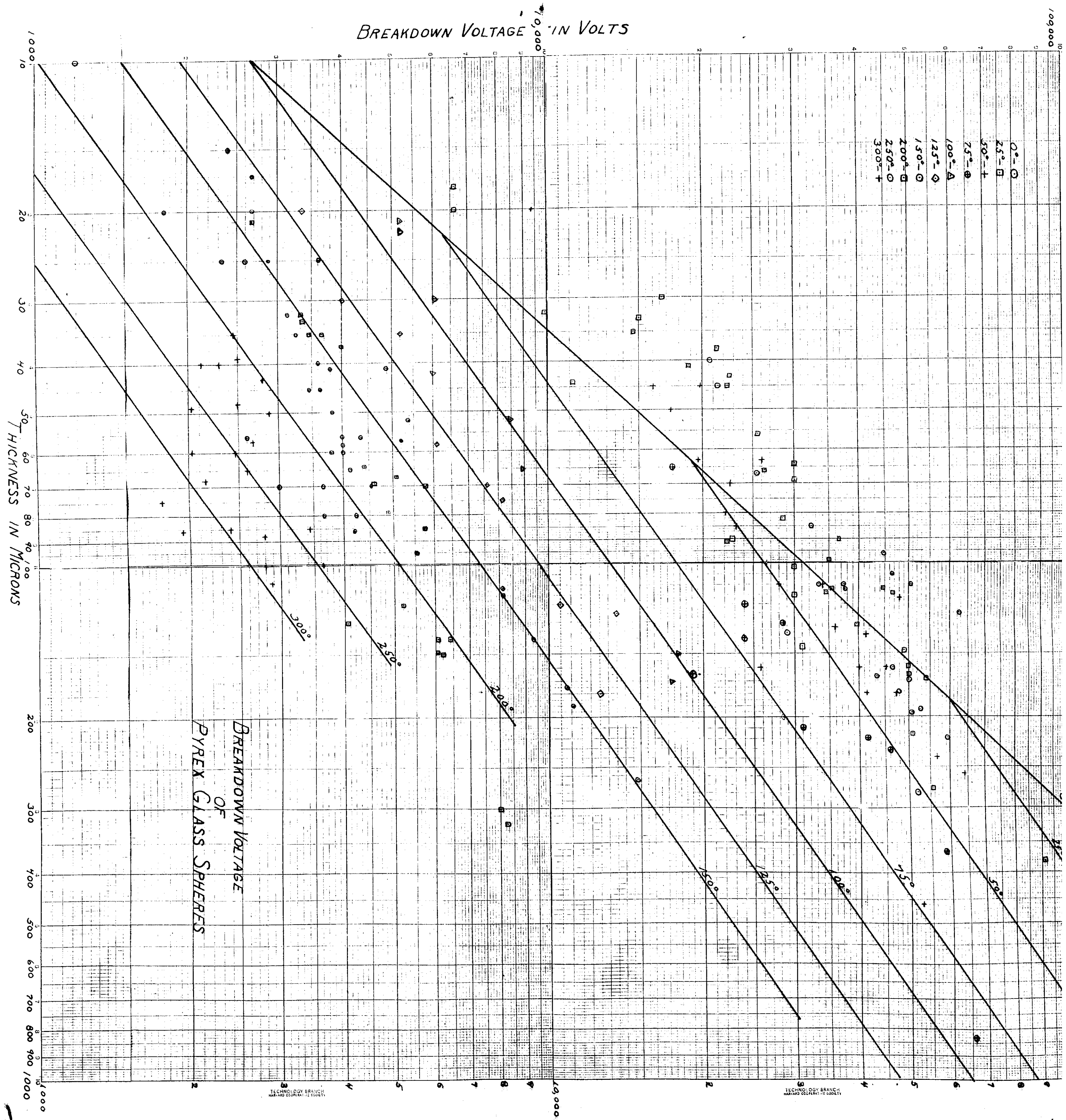
(T= Absolute Temp.) 1/T × 10^-4



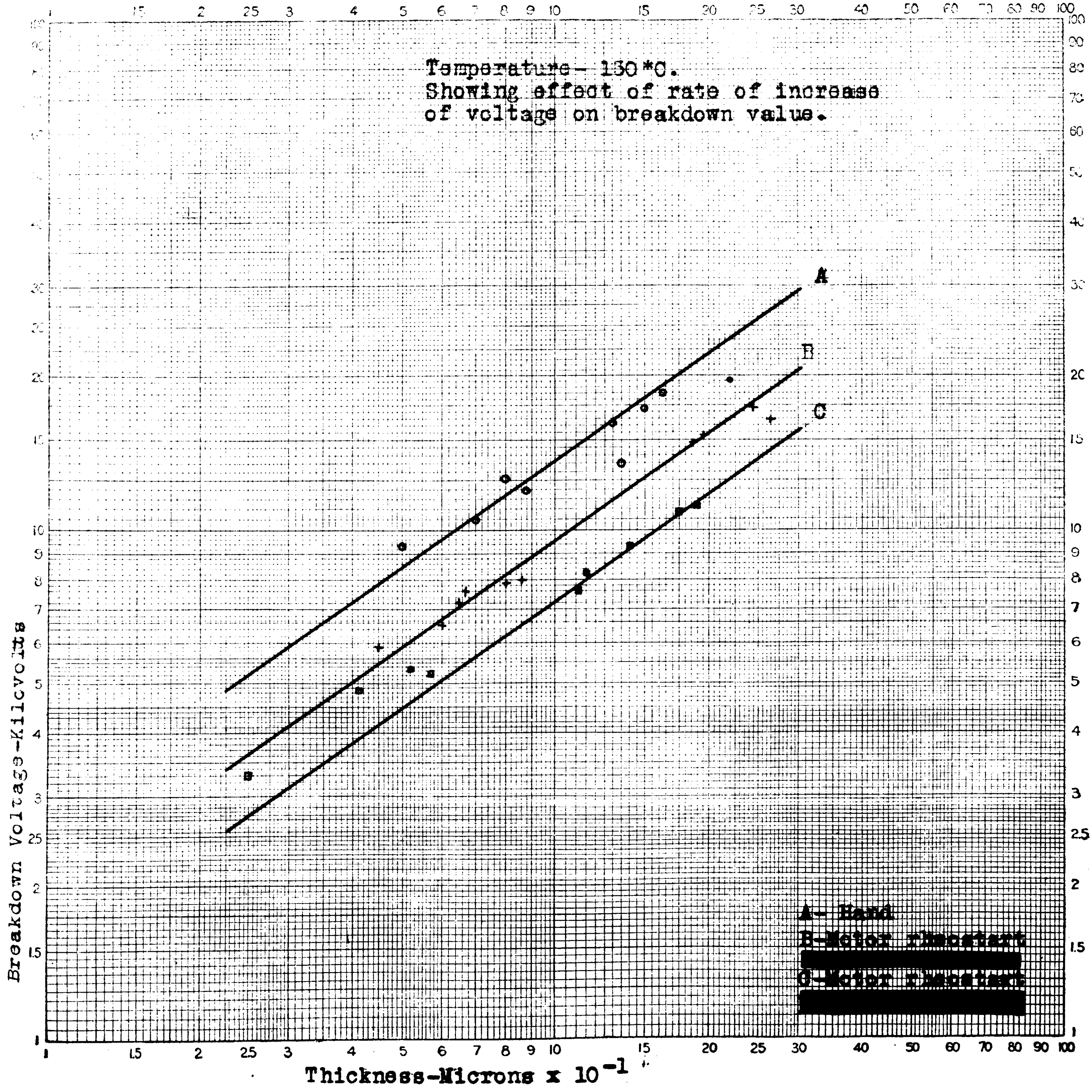
Breakdown Voltage of Pyrex Glass Spheres

To investigate this difficulty we used Wood's metal for an electrode instead of mercury but the tests thus made checked those of mercury (see Table I.) Finally,copper dust was used as an electrode but these results were obviously incorrect probably due to edge effect as previously explained. As a last resort some lime glass spheres were tried with mercury to check the procedure and the results were exactly the same as those of Moon.

We then examined bits of the Pyrex glass around the rupture through a microscope, but we were unable to account for the difficulties. Upon further study of Figure 4, it was decided that it was possible to extend the ionization region to include some of the points obtained at 200°, 250° and 300° C. This means that the thermal region occurs above 300° C for the thickness used. Since the breakdown voltage of Pyrex is higher, for a given thickness than that of lime glass, it is reasonable to assume that this is true.

One of the most important variables affecting the results is the rate of application of voltage. At the lower temperature, the effect is not so pronounced but at the higher temperature it is very noticable. At the start the voltage was raised slowly by the induction regulator actuated by hand. One 150° C curve was obtained by raising the voltage by hand. Then a motor-driven rheostat was used to raise the voltage at a much slower rate (3000 volts/min.) and these results gave a somewhat lower curve. The motor was then slowed down to rate of about 1000 volts/min. until a decrease in speed did not lower the curve and a third curve was thus obtained. These curves are plotted on a separate sheet, Figure 6. It was found that about 15 minutes should be allowed for the rheostat to run completely around at temperatures above 150° C. From these results it is apparent that if the rate of increase of voltage is too fast, the specimen does not have time to break down at the proper value so that the voltage reading obtained is too high. A motor-driven rheostat is better as it gives a uniform rate of increase of voltage.

By comparing Figures 5 and 6, the 150° C curve at 6000 volts/min. falls near the correct 100° C. curve. Also that the 150° C curve at 3000 volts/min. falls near the correct 125°C curve. From this it may be seen that the rate of increase of voltage must be carefully watched and kept so slow that a further decrease in speed will



Temperature- 130°C.
Showing effect of rate of increase of voltage on breakdown value.

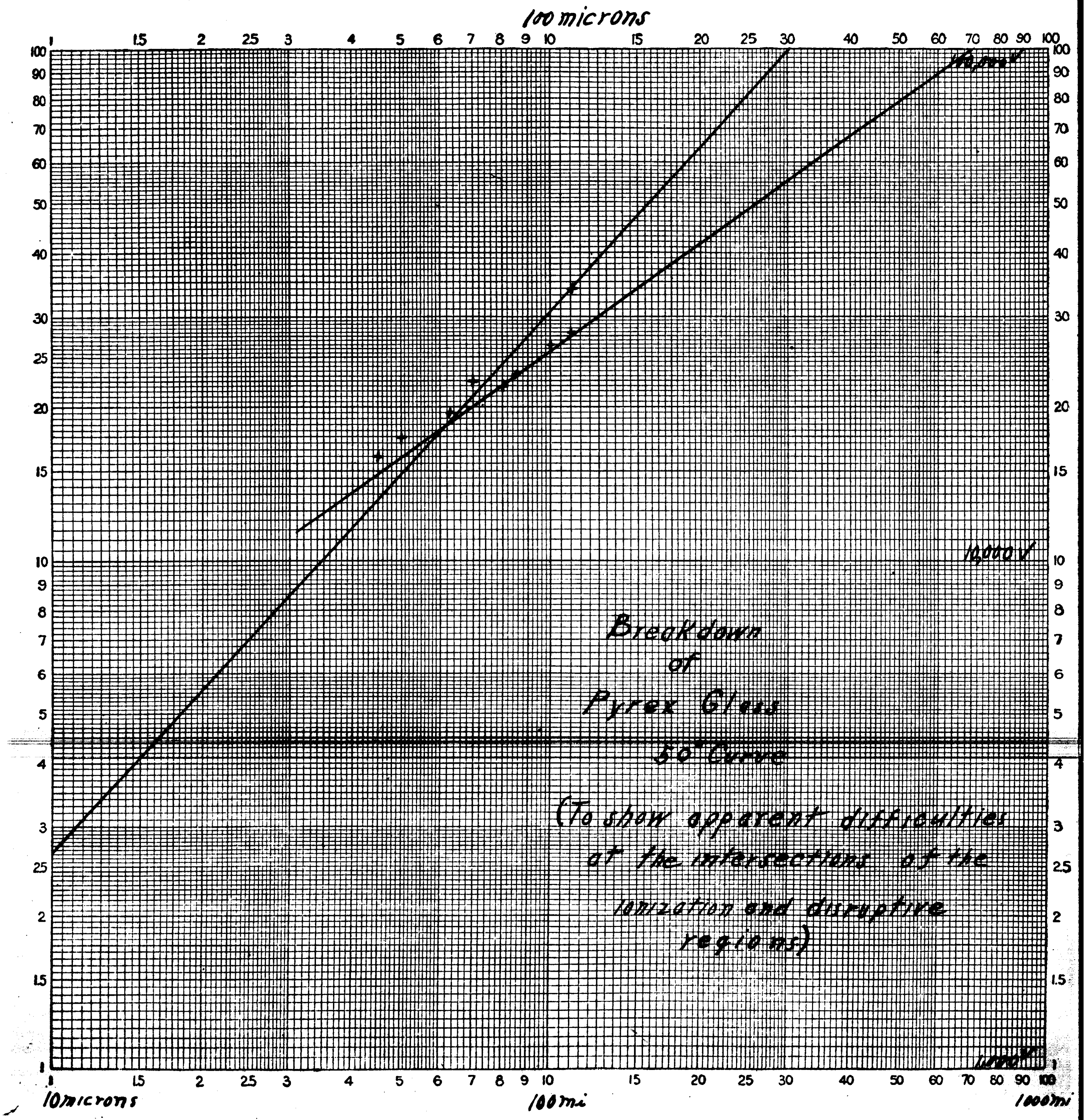
A- Hand
B-Motor rheostart
[redacted]
C-Motor rheostart
[redacted]

not lower the curve.

With the different liquid electrodes used, we are lead to believe that the kind of liquid electrode used has no effect on the specimen because the points obtained using hydrochloric acid and Wood's metal, checked those obtained using mercury. When copper dust was used the results were much below the other curves. This is probably due to the fact that a concentrated field is set up by the particles of copper next to the glass which cannot make a uniform contact and the specimen breaks down at a much lower voltage. This situation is exactly like the edge effect case. This may be seen from a comparison of the values given in Table I.

At the intersection of the ionization and disruptive regions, difficulties were encountered. From Figure 7, it may be seen that the points seem to fall in four groups, two of which fall on the projections of the two regions by the intersections. The intersections of the two regions were never definitely obtainable which seems to indicate an unstable condition at these points. This contradicts the experiments of Moon and Norcross who found these intersections sharply defined. This might explain why Inge and Walther concluded that this intermediate region was a combination of the other two.

TRADE MARK



Breakdown
of
Pyrex Glass
50° Curve

(To show apparent difficulties
at the intersections of the
ionization and disruptive
regions)

During the microscopic examination it was observed that all specimens that had been subjected to voltage acquired a branch-like formation of microscopic dendrites. Those specimens subjected to the hot metal alone did not show this formation. It is interesting to note that Joffé observed the same thing while examining salt.crystals that had been subjected to high voltage. His theory was that due to heating the crystal was softened permitting the electrode to work in causing more conduction which caused more heating. This cycle repeats itself until breakdown occurs. The dendrites were not obtained at lower temperatures with either mercury or hydrochloric acid electrodes. However, with Wood's metal at high temperature, they were noticed but to a lesser degree than with mercury.

RECOMMENDATIONS FOR FURTHER STUDY

(1) Investigation of Pyrex glass at temperatures above 300°C and below 0°C.

(2) Study the effects of heating and cooling during the blowing of spheres on the breakdown voltage. The possibility of annealing is suggested.

(3) Study of flat plates of Pyrex with edge effect eliminated.

(4) Further investigation of points of intersections of different regions.

CONCLUSIONS

(1) The kind of liquid electrode has no effect on results. Powdered electrodes are not satisfactory due to edge effect probably being present.

(2) Pyrex is a better insulator than lead or lime glass particularly in the ionization region.

(3) It is apparent that two mechanisms of breakdown exist in Pyrex glass and it is probable that a third one will be found.

(4) The changing from the Kentron set to the motor-generator set had no effect on the results.

APPENDICES.

APPENDIX I

Pyrex at 0*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
52000	.280	Mercury	Kenetron Set	6000
52900	.193	"	" "	"
50000	.170	"	" "	"
59400	.220	"	" "	"
28000	.137	"	" "	"
62600	.125	"	" "	"
44700	.096	"	" "	"
48000	.179	"	" "	"
37400	.110	"	" "	"
33300	.110	"	" "	"
46600	.105	"	" "	"
37700	.112	"	" "	"
20 600	.040	"	" "	"
43300	.167	"	" "	"
21300	.045	"	" "	"
46700	.160	"	" "	"
50700	.113	"	" "	"
50700	.110	"	" "	"
25400	.067	"	" "	"
32200	.085	"	" "	"

Pyrex at 25*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus		Speed volts/min.
50000	.159	Mercury	Kenetron	Set	6000
22200	.091	"	"	"	"
9900	.032	"	"	"	"
11500	.044	"	"	"	"
21250	.039	"	"	"	"
15000	.033	"	"	"	"
25500	.056	"	"	"	"
39750	.132	"	"	"	"
26250	.066	"	"	"	"
30000	.064	"	"	"	"
16600	.030	"	"	"	"
22500	.043	"	"	"	"
30000	.069	"	"	"	"
6600	.020	"	"	"	"
50000	.165	"	"	"	"
22800	.090	"	"	"	"
34500	.113	"	"	"	"
54000	.169	"	"	"	"
36600	.090	"	"	"	"
14700	.035	"	"	"	"
6600	.015	"	"	"	"
35000	.098	"	"	"	"
30000	.115	"	"	"	"
22300	.045	"	"	"	"
31000	.145	"	"	"	"
44700	.112	"	"	"	"
46800	.114	"	"	"	"
28400	.082	"	"	"	"
35200	.112	"	"	"	"
49000	.148	"	"	"	"
30000	.102	"	"	"	"
91000	.380	"	"	"	"
55200	.275	"	"	"	"

Pyrex at 25*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
9000	.025	Dil. HCl	Kenetron Set	3000
18660	.050	"	" "	"
4440	.012	"	" "	"
4440	.014	"	" "	"
19300	.050	"	" "	"

Pryex at 50*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
26500	.100	Mercury	Kenetron Set	6000
19650	.063	"	"	"
16000	.045	"	"	"
22100	.080	"	"	"
9330	.020	"	"	"
41300	,180	"	"	"
23100	.085	"	"	"
28000	.110	"	"	"
17300	.050	"	"	"
25800	.160	"	"	"
41300	.138	"	"	"
45300	.160	"	"	"
36000	.133	"	"	"
19800	.045	"	"	"
22700	.070	"	"	"
26000	.063	"	"	"
40000	.160	"	"	"
52700	.460	"	"	"
56600	.240	"	"	"
47300	.180	"	"	"
34000	.110	"	"	"
64000	.259	"	"	"
48000	.117	"		

Pyrex at 75°C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min
17350	.065	Mercury	Kenetron Set	6000
46000	.232	"	" "	"
24000	.140	"	" "	"
41300	.220	"	" "	"
28500	.132	"	" "	"
66000	.830	"	" "	"
19600	.165	"	" "	"
58700	.365	"	" "	"
24000	.120	"	" "	"
31000	.210	"	" "	"

Pryex at 100*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed Volts/min.
6000	.042	Mercury	*	3000
5200	.021	"	*	"
8480	.052	"	*	"
5200	.022	"	*	"
8920	.065	"	*	"
17400	.170	"	#	"
6080	.030	"	#	"
17900	.150	"	#	"

* - Taken with one Kenetron on 50 kv. connection.

\# - Taken with two Kenetrons on 50 kv. connection.

Pyrex at 125*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
10500	.120	Mercury	Kenetron Set	3000
13500	.125	"	" "	"
4000	.030	"	" "	"
12500	.180	"	" "	"
6100	.068	"	" "	"
3360	.020	"	" "	"
5200	.035	"	" "	"
7600	.070	"	" "	"
17400	.230	"	" "	"
8160	.075	"	" "	"
11600	.125	"	" "	"

Pyrex at 150*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
7600	.112	Mercury	Kenetron Set	1000
4840	.041	"	" "	"
5320	.052	"	" "	"
11100	.190	"	" "	"
9320	.140	"	" "	"
10800	.175	"	" "	"
3600	.025	"	" "	"
14800	.265	"	" "	"
5240	.057	"	" "	"
8120	.115	"	" "	"

Pyrex at 200°C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
6400	.140	Mercury	Kenetron Set	1000
8280	.322	"	" "	"
6080	.140	"	" "	"
6220	.150	"	" "	"
6040	.148	"	" "	"
4600	.069	"	" "	"
2360	.010	"	" "	"
4000	.037	"	" "	"
3800	.060	"	" "	"
4880	.074	"	" "	"
2680	.021	"	" "	"
3440	.035	"	" "	"
5522	.095	"	" "	"
5200	.120	"	" "	"
4040	.130	"	" "	"
3360	.033	"	" "	"
3320	.032	"	" "	"
4400	.064	"	" "	"
5080	.067	"	" "	"
5750	.085	"	" "	"
3680	.035	"	" "	

Pyrex at 250*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
4320	.056	Mercury	Kenetron Set	1000
4240	.080	"	" "	"
2640	.017	"	" "	"
3600	.040	"	" "	"
4000	.058	"	" "	"
3800	.041	"	" "	"
2840	.030	"	" "	"
2320	.035	"	" "	"
2680	.020	"	" "	"
3120	.032	"	M-G Set	"
3260	.035	"	" "	"
2600	.056	"	" "	"
2400	.015	"	" "	"
1800	.020	"	" "	"
2600	.025	"	" "	"
3650	.045	"	" "	"
3450	.045	Wood's Metal	" "	"
3670	.080	" "	" "	"
4200	.086	" "		
1300	.025	Copper Dust	" "	"

Pyrex at 300*C.

Volts	Thickness in m.m.	Electrodes Material	Apparatus	Speed volts/min.
2600	.065	Mercury	Kenetron Set	1000
2800	.100	"	" "	"
2880	.050	"	" "	"
1760	.075	"	" "	"
2800	.043	"	" "	"
2800	.038	"	" "	"
2400	.085	"	" "	"
3440	.085	"	M-G Set	"
2130	.040	"	" "	"
2500	.048	"	" "	"
2020	.049	"	" "	"
2150	.068	"	" "	"
3640	.100	"	" "	"
2020	.060	"	" "	"
2890	.108	"	" "	"
2500	.039	"	" "	"
1930	.036	"	" "	"
2450	.035	"	" "	"
2670	.057	"	" "	"
2470	.060	"	" "	"
2300	.040	"		
1200	.105	Copper Dust	" "	"

Lime Glass at 250*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
1580	.027	Mercury	M-G. Set	1000
1200	.100	"	" "	"

Pyrex below 0*C.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
25500	.040	Hydrochloric Acid.	Kenetron Set	6000
16500	.030	" "	" "	"
15000	.028	" "	" "	"
18750	.040	" "	" "	"
6750	.010	" "	" "	"
18750	.030	" "	" "	"

These temperatures were obtained by the use of carbon dioxide snow (solid)

Data for Figure 6

To show effect of rate of application of the voltage.

Volts	Thickness in m.m.	Electrode Material	Apparatus	Speed volts/min.
12000	.088	Mercury	Kenetron Set	6000
12700	.080	"	" "	"
16200	.130	"	" "	"
19600	.220	"	" "	"
18450	.163	"	" "	"
10450	.070	"	" "	"
9340	.050	"	" "	"
17150	.130	"	" "	"
13550	.135	"	" "	"
16450	.240	"	" "	3000
8000	.080	"	" "	"
7600	.067	"	" "	"
7200	.065	"	" "	"
5920	.045	"	" "	"
17400	.245	"	" "	"
14800	.186	"	" "	"
7890	.080	"	" "	"
15300	.195	"	" "	"
6520	.060	"	" "	"
7600	.112	"	" "	1000
4840	1041	"	" "	"
5320	.052	"	" "	"
11100	.190	"	" "	"
9320	.140	"	" "	"
10800	.175	"	" "	"
3600	.035	"	" "	"
5240	.057	"	" "	"
8120	.115	"	" "	"

APPENDIX II

Data on 100 kv.Testing Set

Kenetrons
Two G.E.,250 ma.,50 kv.
Filiaments take 30 a. at 9 v.

Main Transformer
Acme No. 2178
Three separate transformers in one tank
Each transformer - 1.67 KVA.,220 to 57000 volts
Secondary current - .029 a.
Total reactance referred to primary - .57 ohms.

Condensers
Four sections of 35 plates each
Thickness of glass - .120 inches
Safe working voltage per plate - 25 kv.
Capacity per section - .332 mfd.
Grounded side is always charged positively
Foil sheets are 26 inches square

Filament Transformers
One,600 volt insulation,750 watts,230 to 12 volts
One,100,000 volt insulation,800 watts,230 to 12 volts

Fixed Resistors for Filaments
#1 Kenetron - 34.2 ohms,170 turns #20 B&S Advance wire
#2 Kenetron - 18.8 ohms, 97 turns #20 B&S Advance wire

High Tension Bus
Brass Tubing; outside diam.-.750 inches,inside diam.-.688 inches

Induction Regulator
100 volts,buck or boost,range 30 to 230 on 133 volt supply
1.5 KVA.,primary - 130 volts, 15 amps.

Motor-driven Rheostat
115 volts D.C.
Two speeds by change of gears,others by speed control of driving motor.

Electrostatic Voltmeter
See bibliography

Data on 4000 volt M.G. Set

Motor-generator Set
230 volt D.C.,1750 r.p.m. driving motor
4000 volt D.C. generator,two armature windings each 2000 volts
Windings can be connected in series or parallel.
Field of generator - 115 volt D.C.

Meters Used

Balance Current of Electrostatic Voltmeter
MA-98,0-150 ma. ½% accuracy

Primary Voltage of Main Transformer
#2352 M.I.T. D.E.M. Lab.
A.C. or D.C. Voltmeter,0-50-150-300 volts

Primary Current
MA-73,0-10 amps.
MA- ,0-25 amps.

Secondary Voltage
Total voltage range - 20,000 volt D.C.
MV-66,0-500 volts D.C.,Weston.
Two Weston multipliers for that range (300)
Special multiplier consisting of six 249,000 ohm units in
with the Weston meter and its multipliers.

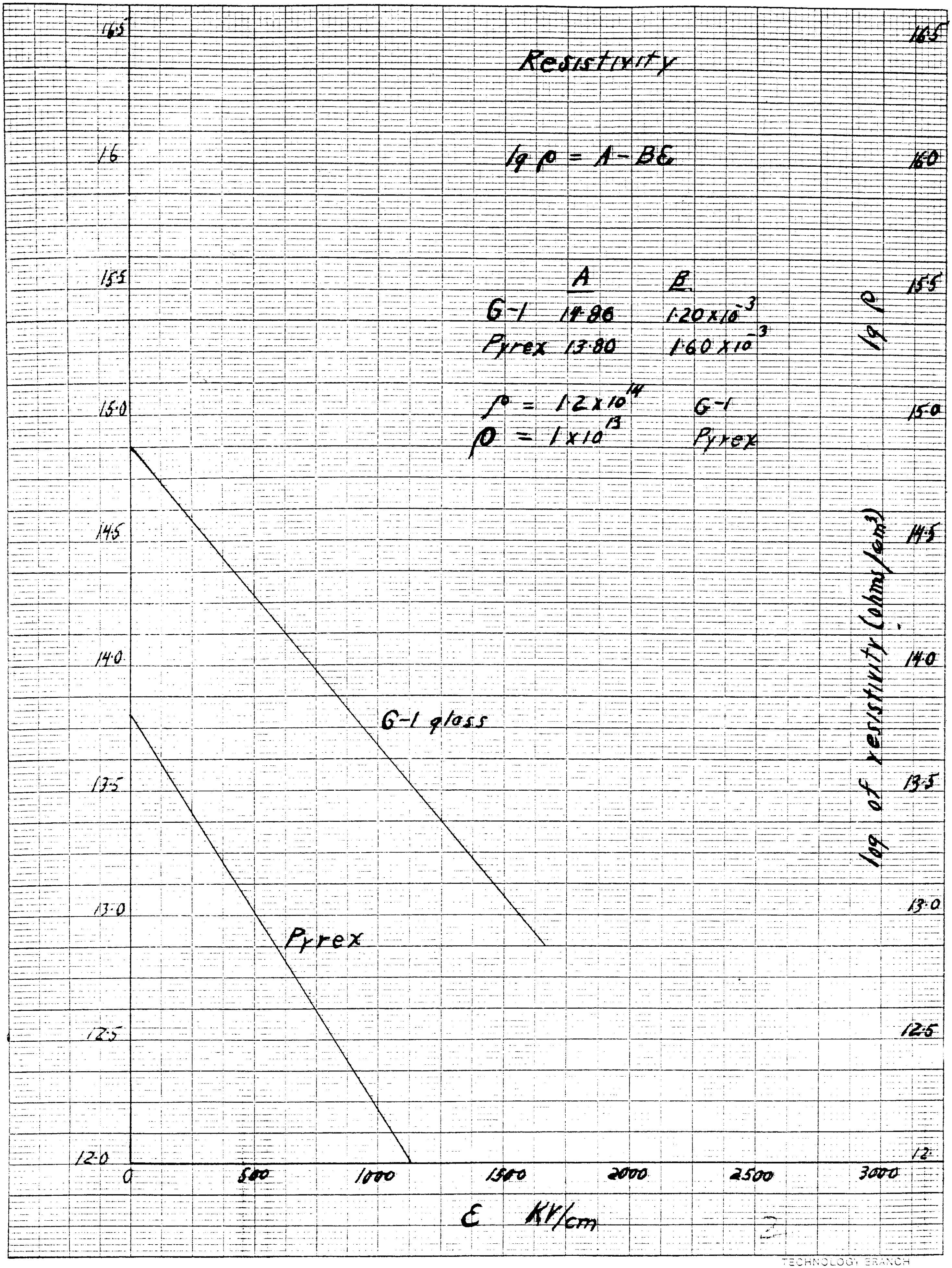
Resistivity

$$\lg \rho = A - BE$$

	A	B
G-1	14.86	1.20×10^{-3}
Pyrex	13.80	1.60×10^{-3}

$\rho = 1.2 \times 10^{14}$ G-1

$\rho = 1 \times 10^{13}$ Pyrex



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Calibration of Electrostatic Voltmeter.

Grams	Milliamperes	Calculated KV.
0.5	12.5	12.5
1.0	17.4	17.7
2.0	24.0	25.0
4.0	34.8	35.4
6.0	42.6	43.3
8.0	49.0	50.0
12.0	60.0	61.2
16.0	69.8	70.7
24.0	85.8	86.6
32.0	99.0	100.0
48.0	121.0	122.5
64.0	138.5	141.4

The above calculations are for 2 " spacing.

Weston ammeter # 26104 (MA-98) was used.

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