FLASHOVER OF INSULATORS IN HOMOGENEOUS ELECTRIC FIELDS.

Thesis by

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and
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I. INTRODUCTION. The problem of flashover of insulating materials, by which we mean the failure of the insulating material to insulate the conductor due to an electrical discharge of one form or another completely around but not through the insulating material, is one of increasing importance in electrical engineering problems and one that is little understood. Since in practice nearly all insulators of transmission conductors will cease to insulate because of a flashover at a much lower voltage than they will because of puncture of the insulating material, it is extremely important to be able to calculate the flashover characteristics. In many other insulation problems, also, flashover voltage is the determining factor in insulator failure.

The problem is a rather broad one and is dependent upon many factors. When the surrounding medium is air, all of the following factors must be considered, since they are either known to have or thought to have an influence on the flashover voltage. They are: shape of insulating material, shape of conductors, dielectric constant of the insulating material, homogeneity of the insulating material, moisture absorption and surface chemistry of the material, temperature and pressure of the air, relative or absolute humidity, joints between materials, ionization, etc.

The previous work on this problem in this country, so far as is known to the writers, is summed up in two papers before the A. I. E. E., one in 1913 by Messrs. Fortescue and Farnsworth of the Westinghouse Co. and the other in 1917 by Mr. Rice of the General Electric Co. Both of these papers, while, excellent, have as a primary object the development of insulators for special conditions and therefore do not enter primarily into the subject of flashover from a purely scientific point of view. Mr. Rice, however, conducted work very similar to that covered by this paper and comparison of results will be made later. It will be shown that Mr. Rice's results differ from those of the present experiments particularly with regard to moisture.

In order to render certain factors negligible or constant, the simplest possible shape was chosen for the form of the electrodes and insulating materials, namely, parallel plate electrodes and insulating right circular cylinders arranged between the plates with elements perpendicular to the plate surfaces. With this arrangement the lines of force are parallel to the cylinders and thus are not cut by their surfaces. Hence the form and direction of the field is not altered by the insertion of the insulation cylinder, although the actual number of lines of force running through the space occupied by the cylinder is different in the two cases.

This arrangement eliminates any difficulty in calculation due to dielectrid refraction.

To be sure, a knowledge of refraction and of the paths of the lines of force passing thru the various dielectrics is very important for the design of insulators, since refraction in many cases has a tendency to crowd the flux lines, thus increasing the stress at a particular point. In this research, however, it was thought best to defer work on this part of the problem until the other effects had been investigated.

By introducing cylinders of various dimensions and various materials, and comparing results, the effect of dimensions and constants of the materials could be determined. Also by observing atmospheric conditions for a large number of readings, the effect of air temperature, pressure and humidity could be determined over the rather narrow range encountered.

II. DESCRIPTION OF APPARATUS.

The fundamental piece of apparatus is, of course, the plate gap, outside of the transformers and regulating equipment which are a part of the regular laboratory equipment. The apparatus required for this set of experiments is described below.

A. Plate Gap. The original design of plate gap consisted of two brass plates 12" x 12" x 3/16" thick, with rounded edges, mounted in a soft wood sphere gap frame which was not in use at the time. The original plates had no shielding at the edges other than the rounded finish. It was believed at first that shielding might not be necessary because the usual rule used in design is that creepage distance should be about three times puncture distance and it was also known that the field concentration at the edges would be about two and one half times that at the center. If the above rule were valid in this case, then flashover of the insulator should occur at a lower voltage than spark over of the plates at the edges.

However, with the first specimen tried, a piece of rubber, spark over occurred consistently at the corners of the plates, thus demonstrating that shielding was required. As the size of the plates used was such that no shielding could be added without touching the sides of the stand, and also as corona was observed on the surface of the wood, it was obvious that a new stand was required unless the size of the plates was greatly reduced. The latter alternative did not seem desirable, as the field would probably no longer remain homogeneous at the large plate spacings sometimes required. Hence it was necessary to construct a new stand with increased dimensions.

This stand was made from carefully dried maple, surfaced four sides. The dimensions of the stand are shown in figure 1, and the completed stand is shown in the photograph, figure 2. No metal was used in the

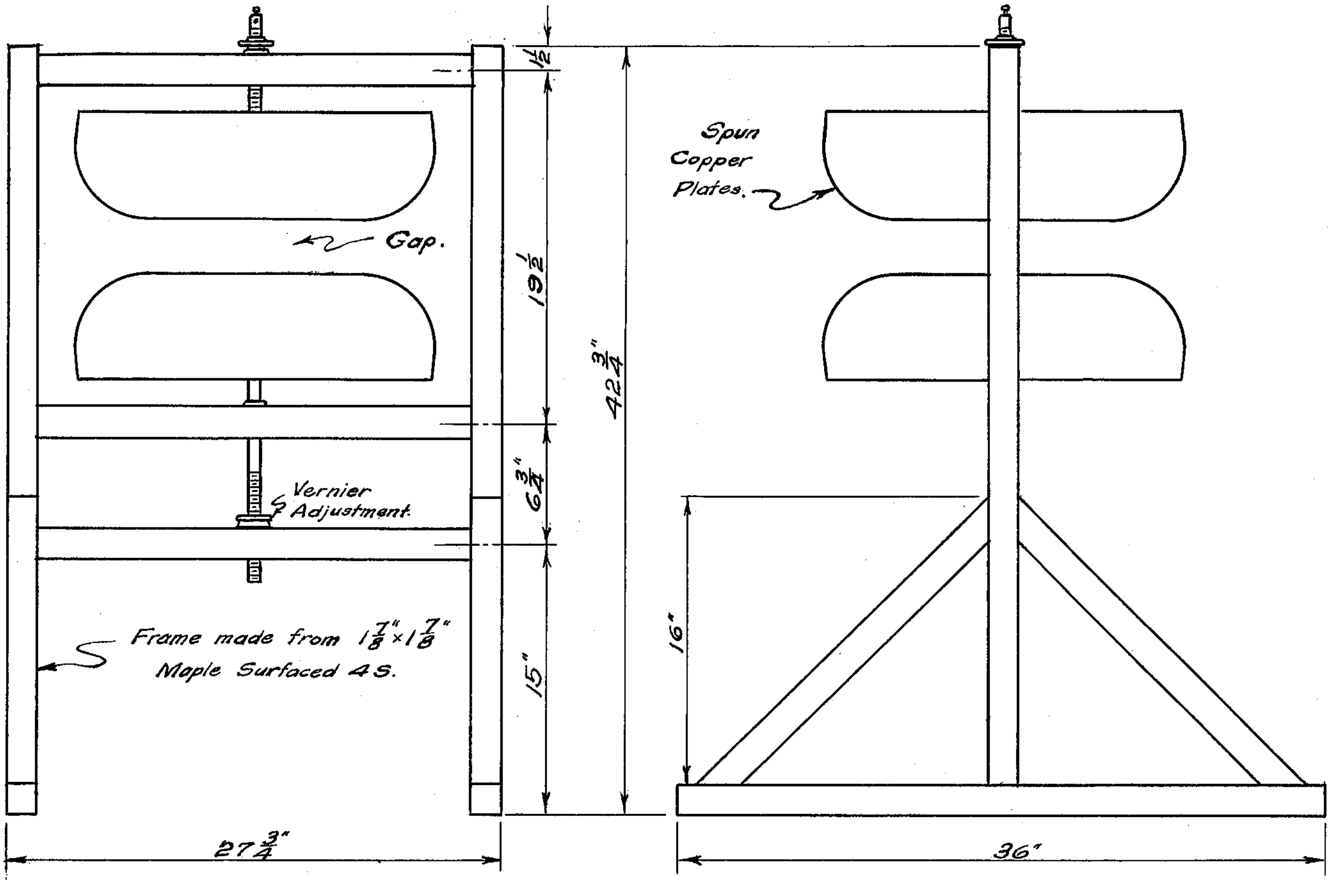


Fig. 1.

PLATE GAP.

joints except two screws which were placed in the joints connecting the base pieces with the vertical members. They were used for increased rigidity at this point and as they were in contact with the ground, it was expected that they would give little trouble. The stand was assembled with hot glue and given a coat of bakelite varnish. It was arranged to use the same hardware, that is, adjusting screws, bushings, etc., as were used in the first arrangement.

The plates were tried in the new stand to see if the previous sparking at the edges could have been due to the proximity of the wood, but sparkover continued as before, although the corona at the wood was eliminated. Hence we proceeded to shield the edges of the plates by attaching curved copper strips, rolled on approximately 2" radius, to the edges. At the corners small triangular pieces were bent and hammered into proper shape to continue the rolled edge smoothly from one curved strip to the next. The strips were fastened in place with solder and all surplus removed by chiseling, filing and sandpapering. Any hollows were filled with solder and smoothed off, so that the finished plates were fairly smooth. The shielding extended approximately 90 deg.

This shielding appeared adequate at first, but as work progressed it became apparent that to obtain accurate results over a wide range, plates must be

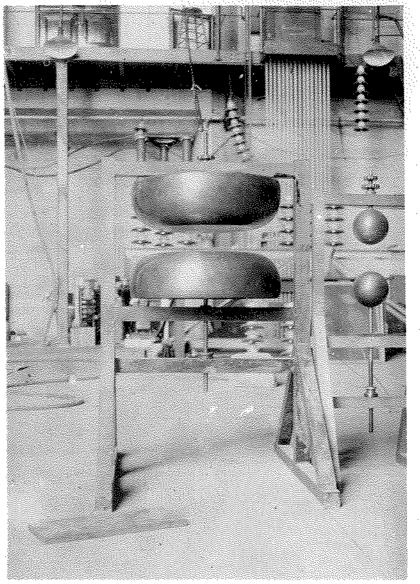


Fig. 2.

PLATE GAP.

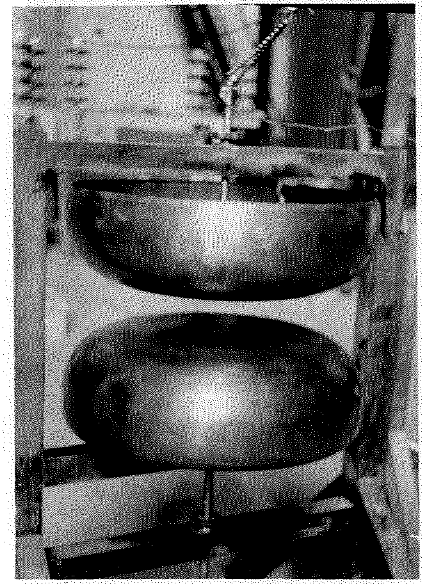


Fig. 4.

Detail of PLATES.

obtained which sparked over at, or near, the center of the flat portion when no cylinder of insulating material was interposed. For this purpose, two plates were designed, which were to be spun from sheet copper and have a radius of curvature of 4" for the shielding at the edges. From Mr. Rice's paper evidence was obtained to indicate that the above radius would be adequate for the purpose. The flat portion of the plates was 12" in diameter. The material used was 18 gauge sheet copper. Dimensions and appearance of the plates are s shown in figures 3 and 4.

In order to support these plates, a lug was specified for the center, to which the hardware could be attached. The flanges used to make the connection to this lug were provided with 6 screws, 3 for fastening and 3 for adjusting, so that any inaccuracies in paralleling of the plates could be compensated for. It was specified that the lug should be soldered to the plates to prevent any trouble from screw heads, etc., on the insulation side. The manufacturer, however, did not heat the entire plates during the soldering action with the result of a slight expansion at the center, so that the surfaces are not quite plane, but slightly convex. However, it was believed that this error would not cause any large discrepancies, as the field distortion would not be very large.

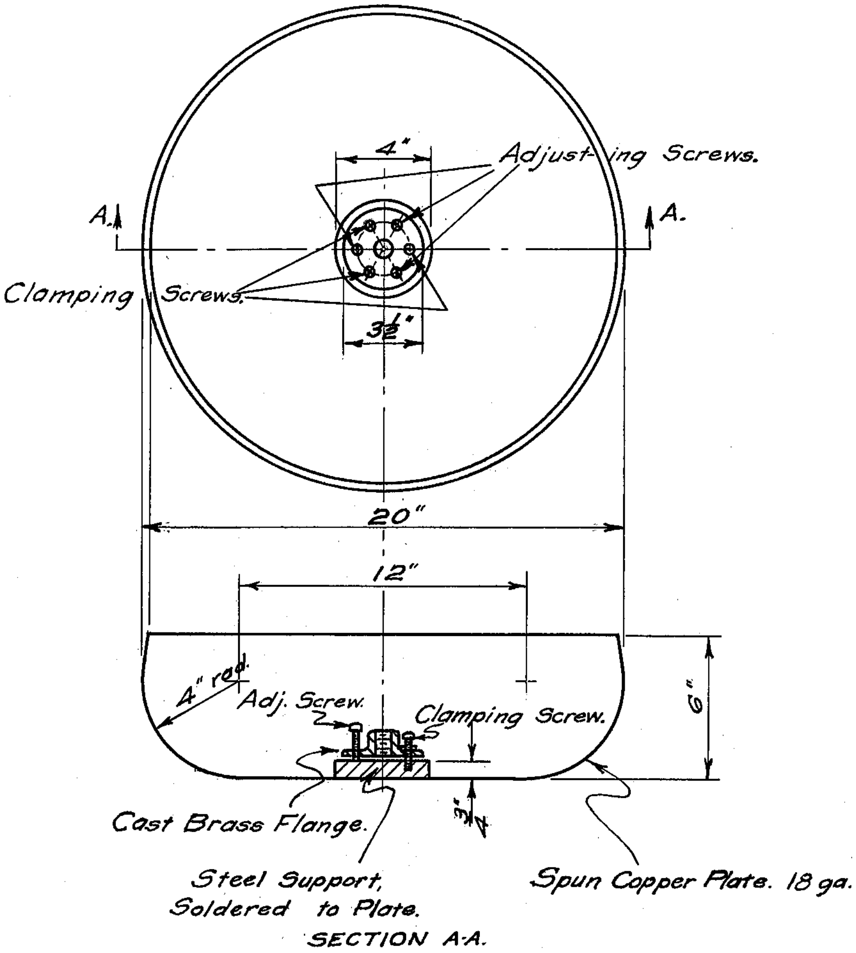


Fig. 3. DETAIL OF PLATE.

Showing Method of Adjustment.

B. Auxiliary Apparatus. For determining air pressure an aneroid barometer was used, indicating both in centimeters and inches of mercury. For determining air temperature and relative humidity a wet and dry bulb hygrometer was constructed from two thermometers, arranged for swinging around the head. For calibrating the tertiary coil of the transformer a 12.5 cm. sphere gap was used.

For reading voltage the regular laboratory voltmeters, Weston Model 155, were used, connected to the tertiary coil.

For drying specimens an electric oven was used. This oven consisted of two packing boxes, one inside the other, with heat insulation between. The heating elements consisted of standard resistance tubes fitted with Edison screw bases. A thermostat was provided to regulate the temperature within narrow limits. The original contacts were found to be unsatisfactory and silver tips were provided to prevent welding of contacts.

For handling specimens without adding moisture from the hands, a pair of tongs were constructed from strap iron and provided with bakelite-micarta tips.

The water resistance consisted of 25' of ordinary 1" garden hose wound in a spiral about a string of 20 post type insulators. A large metal plate was provided top and bottom in order to place the hose in an approximately uniform electrostatic field. The entire resistance was then suspended from the roof by a string of suspension insulators. The tube was filled with ordinary hydrant water.

III. PRELIMINARY RESULTS. This part covers the work done with the first set of plates after the shielding had been added. Due to the fact that the plates sparked over at the edges of the shielding at a voltage considerably lower than that which would have been required to spark over at the flat portion, and other troubles which were not definitely located until later, all preliminary results are very largely qualitative in nature but served to call attention to some principles and suggest lines for more accurate work.

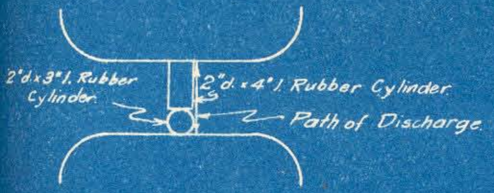
The main thing observed was the effect of the accumulation of moisture. When the plates were first tried with a rubber cylinder, it was found that spark over occurred at the edges, just as if no cylinder were present. However, the same cylinder was tried a few days later with the result that discharge occurred on the surface. During the intervening time the floor of the laboratory was almost continually wet due to rain tests, the logical conclusion being that the rubber had collected sufficient moisture to cause surface discharge at a much lower voltage. Similar phenomena were observed with glass but the time required from the first readings at which discharge occurred at the edges until discharge occurred on the surface was much less. In fact, for some pieces, this change occurred so soon that it cast some doubt on the initial readings. However, readings were irregular and inconsistent for the same piece, so that it did not seem worth while to record data.

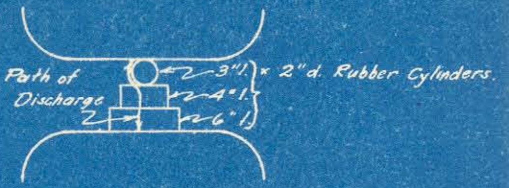
This phenomena suggested drying the specimens in the oven to remove moisture and again subjecting to voltage. The pieces were heated in the oven for several days at a temperature of about 80 deg. C.

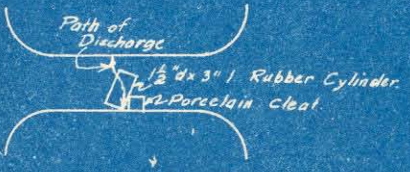
Several pieces of glass and rubber were removed from the oven simultaneously and taken to the laboratory. First a piece of glass was tested and spark over occurred at the edges of the plate. Next a piece of rubber was tested with similar results. A second piece of glass which had been exposed to the air during the above tests, about twenty minutes in all, was now tested with the result that flashover occurred along the surface. The first piece of glass was again tested with a similar result. The rubber, however, continued to cause spark over at the edges until finally, after several days exposure to damp air, the rubber flashed over on the surface. The conclusions to be drawn from the above was that flashover of a dry surface occurred at a much higher voltage than for a moist one, even though the moisture was only that which accumulated on the surface under normal air conditions. This suggested that rather important information could be obtained by plotting readings of flashover voltage against time for a specimen just removed from the oven. This proceedure was carried out for several specimens of rubber, glass and porcelain and the results are given later.

Another series of experiments was performed in order to obtain a qualitative knowledge of the effect of insulator shape, grooves, ridges, etc. although no attempt was made to treat this phase of the problem in a complete manner. Various combinations of specimens of the same and different materials were arranged between the plates with their axes in various directions so that the pattern of the lines of force would vary widely. Voltage of complete flashover was observed for various cases and it seemed to be the rule that where the enlargements, contractions, etc. followed approximately either the lines of force or the equipotential surfaces, flashover voltage was the same or perhaps increased, whereas if the insulation surfaces were at irregular angles the flashover voltage was much reduced and flashover occurred very close to the surface. This seemed to lead to the conclusion that ridges, grooves, etc., if properly designed, would be of advantage, but that, if improperly designed, they would be a detriment. Several of the arrangements tried are shown in the figures with the path of flashover if it occurred other than at the edges of the plates.

Another phenomena noticed might be called spark drying. During all the above work one transformer was energized and the secondaries of the remaining three were used as impedance in series with the gap. It was found that in many cases where the discharge occurred along the surface of the insulation, the discharge would start at a relatively low voltage, continue for a few moments and then stop. Discharge would not begin again until the voltage was raised. This phenomena would sometimes be repeated several times before a voltage was reached at which continuous discharge occurred. During the entire process the spark remained in the blue form, as the impedance was sufficient to prevent formation of an arc. Although there was undoubtedly some surging due to this connection, the increased frequency of the occurrence of the phenomena when discharge occurred along the surface would indicate that something, perhaps the drying effect of the spark was increasing the flashover voltage. Additional weight was given to this explanation during later work when a water resistance replaced the transformer secondaries as impedance. In the latter case, although the resistance was of the order of two megohms, the discharge took the form of an arc. If several readings were taken at very close time intervals, the flashover voltage at the conclusion was invariably higher than at the beginning, especially for the shorter specimens.







DISCHARGES BETWEEN PARALLEL PLATES INFLUENCED BY IRREGULAR COMBINATIONS.

IV. THE SPECIFIC PROBLEM. PROCEEDURE AND PRECAUTIONS. The first of the general conclusions given above, namely, that the moisture condition of the surface determines to a large extent the flashover voltage, was chosen as the first problem for a more detailed study. As no means was available for studying this problem directly, controlling the humidity of the surrounding air, etc., it was decided to dry the specimens in the oven and then subject them to voltage, plotting flashover voltage as a function of the time since removal of the specimen from the oven.

For this purpose the final design of the plate gap was used, and various specimens were introduced directly from the oven, readings being taken immediately and continued at definite intervals as long as possible or until the voltage became practically constant. The diagram of connections employed for this work is shown in the diagram, figure 5.

To obtain voltage as accurately as possible, the tertiary coil was calibrated with the plate gap in parallel with the sphere gap, with, however, a sufficient spacing to cause spark over always at the spheres. During readings on the plate gap, the sphere gap was always connected in parallel but set sufficiently high to cause discharge at the plates. Of course the capacity would change each time the spacing of either was changed, but the difference in calibration thus caused was found to be within the

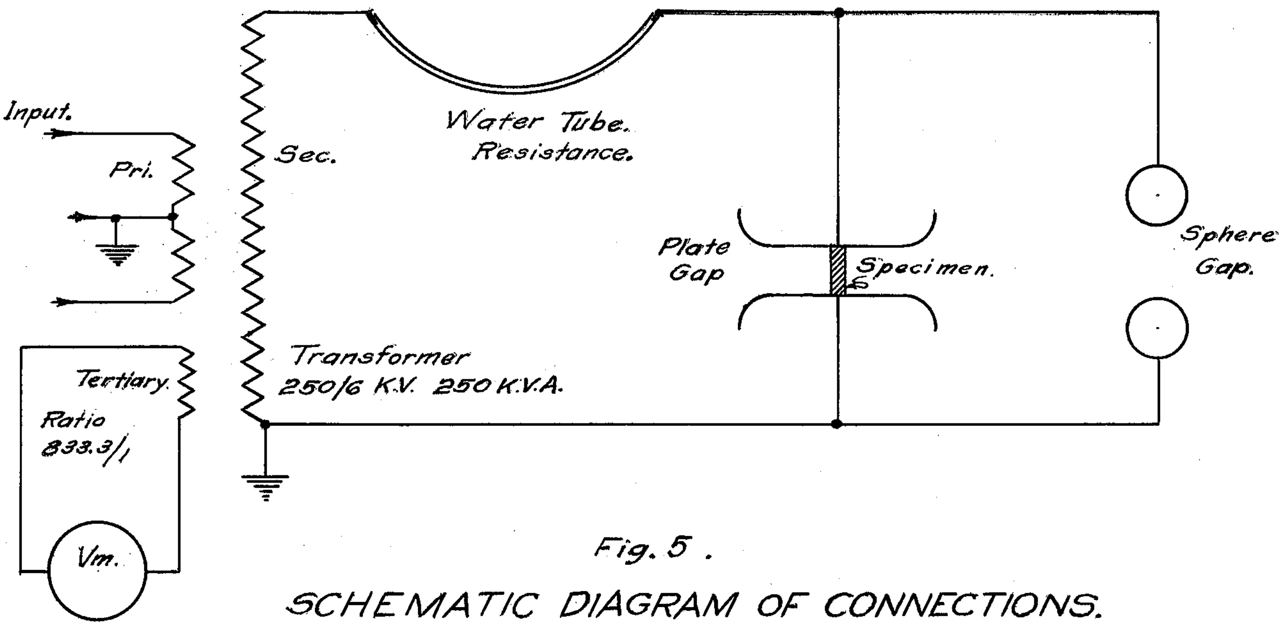


Fig. 5.

SCHEMATIC DIAGRAM OF CONNECTIONS.

Using Water Tube Resistance.

limits of error found amoung several readings for the same settings.

As the terminal of the first transformer is connected permanently ot the case of the second, it was undesirable to remove this connection. As the other transformers are connected in a similar way to the preceding one, a considerable capacity load is applied in this manner to the first transformer. To determine if this capacity changed the readings appreciably, the winding of the second transformer was disconnected from the case by inserting a scrap of heavy paper in the ammeter film cutout and a calibration curve of tertiary volts against sphere gap volts taken under this condition. This was compared with a similar curve in which the above precaution was not taken. No appreciable difference was found in the two curves. For simplicity, therefore, the other units were left connected during the tests, the primaries of course being opened to prevent excitation.

In order to facilitate calculations, various curves were made up which might be of value in other laboratory work. One of the most convenient was an alignment chart by means of which air density factor and sphere gap correction factor could be read directly if air pressure and temperature were known. A copy of this chart is attached hereto.

Voltage applied to the specimens was increased steadily from zero to flashover in each case. No accurate determinations were made of the rate of increase but it did not exceed 6 KV. per second. It was attempted to keep this rate of increase constant for all readings for a particular curve, but this was not always possible, due to circumstances beyond our control. Some readings were taken in which the voltage was increased in steps, voltage first being raised to about half of estimated flashover, held 10 seconds, then increased by 10 volts of the tertiary coil, held until the end of the next 10 seconds, then increased in the same manner until flashover occurred. Marked differences were not observed in the two methods, although flashover occurred sometimes during the interval of constant voltage, thus indicating that the readings were lower with the step by step method than the same readings would have been by the other method. However, the first method was found to be more consistent and so the latter was abandoned. While some values obtained might be too high, the difference was not expected to be very large. Voltages held for long periods would have rendered difficult plotting against time.

RESULTS AND CONCLUSIONS.

BEHAVIOR OF SPECIMENS. Of the materials which have been investigated to date, glass was the most consistent. Only two porcelain specimens have been tried, and the results were not sufficiently satisfactory to warrant plotting curves. Rubber was found to have a much higher flashover voltage, but results were very erratic.

GLASS. The pieces of glass used were accurately cut by means of a diamond saw and the ends ground until they were flat and perpendicular to the sides, and consequently good fit with the plates was obtained. Although the sides contained small imperfections, no discrepancies due to them were discernable. The results obtained were quite consistent and led to the formulation of such general conclusions as are given, these conclusions being tested by the results of other samples. Several samples were tested, all giving the same general shape of curve. The results for two pieces about 2" long of different diameters, and one piece about 3" long are given in the form of curves at the end of the paper. All curves begin at a low value, rise to a maximum, remaining for a short time and decreasing again to a constant value. The longer piece showed the most marked peak.

Although practically all discharges appeared to be at some distance from the surface, photographs showed that the discharge started at the surface and travelled out to the point observed.

PORCELAIN. None of the porcelain pieces were very accurate, the end surfaces not being parallel to each other and perpendicular to the sides. As this factor apparently has quite an~~d~~ influence, as shown for rubber, the results were not very satisfactory. Various readings were taken, but found to be very erratic, although the curve followed the same general trend as the others, first rising to a maximum, remaining constant for a longer period than for glass, then falling to a constant value which did not change with time.

RUBBER. As rubber pieces were more plentiful than any of the other materials, more work was done with this material than with any of the others, although the results were not as consistent as for glass. The results for three pieces are given, all about 3" long but of varying diameter. The smallest and the largest gave curves which began at low values, rose rapidly to a maximum, remained practically constant for some time and then began to drop. The samller piece, tested under quite humid conditions, began to show decrease from mamimum much more rapidly than the larger, and reached a practically constant value at the end of

3 hours. The larger piece did not show a consistent drop, but several readings gave low values, and a curve drawn in their vicinity appears to be coming down slowly. However, after several days exposure the voltage was found to be consistently lower, being about that of the smaller piece. The maximum points of both curves were found to be at the same voltage as the puncture voltage of air with the plates at the same sapcing ant the rubber removed.

The intermediate piece, which had a slight rise at the center of one end surface so that the entire surface~~s~~ was not in contact with the plate, but left a small air gap at the circumference, was found to give a curve which did not rise as high, was more erratic, and did not fall to the same extent as the others.

Photographs showed that the discharges for the first two pieces began on the side surfaces, while discharges for the intermediate piece appeared to begin at the end surfaces, but then to leave the sides and continue in the air, thus leading to the conclusion that the condition of the joints has a large effect on the flashover voltage, and accounts for the curve not rising as far as for the other pieces.

After the flashover voltage for the smallest rubber piece had reached its constant value, several readings were taken in rapid succession. The next reading was found to again be that of air puncture, and succeeding readings were found to oscillate between the lowest value obtained and the air puncture voltage.

Another small sample about 1 3/8" long was tested in the usual manner, readings being taken at regular intervals of 5 minutes. After constant value had been maintained for some time, the flashover voltage began to rise again and finally reached air puncture voltage. A few drops of water were allowed to run onto the plate and touch the rubber. This immediately brought flashover voltage down to less than half its preceding lowest value. Repeated discharges raised the flashover voltage again, but failed, during the time available to bring it back to its previous minimum value.

CONCLUSIONS. Careful analysis of the curves led to the following explanation of their shape. The initial rise is undoubtedly due to the decrease of temperature of the film of air surrounding the the specimen, and this continues until room temperature is reached or some other effect overbalances that due to temperature. If no~~t~~ other factors entered, flashover voltage should remain constant at the puncture voltage of air under room conditions. With rubber the maximum readings appear to do this for some time.

The fall of the curve is attributed to the absorption of moisture, and the voltage decreases until the specimen has absorbed all moisture possible under surrounding humidity and temperature conditions.

Here flashover voltage remains constant. Glass, being very hygroscopic, begins to accumulate moisture as soon as the temperature begins to fall, and in this case the maximum point is reached where the reduction in voltage due to moisture absorption just overbalanced the increase due to fall of temperature. If room temperature is reached before the surface has absorbed sufficient moisture to reduce the voltage, air puncture voltage will be recorded. Rubber, which absorbs moisture much more slowly, is affected only after a considerable time. The rate of decrease and time before decrease seem to be affected by size of the piece and the humidity conditions.

This conclusion is the most important one obtained, and, we believe, should be verified by work done under conditions where humidity and temperature can be accurately controlled.

Eccentricities in the readings of rubber are explained in the following manner. It is assumed that moisture and dust particles collect irregularly on the surface. A discharge which takes a given path causes destruction of the particles which lie along that path and unless some other path is formed at which discharge takes place at the same voltage, the next discharge must occur at a higher voltage. At the same time, the presence of the electrostatic field tends to line up the particles in a bridge of conducting material between the plates, so that the longer the stress is applied the more chance that the next discharge will occur at a lower voltage. At the same time heat from the spark drives off some of the moisture on the surface, tending to raise the voltage. The limiting conditions are the air puncture voltage and the voltage obtained when the surface has absorbed all the moisture which it will under these conditions.

Inaccurate fitting at the ends of the specimen appears to reduce the maximum voltage which will be reached but does not seem to affect the lower limit of voltage appreciably. The inference is that the effects of moisture and poor fitting are more or less independent, and that if the moisture reduces the voltage below that determined by the end effect, the latter can reduce the voltage no farther.

Small inaccuracies in the plates and the side surfaces of the insulators did not seem to have any marked effect, but accurate work requires that their effect be reduced to a minimum.

COMPARISON OF RESULTS WITH WORK OF OTHERS.

Fortescue maintained that a sphondiloidal body should flashover at a voltage equal to the puncture voltage of air. This was apparently verified for homogeneous fields when the surface was perfectly true, clean and dry, no moisture was absorbed by the material, and perfect joints were obtained between plates and insulators. However, the results of this work definitely show that moisture and joint effects reduce flashover voltage to a marked extent, even though moisture is only that absorbed under normal air conditions.

The above effects were apparently established by Rice with the exception of the effect of moisture absorbed from the air under normal humidity conditions. He did not detect this effect, if we understand his report properly, but found wet by rain or other direct means had a much lower flashover. He also found that old rubber pieces, for example, showed a lower flashover than new ones. We found on the contrary, that if prpoerly dried and surfaces smooth, no difference could be detected.

Schwaiger was apparently the first to conclude that flashover was effected by humidity, and he has reached the conclusion that at zero humidity, flashover will occur at the same voltage as air puncture. He found, however, that materials which form surface films were more erratic than materials which did not, whereas for glass and rubber we have found the reverse. His results are not so expressed that a direct comparison of values can be obtained regarding effect of humidity.

SUGGESTIONS FOR FUTURE WORK. The following outline is suggested as a guide for future work on this subject.

A. Continuing present method with the same materials and in additon with lacquered surfaces and oiled surfaces, sulphur and paraffine.

B. Checking results against known data regarding surface chemistry, to determine if any connecting relation can be found.

C. Checking results against all known theories of gas breakdown.

D. Building a suitable container in which gap and other apparatus can be enclosed, and the moisture and temperature of the surface controlled by direct control of air conditions within.

E. Investigating definitely effect of ridges, grooves, etc. by first assembling various combinations of regular specimens and later building specially shaped pieces along the lines suggested by the earlier investigation.

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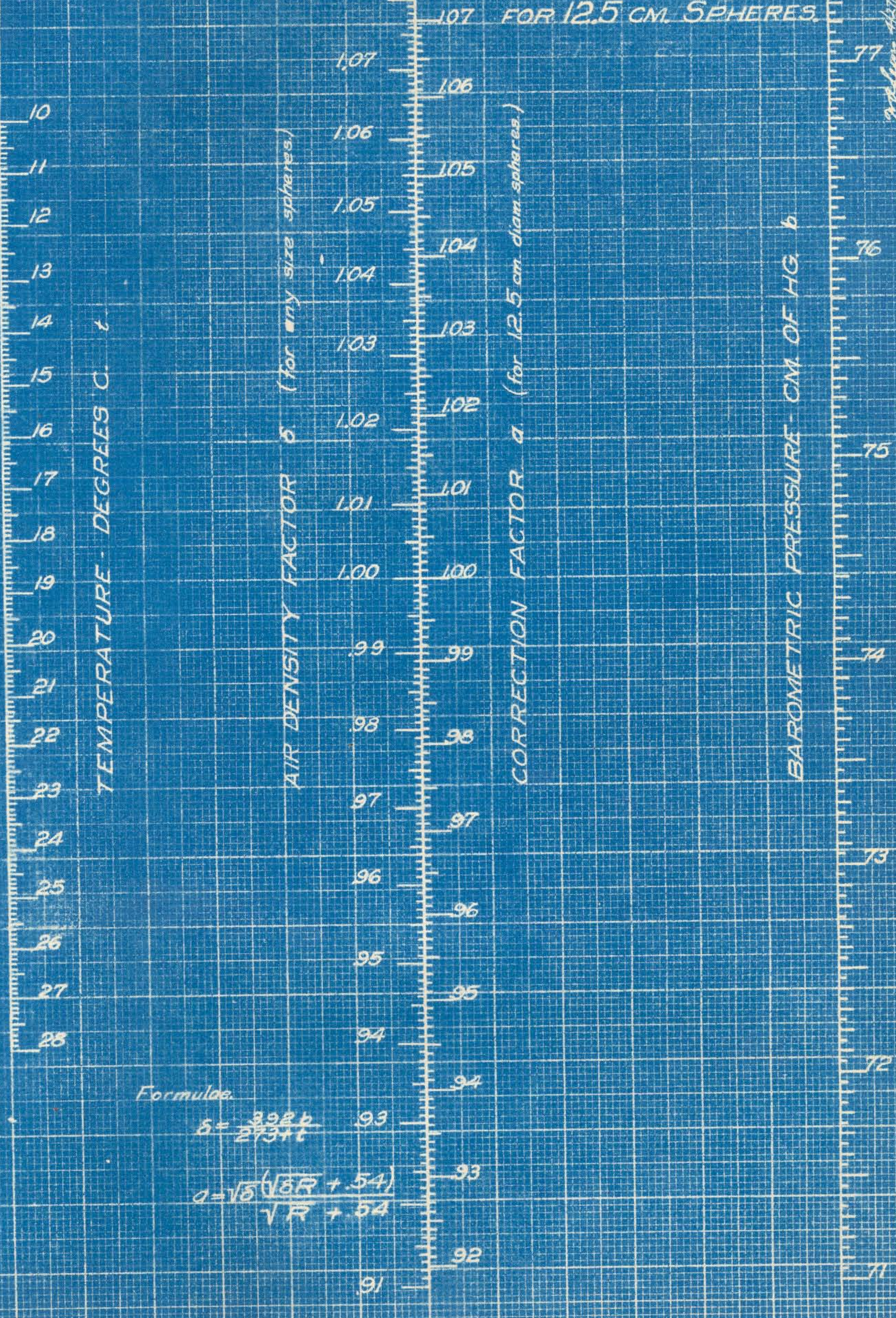
TEMPERATURE AND PRESSURE CHART.

AIR DENSITY FACTOR AND CORRECTION FACTOR FOR 12.5 CM. SPHERES.



Formulae.

$$\delta = \frac{3.92b}{273+t}$$

$$a = \sqrt{\delta}\,\frac{(\sqrt{\delta R} + .54)}{\sqrt{R} + .54}$$

W.A. Lewis 4/27/27

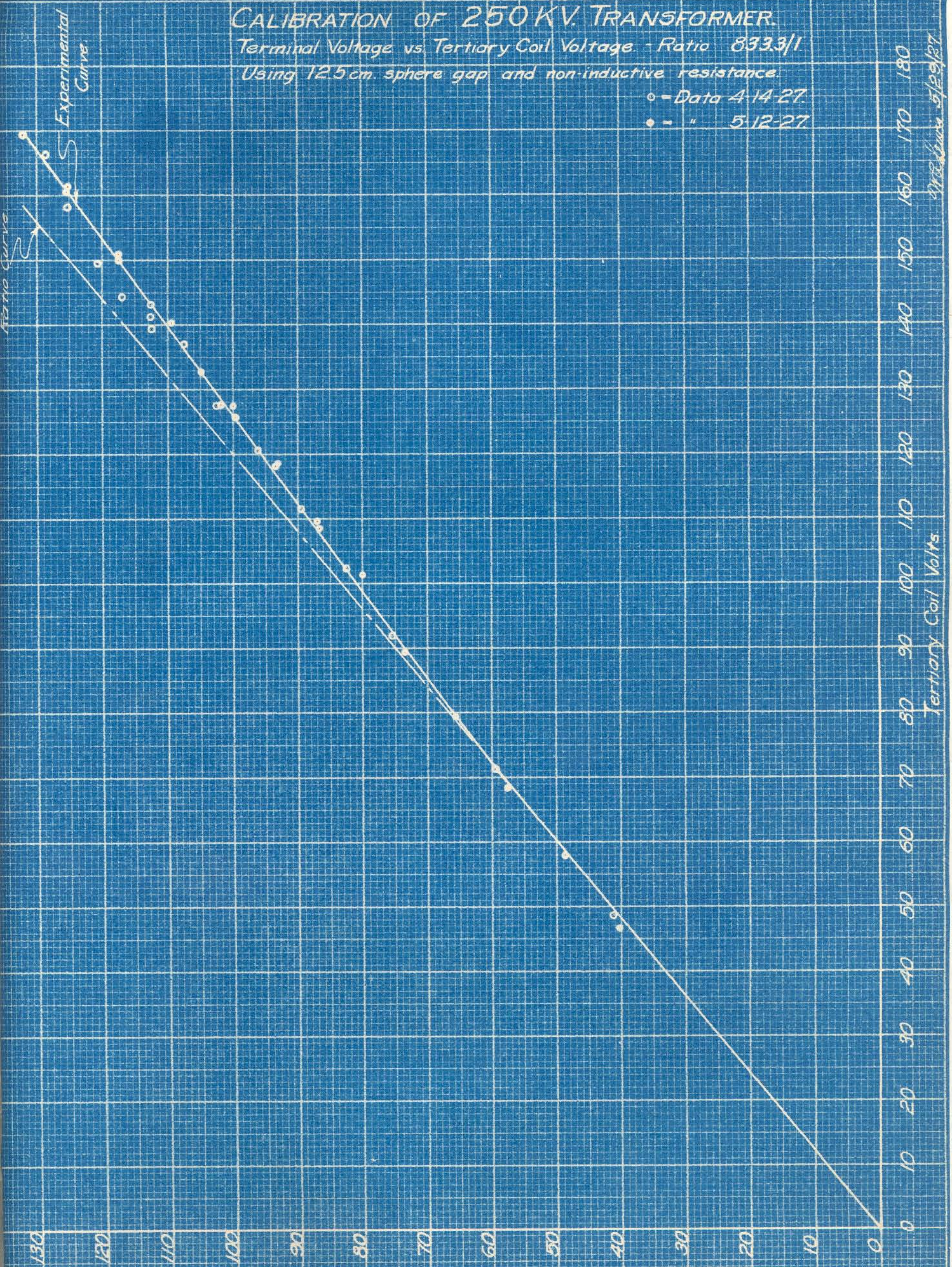
W.A. Lewis 5/29/27

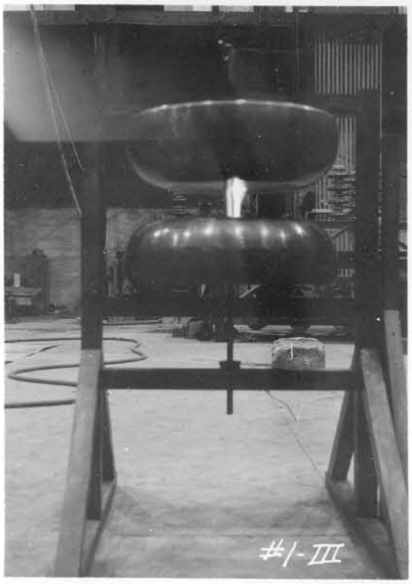
Tertiary Coil Volts

CALIBRATION OF 250 KV. TRANSFORMER.

Terminal Voltage vs. Tertiary Coil Voltage. - Ratio 833.3/1

Using 12.5 cm. sphere gap and non-inductive resistance.





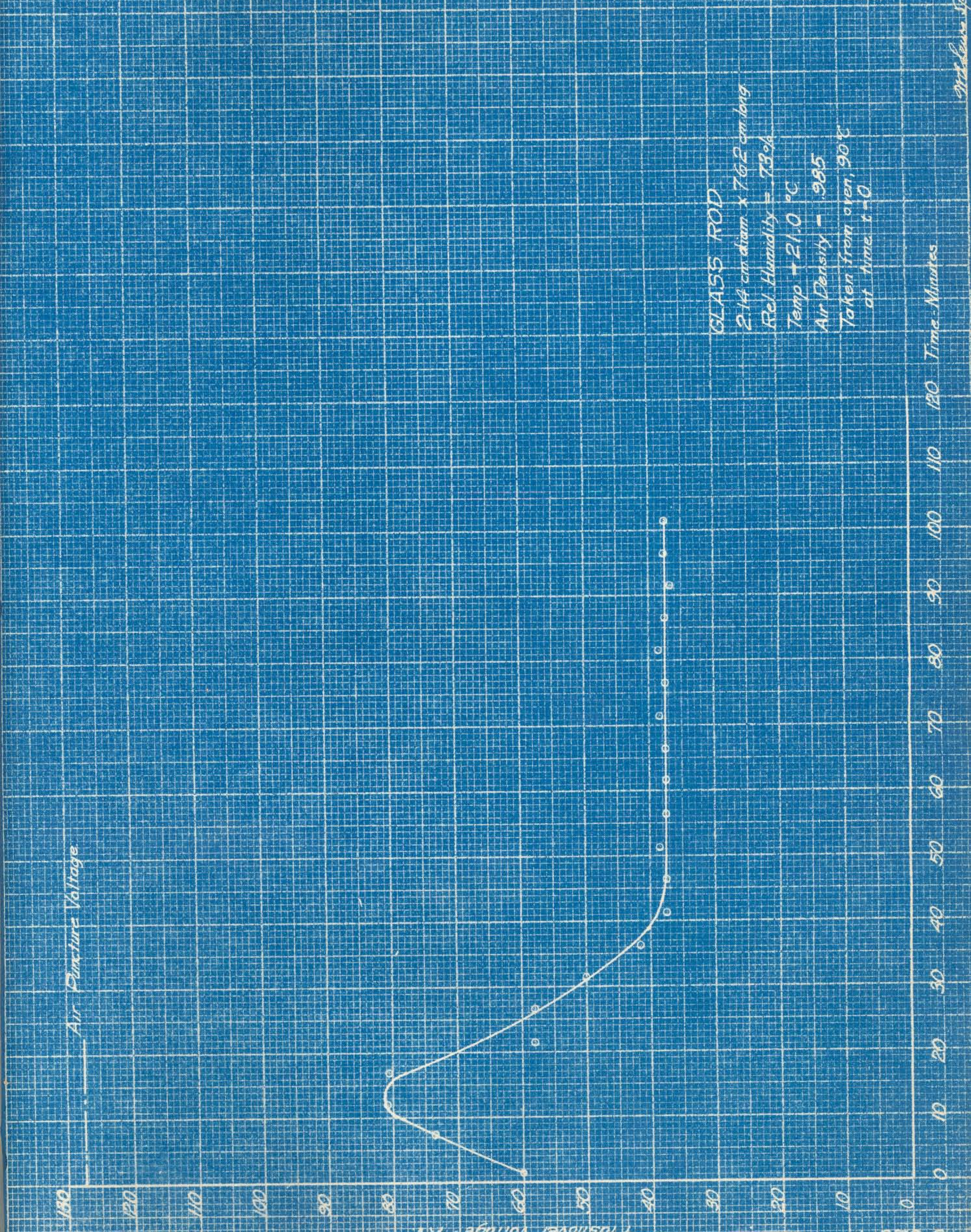
Glass Cylinder.

Glass Cylinder.

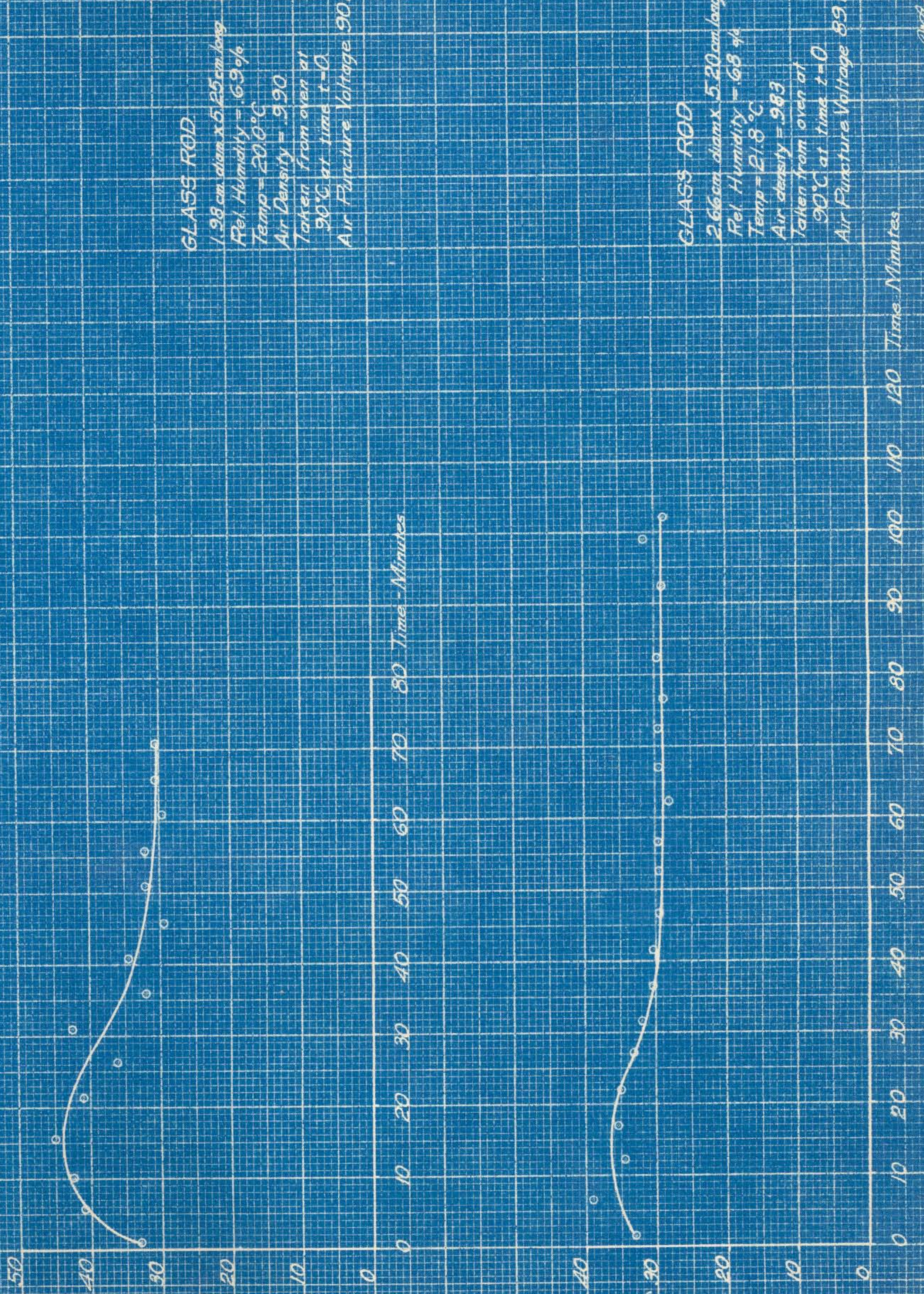
Porcelain Cylinder.

Porcelain Cylinder.

VARIATION OF FLASHOVER VOLTAGE OF DRIED GLASS CYLINDERS WITH TIME. 1.

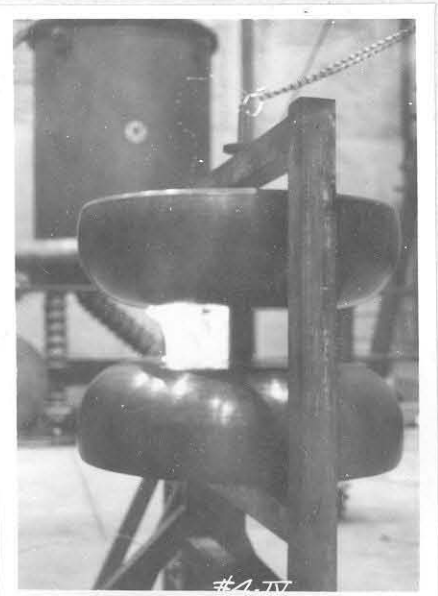


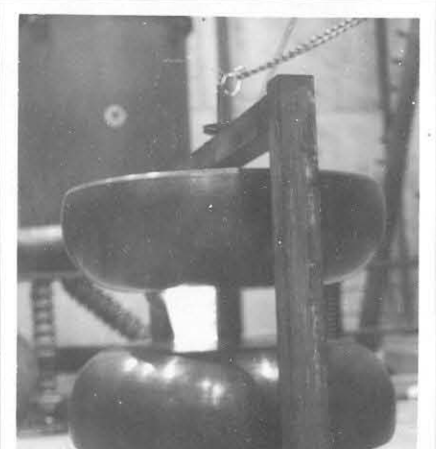
VARIATION OF FLASHOVER VOLTAGE OF DRIED GLASS CYLINDERS WITH TIME. 2.



Intermediate Piece.

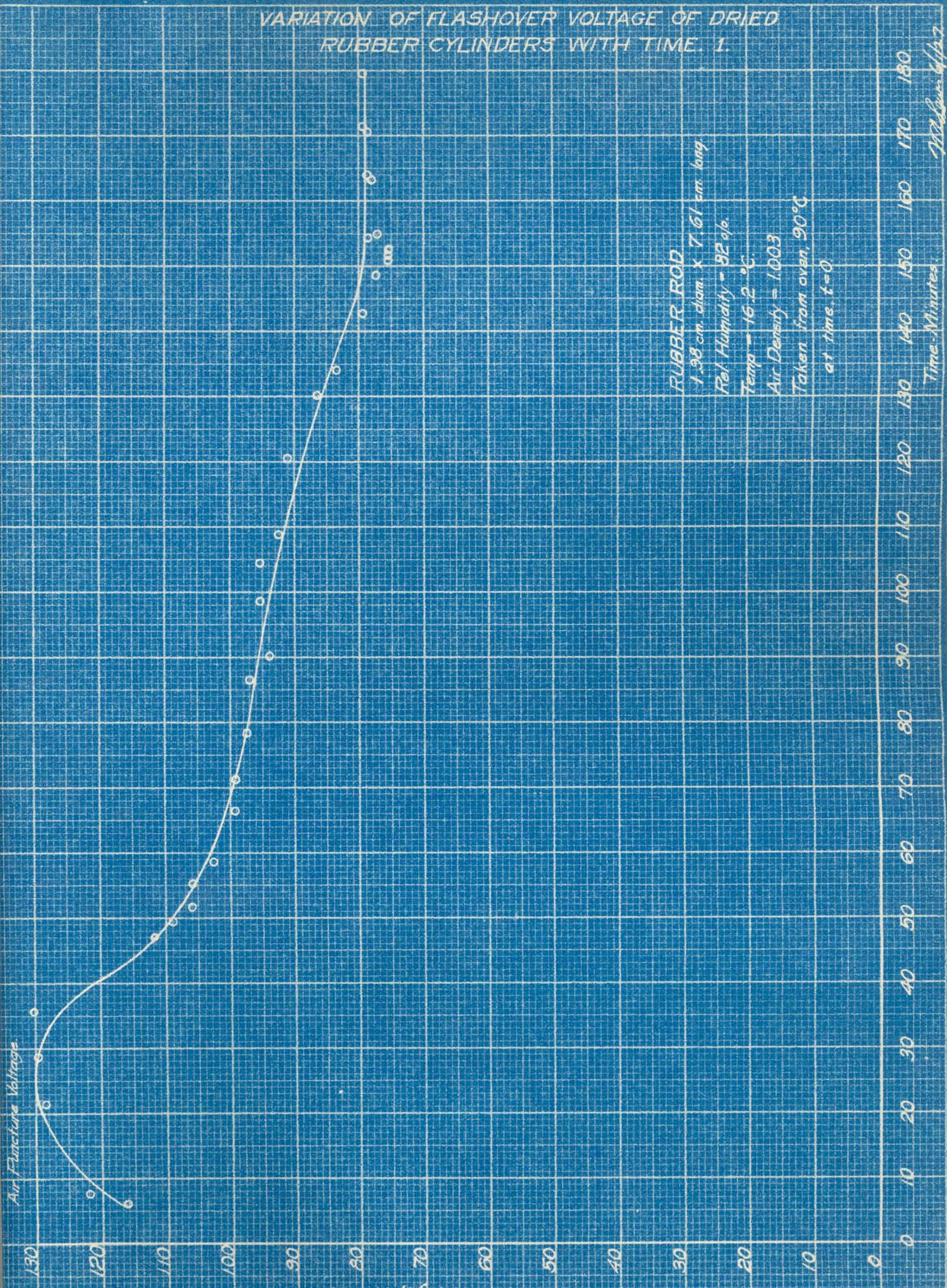
Rubber Cylinders.



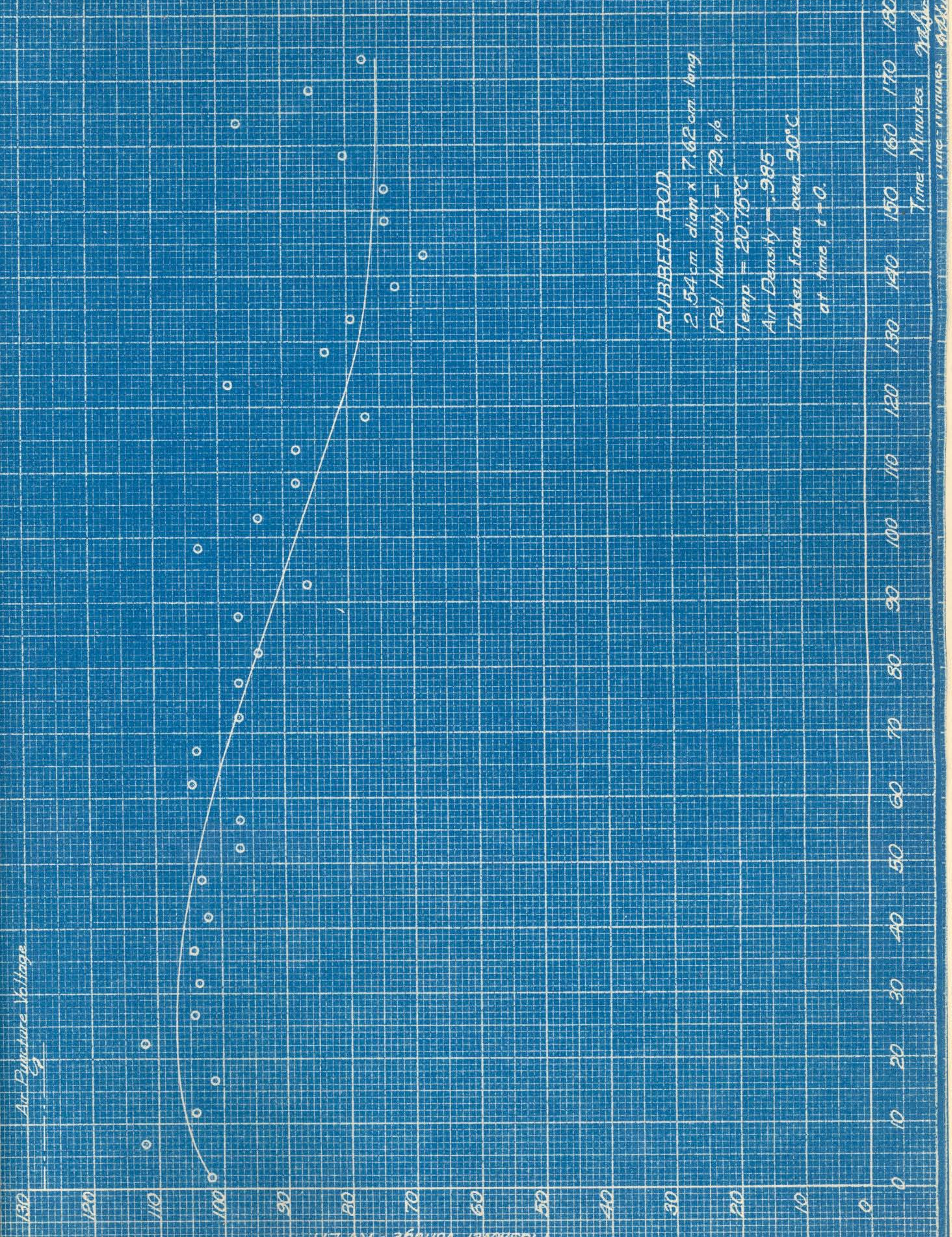


Large Piece.

VARIATION OF FLASHOVER VOLTAGE OF DRIED RUBBER CYLINDERS WITH TIME. 1.



VARIATION OF FLASHOVER VOLTAGE OF DRIED RUBBER CYLINDERS WITH TIME. 2.



VARIATION OF FLASHOVER VOLTAGE OF DRIED RUBBER CYLINDERS WITH TIME. 3.