THE IMPULSE CHARACTERISTICS OF OIL GAPS FROM THE STANDPOINT OF INSULATION COORDINATION

Thesis by

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CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

The development and use of high voltage surge generating equipment are described in this thesis.

Impulse equipment capable of producing and recording standard test surges up to 2,000,000 volts for both research and commercial testing have been developed.

The present status of insulation coordination shows the need for more data on the impulse characteristics of large oil gaps.

A new type of oil test tank has been constructed which permits less gap field distortion and better conditioning of oil and electrodes than was formerly possible for large gaps at high voltage.

The impulse characteristics of oil gaps having spacings ranging from one-half to eight inches formed by circular brass rods with spherical ends from one-fourth to two inches in diameter have been determined.

It is found that such gaps have impulse strengths which are greatly affected by slight changes in conditions of both the oil and electrode

surfaces.

Their impulse values are much higher than their 60-cycle strengths and are functions of the wave shape of the surge.

The most probable type of breakdown mechanism was found to be the thermal electric breakdown initiated by impurities in the oil.

INTRODUCTION

One of the most important and difficult problems confronting transmission and distribution engineers is the insulation of power systems against the voltages to which they are subjected. These voltages may be conveniently grouped into three classes; power frequency voltages, switching surges and lightning disturbances.

A system must be insulated to withstand the power frequency voltages of normal operation. Today transmission voltages of over 200,000 volts are not uncommon and the limit is steadily being increased. Also, due to system faults, over-voltages of power frequency as high as two and one-half to three times normal can be developed.

Transients produced by such disturbances as circuit breakers switching in and out sections of systems during fault conditions are of short duration, lasting only a fraction of a cycle of power frequency. However, they may cause over-voltages of three to four times normal operating voltage.

The highest voltages to which systems are subjected are due to direct lightning strokes. Voltages produced depend not only on the variable character of the stroke itself, but upon the ground conditions of the piece of apparatus struck. Thus a wide range of voltages may be encountered. The most common place for a stroke to occur is on a transmission line tower, and the voltage developed depends primarily upon the tower footing resistance. Calculations based on a footing resistance of ten ohms (an average value) show that voltages of the order of magnitude of 16,000,000 volts may be developed,[(1)*] and values as high as 5,000,000 volts have been recorded.[(2)] The wave shape of the main portion of a lightning surge has never been found to vary over wide limits. It usually consists of a unidirectional wave rising to crest value in from one to ten microseconds and decaying to substantially zero in about one hundred microseconds. Evidence has recently been found that the tail of the wave frequently has a relatively low magnitude component that lasts for several thousand microseconds.[(3,4)] This long duration component is

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*See Bibliography for all references.

important from a standpoint of the current flowing in certain pieces of power equipment, but is not important for insulation considerations.

It is economically impossible to insulate completely all portions of a power system to withstand such a wide range of voltages, so it is necessary to provide protective gaps and to grade the insulation in such a manner that the least vulnerable points break down first. This general problem is commonly known as insulation coordination and requires the knowledge of the insulation characteristics of the various types of gaps and flashover surfaces formed by the insulating power equipment.

There are a large variety of gaps used in practice involving odd shaped electrodes and usually non-uniform fields, with gaseous, solid and liquid dielectrics and their combinations as the insulating medium. The problem of determining the electrical characteristics of these has been a difficult one and this work is at present by no means complete. The most common type of gap is the air gap. This has been studied rather thoroughly because, since air is a self-healing dielectric, it is used in all the types of gaps which are designed to break down first. Furthermore, it is subject to a fundamental and consistent mechanism of breakdown, so that more is known about it and more accurate results are obtainable.

Such air gaps have an insulation strength that is a fixed value for power frequency and normal switching surge voltages. However, for transients as fast as lightning surges, it is a function of wave shape. The fundamental character of this can best be studied by means of a square voltage wave such as shown in Fig. 1(a). If the time required for breakdown be plotted as a function of applied voltage for such a wave, a curve similar to that shown in Fig. 2(a) is obtained. Such a curve is called a time lag curve. It shows that as the voltage is decreased from very high values, longer and longer time lags are required for breakdown until finally the minimum voltage for which breakdown can take place and its corresponding maximum time lag are reached. Voltages requiring substantially longer times to reach crest value than this maximum time lag will break down the gap at this same minimum voltage.

Townsend[(5)] was the first to propose the mechanism

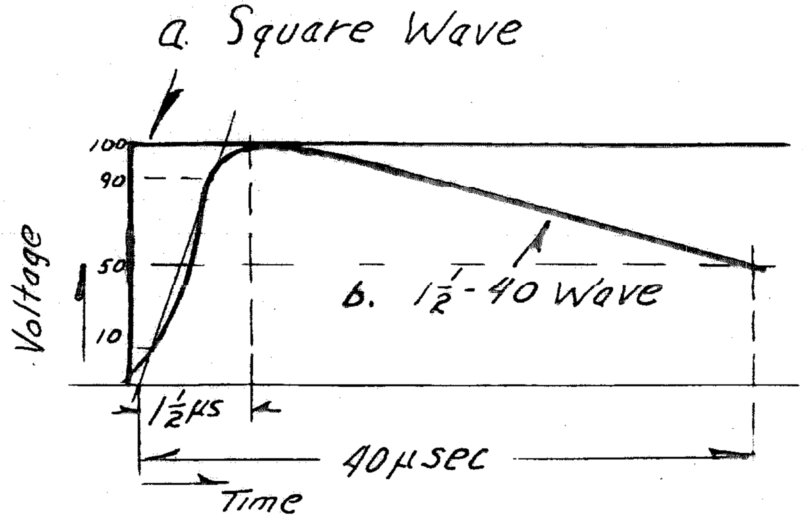


Fig 1 Impulse Waves for Testing.

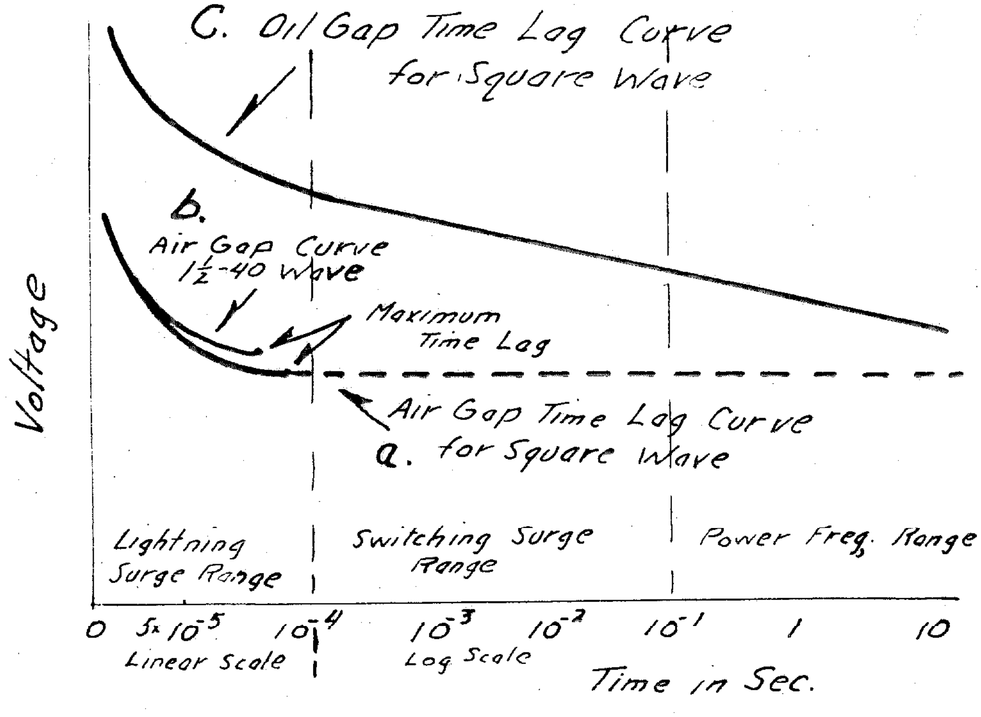


Fig. 2. Typical Time Lag Curves.

of breakdown in gases as a development of an electron avalanche from the collision of atoms by free electrons, and with some modifications[6] this is the accepted theory for breakdown of gaseous dielectrics. It is found that even for the most non-uniform fields, the maximum time possible for breakdown to occur cannot be over one to two hundred microseconds for gaps no larger than those used in practice. This can be definitely determined from the study of large point gaps and in the extreme case, the lightning stroke. For these cases the discharge mechanism starts at one electrode at some definite gradient and progresses as an ionized channel at the tip of which the ionizing mechanism is taking place until it reaches the other electrode. As long as the ionizing mechanism is confined to this tip and does not start at several places simultaneously, this is the slowest type of breakdown obtainable in air gaps. It is found that corresponding to the minimum gradient at which the spark will advance, there is a minimum velocity at which stable propagation is obtainable. Observations of lightning discharges by Schonland in South Africa[7] show that the minimum velocity for propagation of a lightning stroke is of the order of 10^7 centimeters per second, and Allibone[8] has found for long sparks in the laboratory a minimum velocity of propagation of about 10^6 centimeters per second. Voltages higher than the minimum voltage, of course, produce higher velocity of propagation. Using 10^6 centimeters per second, the time lag for a gap of four feet in length would have a maximum value that could not be over one hundred and twenty microseconds. Actually, common air gaps used in practice have maximum time lags that are much less.

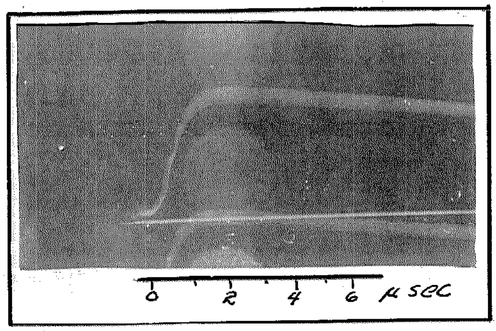
The time lag curve is a function of wave shape. Curves determined with square topped waves will always lie below those obtained with waves having the shape of lightning surges, Fig. 2(b). The use of the square topped wave would give the most conservative results in coordinating gaps. However, it is both mechanically and economically impractical to construct an impulse generator capable of providing the high voltages necessary for testing and which would have sufficient capacity to give a wave with a flat enough tail to provide the same practical results as a square wave.

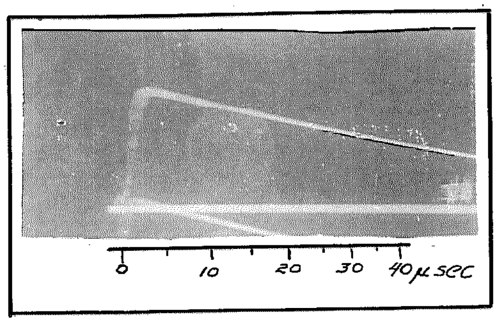
It has been primarily this condition which led to the adoption by impulse laboratories and the

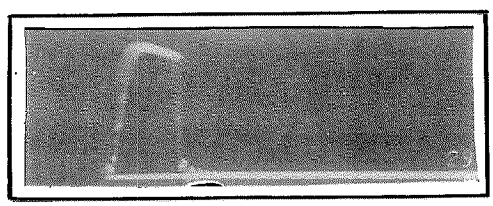
Standards of the American Institute of Electrical Engineers of the 1½-40 wave for impulse testing on the tail of the wave. This standard wave is defined in Fig. 1(b), and oscillograms of typical standard waves produced in the High Voltage Laboratory at the California Institute of Technology are shown in Fig. 3. When flashover is confined to the tail of the wave, Fig. 3(c), the front of the wave is relatively unimportant, and in actual practice little consideration is given to this by most of the laboratories.

In general, time lag curves are found to be a function of polarity. Most common gaps, except the sphere gaps, have a lower breakdown strength for positive surges than for negative ones. For this reason, it has been the custom until recently to use the positive polarity for impulse testing. However, it has now been definitely established[9,10] that practically all lightning strokes are of negative polarity. This point, therefore, is now in controversy.

The proper application of one gap to protect another requires that the time lag curve for the protecting gap always lie below that for the gap being protected. Time lag data obtained with the 1½-40 wave have produced fairly satisfactory results.







Oscillograms Showing the Standard $1\frac{1}{2}$-40 Wave Used for Breakdown on the Tail of the Wave Testing.

Fig. 3.

This is not necessarily due to the fact that it has a duration as long as that of the most severe lightning strokes. Since the curves for most common air gaps have flattened out to practically their minimum value in five to twenty microseconds and the $1\frac{1}{2}$-40 wave has not dropped a great deal in this time, the time lag curve is not much different from that which would be obtained with a square topped wave. This is shown by the fact that the minimum impulse strength of most air gaps is not over twenty or thirty per cent higher than the power frequency strength. Reference 11 gives a good resumé of the standard impulse data on apparatus involving air gaps, and discussions of the present status of the standardization of insulation coordination are given in References 12 and 13.

Coordination data for oil gaps are much less complete. This is due primarily to the fact that the possible mechanisms of breakdown are varied and complex, and also to the fact that the performance of oil as an insulating medium is subject to a marked degree to its condition of impurity. In practical applications it is virtually impossible to keep the oil free of foreign material; most notably water, fibrous particles, absorbed gases and products of oxidation. These foreign substances cause breakdown mechanisms which differ from those mechanisms which occur in pure oil, and they are known to be the most important cause of breakdown at power frequencies. Just how important a part they play in the breakdown for impulse voltage and switching surges is not accurately known.

The mechanism of breakdown produced by impurities and certain other mechanisms possible in pure oil can be relatively slow. As a consequence, time lag curves for oil are a function of time over their entire range, such as shown in Fig. 2(c). The fact that even for times as long as several seconds the curve is still dropping is very important, since it means that not only must the time element be considered for lightning transients, but for switching surges and 60-cycle voltages as well. One reason that more work has not been done on the impulse strength of oil is because it is so much higher than that for 60 cycles. An oil gap having a 60-cycle breakdown value above that of a given air gap will have an impulse strength even higher. However, it is frequently important to consider the relative characteristics of several oil gaps and there is a definite need for such reliable data.

Bellaschi[14] has studied small oil gaps with fuller board barriers of such a type as to assimilate transformer insulation, and work has been done from a theoretical standpoint on very small oil gaps.[15,16] However, little has been done at large spacings and with large electrodes.

From a practical standpoint the greatest need for more knowledge of the behavior of this type of gap is in connection with the design of oil circuit breakers. Insulation of the high voltage portions of breakers from the grounded framework and the tank relies upon free oil for the insulating medium and parallel combinations of porcelain and oil which provide flashover paths in the oil along the porcelain surfaces. In the case of the portion of the breaker being insulated only by oil, sharp corners are usually present and it is necessary to prevent excessive gradients by the use of metal shields.

The study of this type of problem should be started with fundamental gaps, the results of which may be applicable to the more general types found in practice and point the way to further studies of them. This is the logical method of approaching this problem both from a practical and a theoretical standpoint. Accordingly, it was decided to study the sphere gap. Work has been done by Minor[17] with sphere gaps in oil at power frequency in which he found it necessary to make the shank diameters as large as the diameters of the spheres themselves, resulting in electrodes consisting of rods with spherical ends. It was found desirable to use the same type of gaps in the light of Minor's experience and in order to use to advantage the results he had obtained.

DEVELOPMENT OF OIL TEST TANK

The testing equipment for this research was developed in the High Voltage Laboratory of the California Institute of Technology, where high voltage power frequency test equipment capable of supplying one thousand kilowatts at one million volts and high voltage impulse testing equipment are available. A great deal of difficulty has been experienced in the past in developing a tank for oil gaps. It is important that the set-up be of such a standard nature that results can be duplicated in other laboratories. For this reason it would be preferable to have a tank of such shape and dimension that the electric field in the region of the gap would be essentially that of the same gap in an infinite oil medium. The tank must be reasonably small, however, to permit proper treatment of the oil.

Minor, in his work at power frequency voltages, used a metal tank twenty feet in diameter. The electrodes were mounted in a square maple wood frame supported in the oil by the high voltage lead. This lead was a metal cylinder twenty-one inches in diameter. He found it necessary to use such a large tank, not to eliminate its effect on the spark gap, but to prevent corona from the high voltage lead at the surface of the oil. For this same reason the large diameter of the lead was required. It was found that such corona produced sufficient ionization in the oil to lower its electrical strength. This well known effect also made it necessary to have the diameter of the sphere shanks the same as the spheres themselves.

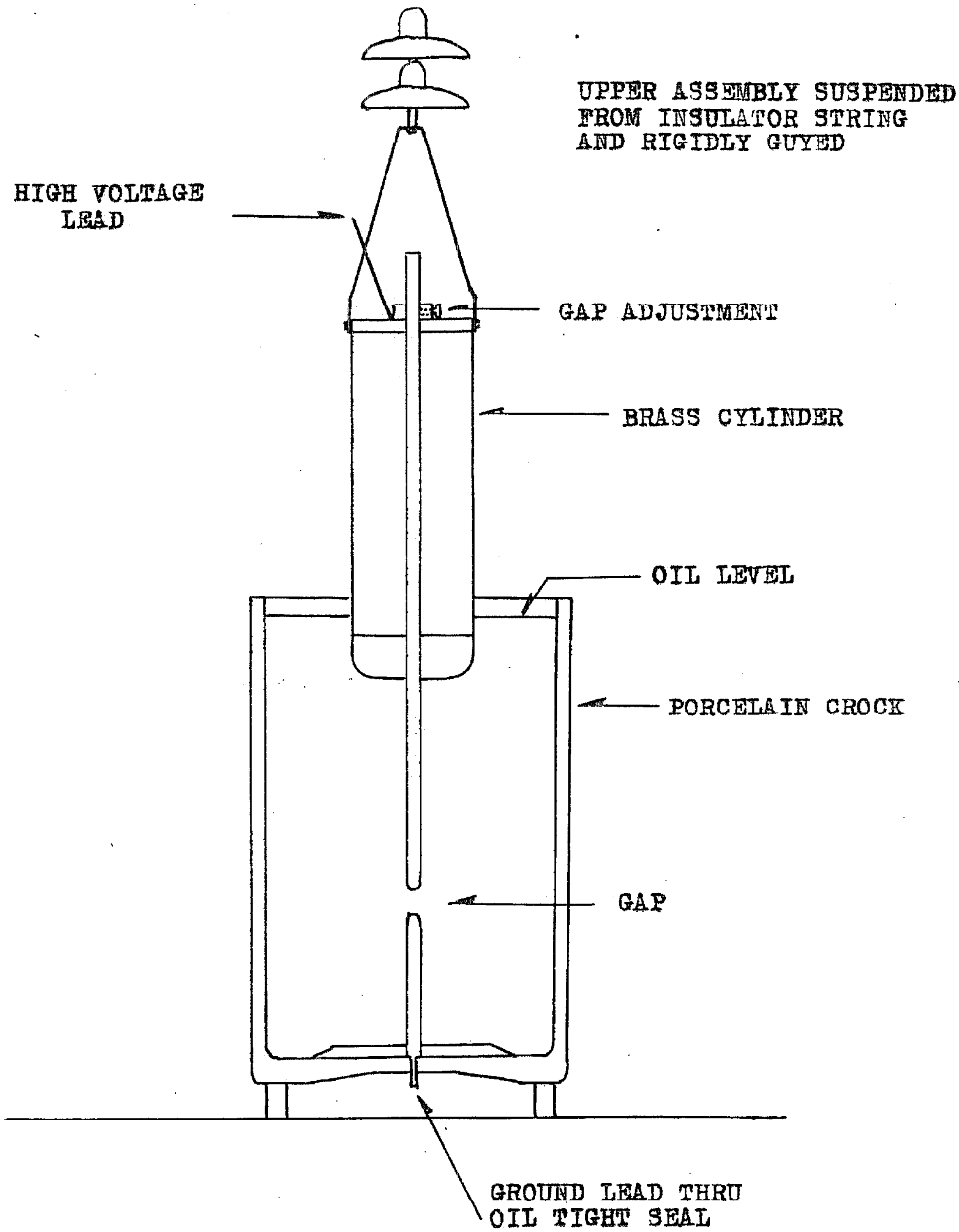
There are two disadvantages to this equipment which it was thought well to overcome. The tank is too large for proper treatment of the oil and the wooden frame was a source of trouble as difficulty was experienced in preventing its failure due to the high electrical stress in it. In trying to eliminate these difficulties, it was first thought that a smaller, totally enclosed metal tank with a standard outdoor type high voltage bushing in the top might provide a means of decreasing the dimensions. It would be necessary that the top be removable and yet allow for complete filling of the tank with oil, so as to prevent any air-oil surfaces under electrical stress.

A circuit breaker tank about eighty inches in diameter and eleven feet high was available. Calculations were made to determine the field distortion produced by a tank this size upon the gaps which would be used. Since it was planned to use various sized rods and spacings whose impulse strengths were not accurately known, it was hard to determine just what sized tank would be suitable. However, it was thought probable that with electrodes about one inch in diameter, twenty-inch spacings would be large enough. For larger electrodes, spacings would be correspondingly smaller.

The calculations are given in detail in Appendix I and these results are applicable to any tank diameter. The curves in Fig. 25 show the amount of gap space which has a distortion of less than one-half of one per cent. Just how small this region can be and not affect the breakdown strength is questionable. For impulse testing it is probable that only a rather limited region around the highest stressed portion of the gap where the arc occurs need be undistorted. For 60-cycle voltage it must be considerably larger. However, Fig. 25 together with Table III indicates that the desired spacings can be reached without getting distorted results.

Before trying this tank, a better plan was devised. If the tank were made of insulating material and all objects which might cause field distortion kept away from it, a much smaller size could be used and the top left open because the stresses at the high voltage lead would be greatly reduced. A model of this type was tried and is shown schematically in Fig. 4.

It consisted of a porcelain crock which is used in the High Voltage Laboratory for testing insulators under oil. It is about four and one-half feet high and twenty-five inches in diameter, with a sealed lead through the bottom providing the ground connection. The bottom electrode is mounted on a flat circular plate whose edges are suitably beveled. The upper electrode is fitted in a brass tube about four inches in diameter, in the bottom of which is a rounded plug to prevent corona. This assembly is suspended from an insulator string and rigidly guyed with light rope to preserve alignment. The upper



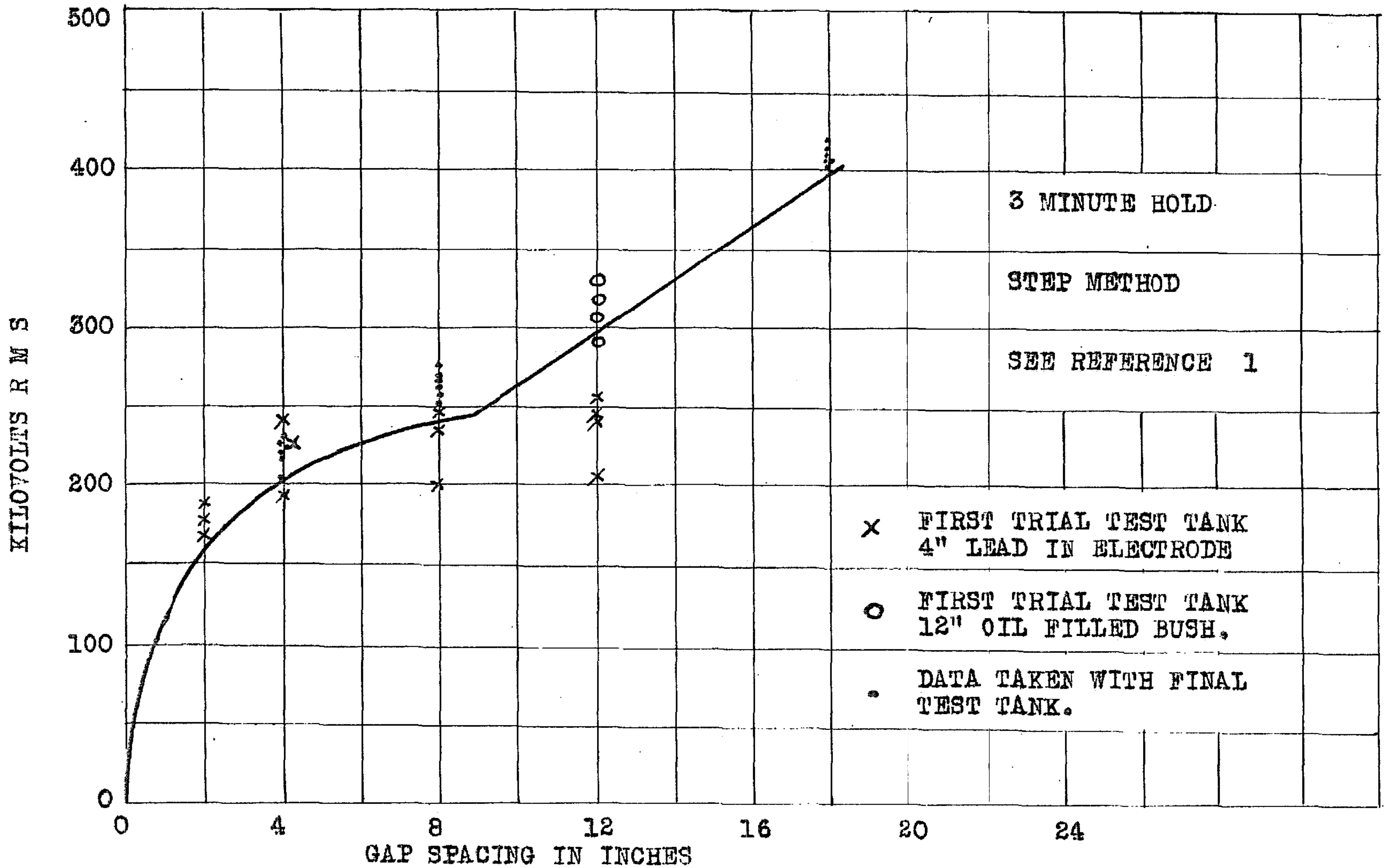
CROSS-SECTION SKETCH OF FIRST TEST TANK TRIED

Fig. 4

electrode is made adjustable by means of a clamping collar at the top. Adjustment of the gap is made by the use of metal templates placed between the electrodes and by a scale at the collar. This method of mounting the electrodes has the advantage that there is no wooden frame in the region of the gap.

Tests were made with this equipment at 60 cycles, using one-half inch electrodes to see what voltages the set-up would withstand and to compare with Minor's results. It was found that the 60-cycle instantaneous breakdowns obtained by raising the voltage at the uniform normal speed of the voltage regulator of the high voltage test equipment until breakdown occurred were quite erratic. Similar results were also obtained by Minor and since longer applications of voltage give more consistent results, the three minute interval was chosen. The standard three minute hold method consists of applying a voltage somewhat below the expected failure of the gap for three minutes. If the gap stands the voltage, it is removed for two or three minutes. Then a somewhat higher voltage is applied. The highest voltage the gap will withstand for a three minute period is taken as the "three minute hold 60-cycle breakdown value" for the gap.

In Fig. 5 is shown the curve for one-half inch electrodes obtained by Minor for three minute holds. The first set of plotted data is that obtained with this equipment. It is seen that for the two-inch and four-inch spacings, the points lie above Minor's curve. However, no higher values can be obtained for larger gap spacings. This is due to the fact that at about two hundred kilovolts corona started at the surface of the oil and the brass cylinder. Even though slight, it apparently produced enough ionization to lower the electrical strength. At a voltage of about two hundred and fifty kilovolts, sparks jumped from the metal cylinder to the rim of the crock and it was evident that improvement would be necessary. An oil-filled bushing was devised to relieve the stress at the surface of the oil. It consisted of a micarta cylinder with an inside diameter of twelve inches placed around the brass cylinder in a manner similar to that shown for the final test equipment in Fig. 7. The bottom was



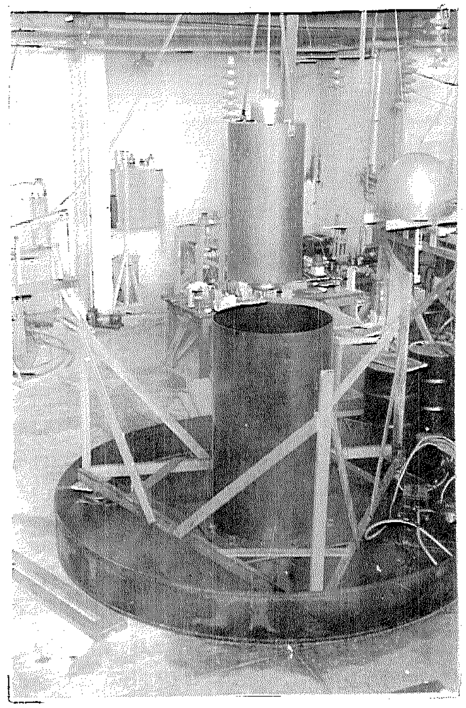
COMPARISON OF 60 CYCLE BREAKDOWN OF ONE HALF INCH ROD GAPS OBTAINED IN TEST TANK WITH THAT OBTAINED BY MINOR.

Fig. 5

plugged with a micarta disk and made oil tight with a shellac seal. Such an arrangement not only reduces the gradient at the micarta cylinder and oil surfaces greatly below the value that a metal cylinder of the same diameter would have, but also increases the voltage at which corona will start at the surface of the brass cylinder.

With this new set-up the second set of data shown in Fig. 5 was obtained. At three hundred kilovolts higher oil strengths than Minor's curve indicated are shown. However, corona started to appear at about three hundred and sixty kilovolts and it was evident that for the voltages that would be required, a set-up of larger dimensions was necessary.

A photograph of the final test barrel and bushing developed is shown in Fig. 6 and a schematic diagram is given in Fig. 7. The dimensions of the tank and bushing were determined by the size of two dielectric cylinders made of paper and varnish which were available. The larger of these is a cylinder seventy-two inches long with an inside diameter of thirty-nine inches and walls one-half inch thick. This is made of material



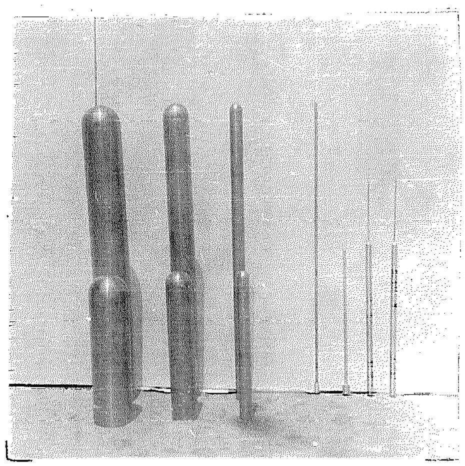
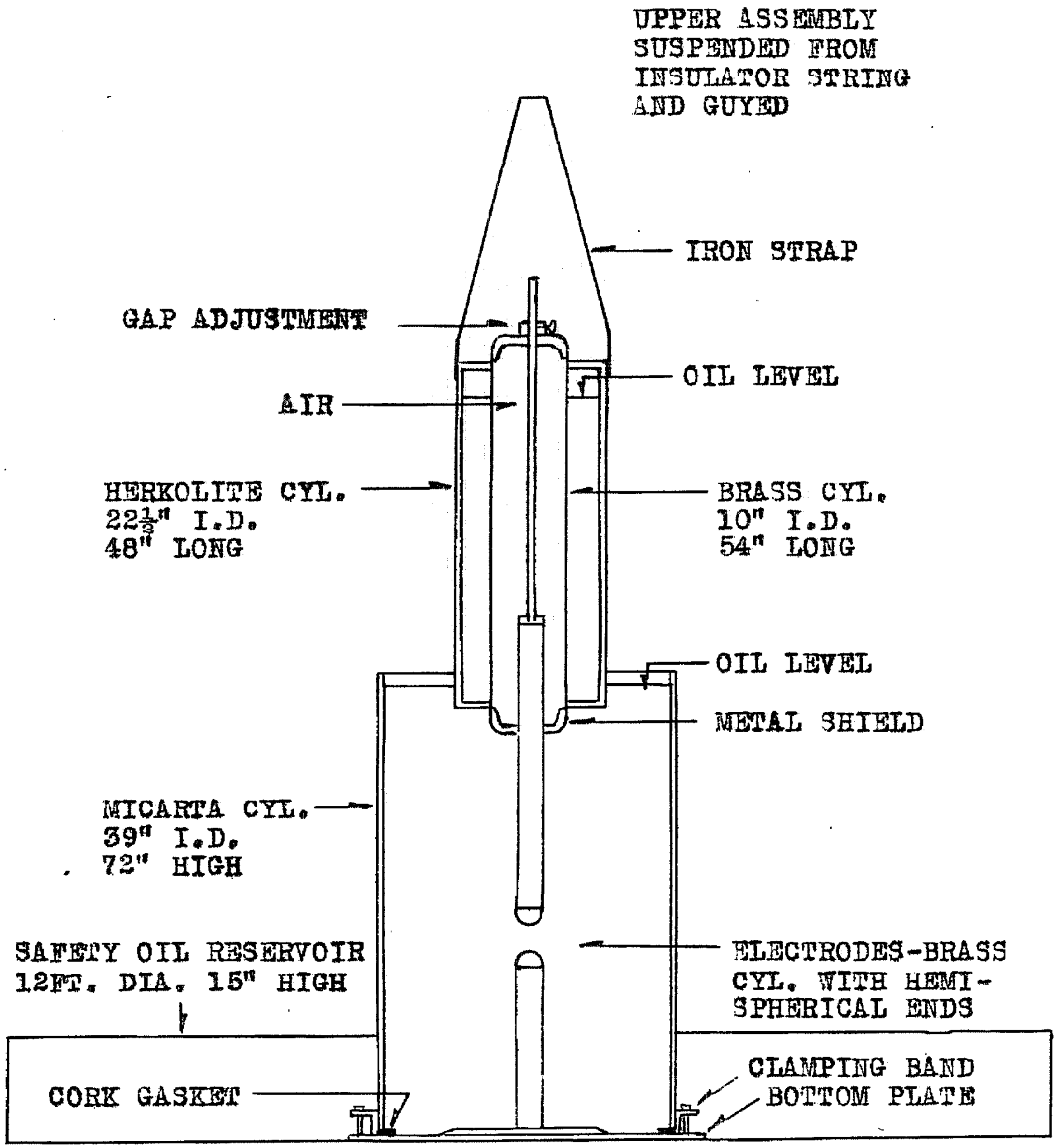


Fig. 6

Photographs of Test Tank and Electrodes



CROSS-SECTION SKETCH SHOWING TEST BARREL ELECTRODES
AND LEAD IN BUSHING

Fig. 7

having the trade name, "Micarta" and is used for the tank proper. The other cylinder is made of a material called "Herkolite." It is forty-eight inches long, has an inside diameter of twenty-two and one-half inches and is used for the bushing.

The tank is formed by clamping the micarta cylinder to a steel plate one-fourth inch thick by means of a steel band clamped around the cylinder and bolted down to the steel plate. A cork gasket is used to prevent oil leakage. This assembly is set in a metal reservoir twelve feet in diameter and fifteen inches high which is capable of holding all of the oil in both the tank and bushing in case of mechanical failure of any of the equipment. It also provides for any leakage that might occur through the cork gasket.

The bushing consists of a brass cylinder ten inches in diameter and fifty-four inches long, placed concentric with the Herkolite cylinder and having a suitably rounded plug in its bottom and a plug in the top in which concentric holes are bored to allow the upper electrode to slide up and down in it. The weight of this cylinder and assembly is borne by a wooden disk fastened to it by small bolted angles and fastened to the top of the Herkolite cylinder with a lap joint. In this manner no stress need be placed on the bottom plug of the Herkolite cylinder which can, therefore, be made oil tight more easily. This bottom plug is a circular micarta disk three-fourths of an inch thick. The whole of the upper electrode and bushing assembly is suspended from an insulator string and guyed with ropes. The insulator string is suspended with a block and tackle so that the bushing can be lifted out when changing or cleaning gaps.

Calculations have not been made of the field distortion of such a tank. However, in the light of the calculations in Appendix I and the fact that this configuration produces much less distortion, it is safe to say that for the gap spacings and electrode sizes reported here there is no appreciable distortion. Ground plane distortion should also be negligible at these spacings. This can easily be shown by calculating its effect on two point charges representing the field in the gap. Calculations made of the effect of the resulting image charges show negligible distortion at gap spacings less than fifteen inches where the height of the center of the gap from the ground plane is at least thirty inches. This much clearance is always maintained.

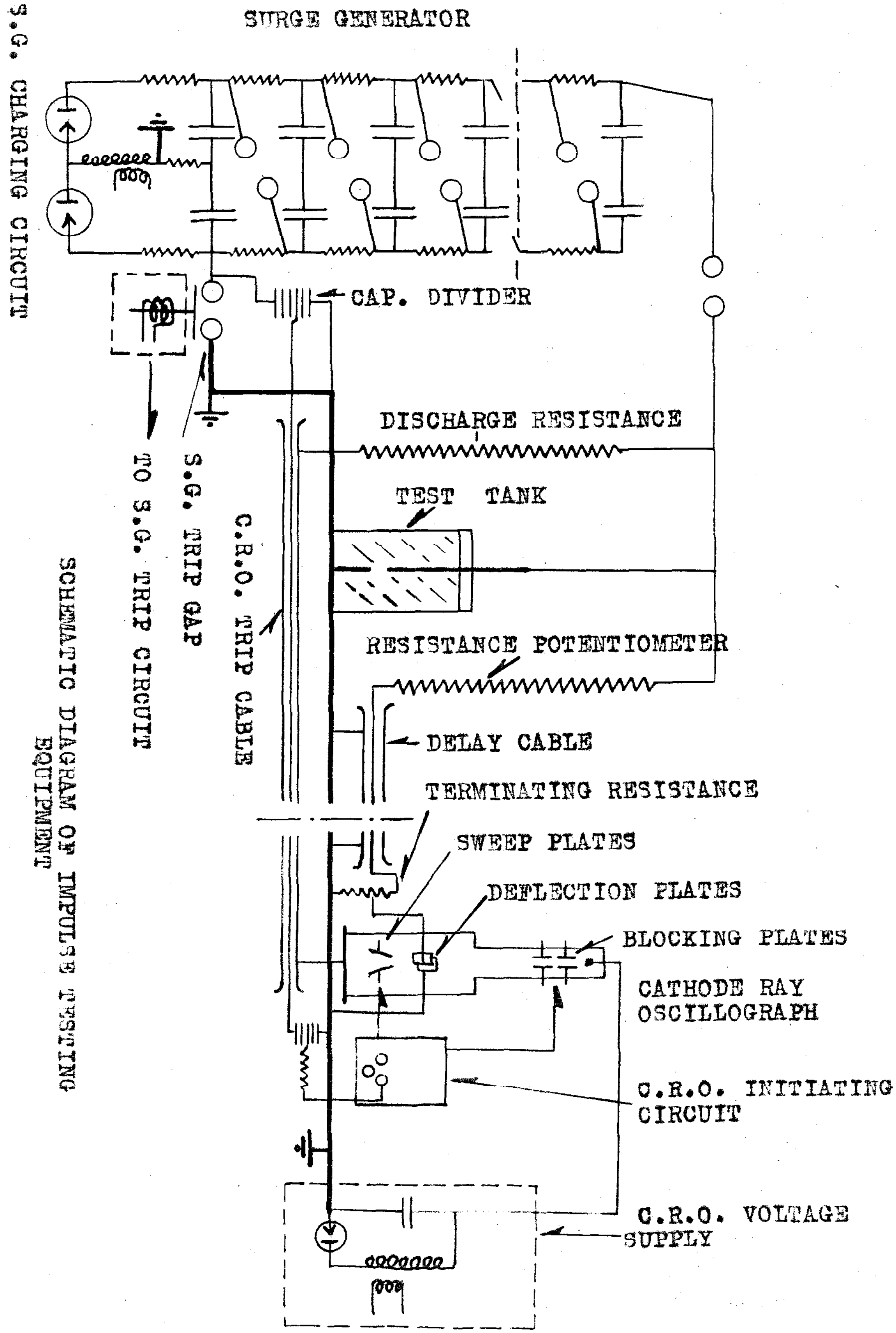
The electrodes designed to be used are all circular rods with hemispherical ends. Sizes ranging from one-fourth inch to six inches in diameter were constructed, some of which are shown in Fig. 6. They were constructed in this manner: the one-fourth inch, one-half inch and one inch electrodes were made of solid circular brass rods; the two inch, four inch and six inch electrodes were made of a solid brass hemisphere fitted into a brass tube.

The results of preliminary tests made with this set-up using one-half inch electrodes are shown in Fig. 5. For voltages up to four hundred kilovolts and spacings up to eighteen inches, the points all lie above Minor's curve. The probable explanation of this is that the oil was in better condition due to smaller volume and the consequent greater ease of handling it. At the beginning of the testing, higher voltages were not tried because it was thought wise to make all of the impulse tests below the corresponding value of four hundred kilovolts (six hundred kilovolts crest) before going to higher voltages and incurring the chance of damage to any of the equipment due to failure of the insulation. However, it has, so far, stood impulses of over 1,300,000 volts without showing any sign of failure or corona at the oil surface.

IMPULSE TESTING

The impulse testing equipment in the High Voltage Laboratory of the California Institute of Technology is of the standard type for producing high voltage surges. A schematic diagram of the set-up used for the impulse testing of the oil gaps is shown in Fig. 8. It consists of a surge generator employing the conventional Marx circuit for charging the condensers in parallel at low voltage and discharging them in series. Wave shape is controlled by means of discharging the surge generator through a main discharge resistance and damping resistances distributed throughout the surge generator in the leads of the discharge gaps.

The impulse voltage source used at the beginning of the oil gap tests is a stationary unit with a nominal voltage rating of one million volts. It has twenty fifty thousand-volt one-half microfarad condensers charged in banks of two by a one hundred kilovolt voltage doubler circuit. Its features are described in detail in Reference 19. As the work on oil gaps was extended to larger electrodes and gap spacings, this voltage was found inadequate and an



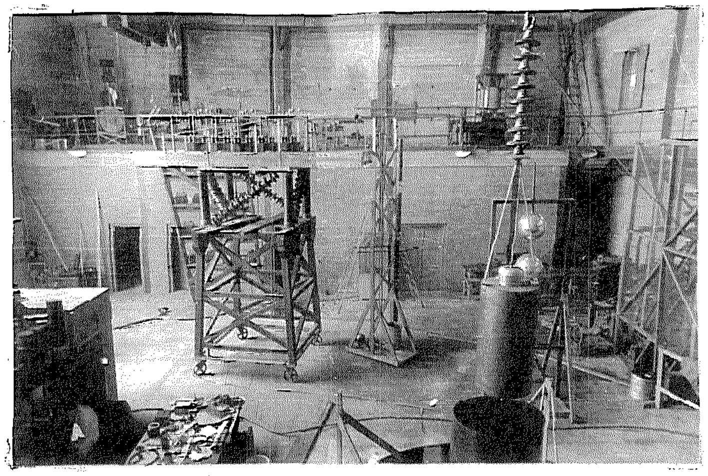
SCHEMATIC DIAGRAM OF IMPULSE TESTING EQUIPMENT

Fig. 8

additional one million volt portable unit having the same type of condensers and circuit features was designed. Fig. 9 shows photographs of these two units. The portable unit is mounted on an insulating tower constructed of redwood and porcelain pedestal insulators and is made movable by means of casters. It is so designed that when more voltage than can be provided by the original unit is needed, it can be connected directly to the first unit; thus charging it from the same voltage source.

The recording equipment consists of a ten thousand volt cold cathode ray oscillograph designed and constructed by Dr. Howard Griest[18] and a non-inductively wire wound resistance potentiometer. Fig. 10 shows photographs of the cathode ray oscillograph and one of the four units of the potentiometer. These units are placed in an oil-filled tube to obtain better insulation.

The voltage across the discharge resis[illegible]s applied to the test gap and the resistance potentiometer which is connected through a shielded cable to the cable terminating resistance. This resistance has a value equal to the surge impedence of the cable



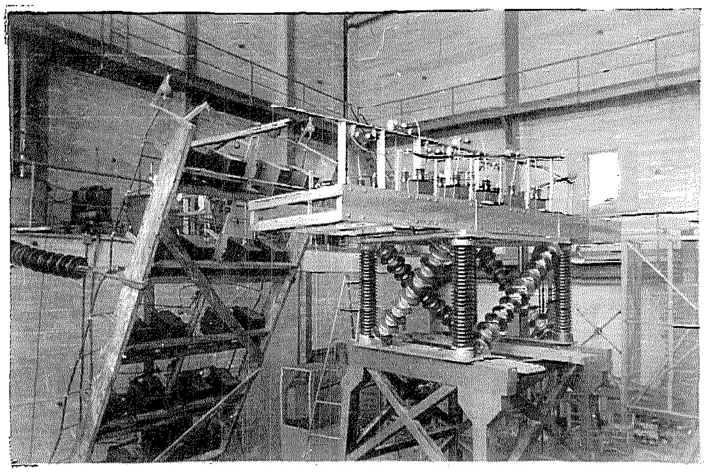
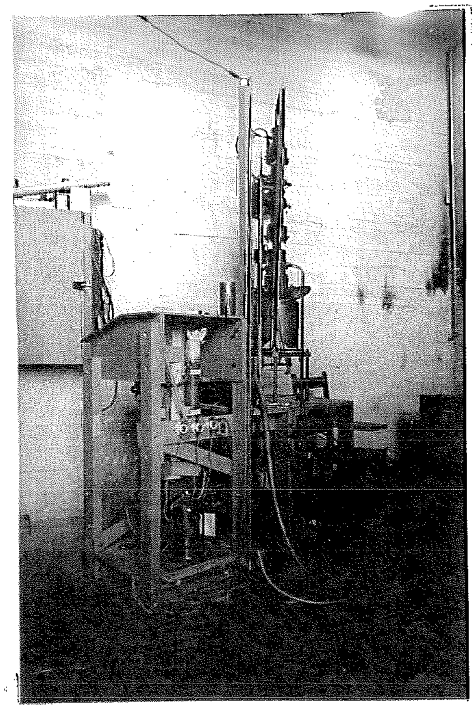
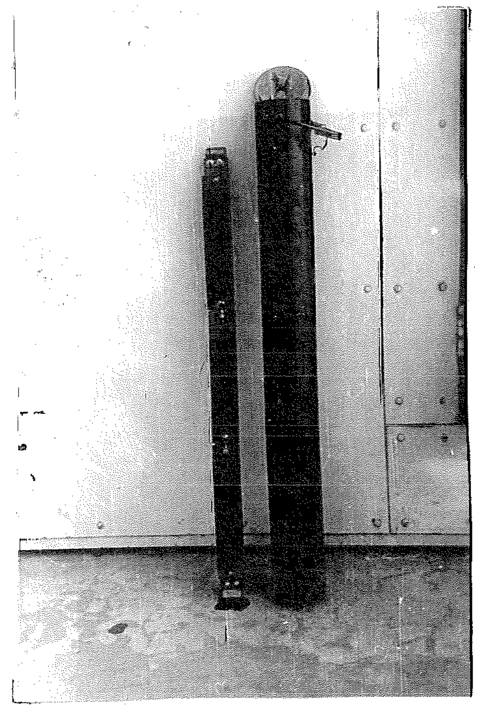


Fig. 9

The Stationary and Portable Surge Generator Units



The Cathode Ray Oscillograph



One Unit of the Resistamce Potentiometer

Fig. 10

to prevent reflections and consequent distortion of the voltage. The deflection plates of the cathode ray oscillograph are connected across a portion of the terminating resistance, providing a voltage across the plates which is a known fraction of the actual surge. The resistance potentiometer has been proven to be a satisfactory method for recording waves no faster than the standard $1\frac{1}{2}$-40 wave.[20] Auxiliary voltage calibration is provided by means of a standard fifty centimeter sphere gap.

Coordination between the cathode ray oscillograph and the surge generator is obtained through the use of the cathode ray oscillograph trip cable shown in Fig. 8. When the surge generator is tripped, an impulse from the surge generator trip gap is applied to the oscillograph tripping circuit.

Since this equipment is designed not only for use in this particular work, but also for other research and commercial testing, the pertinent features pertaining to its use are given in Appendix II. It was found in checking the calibration of the equipment by means of the fifty centimeter sphere gap that the performance of the spheres for impulses was greatly affected by dirt and roughness of their surfaces. Since this is important in using them for surge calibration, but not in this particular research, the details of this are given in Appendix III.

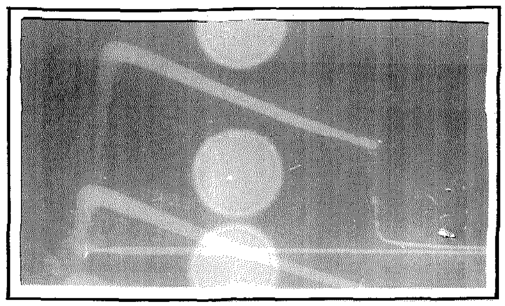
Control of the discharge voltage is effected by means of an auto-transformer provided with seven taps with intermediate adjustment by varying the charging time of the condensers. When it is found desirable to reproduce a given voltage, an ammeter is used in the primary voltage supply of the charging circuit and the generator is tripped at a fixed value of the logarithmic charging current curve. When it is necessary to produce successively varying voltages, it is found more convenient to control the charging time with a stop watch.

OIL TESTING TECHNIQUE

The actual testing procedure and treatment of the oil gap were developed after extensive experiments with the one-half inch electrodes at a one inch spacing. Tests made over the first few days' work gave very erratic results. A great deal of this inconsistency was found to be due to the following causes:

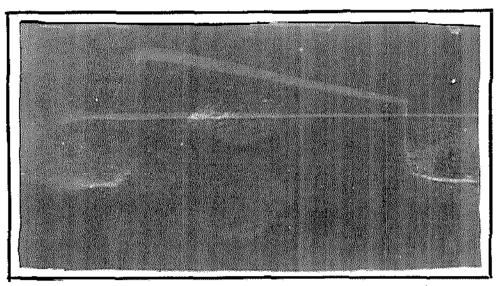
After fifteen or twenty shots, the electrodes would become marked with fine pits which lowered the gap strength. Dirt and grease on the electrodes had the same effect. If the oil were allowed to stand for more than a day in the open tank without filtering, it absorbed enough water to lower its impulse strength. After each shot, carbon and gas bubbles formed in the gap. The effect of these could only be eliminated by sweeping this oil out of the gap and waiting at least five minutes before again surging it.

Any cause of impurity in the oil not only produced lower breakdown values, but also longer time lags. In Fig. 11(a) are shown oscillograms where as high as fifty-six microseconds were required for breakdown of a one-half inch gap of the one inch



400 KV 41 μ-sec

Pitted Electrodes a.



410 KV 39μ-sec.

Poor Oil Test -24KV. b.

352KV 56 μ-sec.

One Inch Rods - One Half Inch Gap.

Effect of Pitted Electrodes and Poor Oil on Minimum Impulse Strengh Fig. 11.

electrodes. Occasionally, long time lags also occurred when the oil was in good condition, but the electrodes were known to be pitted. An example of this is shown in Fig. 11(b).

It would, of course, be very difficult to maintain such a set-up completely clean. It would have to be reconditioned by a tedious method after each surge. Furthermore, the purpose of this research is to determine the characteristics of practical oil gaps. However, certain condition standards must be maintained to obtain at all consistent results and also to determine the effects of the different variables which occur in practice.

A technique of treatment was finally developed which gave the most satisfactory results. After ten or fifteen surges of the gap, the following conditioning was performed: The electrodes were removed from the oil, polished with fine crocus cloth and cleaned with carbon-tetra-chloride. The oil was circulated through clean baked filter papers for several hours by drawing it out of the bottom of the tank and replacing it at the top.

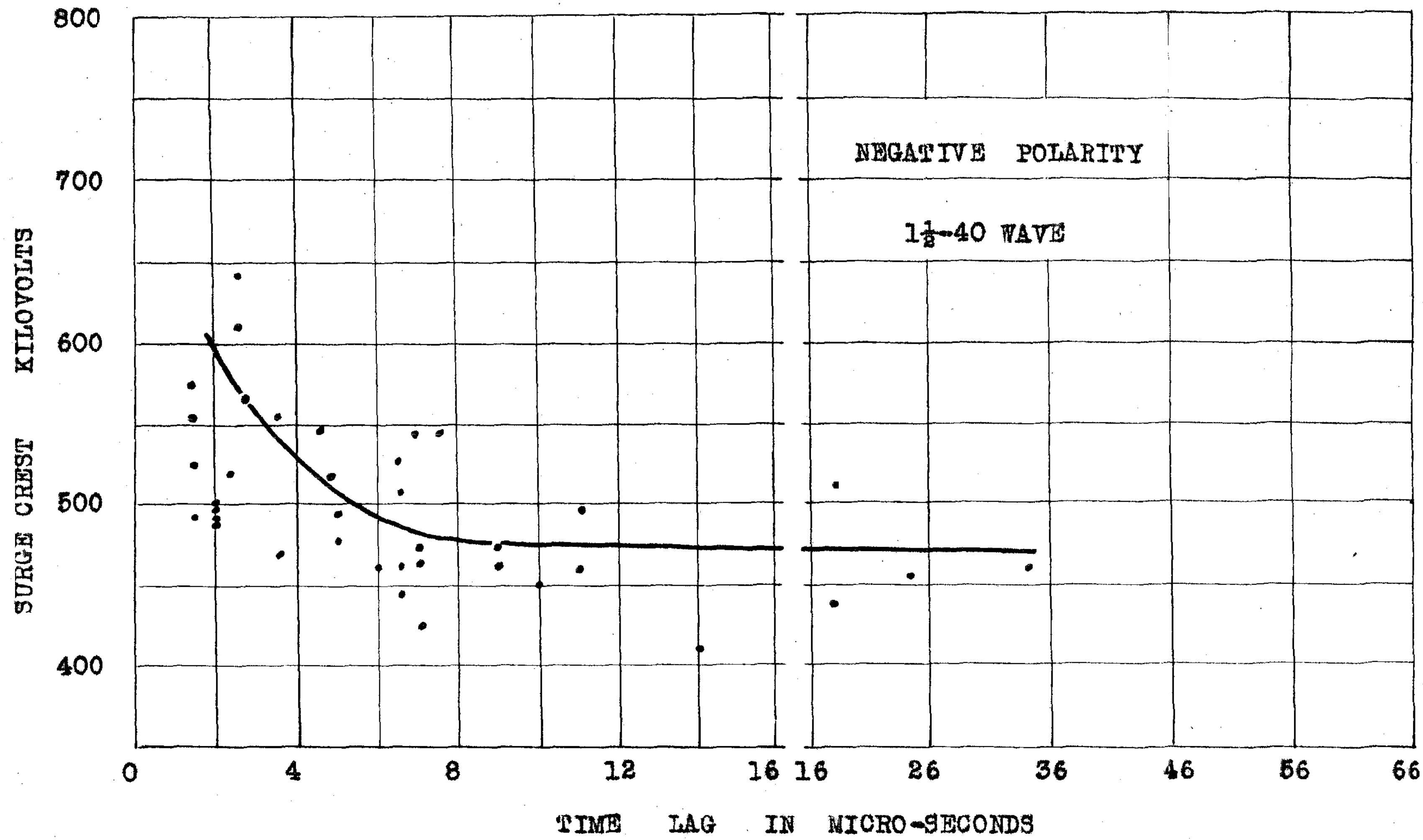
This was found preferable to filtering the oil completely out of the tank and into the original oil barrels in which the oil was supplied and then filtering it back into the tank, because the empty tanks absorbed water which the oil picked up. The dielectric strength of the oil as measured with the standard test cup was always kept above twenty-five kilovolts. Between each impulse, the disturbed oil was swept out of the gap with a brass rod and five to fifteen minutes were allowed before again applying a surge.

To obtain the time lag curves for each gap, it was thought that the following procedure would be the most feasible: First obtain the minimum impulse breakdown strength by starting from a voltage below breakdown and gradually raising the voltage until a point is reached where breakdown occurs about fifty per cent of the time. Then having established this point, gradually raise the voltage taking a few shots at each particular value until the complete time lag curve is determined.

The first time it was attempted to determine the minimum breakdown voltage for the one-half inch electrodes at a one inch spacing, it was found that the voltage was rather critical. Any variance above or below this point by the smallest step that could be maintained accurately (about three per cent) produced either breakdown one hundred per cent of the time or no breakdown at all. However, the oscillograms of the minimum breakdown shots showed great variance as to time lag, values anywhere from four to sixteen microseconds being obtained.

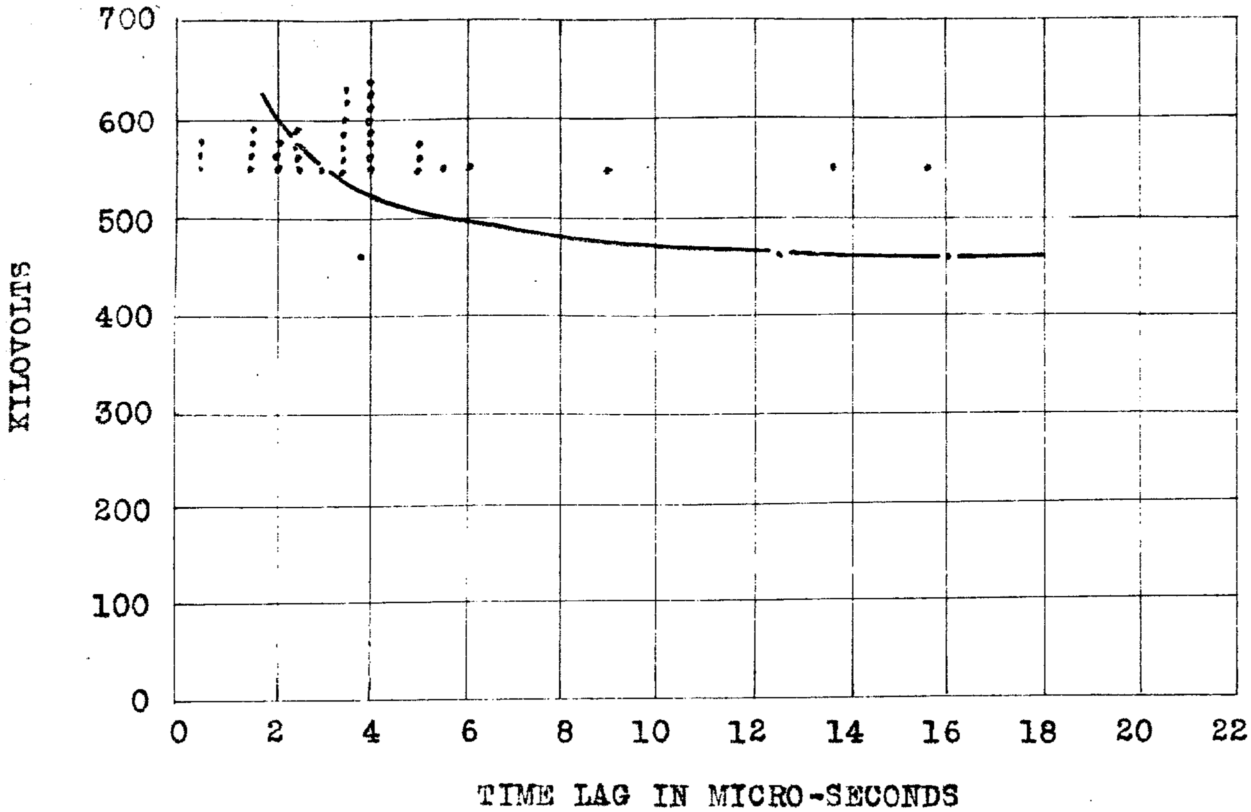
Having supposedly determined this point, it was impossible in the same day's testing to take more than a few shots at increasing voltages. Determination of the minimum voltage on successive days of testing, however, produced varying results. This seemed to be the case no matter how much care was taken to maintain a uniform condition of the test set-up. The maximum deviation from the mean value was about ten per cent.

In eight days of testing, thirty-eight points were obtained for this gap, exclusive of those taken at minimum voltage and under improper conditions. This is plotted in Fig. 12, where it is seen that no very well defined time lag curve can be drawn through

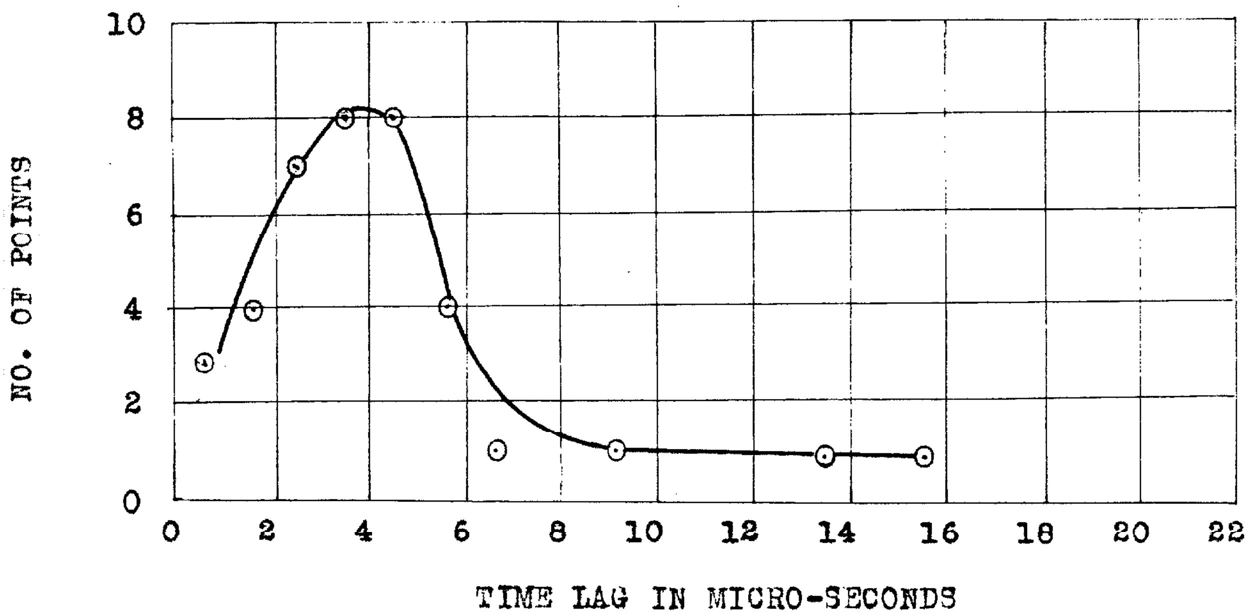


CURVE SHOWING DISTRIBUTION OF POINTS FOR ONE HALF INCH RODS
ONE INCH GAP

Fig.12

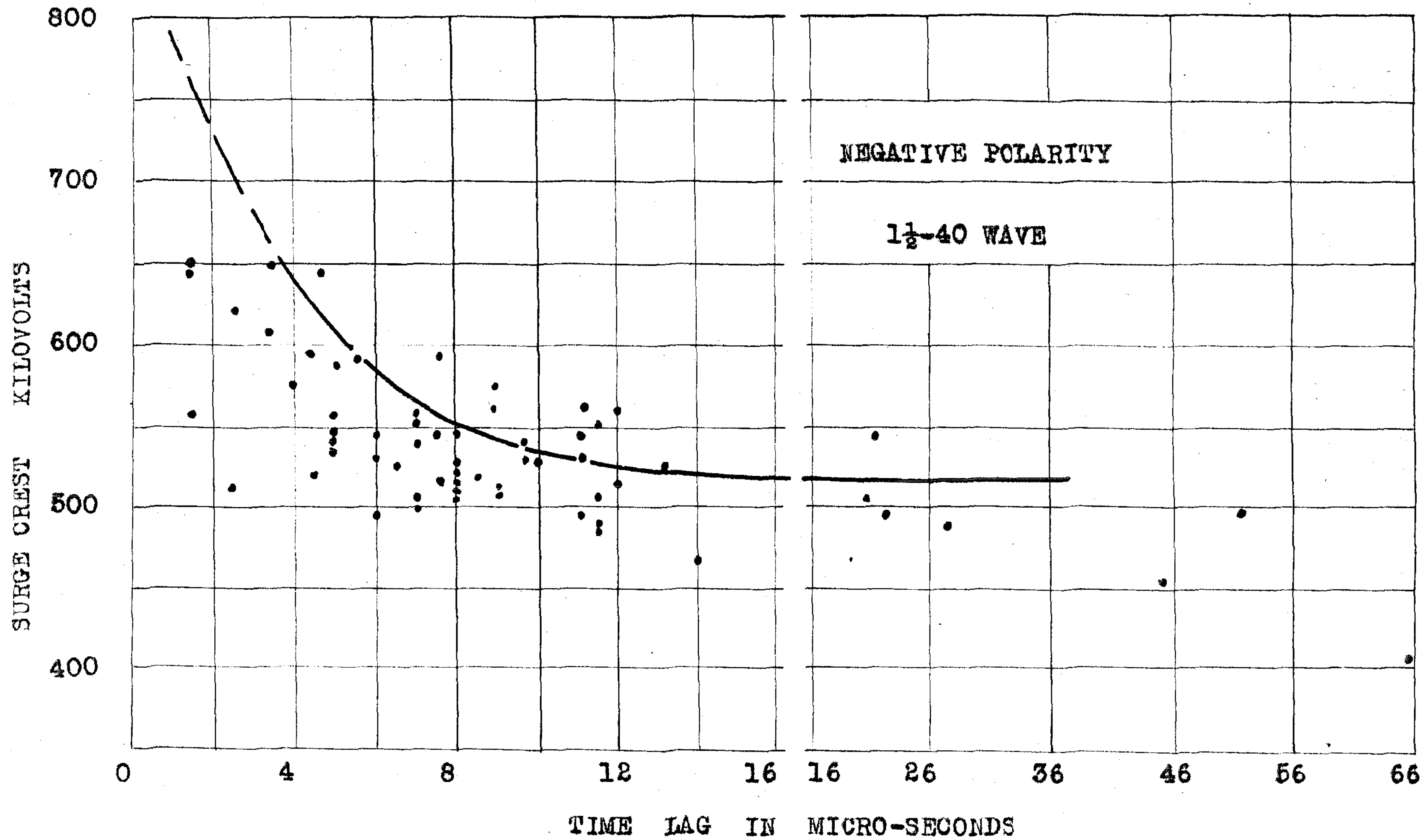


DISTRIBUTION OF POINTS FOR 550 KV. AND MINIMUM OF 465 KV.
ONE HALF INCH RODS ONE INCH SPACING



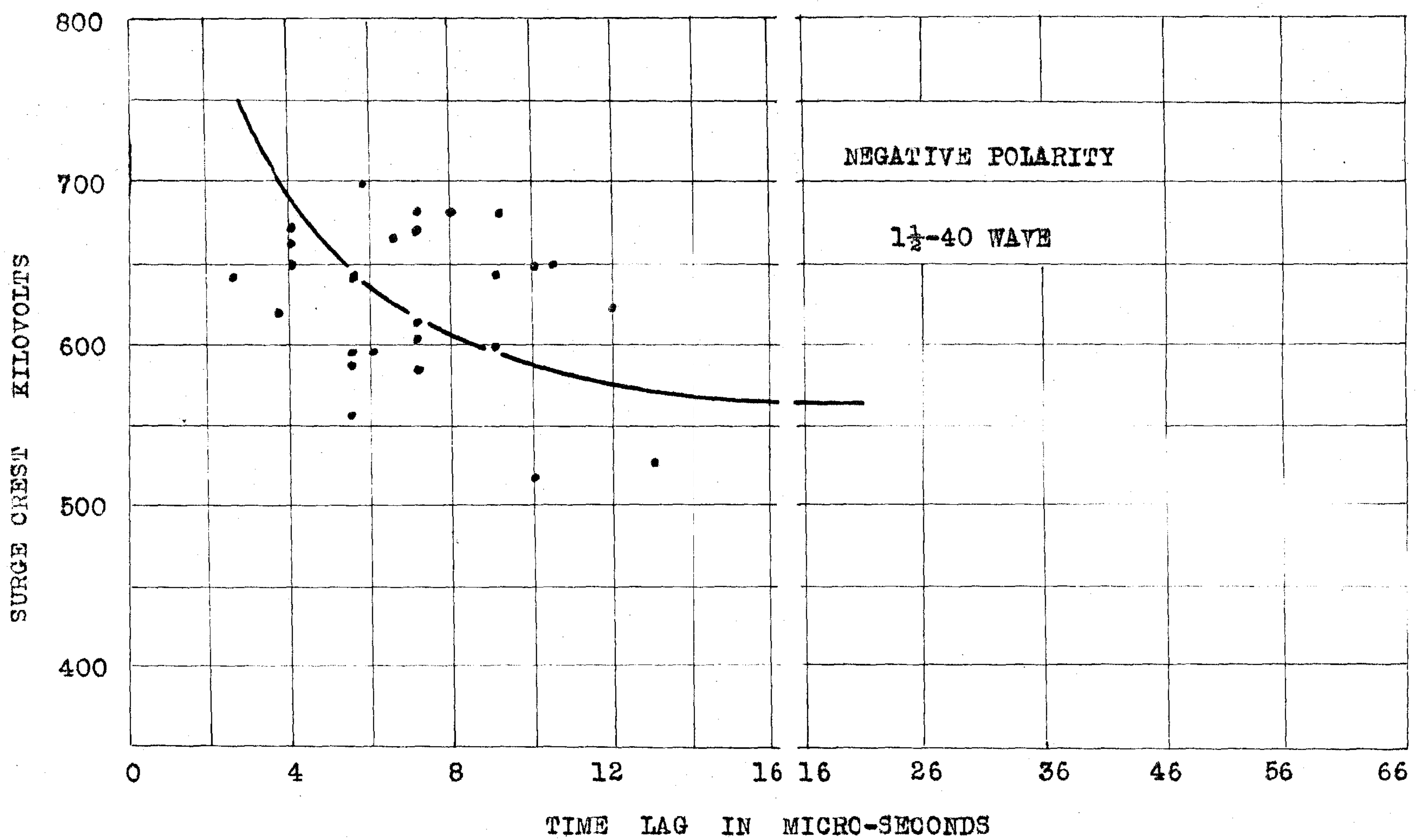
TIME LAG PROBABILITY CURVE FOR 550 KV. ONE HALF INCH
RODS ONE INCH GAP.

Fig. 13



CURVE SHOWING DISTRIBUTION OF POINTS FOR ONE HALF INCH RODS
TWO INCH GAP

Fig.14



CURVE SHOWING DISTRIBUTION OF POINTS FOR ONE HALF INCH RODS
THREE INCH GAP

Fig.15

the points. To ascertain whether or not the data for such an oil gap should be represented by a curve or a band, in other words whether or not the oil gap has a definite characteristic or a certain random characteristic, a large number of shots were taken at a fixed voltage of five hundred and fifty kilovolts which appears to be on a fairly steep portion of the time lag curve--a point where time lag should not vary over a wide range. In Fig. 13 these points are plotted, together with their probability curve, which shows that for this voltage there is a definite statistical time lag. Thus it is possible, if enough data were taken, to find the curve. Such accuracy is not warranted for this work at the present time, however, and it was decided in determining the time lag curves for the various gaps to take only enough data to establish the curve in a range of five to ten per cent.

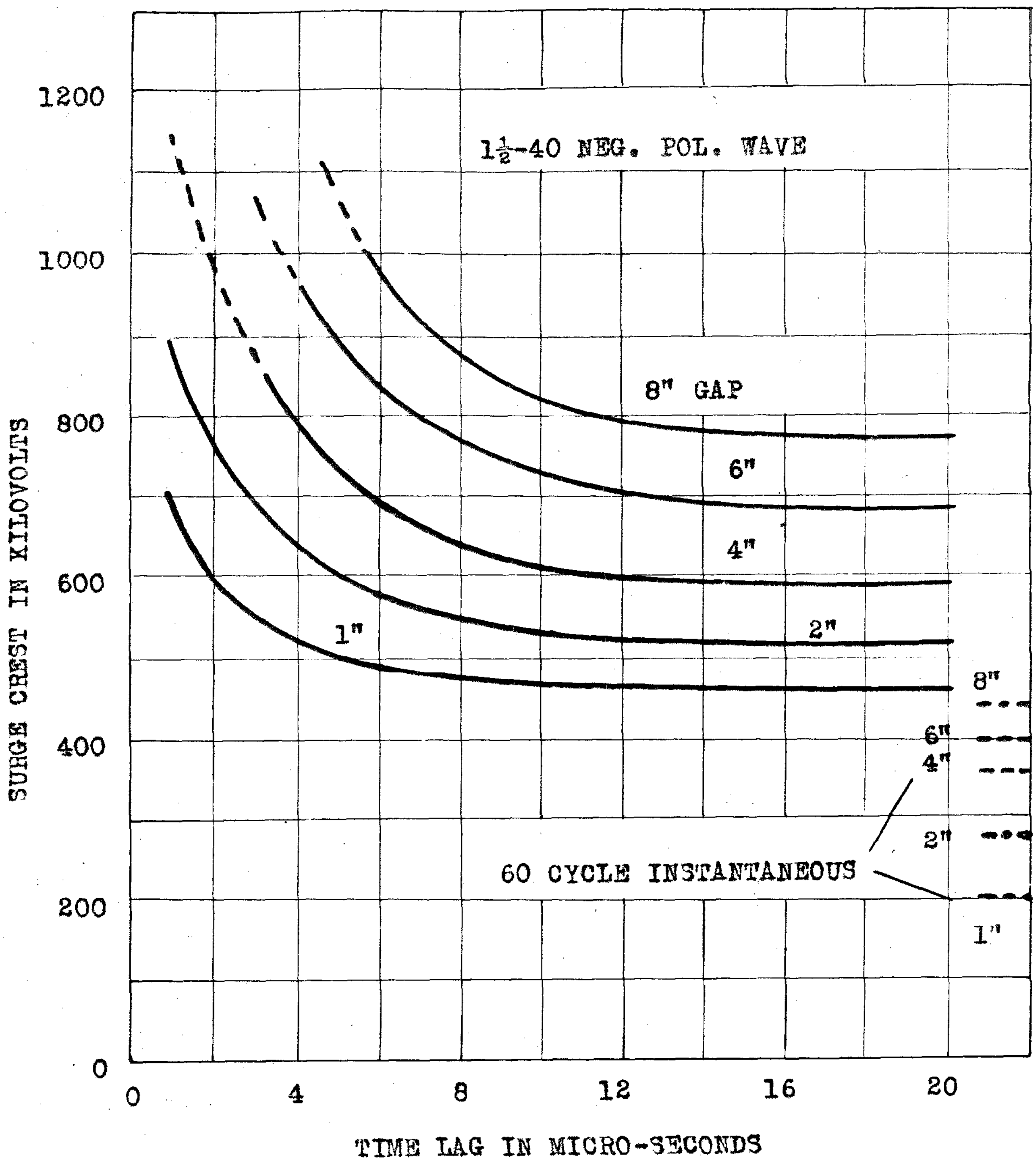
Figs. 12, 14 and 15 show the data obtained for the one inch, two inch and three inch spacings of the one-half inch rods. At the time the data were taken, the second one million volt unit of the surge generator had not been completed and sufficient voltage was not available to determine the upper portion of the curves.

It was found that the curves could be plotted with greater accuracy if all of the points for each gap spacing of a particular electrode size were plotted on one curve sheet and then the curves drawn, taking into account not only the data for each particular spacing, but the relationship between the various curves themselves. It is in this manner that the time lag curves shown for the various sized electrodes, Figs. 16, 17 and 18, are obtained, with some modification. They were first plotted as indicated above, then curves were plotted from them of time lag versus gap spacing for each sized electrode and adjustment made so as to obtain smooth curves in both cases. Such a curve is shown in Fig. 22 for the one-half inch electrodes. If greater accuracy should be desired in obtaining time lag curves for oil without resorting to the almost hopeless task of tediously obtaining a statistical point, as indicated in Fig. 13, for each voltage of the curve, the following method might prove feasible: The time lag curves might be determined accurately for three or four values of spacings for each gap size. These, then, could be plotted on curve sheets and from them, smooth curves of time lag versus spacing for each rod size made on another curve sheet, and finally on a third curve sheet, curves made for each time lag at fixed spacing as a function of rod size. From the last two curves, the time lag curves for other spacings could be determined by chosing points which are mean values of those obtained from the curves.

DISCUSSION OF EXPERIMENTAL RESULTS

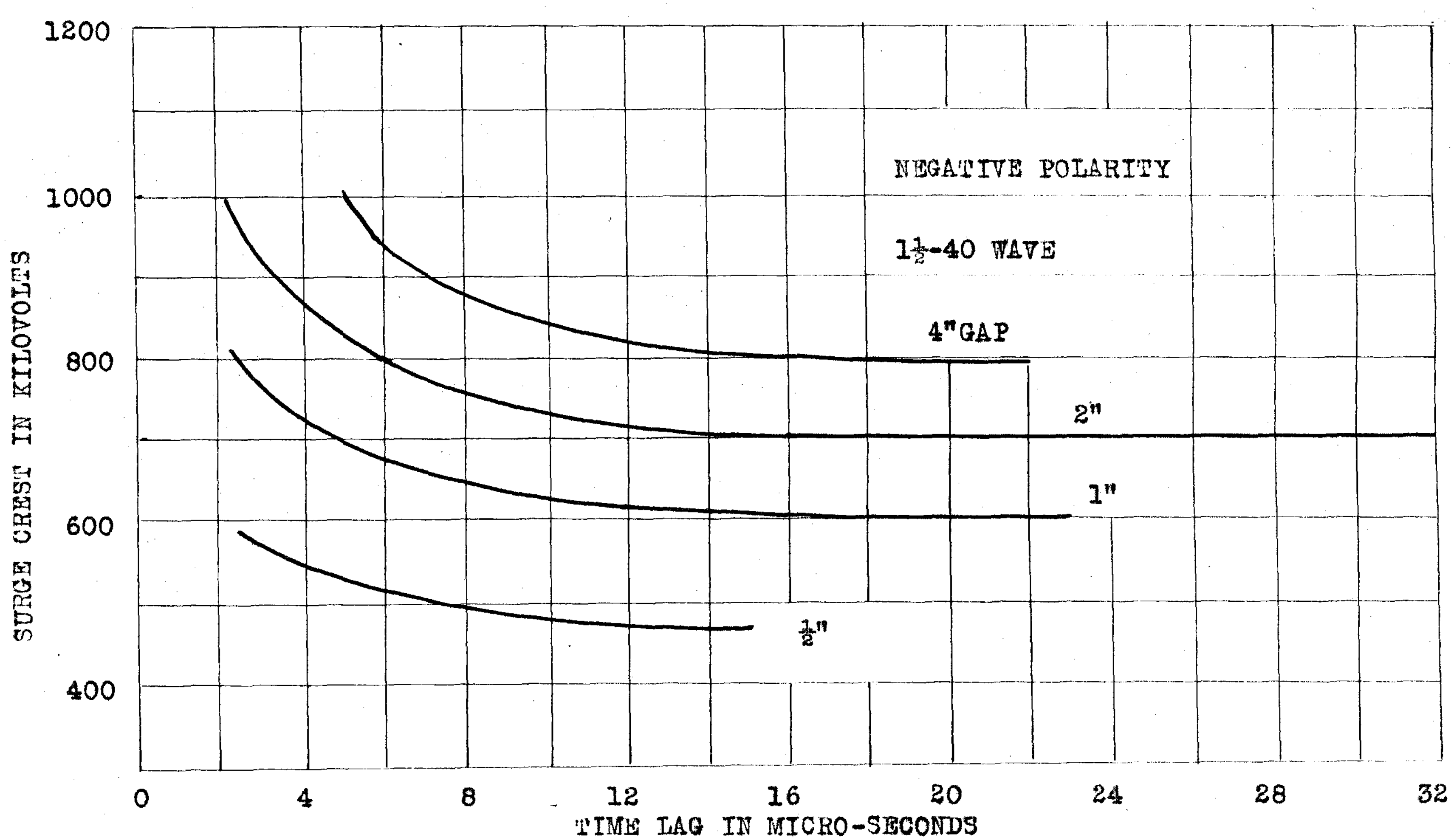
All of the impulse data presented here was obtained with negative polarity surges. No effect of polarity was found at spacings up to three inches, but this has not yet been examined for larger spacings. In Fig. 19 are plotted the curves showing the minimum impulse strength as a function of spacing for the one-fourth inch, one-half inch, one inch and two inch electrodes with hemispherical ends, and in Figs. 16, 17 and 18 are plotted the time lag curves for the one-half inch, one inch and the one-fourth inch rods, respectively. These curves represent all of the data that had been taken up to August, 1938. However, the time lag curve data for the one-fourth inch rods, except for the minimum impulse values, have not yet been checked carefully.

In Figs. 20 to 23 these data are replotted in several forms, together with the data obtained in other laboratories for comparison purposes. It is indicated on the figure wherever such data are used. It was found that the available 60-cycle data were not complete enough for comparison purposes and the



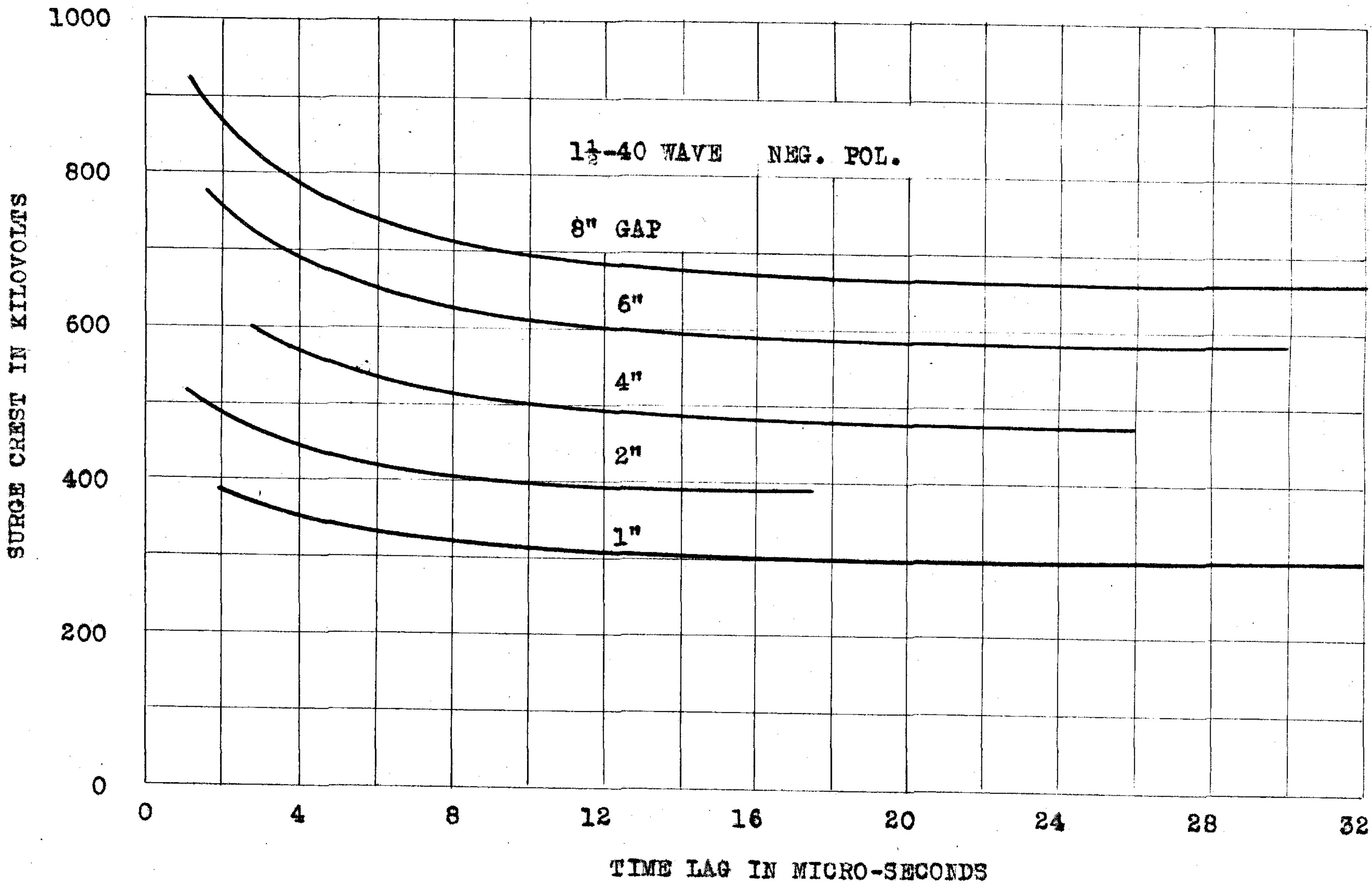
TIME LAG CURVES FOR ONE HALF INCH ELECTRODES

Fig. 16



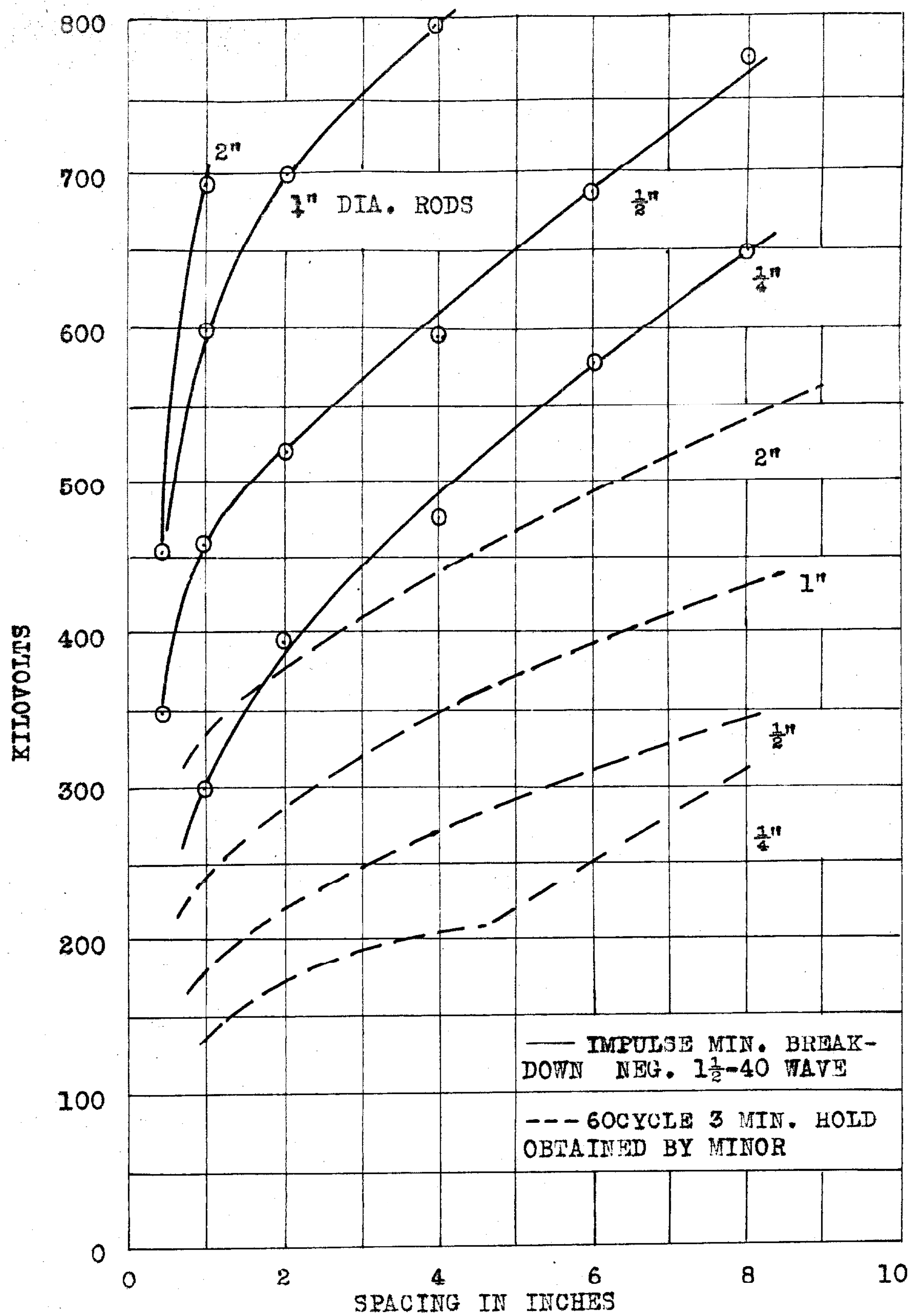
TIME LAG CURVES FOR ONE INCH ELECTRODES

Fig. 17



TIME LAG CURVES FOR ONE FOURTH INCH ELECTRODES

Fig. 18



800
700
600
500
400
300
200
100
0
KILOVOLTS
0
2
4
6
8
10
SPACING IN INCHES
2"
1" DIA. RODS
1/2"
1/4"
2"
1"
1/2"
1/4"
—— IMPULSE MIN. BREAK-DOWN NEG. 1½-40 WAVE
---60CYCLE 3 MIN. HOLD OBTAINED BY MINOR

Fig. 19

data shown in curves A and B of Fig. 20 were taken.

The time lag curves have the conventional shape pertaining to all non-uniform gaps, including those having air as the dielectric medium. They flatten out to the maximum time lag that is obtainable for each particular case. It would be expected that the maximum time lag would increase with the non-uniformity of the gap. The data do not show this clearly. However, such a trend might very well be masked by any change in the condition of the oil or the electrode surfaces. It was shown that poor conditions of either of these produced breakdowns of longer time lags at lower voltages. Furthermore, the time lags at minimum voltages were quite erratic.

The most evident fact shown by the data is the much greater strength of the oil gap to impulse than to power frequency voltages. A simple measure of this is a quantity used commonly in practice, known as the impulse ratio of the gap. This is the ratio between the minimum impulse strength of the gap and its instantaneous 60-cycle crest strength. The impulse ratios for the various gaps for which data are available are given in Table I. Work done by Peek[21] indicates that this quantity should not vary greatly. However, as shown by the data presented here, the ratio varies from a minimum of 1.78 for an eleven inch spacing of the needle gap to a maximum of ten for the twelve and one-half centimeter sphere and plane gap of two-tenths of one inch. In general the data indicate that the larger the electrodes, the greater the ratio for a given spacing. For a given set of electrodes, the ratio seems to increase with spacing up to a certain point, then to decrease.

One obvious but significant fact brought out by such high impulse ratios is that to apply properly oil gaps for switching surge voltages, more experimental dataare necessary. Figs. 20 and 21 show the minimum impulse values for the one-half inch and one inch rods, compared with the instantaneous 60-cycle, the three minute hold 60-cycle, and the ten minute hold 60-cycle curves, showing to what a great extent the time element must be considered in applying these gaps even to power frequency voltages.

TABLE I

IMPULSE RATIOS FOR VARIOUS OIL GAPS

Quarter Inch Rods Hemispherical Ends		Half Inch Rods Hemisph. Ends		One Inch Rods Hemisph. Ends	
Gap Inches	Impulse Ratio	Gap Inches	Impulse Ratio	Gap Inches	Impulse Ratio
1	2.07	1	2.25	½	2.25
2	2.26	2	1.80	1	2.30
4	2.12	4	1.70	2	2.20
8	2.06	8	1.78	4	2.00

Gap with Uniform Field (1)		Needle Gap (2)		6.25 Cm. Sphere Gap (2)		12 Cm. Sphere Gap (2)	
Spacing Millimtrs.	Impulse Ratio	Spacing Inches	Impulse Ratio	Spacing Inches	Impulse Ratio	Spacing Inches	Impulse Ratio
.2	2	1	2.22	0.25	4.29	0.2	10
.5	2.6	2	2.08	0.50	4.32		
1.0	3.0	4	1.91	0.75	4.19		
2.0	3.1	8	1.85	1.00	3.95		
3.0	3.1	11	1.78	2.00	3.34		
				3.00	3.27		

(1) Compiled from data taken from Reference 15.

(2) Compiled from unpublished data given by P. H. McAuley.

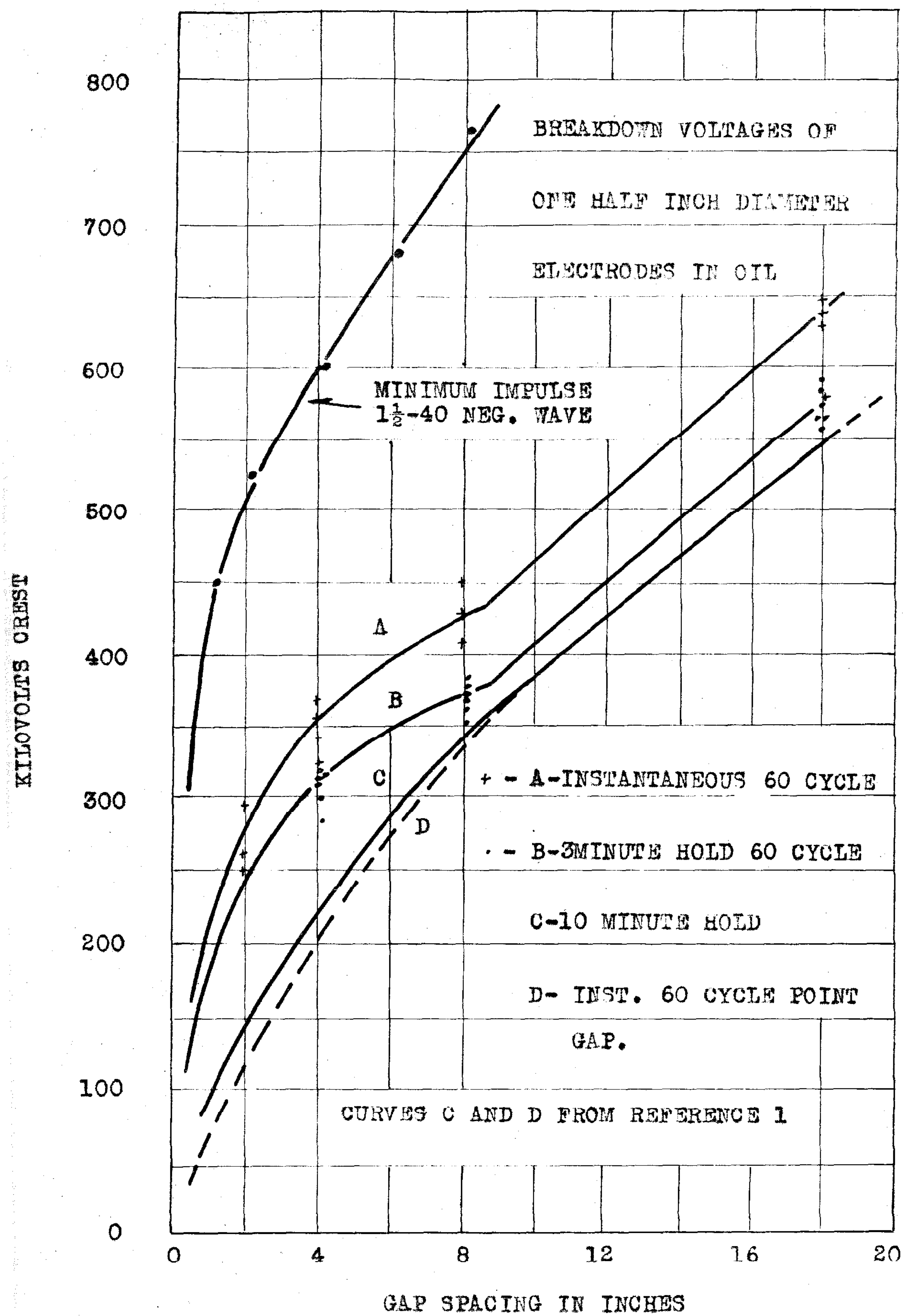

BREAKDOWN VOLTAGES OF
ONE HALF INCH DIAMETER
ELECTRODES IN OIL
MINIMUM IMPULSE
1½-40 NEG. WAVE
A
B
C
D
+ - A-INSTANTANEOUS 60 CYCLE
· - B-3MINUTE HOLD 60 CYCLE
C-10 MINUTE HOLD
D- INST. 60 CYCLE POINT GAP.
CURVES C AND D FROM REFERENCE 1
KILOVOLTS CREST
800
700
600
500
400
300
200
100
0
0
4
8
12
16
20
GAP SPACING IN INCHES

Fig. 20

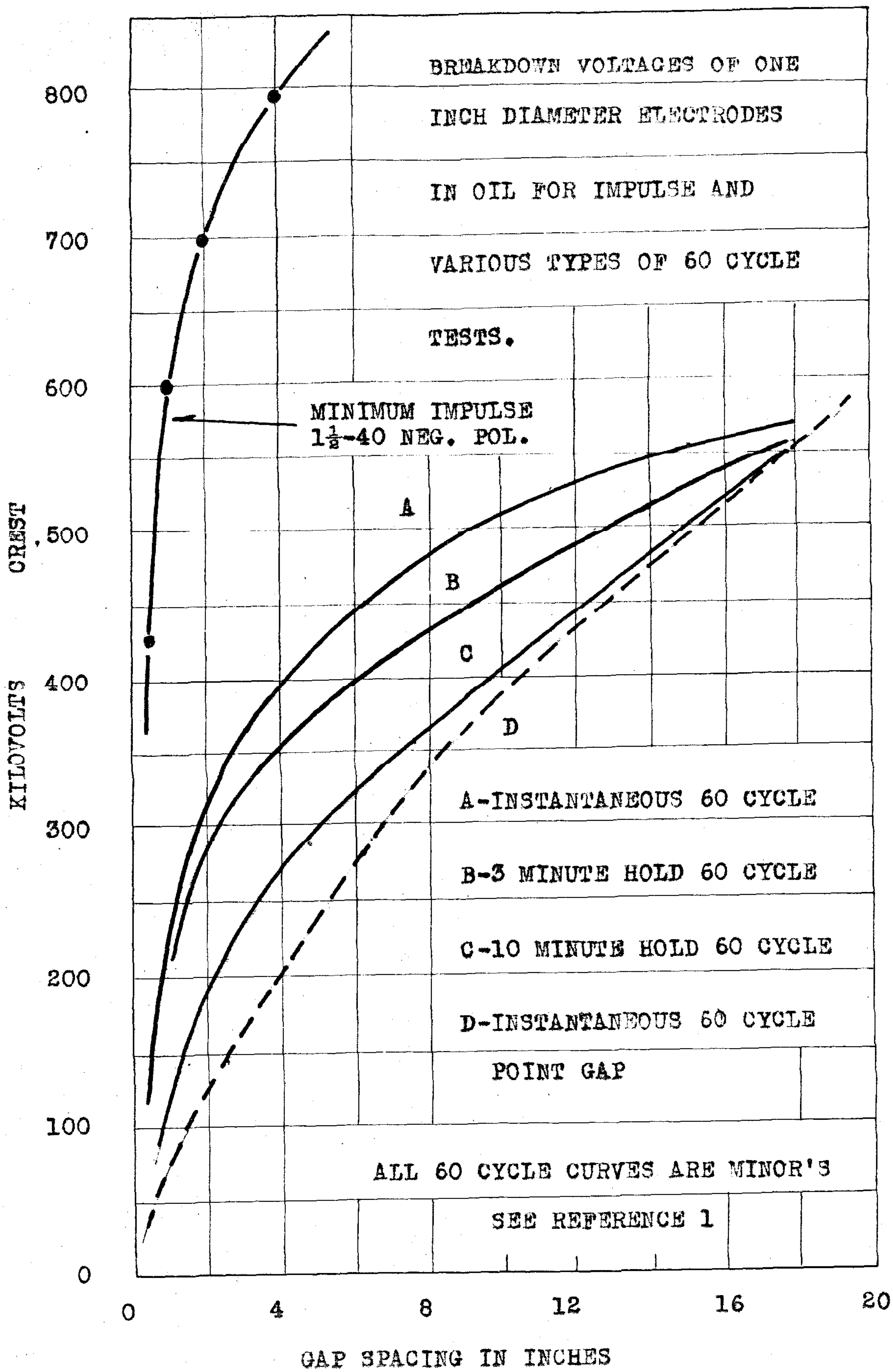
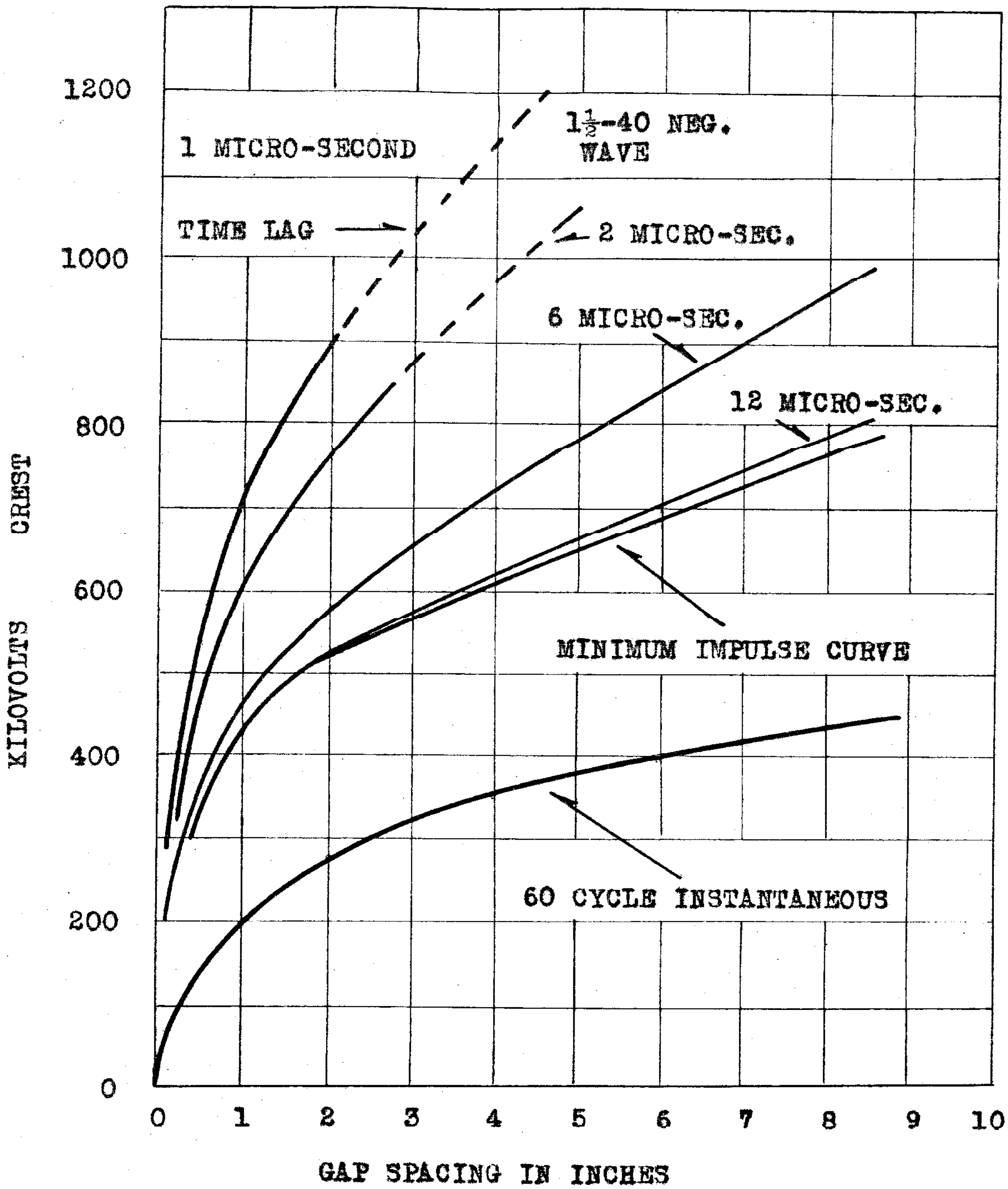
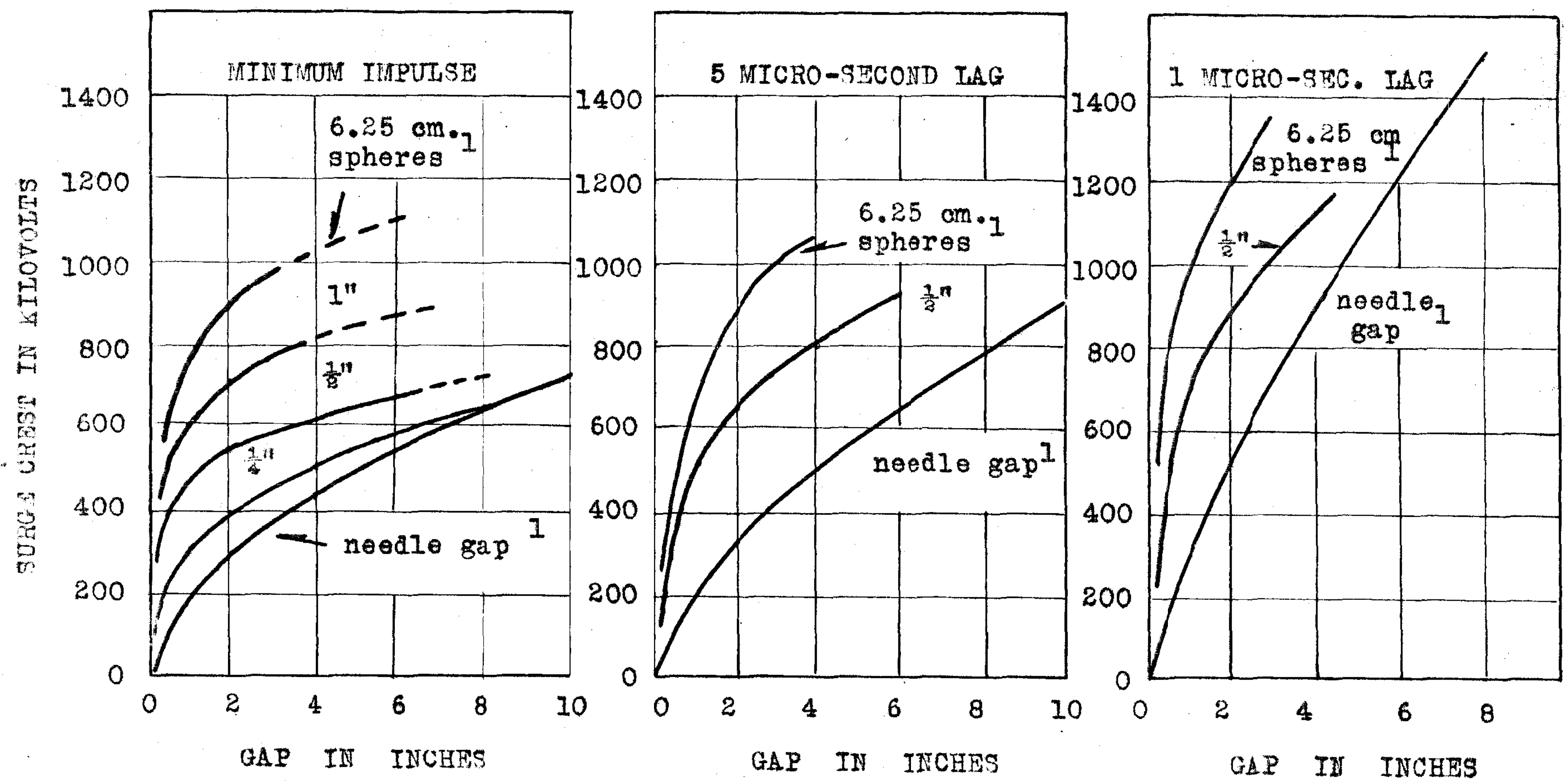

BREAKDOWN VOLTAGES OF ONE INCH DIAMETER ELECTRODES IN OIL FOR IMPULSE AND VARIOUS TYPES OF 60 CYCLE TESTS.
MINIMUM IMPULSE 1½-40 NEG. POL.
A
B
C
D
A-INSTANTANEOUS 60 CYCLE
B-3 MINUTE HOLD 60 CYCLE
C-10 MINUTE HOLD 60 CYCLE
D-INSTANTANEOUS 60 CYCLE POINT GAP
ALL 60 CYCLE CURVES ARE MINOR'S
SEE REFERENCE 1
800
700
600
500
400
300
200
100
0
CREST, KILOVOLTS
0
4
8
12
16
20
GAP SPACING IN INCHES

Fig. 21



TIME LAG CURVES FOR ONE HALF INCH ELECTRODES IN OIL

Fig. 22



COMPARISON OF SPHERE GAP TIME LAG CURVES AND NEEDLE GAP CURVES

Fig. 23

[1]Curves obtained from McAuley.

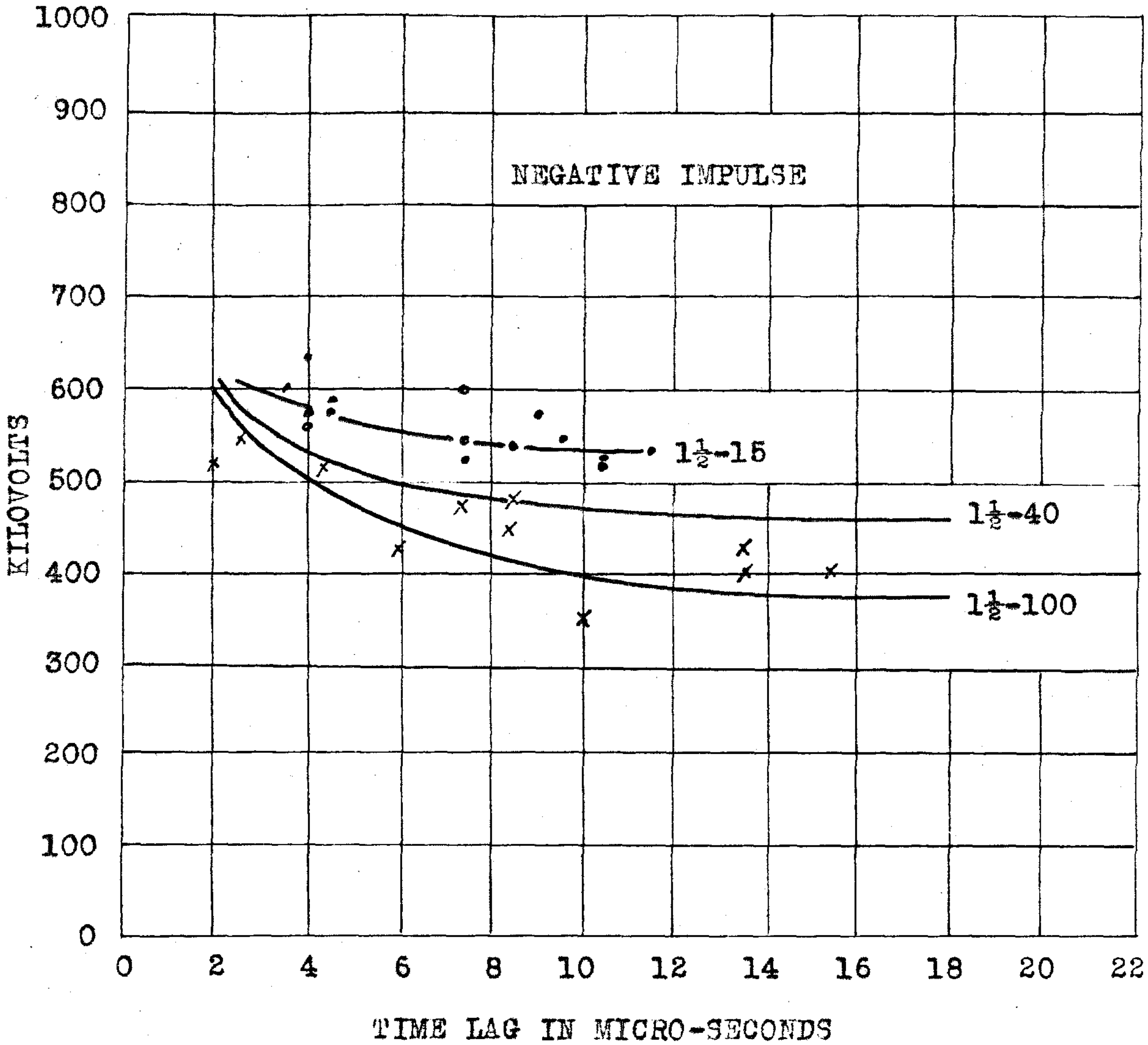
There is an interesting relationship that has been found to exist between the 60-cycle strength of sphere gaps and needle gaps. When the breakdown strength of a sphere gap is plotted as a function of spacing, the characteristic curve is an exponential one up to a certain critical spacing, where it becomes almost linear and very similar to that of a needle gap curve which is more linear over its whole range. This point of discontinuity was found by Schwaiger[22] for air gaps to be at the spacing for which the field became non-uniform to such an extent that a glow or corona discharge took place before breakdown. Minor[17] found a similar characteristic for oil gaps. He found that both the three minute hold and ten minute hold 60-cycle breakdown curves coincided with the needle gap curve after a certain critical spacing had been reached. (Needle oil gap data have been found to be much more consistent than that for sphere gaps, the instantaneous breakdown values coinciding with those of longer applications of voltage.)[17] Power frequency tests made in this laboratory (shown in Fig. 20) do not agree exactly with Minor's work. Instantaneous and three minute hold 60-cycle curves obtained for one-half inch electrodes do not come together at the critical spacing, but become parallel to each other and to the needle gap curve data given by Minor.

Somewhat similar results are indicated by the impulse characteristics of the sphere and needle gaps. In Fig. 23 are plotted the minimum impulse strength, the five microsecond breakdown voltage and the one microsecond breakdown voltage of the needle gap and various sized sphere gaps. The curves, unfortunately, have not yet been extended to high enough voltages and large enough spacings to show a definite break in their character. However, they do show a tendency to be approaching the needle gap curves and in the case of the largest spacing for which data have been taken for the one-fourth inch rods for minimum impulse voltage (a spacing of eight inches), the one-fourth inch rod curve has coincided with the needle gap curve.

In the light of this comparison, it is thought that the time lag curves for the one-fourth inch rods are in error. All but the minimum impulse values are found to drop below the corresponding values for the needle gap.

To determine the effect of the impulse wave shape, the data plotted in Fig. 24 were taken, using two other wave shapes; one having a fifteen microsecond tail and the other having a one hundred microsecond tail. The results show that as the time lag decreases, the curves tend to approach each other. The one hundred microsecond wave gave a minimum impulse value about twenty per cent below that for the standard forty microsecond wave, and the fifteen microsecond wave gave a value about seventeen per cent higher. The maximum time lags obtainable were greater for the longer tailed wave. These are results which would be expected where breakdown mechanisms requiring long time lags, as is the case for oil, are possible.

There is one important fact brought out by these results. It seems evident that for coordination purposes even in the lightning impulse range of voltages, the performance of the oil gap is not completely determined from time lag curves obtained by the use of the standard $1\frac{1}{2}$-40 wave. If gaps having very close insulation strength are to be



CURVES SHOWING THE EFFECT OF WAVE SHAPE ON TIME LAG FOR FLASH OVER ON THE TAIL OF THE WAVE ONE HALF INCH RODS ONE INCH SPACING

Fig. 24

coordinated, a flatter topped wave must be used. It is, thus, seen that over the whole range of voltages which must be considered in coordination work, wave shape and time of application of voltage must be considered for oil gaps. Until more data are available, however, results obtained with the $1\frac{1}{2}$-40 wave are applicable as long as this fact is realized and sufficient safety factors are employed.

The wide spread of possible time lags for a given voltage is also a disturbing fact when coordination of gaps is being considered. From this it seems more feasible to consider the time lag characteristics of such oil gaps as a band instead of a definite line for practical applications.

It is interesting to consider the results from a theoretical standpoint. It is now well established that there are three general types of breakdown which may take place in oil. Pure electric breakdown due entirely to electronic ionization by collision is found very rarely. Only with the most carefully cleaned oil and electrodes or at time lags less than one microsecond[23] is this breakdown possible. Koppelmann[24] sets 1.5×10^6 volts per centimeter as the lowest gradient at which such a mechanism is possible.

The most common type found in practice is the thermal electric breakdown due to the liberation of gases by heating and the consequent gaseous breakdown. Under some conditions the gases are already present in the oil, as is the case directly after breakdown of the gap. It has been found possible to produce heating in several ways. Oils normally having too high a resistance may have it lowered by the application of a field. This is most commonly caused when impurities of relatively high conductivity are forced into the stronger parts of the field by the high dielectric stresses. They tend to line up and form conducting paths. Suspended moist dust or fibres can cause this, whereas either the moisture or dust alone will not. Dielectric losses at sustained applications of frequencies above one megacycle[25] cause this type of breakdown. There is another type of thermal electric breakdown which is possible in pure oil at high field strengths. The conduction current of pure oil is a function of the electric field and at high stresses increases exponentially with it. Nikuradse[26] found that at fields greater than 10^6 volts per centimeter, it is possible to generate enough heat by this mechanism to cause breakdown.

A third known mechanism is mechanical breakdown. This was first suggested by Gemant[27] and later perfected by Koppelmann.[24] An electric layer of high stress is present at the electrode surface due to space charge acting on a layer of absorbed gas. This creates a gas pocket which either produces gaseous ionization or finally the development of a larger gas bubble which shoots across the gap to the other electrode.

The gradients at which breakdown occurred in all cases of this research seem too low for either the electrical or Nikuradse mechanism. A study of the maximum gradients obtained shows the highest to be about eight hundred kilovolts. There are indications pointing to both the mechanical breakdown and the thermal mechanism due to impurities. Each is possible at the gradients and time intervals occurring in this research, and the irregularities experienced in time lag and dielectric strength are characteristic to both.

One would expect the thermal breakdown mechanism to be indicated by variations in the oil itself, while the mechanical mechanism would be affected by electrode conditions.[(24)] The presence of thermal breakdown due to moist particles is almost definitely established by the low dielectric strength obtained when the oil had been allowed to stand for some time in a damp atmosphere.

The results shown by rough electrodes can be explained by Koppelmann's theory, as it is easier to separate the electrode and oil surfaces when slight irregularities are present. However, the critical effect of electrode conditions can be explained in other ways. If electrical breakdown were present, the slightest irregularities would be very important. From a consideration of the Law of Similitudes, one can expect a dimension of 10^{-5} centimeters in oil to be as important as one of 10^{-2} centimeters in a gas. Another possible electrode effect is grease or any impurity which prevents good contact between the electrode and oil.

There are too many variables present in a set-up of this kind to permit one to obtain many conclusive theoretical results. It is important, however, to recognize their effects with a view to improving conditions in the practical application of oil as an insulating medium.

CONCLUSIONS

The following conclusions may be drawn from the work done on the impulse strength of large oil gaps:

1. The oil tank developed provides a more satisfactory method of determining the insulation characteristics of large oil gaps than those used in the past.
2. The impulse strength of oil is erratic and subject to slight variations in both oil and electrode conditions.
3. Until better means are developed to control such conditions in commercial apparatus, the time lag characteristics would best be represented by a band instead of a definite line.
4. Although the impulse ratios for the gaps studied did not vary over a wide range, it is possible to obtain much larger values for larger electrodes at smaller spacings.
5. The high impulse ratios indicate a need for more data on the performance of oil gaps to switching surge voltages.

6. The wave shape of the surge is more important for oil gaps than for air gaps.
7. The thermal electric breakdown is the most probable cause of oil failure for impulses, as it is at power frequency voltages.

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APPENDIX I

CALCULATIONS OF FIELD DISTORTION PRODUCED BY METAL TANK

An estimate of the distortion of the electrostatic field in the gap due to the side walls of a conducting tank may be obtained by considering the effect on two point charges situated as shown in Fig. 25(a), a distance 2c apart on the axis of symmetry of a cylindrical conducting shell of radius a.

The solution is given by Smythe* for a point charge, a distance c from the bottom of a metal cylindrical box of height L. The expression for the potential inside the tank is given by the following equation expressed in the cylindrical coordinates ρ, z (see Fig. 25(a).

$$V = \frac{8q}{a^2} \sum_{r=1}^{\infty} \frac{\sinh \mu_r (L-c) \sinh \mu_r z}{\sinh \mu_r L} \frac{J_0(\mu_r \rho)}{2\mu_r (J_1(\mu_r a))^2}$$

This is an equation involving the Bessel Functions J_0 and J_1 and the values of μ_r are determined from the equation

$$J_0(\mu_r a) = 0$$

*Smythe, W. R., Static and Dynamic Electricity, Edwards Brothers, Inc., 1936, page 53.

This can be applied to the desired case by neglecting the effects of the ends of the cylinder, letting L be infinite, and taking the bottom plane of the box as the zero potential plane between the two point charges. The equation for the potential then takes the form

$$V = \frac{2\mathcal{E}}{a^2} \sum \frac{\left[\epsilon^{-\mu_r(z-c)} - \epsilon^{-\mu_r(z+c)}\right] J_0(\mu_r \rho)}{\mu_r \left(J_1(\mu_r a)\right)^2}$$

To determine the relative amount of distortion produced at any point in the field, the potential calculated with this equation may be compared with that for the two point charges alone. This should give a reasonably good indication of the effect of the tank. The field of a sphere gap alone would be represented* by a series of images on the axis of symmetry of the spheres. This calculation gives the effect of the field produced by the principal charges of the series situated at the centers of the two spheres and the relative effect on the other charges should be of less magnitude.

Calculations were made to determine the region

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*Jeans, J. H., Electricity and Magnetism, Cambridge Press, 1933, page 196.

TABLE II.

SAMPLE OF FIELD CALCULATIONS

A	B	C	D	E	F	G	H	I	J	K
$\mu_r a$	$J_1^2(\mu_r a)$	$\mu_r J_1^2(\mu_r a)$	$\mu(z-c)$	$\mu(z+c)$	$\varepsilon^{-\mu(z-c)}$	$\varepsilon^{-\mu(z-c)}$	$F-G$	$\frac{H}{C}$	$J_0(\mu\rho)$	$I \times J$
2.405	.27	.00651	.361	1.08	.700	.340	.360	55.30	+.985	+54.51
5.52	.115	.00635	.828	2.48	.436	.0830	.353	55.60	.926	51.55
8.65	.073	.00632	1.295	3.88	.273	.0206	.252	40.01	.824	32.95
11.79	.053	.00625	1.77	5.32	.170	.0049	.165	26.41	.631	16.64
14.93	.044	.00655	2.24	6.73	.106	.00178	.104	15.92	.517	8.24
18.07	.036	.00652	2.71	8.13	.0760	.000295	.073	11.25	.334	3.74
21.21	.029	.00615	3.18	9.55	.0412	.000071	.0412	6.65	.155	1.03
24.49	.025	.00608	3.66		.0257			4.23	-.018	- .760
27.49	.0225	.00614	4.27		.0140			2.28	.164	.375
30.63	.0210	.00644	4.59		.0100			1.55	.280	.419
33.77	.019	.00640	5.07		.0063			.98	.361	.359
36.92	.017	.00627	5.52		.0049			.78	.399	.311
40.06	.016	.00641	6.00		.0029			.45	.397	.178
43.20	.014	.00604	6.48		.0015			.25	.358	.091
46.34	.0135	.00628	6.915		.0010			.16	.288	.045
49.48	.0124	.00594	7.410		.0006			.10	.194	.019
52.62	.012	.00631	7.860		.00038			.06	.090	.0054
55.76	.011	.00649	8.350		.00024			.04	+.020	+.0008
58.91	.01	.00589	8.850		.00015			.02	.119	
62.05	.01	.00621	9.330		.00009			.02	.204	
								Sum 221.85		Sum 167.09

(a) at $z = 15$, $\rho = 0$

$V = 4.44 \times 10^{-2} q$

Undistorted

$V = 4.45 \times 10^{-2} q$

(b) at $z = 15$, $\rho = 10$

$V = 3.34 \times 10^{-2} q$

Undistorted

$V = 3.35 \times 10^{-2} q$

of the gap where the distortion is less than one-half of one per cent for three cases. Values of the distance between charges having 2c equal to .1d, 2c equal to .3d and 2c equal to .5d were chosen as covering the range of gap spacings that were desired to use in the actual test tank.

Calculations were made by picking increasingly larger values of ρ for a series of values of z until a variation between the calculated field and the undistorted field was more than one-half of one per cent. A sample of the calculations is given in Table II. They were made for a equal to 100 centimeters and 2c equal to .3d, but apply to any scale having the same ratio of c and d. This is necessarily a very tedious calculation and only enough points were found to determine roughly the regions as shown in Figs. 25(b) (c) and (d), which give the results of the calculations for the three cases.

In Table III are given the approximate gap spacings for the various sized electrodes to be used, corresponding to the three values of 2c and a tank diameter of eighty inches. For a forty-inch tank the spacings would be one-half as great. An examination of this table and Fig. 25 enables one to determine for any particular case the extent of the undistorted field.

TABLE III.

Electrode Diameter	Corresponding Appr. Spacing		
	2c = .1	2c = .3	2c = .5
¼ in.	8 in.	24 in.	40 in.
½ in.	7½ in.	23½ in.	39½ in.
1 in.	7 in.	23 in.	39 in.
2 in.	6 in.	22 in.	38 in.
4 in.	4 in.	20 in.	36 in.
6 in.	2 in.	18 in.	34 in.

DIMENSION FACTORS IN FIELD DISTORTION CALCULATIONS

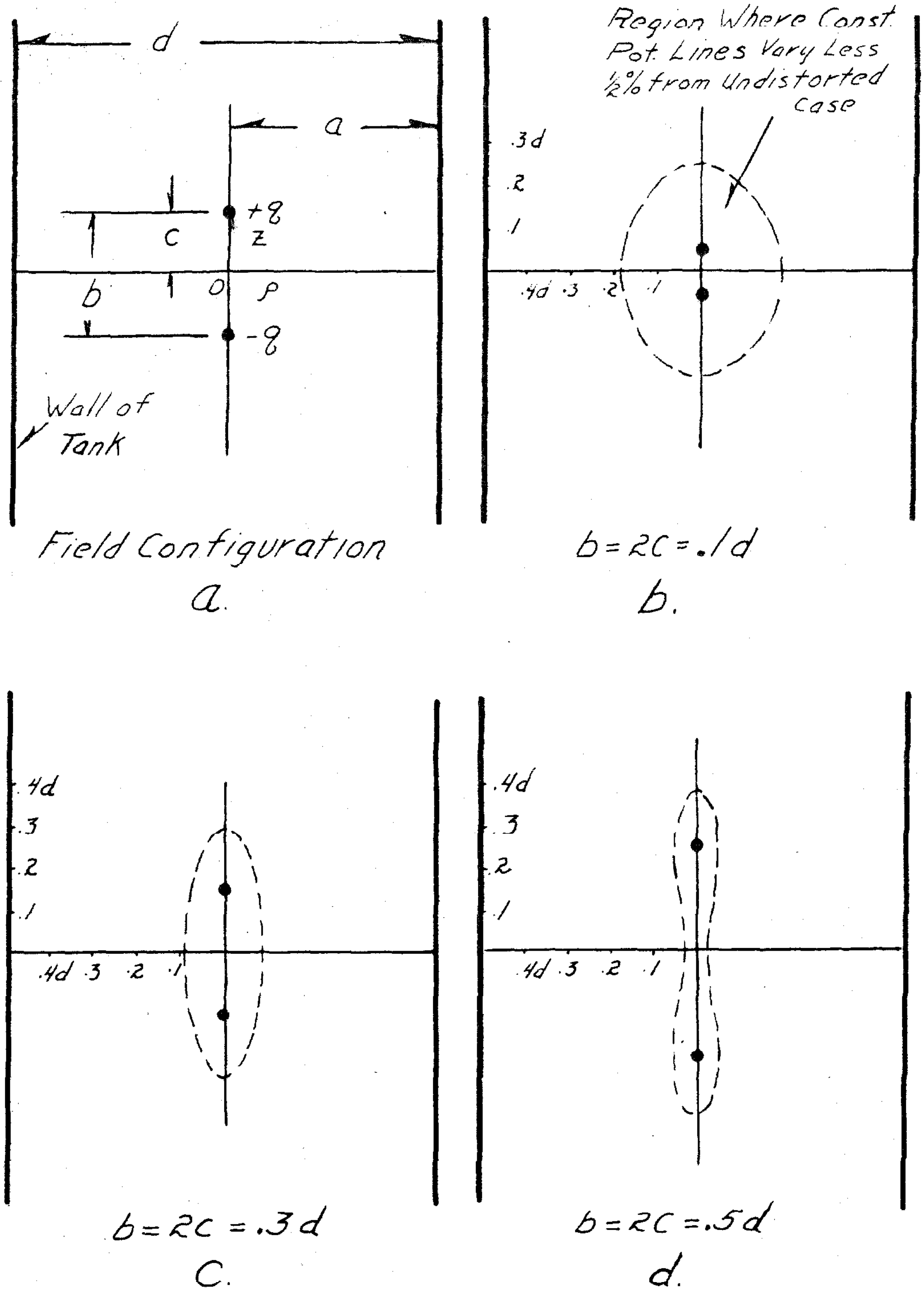


Fig. 25 Diagrams Showing the Extent to Which the Field Between Point Charges is Affected by the Walls of a Cylindrical Metal Tank.

APPENDIX II.

IMPULSE TESTING TECHNIQUE

Surge Generator Calibration:

The use of the surge generator for standard surge testing requires a knowledge of the effect of its characteristic circuit constants to such an extent that the desired wave shapes may be obtained by the proper adjustment of the controllable constants. The calibration of a surge generator can be facilitated by the use of theoretical calculations based upon simplified equivalent circuits. The circuit used most generally for this purpose is that shown in Fig. 26(a). The solution of this circuit for the voltage across the discharge resistance is given by the equation:

$$e = \frac{\frac{E}{L_s C_L}}{(\lambda-\alpha)^2+\omega^2}\left[\epsilon^{-\alpha t} - \epsilon^{-\lambda t}\left(\frac{\lambda-\alpha}{\omega}\sin\omega t + \cos\omega t\right)\right]$$

Where

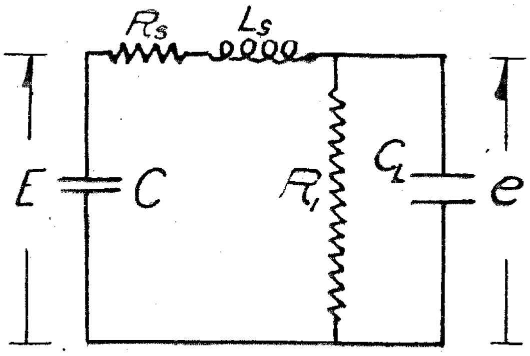
$$(p+\alpha)\left[(p+\lambda)^2+\omega^2\right] = p^3 + \left(\frac{R_s}{L_s} + \frac{1}{R_1 C_L}\right)p^2 + \left(\frac{1}{L_s C} + \frac{1}{L_s C_L} + \frac{R_1}{L_s C_L R_s}\right)p + \frac{1}{L_s C C_L R_1}$$

However, it is necessary to calibrate by test to determine satisfactorily the proper constants to use for controlling the wave shape and determining the primary charging voltage necessary to obtain a given discharge voltage.

The inherent inductance of the stationary one million volt surge generator at the California Institute of Technology is so large that no inductance need be added to obtain a standard wave front. The value of damping resistance required to provide ample damping of oscillations produced by the combination of the inherent inductance and the shunt capacity provided by the distributive capacity of the surge generator and the capacity of equipment being tested is three hundred ohms distributed throughout the surge generator at the discharge gaps. Control of the duration of the wave is obtained by varying the main discharge resistance. In Fig. 27(a) is given the calibration of the duration of the wave as a function of discharge resistance as determined with the cathode ray oscillograph. In Fig. 27(b) is given the discharge voltage calibration of the surge generator for a standard 1½ x 40 wave. Theoretically, this calibration curve should be a straight line. However, this surge generator has always had a slight droop in its curve at the higher voltages. This was found to be due to conduction of current on discharge through portions of the maple wood frame, when at one time complete breakdown of a portion of this insulation took place, giving the calibration shown by the broken line in Fig. 27(b). The failure was found to be in a section of the frame where the condenser rested on the maple wood and was stopped by suitably insulating the condensers from the maple.

The nominal capacity of this surge generator, .025 microfarads, is much higher than that normally used. This high capacity has a distinct advantage in improving the regulation of its output voltage as affected by the shunt capacity of attached testing equipment. In Fig. 26(b) is shown the regulation curve of the output voltage of any surge generator as a function of the ratio of the load capacity and main surge generator capacity. The capacity of the equipment usually tested, such as insulator strings and circuit breakers, is generally never more than three hundred micro-microfarads. Such a load would give negligible regulation as shown by the curve.

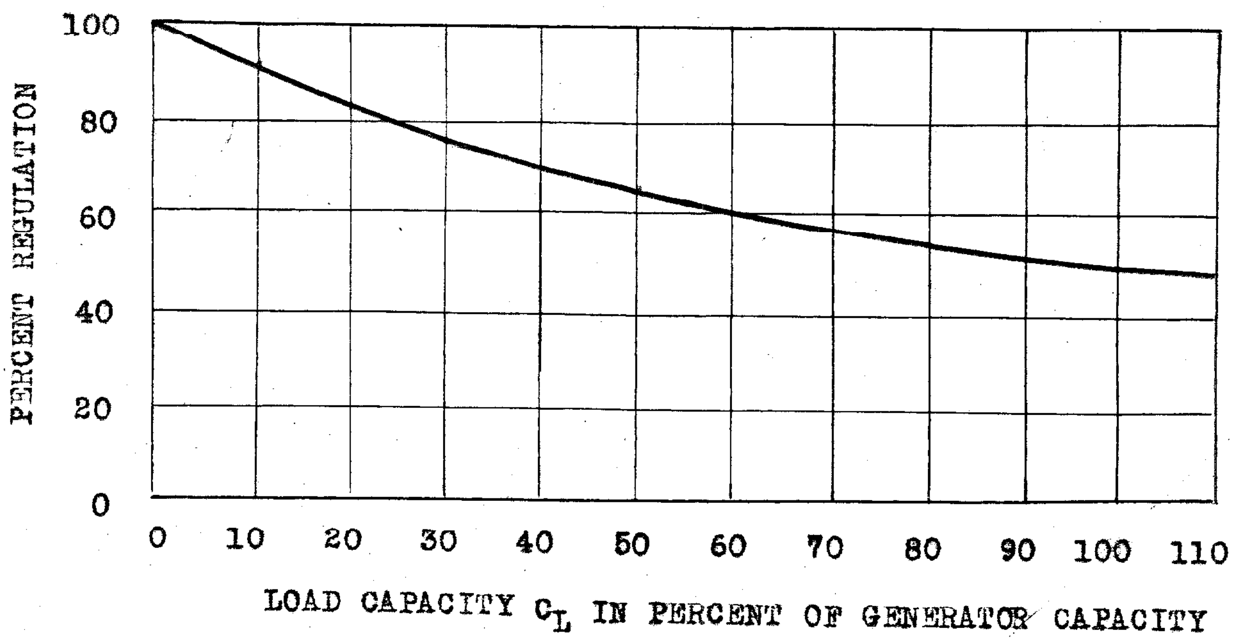
A.



$$e = \frac{\frac{E}{L_s C_L}}{(\lambda-\alpha)^2+\omega^2}\left[\mathcal{E}^{-\alpha t} - \mathcal{E}^{-\lambda t}\left(\frac{\lambda-\alpha}{\omega}\sin\omega t + \cos\omega t\right)\right]$$

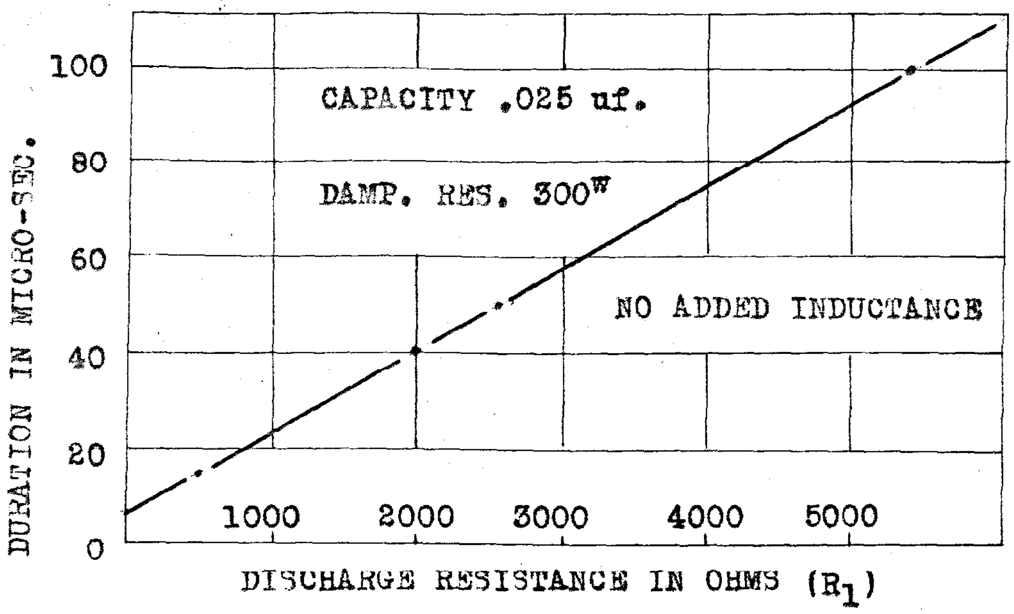
EQUIVALENT CIRCUIT AND EQUATION FOR CALCULATING SURGE GENERATOR PERFORMANCE.

B.



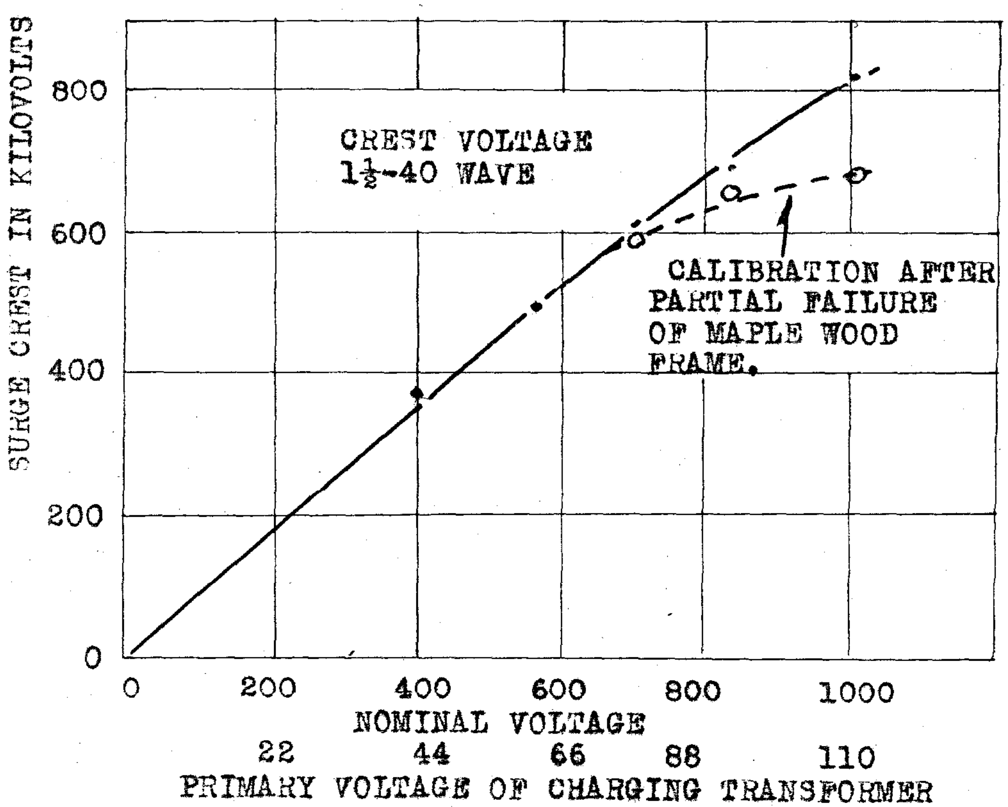
CURVE SHOWING REGULATION OF OUTPUT VOLTAGE OF ANY SURGE GENERATOR AS A FUNCTION OF THE PERCENT LOAD CAPACITY

Fig. 26



A.

CALIBRATION CURVE FOR DURATION OF 1½ MICRO-SEC. FRONT WAVE AS A FUNCTION OF R_1 FOR ORIGINAL 1000 KV. UNIT OF C.I.T. SURGE GENERATOR



B.

VOLTAGE CALIBRATION OF ORIGINAL 1000 KV. UNIT OF C.I.T. SURGE GENERATOR.

Fig. 27

<u>Surge Generator Tripping Circuits</u>:

The tripping circuits finally adopted for initiating discharge of the surge generator are of the mechanical type shown in Fig. 28. Fig. 28(a) shows the arrangement used for the impulse work on oil gaps. It consists merely of a solenoidal operated switch which shorts out the trip gap. It is occasionally desired in test work to coordinate the impulse with some portion of a power frequency voltage, and the synchronizing circuit, Fig. 28(b), was tried and found suitable for this purpose. This circuit consists of two sphere gaps in series; one which may be shorted by a solenoidal operated switch which is left open until tripping is desired; the other which is periodically shorted by means of a rotating arm run by a synchronous motor from the power supplying the 60-cycle voltage with which synchronization is desired. By adjusting the position of the arm on the motor shaft, synchronization on any part of the wave may be obtained. However, polarity cannot be controlled. When tripping the surge generator is desired, the solenoidal operated gap is shorted out; then the next time the metal portion of the rotating arm comes between the spheres of the other gap, the discharge of the surge generator is obtained.

Previously tried trip circuits of the impulse type are shown in Fig. 29. These circuits rely upon the discharge of a miniature surge generator through a control tube. Both an RCA-885 Thyratron and a General Radio Gridglow tube were tried for this purpose and found satisfactory. After suitable amplification by means of a low inductance transformer, the resulting impulse is applied to the third sphere of the trip gap of the surge generator. More positive tripping was obtained, however, by means of the mechanical circuits which lessen the chance of any damage to the tripping equipment.

Control Circuits of the Cathode Ray Oscillograph:

The cathode ray oscillograph used in the impulse testing with oil gaps was constructed by Dr. Howard Griest and is described in detail in his thesis.[(18)] It is of the cold cathode type; voltage between the cathode and the grounded anode being obtained from the ten thousand volt direct current circuit shown schematically in Fig. 8. In Fig. 30

are shown schematic diagrams of the cathode ray tube and the auxiliary unblocking and sweep circuits. In operation the beam is on constantly, being deflected to the side of the tube by means of the blocking plates which have constant potentials of opposite polarity on the two sets. Initiation of the beam is obtained by removing this voltage. This blocking arrangement differs from the conventional Norinder circuit where a trap is provided for blocking the beam when it is in the center of the tube and no voltage is on the blocking plates before initiation. To initiate the beam for the Norinder circuit, voltage is applied to the plates, deflecting them around the trap and on to the screen.

The unblocking and sweep circuit shown in Fig. 30 operates as follows: Before initiation of the triple gap by an impulse from the surge generator, a constant potential of three thousand volts is across the blocking plates and the condensers C_1. Tripping the sphere gap shorts out the blocking plates and removes the voltage from them. This allows the beam to come down the center of the cathode ray tube where it would start its sweep if suitable deflection to the side of the screen were not provided by the beam bias circuit.

Various values of sweep speed are obtained by varying the values of the resistance R_7 and the condensers C_2. Calibration of the sweep is obtained by means of a calibrating oscillator. The sensitivity of the deflection plates of the cathode ray oscillograph is obtained by applying a known direct current voltage to the plates and noting the deflection in inches. During the period that the impulse work on oil gaps was being done, difficulty was experienced in maintaining constant beam current. This resulted in a variable sensitivity of the beam and it was found necessary to calibrate with each record that was obtained. This was done by marking on the florescent screen a deflection of one inch and after each surge, applying sufficient voltage to deflect it to this point.

Voltage Calibration of the Cathode Ray Oscillographs:

The resistance potentiometer used is of the non-inductively wire wound type. The wire, however, was wound in a different manner from that commonly used for such potentiometers. Instead of winding two layers of wire, one on top of the other in opposite directions, so that the inductance of one cancels the other, the wire was wound back on itself and the resulting free ends at one side of the micarta sheet upon which it was wound were laced together with thread. The value of resistance used with the one million volt stationary unit of the surge generator is 10,670 ohms. The cable terminating resistance is 50.8 ohms, having five taps, as shown in Fig. 30, to which the ungrounded deflection plate may be connected to give various sensitivities.

In Tables IV and V are given samples of the experimental data taken from the work done on oil gaps and the calculations used in determining the crest voltage applied to the gap.

TABLE IV

SAMPLE EXPERIMENTAL DATA SHEET

Date	Data on C.R.O.				Data on S.G.		Gap being Tested		
	Film No.	Sweep Speed No.	Cable Term.Res. Tap No.	Beam Defl. Sens.in Volts/In.	Auto Transf. Tap No.	Dischg. Res.Ohms	Elect-rodes	Gap Spac. Ins.	No.of Shots Since Treat.*
3/2/38	KE-C-16	5	2	1280	5	1950	$\frac{1}{2}$ in.	1	16
3/5/38	KE-G- 3	5	2	1280	7	2060	$\frac{1}{2}$ in.	2	3
3/24/38	KE-N- 6	5	2	1325	5	2100	1 in.	$\frac{1}{2}$	4
3/24/38	KE-N-11	5	2	1315	5	2100	1 in.	$\frac{1}{2}$	5
3/24/38	KE-N-13	5	2	1315	5	2100	1 in.	$\frac{1}{2}$	6

*Records were kept of cleaning of oil and polishing of electrodes.

TABLE V

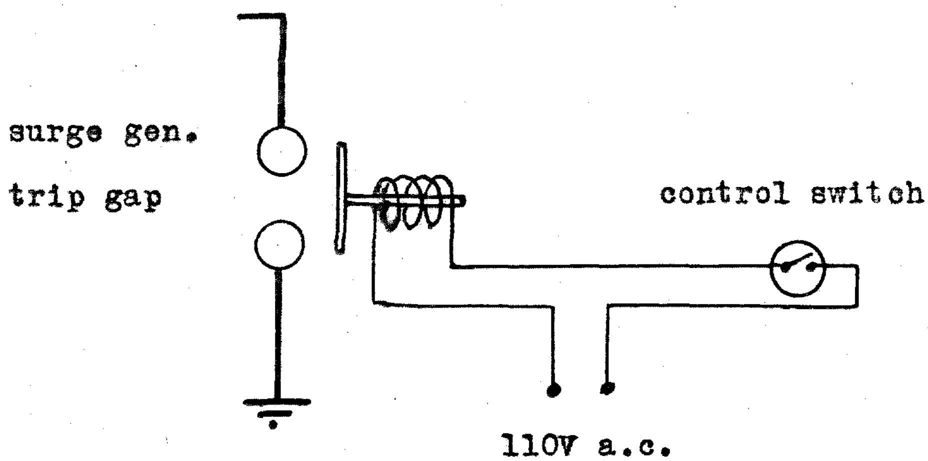
SAMPLE CALCULATION SHEET

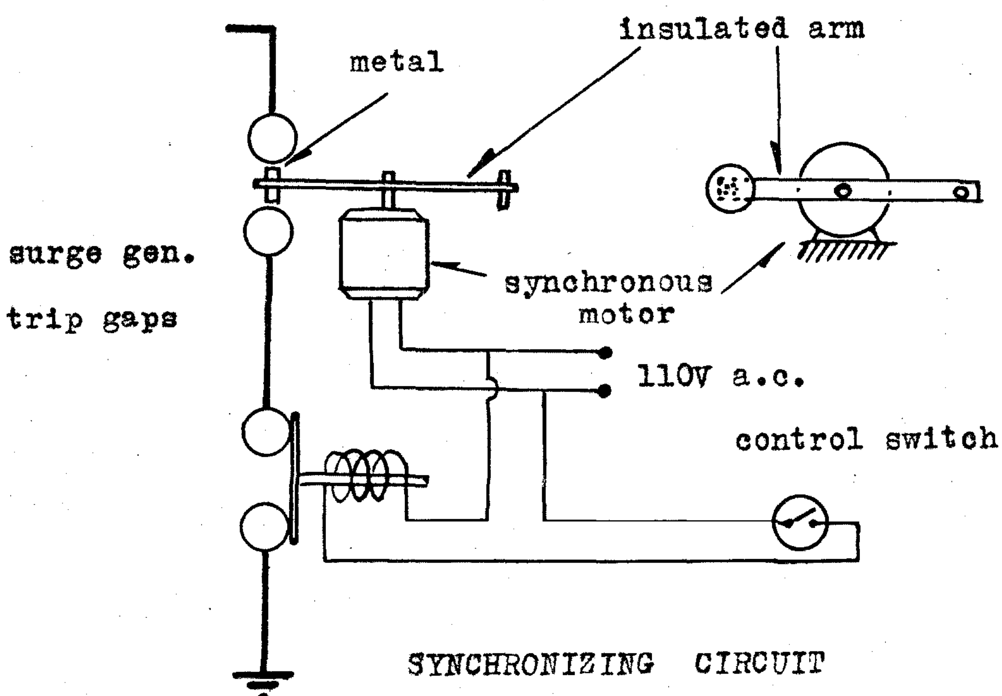
Film No.	Defl. to Peak of Wave in Inches	Beam Defl. Sensitivity Volts/In.	Crest Volts on C.R.O. Defl. Plates	Potentiometer Ratio	Surge Crest Kilovolts	Time lag Microsec.
KE-C-16	.73	1280	935	543.9	508	6.5
KE-G- 3	.78	1280	998	543.9	542	8
KE-G- 6	.60	1325	795	543.9	433	9.5
KE-G-11	.60	1315	790	543.9	430	6.5
KE-G-13	.60	1315	790	543.9	430	6.5

$$\text{Potentiometer Ratio} = \frac{\text{Potentiometer Res.} + \text{Cable Term.Res.}}{\text{Portion of Cable Term.Res. across which Defl.Plates are Connected}}$$

Actual Surge Voltage = Oscillogram Defl. x Defl.Sens. x Pot. Ratio

TRIP CIRCUIT



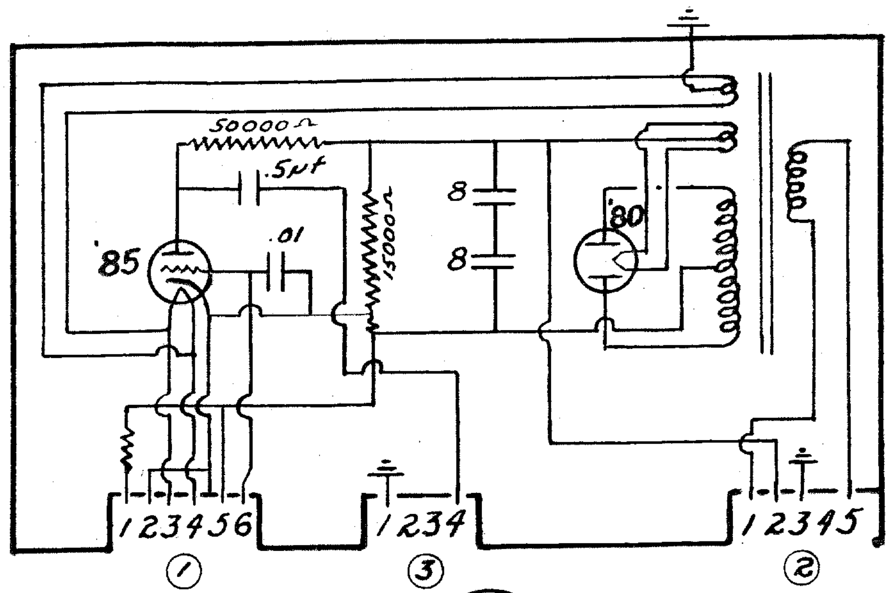


SYNCHRONIZING CIRCUIT

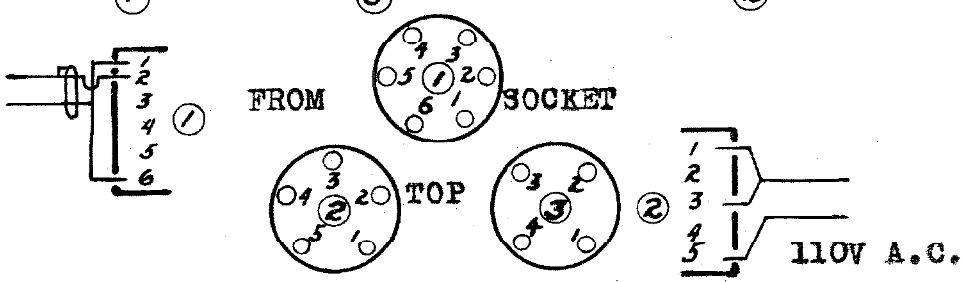
MECHANICAL TYPE TRIPPING CIRCUITS
FOR SURGE GENERATOR

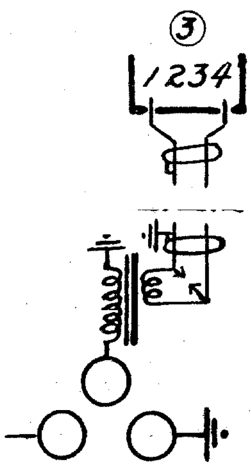
Fig. 28

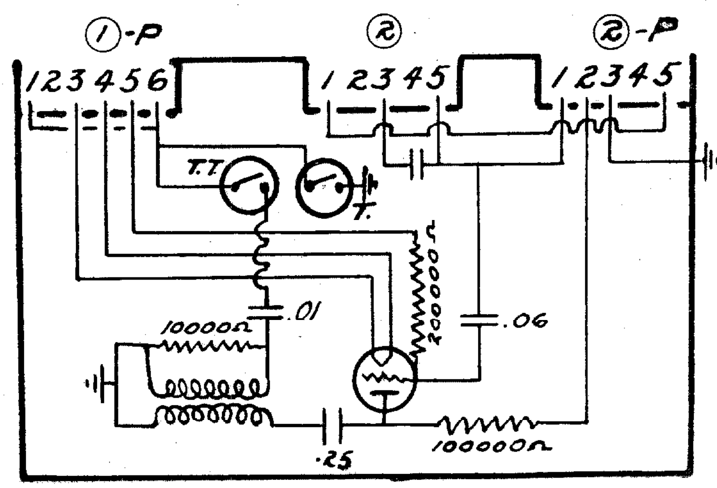
TRIP CIRCUIT



TRIP CONTROL





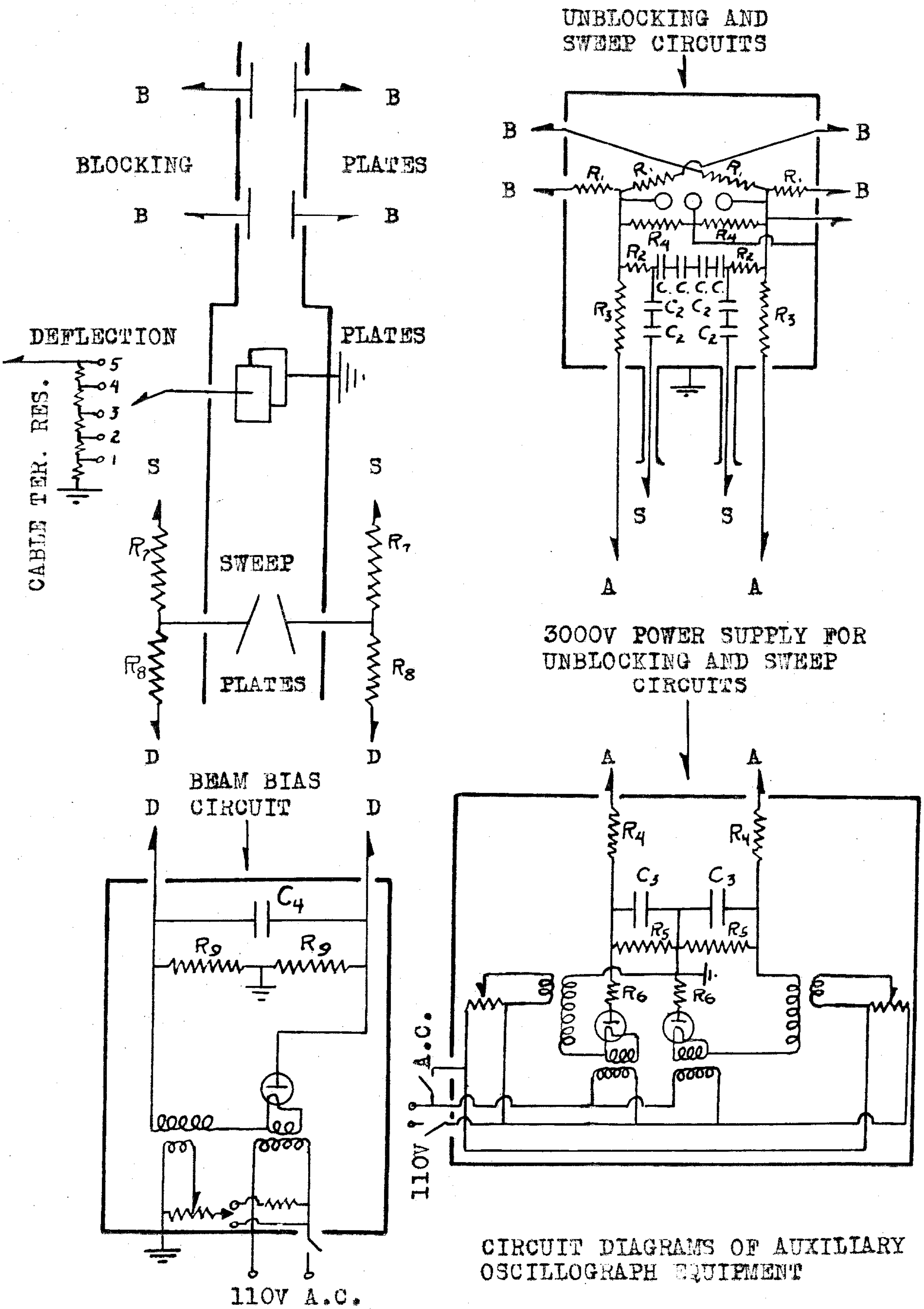


SURGE GENERATOR TRIP GAP

SYNCHRONIZING CIRCUIT

IMPULSE TYPE TRIPPING CIRCUITS
FOR SURGE GENERATOR

Fig. 29



CIRCUIT DIAGRAMS OF AUXILIARY OSCILLOGRAPH EQUIPMENT

Fig. 30

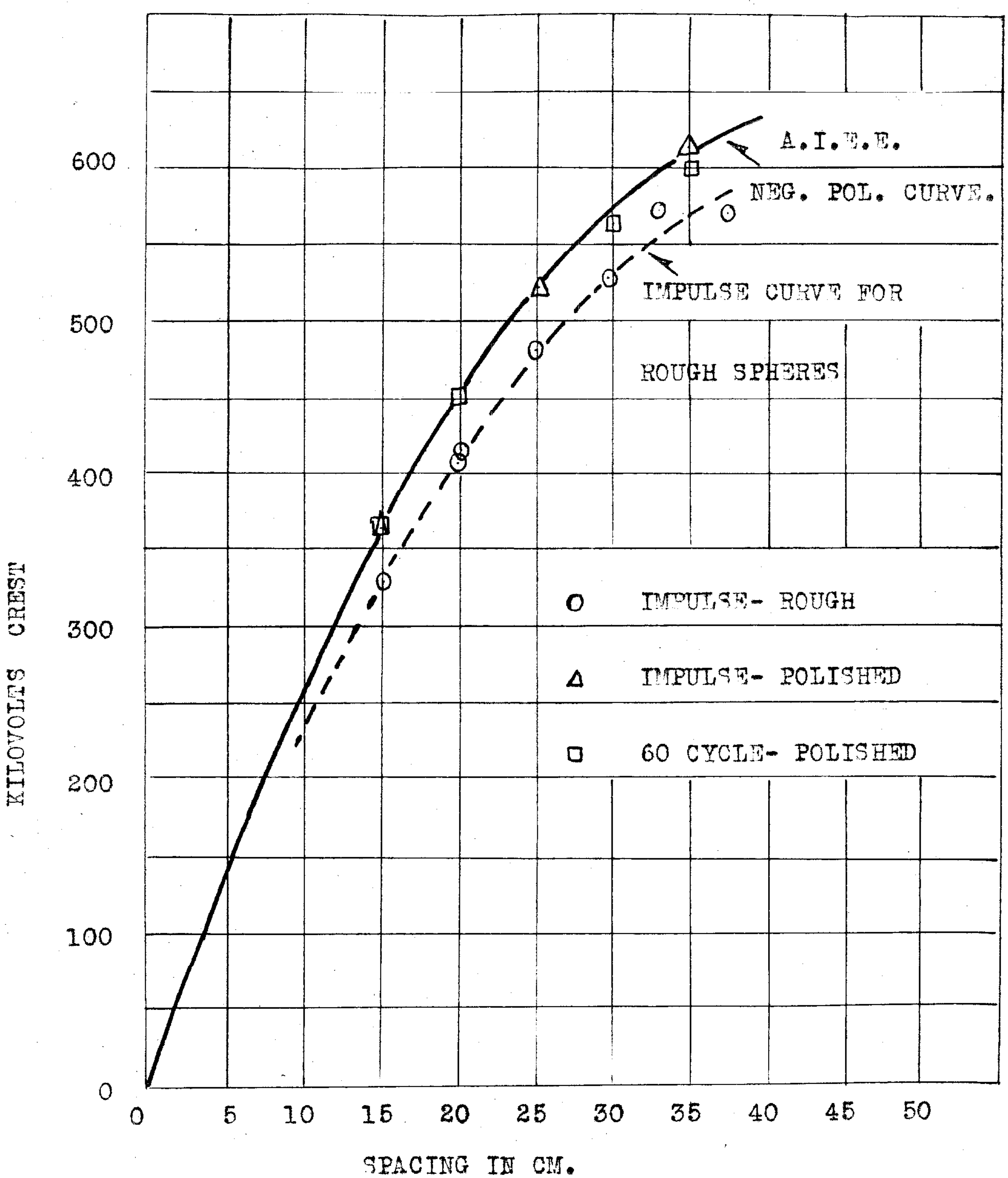
APPENDIX III.

IMPULSE CALIBRATION WITH THE FIFTY CENTIMETER SPHERE GAP

When using the standard fifty centimeter sphere gap as a calibration for impulse voltage, it was found that great care had to be exercized in keeping its surface polished. When flashover occurred, small shallow pit marks were formed by the arc and after ten or twenty shots, the surface became rough enough to noticeably lower its impulse strength. Tests with 60-cycle voltage showed a lowering of the same amount.

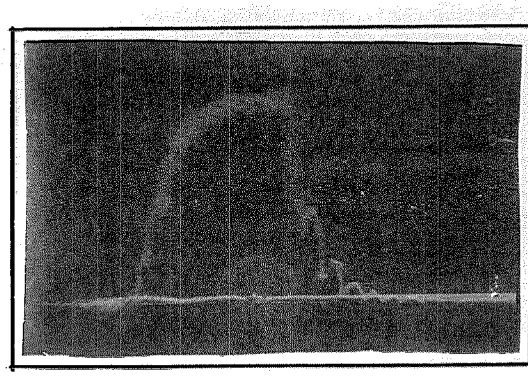
Tests were made to show this effect by first polishing the spheres and determining the minimum impulse and 60-cycle strength, and then applying repeated impulses. After from ten to twenty shots, the breakdown voltage would start to decrease. In Fig. 31 are shown the decidedly lower points obtained when twenty impulses were applied without polishing. Occasionally, the rough spheres would require longer time lags for breakdown than is normal for smooth spheres.

Fig. 32 shows oscillograms of breakdown for the two cases. For polished spheres, breakdown at minimum voltage always occurs with very little time lag. In the case of rough spheres, however, time lags as long as thirteen microseconds were recorded.



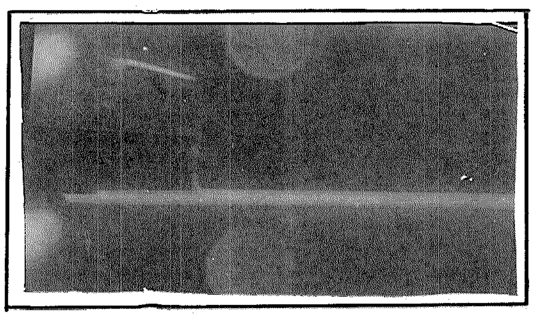
CALIBRATION CURVES SHOWING THE EFFECT OF ROUGHNESS ON THE IMPULSE STRENGTH OF THE 50 CM. SPHERE GAP.

Fig. 31



520 KV 1.9 μ-sec

Polished Spheres



480 KV 13 μ-sec

Rough Spheres

Effect of Roughness on the Minimum Impulse Strengh of the 50 Cm. Sphere Gap - 25 Cm. Spacing.

Fig. 32.