DESIGN AND OPERATION OF A CATHODE-RAY OSCILLOGRAPH FOR EXTERNAL PHOTOGRAPHY.

Thesis by

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Summary.

The prominent features in the design of the instrument are discussed. Novel among these are the design of the metal discharge tube, Lenard window and associated apparatus, and the time sweep and blocking circuits. Investigation of the metal discharge tube showed that there was an optimum spacing between cathode and anode, that decreasing the diameter of the tube increased the ratio of beam current to cathode current, and that raising the cathode voltage increased the current density in the beam. A $2\frac{1}{2}$ x $3\frac{1}{2}$ inch Lenard window using cellophane foil supported by a metal grid is used, and has proved to be quite satisfactory and durable. The sweep and blocking circuits are integral, operating from a triple sphere gap, and are so arranged that the beam sweeps clear across the window without any auxiliary biasing arrangement. Tripping is either automatic from an incoming surge, or semi-manual from a second set of gaps set to trip at convenient intervals. A number of sweep speeds are available, controlled by a selector switch.

The various factors involved in Lenard photography are tabulated and the majority are investigated. The radial current density in the recording spot is measured, and the effects of changes in discharge tube design in this regard are evaluated. Several types of films were tested to find the most sensitive. Eastman Process Nitrate film was finally adopted as sensitive

as most and mechanically superior to the others. The best development time to use for typical oscillograms in several developers was determined. From a photometric investigation of oscillograms taken with a wide range of velocities and cathode voltages, the blackening of this film by cathode rays was established as a function of incident charge density and cathode voltage. An empirical formula $B = K\sqrt{q}$ is found to express the blackening as a function of charge density for a given cathode voltage. From these data the maximum recording speed is computed to be 30,000 km./sec.

Operating experience with the tube is given. Typical oscillograms illustrating automatic recording of surge phenomena, etc., are shown. Various types of distortion encountered in operation are illustrated, and methods for eliminating them are given.

DESIGN AND OPERATION OF A CATHODE-RAY OSCILLOGRAPH FOR EXTERNAL PHOTOGRAPHY.

I. Historical Introduction.

The development of the cathode-ray oscillograph from a delicate instrument used for electronic measurements to a rugged piece of apparatus widely used in commercial tests has been rapid, especially in the last decade. Experimenters have been quick to see the advantages of a recorder having extremely low inertia, and have raised the limiting speed of operation until it is now possible to obtain records with a maximum writing speed of a quarter the velocity of light [32]. Continuous recording over several hundredths of a second of single [96][95][103] or three-phase [102] transient phenomena has been achieved in which events occuring ten microseconds apart may be distinguished clearly. The voltage which may be applied directly to the deflection plates has been raised to 100 to 200 kilovolts. [66][70][19] By the construction of multiple-discharge chamber oscillographs, [102] or single cathode multi-beam instruments, [22][91][97] it is no longer necessary to record only one phenomenon at a time. The same result has been been achieved by the use of ingenious switching arrangements on a

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(32) For references, see bibliography.

single-beam instrument.[38][40][106]

Corresponding to this advance in the instrument itself has been the development of recording processes. Photographic recording is almost exclusively used for any non-recurrent transient, and for convenience in recurrent phenomena. Selenyi[84][83][85] has shown that for slow writing speeds, the utilization of the electronic charge in the beam may be accomplished by tracing oscillograms on insulated dielectric plates. The charges carried by the electrons leak off the plate very slowly, so that by rapidly dusting the plate with powdered sulfur and red lead as a charge indicator, the trace of the beam can be made visible. As far as is known, this process has been entirely abandoned in favor of the several more convenient photographic processes.

Internal photography is the oldest and most popular method of recording. The oscillogram is produced by direct impact of the electron beam on a sensitized plate introduced into the oscillograph. This method has the inherent advantages of highest possible recording speed and sharpness of line. Against these advantages lies the fact that the introduction of the plate into the vacuum takes considerable time and is inconvenient. Because of this, three different methods of external photography have been developed which do not have the disadvantage mentioned above, and which have high recording speeds combined with reasonable line definition.

These three methods of external photography have been defined by one investigator[6] as Lenard photography, fluorescent photography, and photography with camera and lens. Lenard photography is the process of allowing the beam to fall on a thin electron-penetrable foil which forms part of the oscillograph wall. The film or plate is pressed against this foil and is blackened by the electrons penetrating the foil. Fluorescent screen light-contact photography is accomplished by using a transparent end on the tube, coated on the inside with a fluorescent material. The light produced by passage of the beam affects a photographic film placed in contact with the tube. If the light track is photographed with a camera, the process is called photography with camera and lens. All three methods have been developed to a high degree in the last few years, chiefly by the German research workers at Aachen and Berlin. The author knows of only one paper on the recording of transient phenomena with fluorescent-screen contact-photography[(67)] and one on photography with camera and lens[(88)] published in England, and of none on any of the three methods appearing in the American technical press. It should be mentioned, however, that numerous articles have appeared in both countries on external photography of recurrent phenomena with camera and lens.

Processes of External Photography and their Limitations.

1. Lenard Photography.*

After Lenard succeeded in demonstrating that cathode-rays could penetrate a foil into the air,[(61)] a number of investigators

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* Much of this information is from von Borries' thesis (reference 6) to which excellent source of material investigators of external photography are recommended.

attempted to make use of this phenomena in various ways. Coolidge,[27][28] using a nickel foil and later resistol with thickness of 0.0127 mm. and an accelerating voltage of 900 kv., was able to obtain cathode rays of considerable intensity in the air close to the foil. The window used was three inches in diameter and had a honey comb supporting grating of sheet molybdenum, so that 80 per cent of the foil was exposed to the ray. Thaller[93][94] used a supporting grating of copper electro-plated in honey comb shape on a 0.010-0.015 mm. foil. There was a 0.001 mm. plating of gold on the outside of the foil. Knipp[48] used glass to form a Lenard window. Due to the poor mechanical properties of this material when sufficiently thin, he was able to use only a small window. Slack[87] avoided part of this difficulty by using a hemispherical window of 0.010 mm. glass. This of course made special plates a necessity.

Wood[105] suggested the possibility of using a Lenard window in conjunction with his oscillograph, while Lee,[60] five years later, regretted that ".....unfortunately there has yet been no way successfully developed whereby the projected beam can be utilized for measurement purposes." However, in the next year, 1929, Max Knoll[49] of Berlin announced that he had successfully accomplished this result using a Lenard window, and published the first crude oscillograms. 0.011 mm. aluminum foil was used as the window, supported by a steel plate three inches in diameter, perforated with holes bored close enough that 30 per cent of the foil was exposed to the beam. The maximum writing velocity was 20 meters per second.

Progress after this was rapid. A supporting grating of spring steel strips placed endwise to the ray was developed, and windows of cellophane, cellon, and aluminum were used. In a series of papers from the Berlin laboratory (53)(56)(57)(58) stronger and larger windows, and higher and higher writing speeds were announced, until in 1932 (6) 9 x 12 cm. windows were in use, and sharply defined traces at velocities of 2550 km. per second had been obtained. In the last article the maximum obtainable writing velocity was stated to be 4800 km. per second.

Freisewinkel (37) conducted an interesting series of experiments on the relative blackening of film using Lenard photography (0.016 mm. zellon foil) and fluorescent photography (Z_nS with a trace of Cu used as the fluorescent), and found that for accelerating voltages less than 55 kv., fluorescent photography was most advantageous; for voltages over 55 kv., Lenard photography was better for low beam intensity, but that for high beam intensity there was little difference between the two. Using a beam current of approximately 2 microamperes, he was unable to secure satisfactory Lenard photographs at voltages less than 50 kv.

2. Fluorescent-Screen Contact Photography.

This type of photography was discussed by MacGregor-Morris and Mines, (62) who were unable to make oscillograms in the proposed manner. Steenbeck (90) in 1929 was able to press sensitive paper on a rotatable frame against the fluorescent screen of a Braun tube and obtain reproducible tracings of the recurrent phenomena. Rogowski, Flegler, and Rosenlöcher[75] of the Aachen Institute and Knoll and von Borries[53][57] of Berlin were able to obtain true contact photographs at approximately the same date, in fact there has been considerable discussion[54][71] as to the priority of the two schools in this matter. Von Borries[6] obtained approximately equal writing velocities using the two methods, at an exciting voltage of 65 kv. (around 2000 km./sec.). Freisewinkel[36] was also successful in obtaining velocities of 2000 km./sec. Graupner[44] showed that by use of an acceleration grid low voltage oscillographs could be used for this purpose, the high velocity required to excite the fluorescent material being furnished by the acceleration grid. Stekolnikov and Slaschew[91] used contact photography in their double beam oscillograph, and obtained writing speeds in excess of 25,000 km./sec. This is the highest recording velocity obtained so far.

3. Photography with Camera and Lens.

This has proved to be the most popular field for investigation in cathode ray oscillography in the last few years. It is also the oldest form of external photography to be successfully used. Ebert and Hoffmann[33] stated in 1898 that they photographed the Lissajou figures obtained by Braun in 1897. Zenneck[107] published such figures in 1899. He also published oscillograms with linear time axes in the same year.[108] Better methods were developed by Angström,[8] Simon and Reich,[86] Giesel and Zenneck[41], Roschansky,[77][78][79] and Alberti and Zickner.[7] The last mentioned investigators studied oscillations of 3 million cycles with a recurrent sweep. Photography of Braun tubes has been studied by Glatzel,[42] Fassbender and Hupka,[34] Brenzinger,[23] Hull,[45] Johnson,[46] and Jones and Tasker.[47] More recent work on the small, hot cathode tubes is well summarized by Batcher.[9][10]

The type of oscillogram made by deflecting the beam along one axis only and moving the film perpendicular to this axis was initiated by Wehnelt and Donath,[100] and was developed by Zenneck,[109] Kock,[59] Wehnelt,[99] Samson,[82] and Behnken.[14] The highest writing speed obtained was approximately 10 meters per second, due to the mechanical difficulties involved in moving the film. Batcher[9] describes a high speed camera using motion picture film in which the 16 mm. film can attain a maximum velocity of 35 feet per second.

The first really high speed oscillograms with camera and lens were made by Rogowski and Grösser[73] in 1925. They used an exciting voltage of 25 kv., 200 microamperes in the beam, and photographed the back of the fluorescent screen with an f 4.5 Zeis-Tessar lens, obtaining a maximum writing velocity of 6 km./sec. This had been increased to 300 km./sec. by Rogowski and Flegler[72] in 1928. Successively higher speeds were obtained by Rogowski and Szeghö,[74] Flegler, Wolff, Röhrich, and Klemperer,[35] Beyerle,[17] Buss and Pernick,[26] von Borries,[6] and Dodds.[32] The last investigator obtained a maximum writing velocity of 60,000 km./sec. by use of a so-called metal discharge tube of very efficient design operating at 80 kv.

Contemporary with this later development was the construction of tubes of special design. There was a fertile field of investigation in low excitation voltage tubes, and in sealed-off oscillograms (nearly all of the above mentioned modern tubes are of the continuously evacuated type). Boekels[20] determined that the exciting voltage on the Aachen type instruments could be lowered to 15 kv. successfully. Westermann and Malsch[63][64] constructed an instrument which would operate at 6 kv. with a maximum recording velocity of some 100 km./sec. Later Westermann[101] revised the discharge tube, and using a metal discharge tube of very small size, succeeded in obtaining writing velocities of 10,500 km./sec. at exciting voltages of 13 kv. maximum. Becker[11][13] also reported on a tube of somewhat similar design for use at low exciting potentials.

In the advancement of high voltage sealed-off oscillographs Szeghö[92] reported on a tube in which a mercury diffusion pump was included in the blown glass system, arranged to lower the pressure in the deflection chamber and raise it in the discharge tube. At a voltage of 14 kv. a beam current of 4 milliamperes was obtained. No oscillograms were given. However, in a later report from England, Smith, Szeghö, and Bradshaw[88] published oscillograms made by photographing the outside of a sealed tube instrument with an f 1.8 lens. The constructional details of this tube are quite interesting. The various parts of the instrument are mounted on supporting metal tubes quite similar to the usual metal type oscillograph, and the whole is surrounded by a glass envelope. Excellent oscillograms ranging all the way from 50 cycle phenomena to speeds of 300 km./sec. were obtained. The tube was gas filled at a pressure of 5×10^{-2} mm. and no auxiliary pump was provided.

Still a third type of modern cathode-ray oscillograph suitable for either fluorescent-screen contact photography or photography with camera and lens is the relatively low voltage hot-cathode instrument. Graupner,[43] working with an oscillograph of the George[39] type which had been previously used by Rogowski, Sommerfeld, and Wolman,[76] obtained maximum velocities of 196 km./sec. using contact photography, and 62 km./sec. using camera and lens. The exciting voltage was only 2 kv., with a correspondingly high deflection sensitivity of 1.6 mm./volt.

The salient points of the research on modern tubes was well summarized by MacGregor-Morris and Henley[3] in 1936. This is the best work in English on the subject.

II. Design of Present Instrument.

In extending the research program of the High Voltage Laboratory of the California Institute of Technology, it was decided in 1932 to develop a modern high-speed cathode ray oscillograph. At that time the only oscillograph available was a General Electric instrument, Model HC-2, described by Lee (60) in 1928. This oscillograph requires intermittent cathode operation because no blocking system is used, the beam is gas concentrated, and records are made on roll film using internal photography. The time consumed during loading and re-evacuation is at least half an hour. Because of these disadvantages, in considering the design of a new oscillograph, external photography was tentatively chosen. Accordingly, Dr. J. Gibson Pleasants designed and had constructed an oscillograph embodying a constantly operating discharge chamber, blocking system, and an arrangement for external photography using the Lenard system. He was undoubtedly influenced in his choice of external recording system by the work of Knoll and von Borries (6)(57) who had at that time developed the Lenard system until it was as fast or faster than either of the other two recording systems. Dr. Pleasants also used the type of discharge tube developed in the Berlin laboratories, and described by Matthias, Knoll and Knoblauch (65) and by von Borries. (6) This oscillograph was assembled on a temporary mounting and evacuated, but no further work was accomplished before the departure of Dr. Pleasants. In the fall of 1933, the instrument was turned over to the author and his associates for development and completion.

A. Main Tube.

A cross section of the improved instrument is shown in Figure 1, and views of the mounted oscillograph and accessories in Figures 2 and 3. In general the tube is a conventional vertically mounted high voltage cold cathode magnetically focused type of instrument. The overall length is 56 inches, the width is 10 inches, and as mounted, the height of the cathode meter from the floor is 86 inches. It is mounted in a heavy table which also carries the diffusion pumps, vacuum gauge, time sweep circuits, 5000 volt power pack, panel, and associated equipment. The table rests on heavy castors, so that the oscillograph may be moved about the laboratory. The floor space taken by the table is 3 feet 6 inches by 5 feet 6 inches.

The discharge tube used in the present setup is entirely different from that originally designed by Pleasants. It was the result of a long series of experiments which will be taken up later in this paper. It rests on a flat steel plate which forms the top of the blocking chamber. The top of this plate is ground plane, and forms a sliding greased joint with the discharge tube. This allows alignment of the cathode beam with the openings in the blocking diaphragms. The walls of the blocking chamber, like those of the deflection chamber, are of 1/8 inch steel, which helps to eliminate magnetic disturbances from affecting the beam. There are two sets

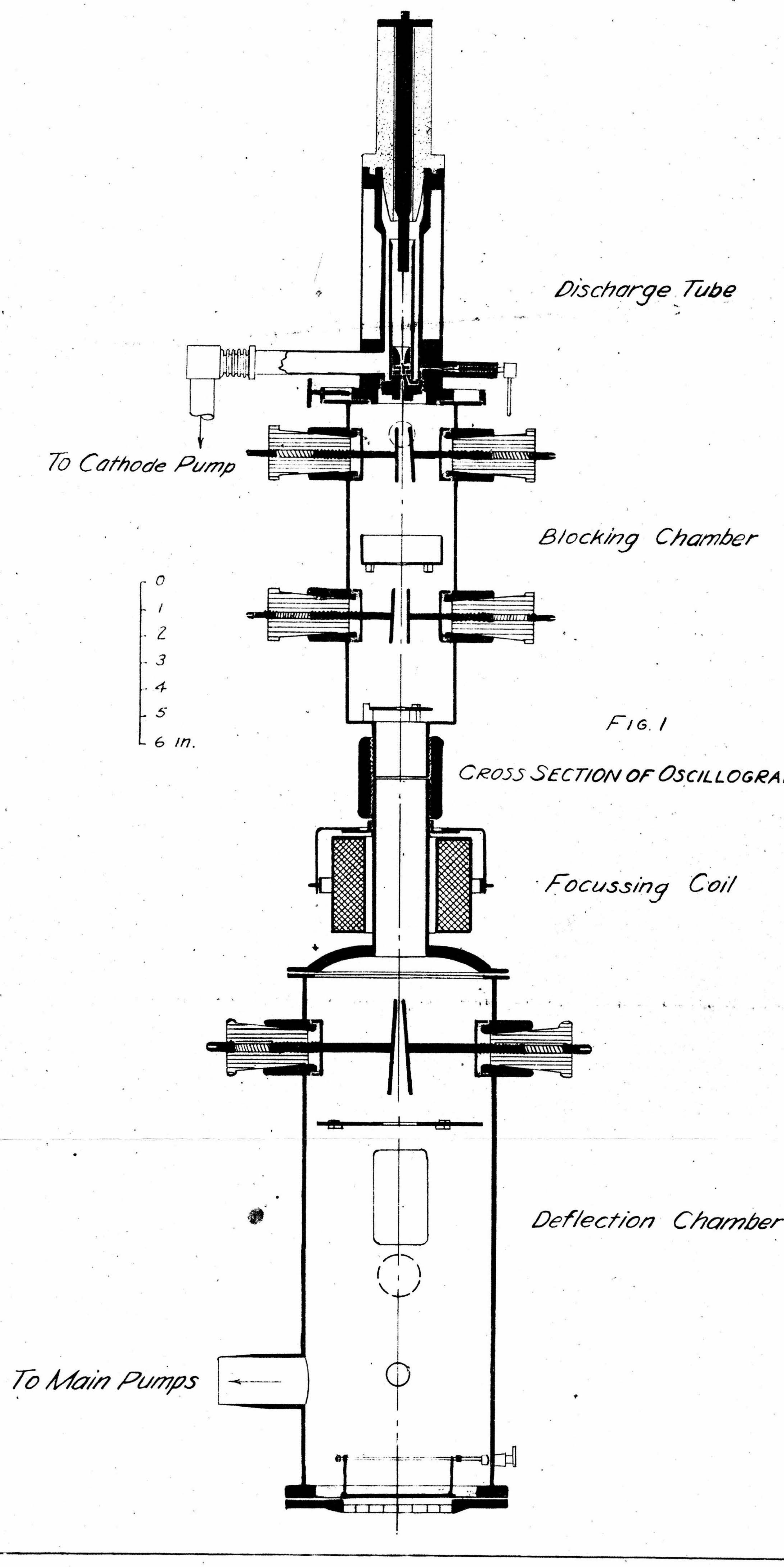


FIG. 1

CROSS SECTION OF OSCILLOGRAPH

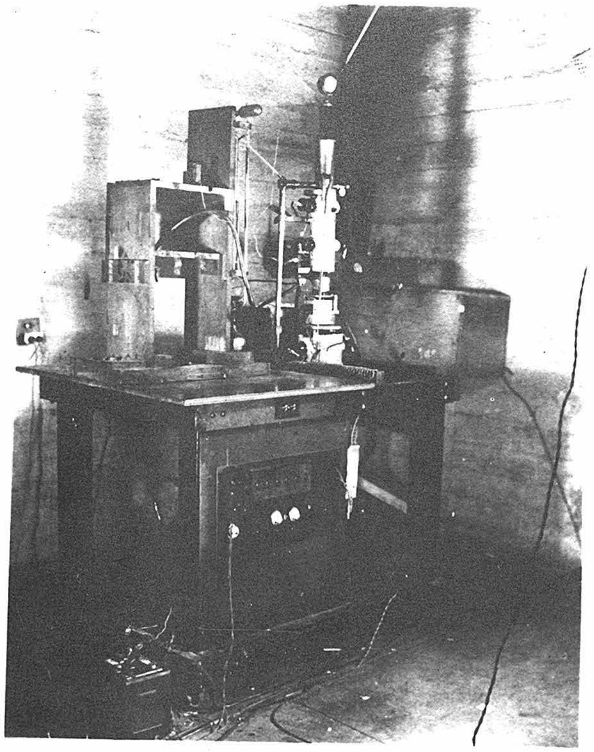


Fig. 2
General View of
Instrument

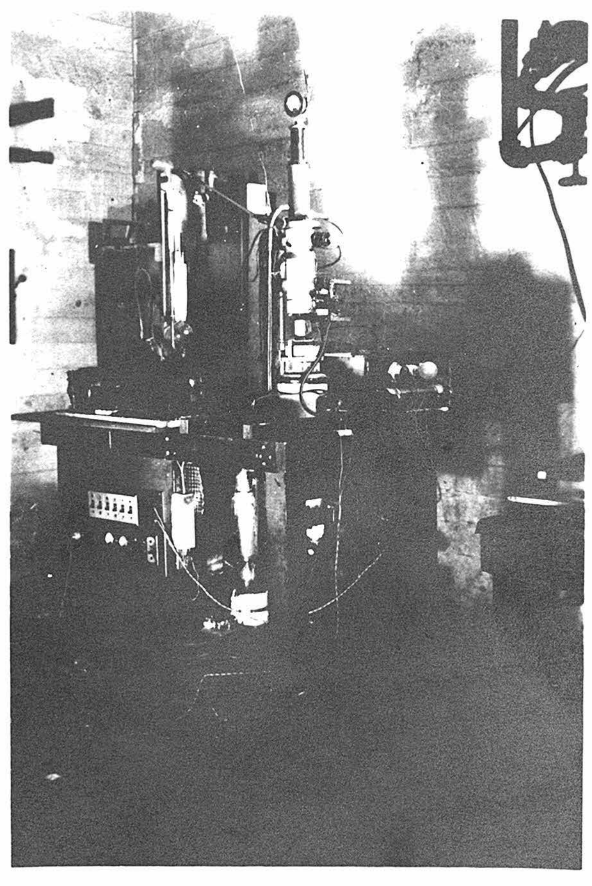


Fig. 3
General View of
Instrument

of deflecting electrodes in the blocking chamber, each with a grounded blocking diaphragm some three inches below it. This follows the work of Gábor[1] and Burch and Whelpton,[24] rather than that of von Borries[6] and Miller and Robinson.[67] In practice, it has been found that one set of deflection plates is sufficient to give very good blocking. This will be discussed in connection with the time sweep circuit later. An interesting deviation from the common practice is in the form of the blocking electrodes. One electrode of each pair is a flat plate placed with the plane face vertical, but the other is a rod electrode with rounded ends, placed at an angle of 10° with the vertical. The field between the two electrodes is non-uniform, being higher close to the rod. In practice, the electrodes are charged so that the beam is deflected towards the rod, thus being forced into a stronger field the closer it approaches the rod. With the spacings used, the field (at the surface of the rod) is approximately 1.3 times the field that would exist between two plane electrodes with the same spacing, so that a greater deflection is obtained with the same blocking voltage. This arrangement is, the author believes, original with Pleasants.

Originally the electrodes were designed to be movable under vacuum. This was to be accomplished by threading the electrode supports into hard rubber cones (seeFigure 1). The supports were kept from turning by being squared for the first section of their length, this square part fitting into a hard rubber disc screwed to the inside of the cone support. The hard rubber cones were greased in place so that by revolving them the electrodes could be drawn in or out without breaking the vacuum. Connection between the end of the support rod and the metal tip on the outside of the cone was made by using a small spiral spring under tension between these two parts.

In practice this arrangement proved unsatisfactory. The hard rubber cones could not be ground to form a good joint with the steel cone support. The abrasives used sank into the rubber surface without grinding it. For this reason, it was found impossible to keep these joints vacuum tight for any considerable length of time. After repeated failures, the arrangement was finally abandoned, and the cones were waxed in place with picein. It is probable that if another material had been used, this arrangement would have proved successful. One further disadvantage with this type of joint is the necessity of using a coil spring as part of the connection. This introduces an inductive element into the circuits which, while small, is quite unnecessary and is of importance in high frequency transients. A number of other methods for accomplishing the same result are found in the literature, generally making use of a metal bellows or sylphon.[(55)(65)(103)] A simple arrangement designed for this instrument by the author is shown in Figure 4. It has no greased joints whatever.

The blocking and deflection chambers are joined by a constriction around which the focusing coil is mounted. A rubber gasket is inserted between these two parts which are held together by a large nut. This joint proved unsucessful, as did all the original gasket

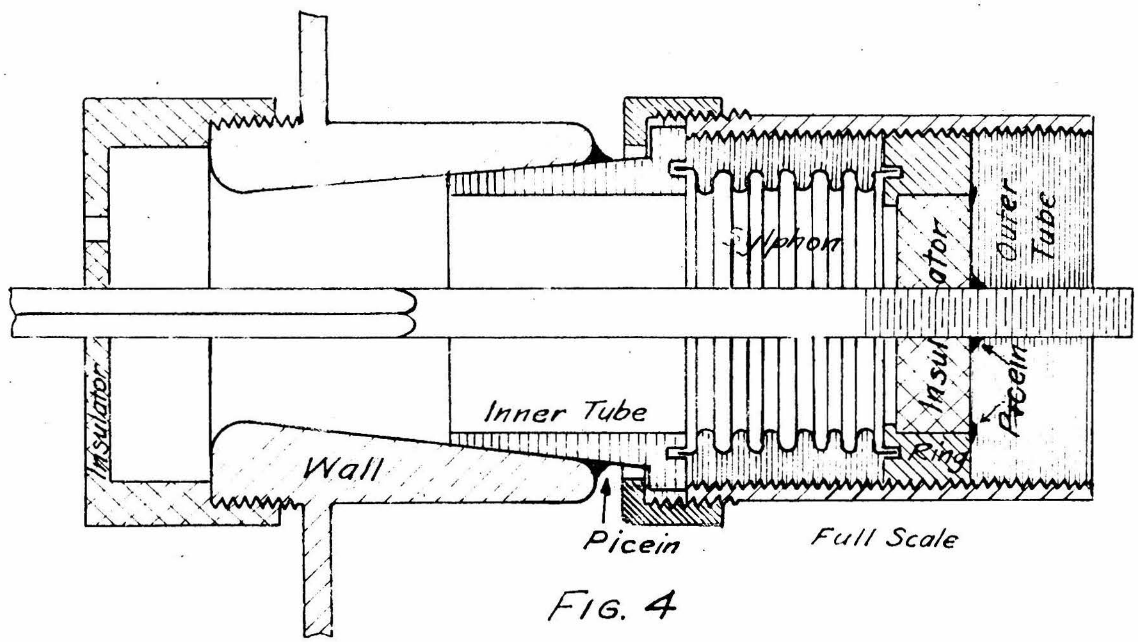


FIG. 4

DESIGN OF PLATE MOUNTING

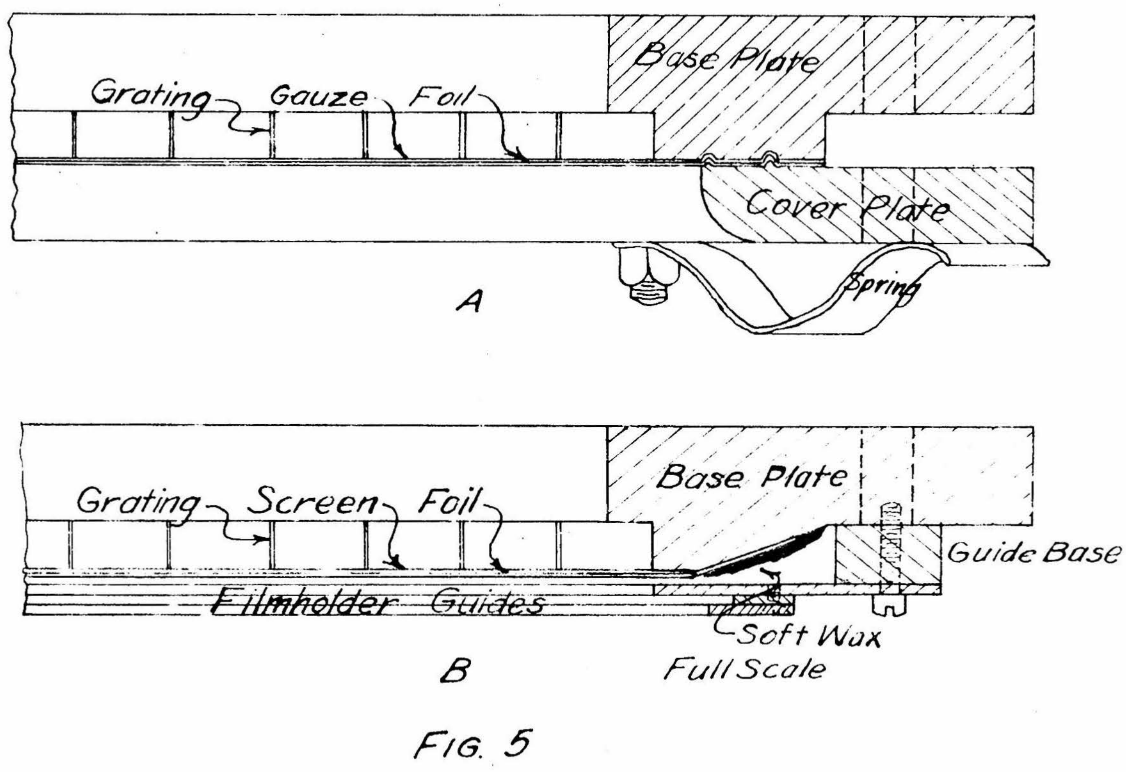


FIG. 5

LENARD WINDOWS

joints. The joints themselves were identical with those of European design [6][65][103] so that the cause of the failure must have been the hard gasket rubber available. The two joints at the nut were eventually closed with glyptal. A cone joint of narrow angle with the female half on the blocking chamber would have been as strong mechanically and much superior from a vacuum standpoint.

The focusing coil is placed approximately equidistant from the anode hole and the Lenard window. It is to be expected that the dimension of the spot on the window would be equal to the size of the hole in the anode.[1] This was not found to hold true in general, as will be seen in the beam analyses given later. The coil is ironclad on the three outer faces, with a brass inner wall. This increases the intensity of the field in the center while decreasing it nearly to zero elswhere. The coil is supported on gymbals from a flat plate resting on a secondary member screwed to the throat. Thus it can be turned about any horizontal axis or be moved parallel to itself in a horizontal plane.

The top member of the deflection chamber is constructed of brass to offer no impedance to the flux of the focusing coil. It is connected to the main body of the deflection tube by a flat rubber gasket joint. The two sets of mutually perpendicular deflection plates are supported like the blocking electrodes with hard rubber cone joints. The plates of either set are inclined so that their planes intersect at a 10° angle, thus allowing greater beam deflection without striking the electrodes. The upper set are placed a mean distance of 17.25 inches from the window; the lower set are 11.25 inches from it, so that the deflection sensitivity of the upper plates is roughly 1.5 times that of the lower. In practice the lower set was consistently used for the phenomena to be studied while the upper were used for the time sweep. This arrangement could be reversed if increased sensitivity were required, although due to the orientation of the Lenard window, the time axis would be shortened. A grounded plate with a slit through the center is placed between the sets of electrodes to eliminate as far as possible mutual coupling between them. This was very successful; no oscillation was ever traceable to interior coupling between the plates. Below the lower deflection plates is a porthole with an interior mirror inclined so that the bottom of the oscillograph is visible. On the opposite side of the tube an opening leads to the vacuum gauge. Originally this was a simple discharge tube equipped with a spark coil. Later it was found more convenient, especially when dealing with the window problem, to have a more quantitative vacuum meter. After some experimentation a successful Pirani gauge was installed, which gave direct readings of the vacuum from 10^{-1} to 10^{-4} mm. This is described in detail in conjunction with the other auxiliary circuits. A short $1\frac{3}{4}$ inch diameter tube leads from the lower part of the deflection chamber to the main diffusion pumps.

The bottom of the chamber terminates in a square plate of half-inch brass. The original plate of $\frac{1}{4}$ inch material was replaced due to warping when this plate was clamped to the window support. Just above this plate are the supports for the fluorescent screen shutter. The shutter consists of a plate slightly larger than the Lenard window, attached by hinged rods to a shaft terminating in a rotatable vacuum joint. The shutter can thus be swung up and out of the way when taking a picture. Normally it covers the Lenard window, and as the upper surface is covered with willimite set in wax, furnishes a convenient means for visually checking the focus of the beam.

B. Lenard Window.

The original design of Lenard window is shown in Figure 5, A. The window itself consists of a $2\frac{1}{2}$ x $3\frac{1}{2}$ inch rectangular opening in a heavy square brass plate. The foil is supported first by a layer of fine wire gauze, then by a grating of 0.25 x 0.015 inch steel rods cut and placed endwise one half inch apart to form a lattice. The foil is clamped between the base plate and a cover plate designed with a shallow tongue-and-groove joint. Flat springs are provided to hold the plates (or film in a suitable holder) against the foil. Experience showed this window design to be unsatisfactory and a second type was evolved.

In the second design the upper ridge of the base plate was machined off on an angle (see Figure 5, B). The gauze was carried only a quarter of an inch over the edge of the window, and gauze and foil laid over it were held in place by a thorough coating of soft red wax.

This design was so successful that an attempt was made to use larger gauze. The original gauze used cut off approximately 60 per cent of the foil from the ray. Accordingly, larger and larger screen was used. The final selection was ordinary copper window screen with 16 wires to the inch each way. The screen efficiency is 70 per cent. This screen was soft soldered to the brass plate around the edge of the window. All surface irregularities were removed by careful polishing with rouge paper.

Two thicknesses of cellophane were used on this window, 0.020 mm. and 0.012 mm. These were obtained in 8 x 12 inch sheets from the Lonza Werke of the Analin Fabrikin, Frankfort, Germany, since no domestic cellophane of this thickness was available. In preparing a window, a sheet of cellophane would be closely scrutinized in front of a light for possible holes. From a piece passing this test a $3\frac{1}{2}$ x $4\frac{1}{2}$ inch rectangle would be cut, and oiled on both sides to prevent water penetration through the sheet (see von Borries)[(6)]. This sheet was then placed over the window, and hot red wax was applied to the edge. This coating was carried up to the edge of the window and down to the bottom of the inclined section of the base plate. Finally a very small gas flame or preferably a hot iron was passed over the wax, smoothing it into one homogeneous layer. This window is shown in place on the oscillograph in Figure 6.

Using this procedure, windows of the 0.020 mm. cellophane have been made which hold vacuum tight under vacuums of 10^{-4} mm. of mercury over a period of several weeks; in fact the limiting

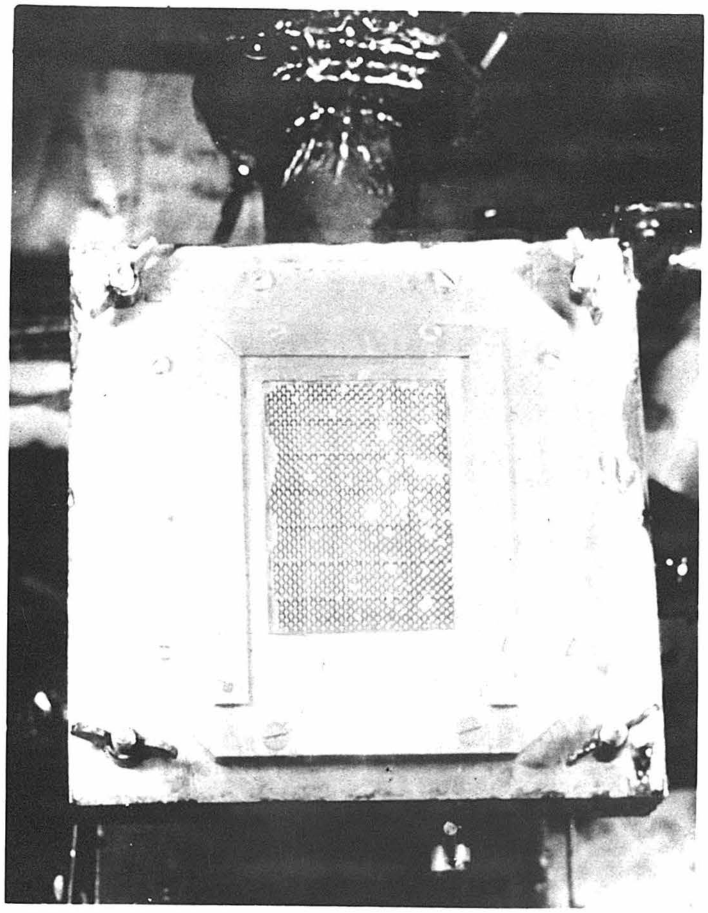


Fig. 6

Lenard Window

Fig. 7

Film Holder

time for such a window is unknown as other factors have always caused its removal with the cellophane still intact. During one such run, over 80 films were pressed against the foil, and approximately 240 oscillograms were taken. No especial care was taken to protect the window from rough handling; it was touched with the fingers repeatedly, and occasionally the film would be projected from the holder into contact with the foil with considerable force. Windows of the 0.012 mm. cellophane did not stand up as well. The longest life for such a window was one week. Little experimentation was done with the thinner foil, and longer periods of operation should be experienced using finer wire screen as a support. There is little reason for using the thinner foil unless the experimenter is working nearly to the limits of the oscillograph. This will be discussed in more detail under the section on photography.

It is important to minimize the sag of the screen and the sag of the cellophane relative to the screen, because this results in a thin film of air between foil and photographic film, causing dispersion of the beam and consequent loss of sharpness in the writing trace. In this window the maximum screen sag was 0.004 inches and the maximum sag of cellophane to screen was 0.010 inches. It will be shown later that pronounced loss of trace sharpness is not experienced until the air space amounts to double this value.

C. Filmholder.

In designing a filmholder for this window, several requirements must be considered. The holder must be simple, compact, light-tight, be arranged so that the film can be placed against the foil, and be quickly loaded and installed. The final design satisfies all these requirements. It is shown in Figure 7. Essentially it consists of a shallow light-tight metal box with a $2\frac{1}{2}$ x $3\frac{1}{2}$ inch opening on one side, fitted with a dark-slide. The film is carried on a velvet-covered metal plate fitted inside the box on springs and held from the bottom by an eccentric latch. As the latch is revolved, the plate rises in the box and finally projects 3/16 of an inch above the opening. The film is held on each side to the plate by a small metal trough which is not as high as the plate, so that the film must be bowed to insert it in the holder. This insures that no part of the holder itself touches the cellophane, a very necessary precaution. Loading in the dark room is a matter of some 15 seconds.

A guide plate is screwed to the base plate of the window, as shown in Figures 5 and 6. This has grooved guides by which the filmholder slides into position directly below the window. The dark slide is then removed and the latch rotated, raising the film into intimate contact with the cellophane. A pressure of one pound is exerted on the foil when the film is in contact.

D. Discharge Tubes.

The first discharge tube used on this oscillograph was designed during the transition period between the use of glass and metal discharge tubes. In this it followed very close to the model developed by Matthias, Knoll and Knoblauch.[65] The constructional details of this tube are shown in Figure 8, A.

Great difficulty was encountered in operating this tube. At first it was impossible to secure the proper gas pressure in the tube, because the relatively slow speed mercury diffusion pumps could not keep the lower system evacuated when the needle valve was just cracked. High-speed Apiezon diffusion pumps were installed, curing this difficulty. When the cathode was excited, a beam could be obtained, but intermittent sparking and glow discharge took place from cathode to side walls (at a point indicated as electrode #2 in Figure 8). This could not be eliminated regardless of the vertical position of the Wehnelt electrode. A very narrow zone here heated rapidly, causing one tube to crack. A film of metallic deposit, undoubtedly aluminum cathode, sputtered on the glass wall, built up over this region and seemed to decrease the discharge. Grounding the Wehnelt cylinder, or using one long enough to touch the anode, helped but did not cure the difficulty. Accordingly a brass ring held to the glass wall by friction was installed at this place. Discharge then took place from cathode to electrode #2 to Wehnelt electrode, and again heating of the wall took place. The tube worked better than before, but could only be operated for ten minute periods. Burch and Whelpton[24] and Dicks[30] experienced the same difficulty with this type of tube, and also used the auxiliary electrode.

The operation of this tube was definitely unsatisfactory.

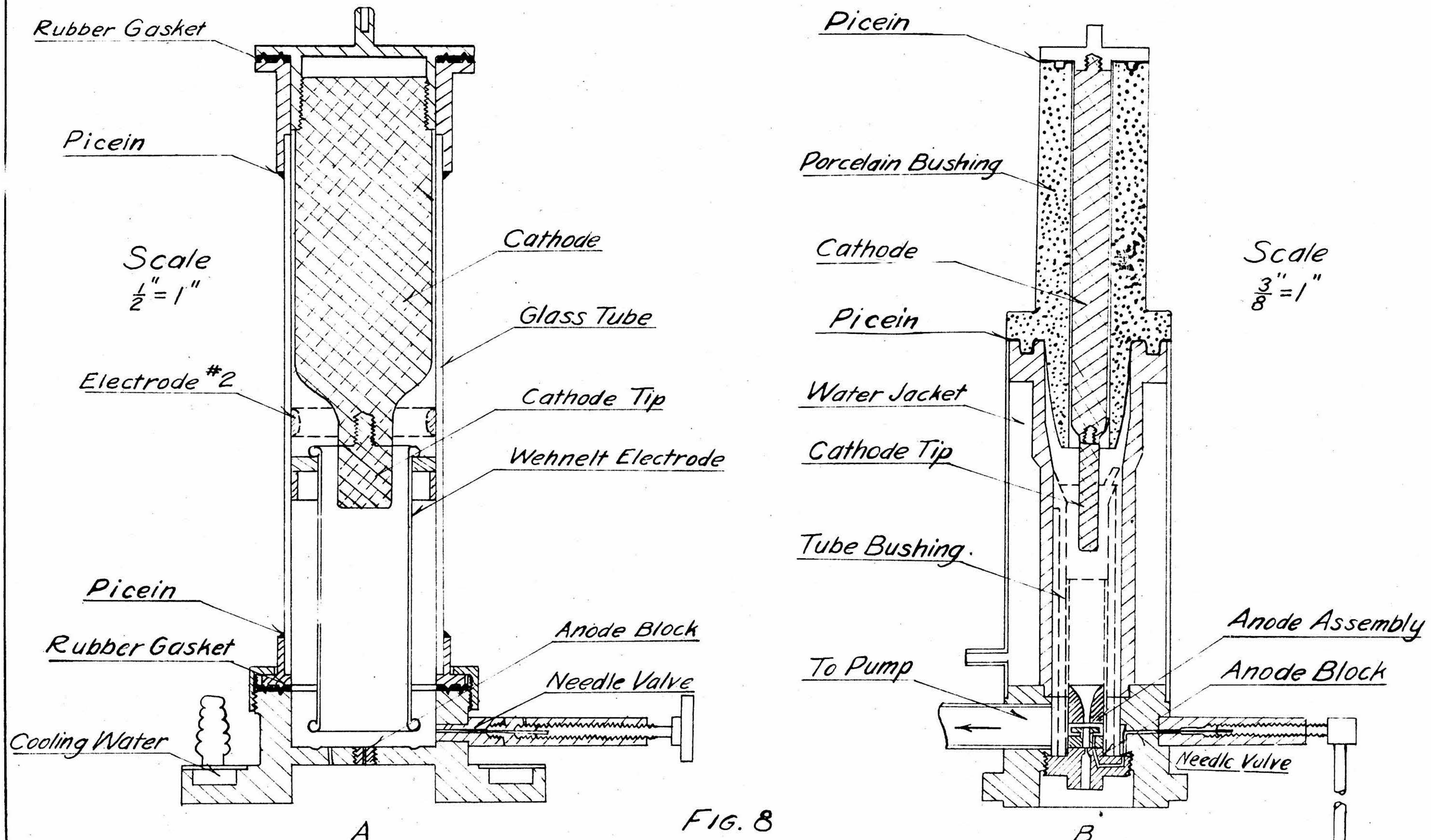


FIG. 8

DISCHARGE TUBES

Accordingly, tube B., Figure 8 was designed by the author. It is of the type used by Burch and Whelpton.(24) The $\frac{3}{4}$ inch aluminum rod cathode screwed into a brass top, is piceined into the top of a long porcelain bushing, which is in turn waxed into the top of the discharge tube proper. This is a heavy brass tube with $1\frac{1}{4}$ inch bore, widened at the top to accommodate the bushing flange, and water jacketed for cooling (actually unnecessary at currents of less than 1 milliampere). It is arranged for continuous evacuation through a 7/8 inch tube leading to a separate Apiezon diffusion pump. The line is provided with a sylphon tube (see Figures 1 and 3) so that the discharge tube can be moved on the greased joint for alignment with the blocking system. The anode opening is a 0.03 inch diameter hole, relieved with a 1/8 inch drill so that the length of the small opening is quite short. This reduces the number of secondary electrons formed at the anode and increases the sharpness of focus of the spot. Air was originally admitted directly from the needle valve to the tube, and a short brass tube was placed on the anode block, with the side next the line removed to give more equal air pressure in the tube. This follows the work of Dodds.(32) Later this was changed, as it was definitely demonstrated that the electron beam was not axial but inclined towards the needle valve opening. Several arrangements were tried to give, as nearly as possible, equal radial distribution of pressure in the tube. Obviously this could only be perfectly accomplished by admitting air along the axis and exhausting around the tube wall, or vice versa. The second possibility is not advisable, because at the pressures in the tube (1 to 6 x 10^{-2} mm.) the discharge tends to follow the path of highest pressure, hence would disperse to the walls. The arrangement which gave the nearest to true axial admission is shown in Figure 8. The entrance to the needle valve hole was plugged and No.60 holes were drilled in the base and anode block, so that the air is actually admitted 0.1 inch from the anode hole. From there it passes through a labyrinth block so that it flows from the funnel-shaped orifice with nearly equal radial distribution of pressure. The anode assembly is placed within a $\frac{3}{4}$ inch tube extending 2 inches from the anode block. This confines the air flow so the highest pressure is between cathode and anode. This arrangement was satisfactory. Previously, the entire surface of the anode block would be blackened after a short period of operation, due to metallic particles cathode-sputtered on the surface. After this installation, only the interior surface of the anode assembly was thus blackened, indicating that the beam had been entirely confined to this region.

Early in the testing of the discharge tube a definite effect of the spacing between cathode and anode on the beam intensity was noticed. A series of tests were made to determine the optimum separation of cathode and anode, cathode shape, cathode diameter, and diameter of discharge tube. These effects have not been previously investigated. A highly insulated Faraday cage (described in a later section) was fastened in the center of the bottom plate of the oscillograph, and a lead brought to a deflection plate.

Measurements of beam current were made by focusing the beam on the center of the cage, and grounding the deflection plates through a microammeter in series with a 45-volt battery. The battery was connected so that the cage was positive with respect to ground to prevent loss of current by secondary emission. This proved to be negligible. A series of cathode tips were prepared from 3/8 inch aluminum rod (cathodes 8 to 12, Figures 10 and 11). These gave spacings of from 5.906 to 3.5 inches. They were made with a plane face and slightly rounded edges. The beam current was measured using each cathode at a cathode current of 1 milliampere and cathode voltage of 60 kv. There is a definite effect of previous operating time on the emission from the cathode (see Rühlemann[80]). To take this into account, each cathode was operated at 1 milliampere for 20 minutes before the measurements were taken. The results of this experiment are plotted in Figure 9, curve A. It is seen that there is a very definite optimum cathode-anode separation of 4.5 inches. An attempt to use a cathode longer than No. 8 was a failure, as the cathode current would not remain steady.

Next, two more cathodes of approximately the same length as No. 10 (i.e., 1 inch) were made (cathodes 1 and 3). The first was 0.75 inches in diameter; the second 0.25 inches. These were tested in the same way as the others, and gave the same value of current within 5 per cent. It was concluded that in this range, the cathode tip diameter had no effect on the beam efficiency.

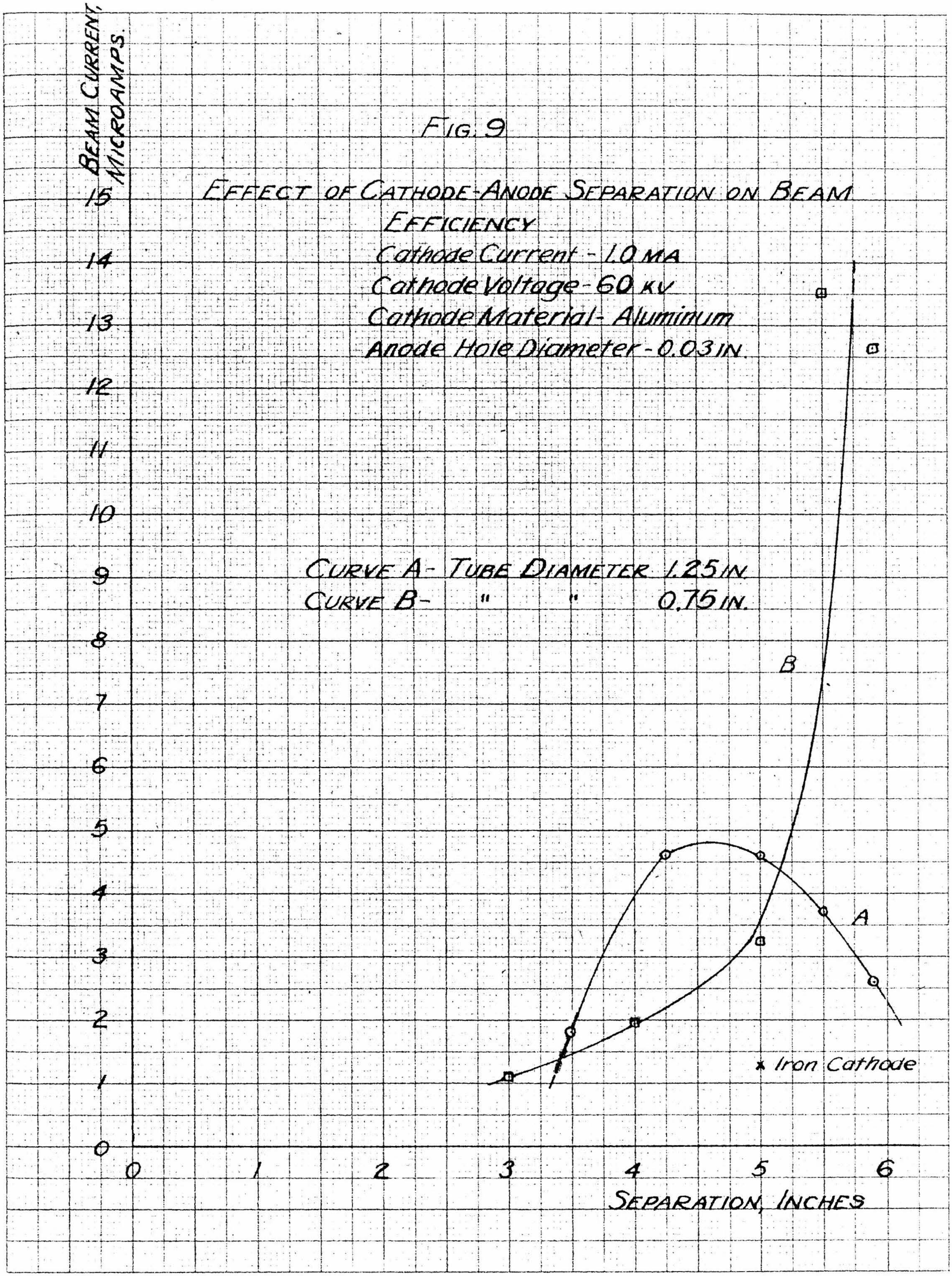


FIG. 9
EFFECT OF CATHODE-ANODE SEPARATION ON BEAM EFFICIENCY
Cathode Current - 1.0 MA
Cathode Voltage - 60 KV
Cathode Material - Aluminum
Anode Hole Diameter - 0.03 IN.
CURVE A - TUBE DIAMETER 1.25 IN.
CURVE B - " " 0.75 IN.
BEAM CURRENT, MICROAMPS.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
1
2
3
4
5
6
SEPARATION, INCHES
A
B
* Iron Cathode

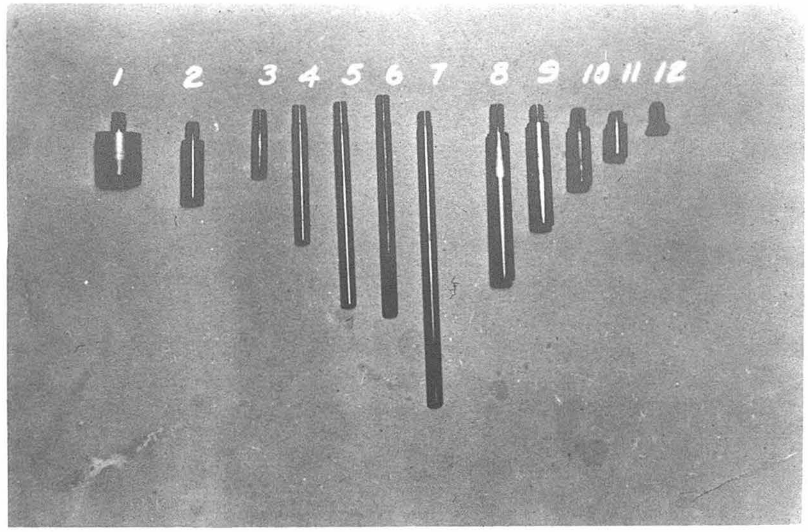


Fig. 10

Cathodes

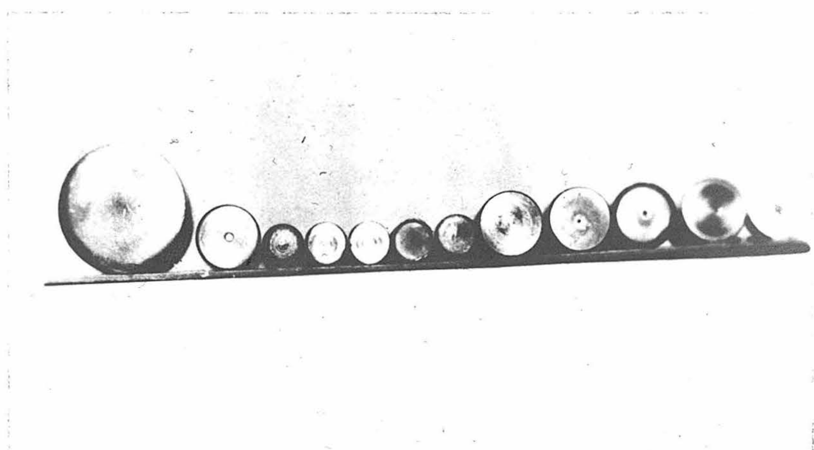


Fig. 11

End View of Cathodes

Von Borries[(6)] used an iron cathode in his photographic studies, claiming that the discharge tube operated more steadily. To test this with the present tube, an iron cathode (No. 2) was investigated. The beam current obtained is plotted in Figure 9. Over a period of several hours no better performance was obtained with this cathode than with the aluminum cathodes. Among aluminum cathodes, the shorter tips gave greater steadiness throughout.

The effect of discharge tube diameter on the tube efficiency was studied by inserting in the tube a brass bushing (see Figure 8, B). This was made of tubing with an inside diameter of 0.75 inches and a wall thickness of 0.125 inches. The lower end fitted snugly over the anode assembly. The upper end was turned off on an angle, and was fitted with three spacers to center it in the tube. The air now had to flow from the anode assembly up and over the tube bushing and down between the bushing and tube wall to the exhaust system. Two cathodes of equal length, one of 0.375 inch and one of 0.25 inch diameter were first tested and were found to give the same beam current. Then a series of 0.25 inch cathodes (Nos. 3 to 7, Figures 10 and 11) were tested as before. The results are plotted as curve B, Figure 9. It will be seen that there has been a surprising increase in beam current using the tube bushing. The tube efficiency is three times as great for a 5.5 inch cathode-anode separation, and four times as great for a separation of 5.906 inches. However, for separations under 5 inches the tube is operating less efficiently than it was without the bushing. There is no optimum cathode-anode spacing unless the value at

5.9 inches separation indicates that the best spacing has been exceeded.

Pressure measurements were made in the discharge chamber simultaneously with the beam readings. A McLeod gauge was connected to the 0.875 inch evacuating line some six inches from the discharge tube. The arrangement can be seen in Figures 2 and 3. Two readings were taken each time as a check against each other. The results are plotted in Figure 12. From the plotted points, it is evident that there was a wide variation in the readings, so that only the general trend can be followed. The two curves form an interesting application of the Law of Similitude (cf Slepian)[(5)]. The dimensions of the discharge tube are decreased by the presence of the bushing roughly in a 5:3 ratio. Thus, in the smaller tube with a cathode spacing of 0.6 of any of the values used in the larger tube, the pressure should be 5/3 as great, which is approximately borne out. Likewise, for either size of discharge tube, the pressure required for a given current should increase with decreased spacing between electrodes, which is also shown.

One more point concerning the discharge tube should be mentioned. Originally the porcelain bushing used was designed for a maximum voltage of 70 kv. During some of the experiments it was operated as high as 85 kv. Operation at this voltage was very unsatisfactory, as considerable corona was present and arcover was imminent. Even at 70 kv. it was found advisable to put rings of 0.25 inch copper tubing around the top and bottom of the bushing where porcelain joined metal. These are shown in Figure 28. This

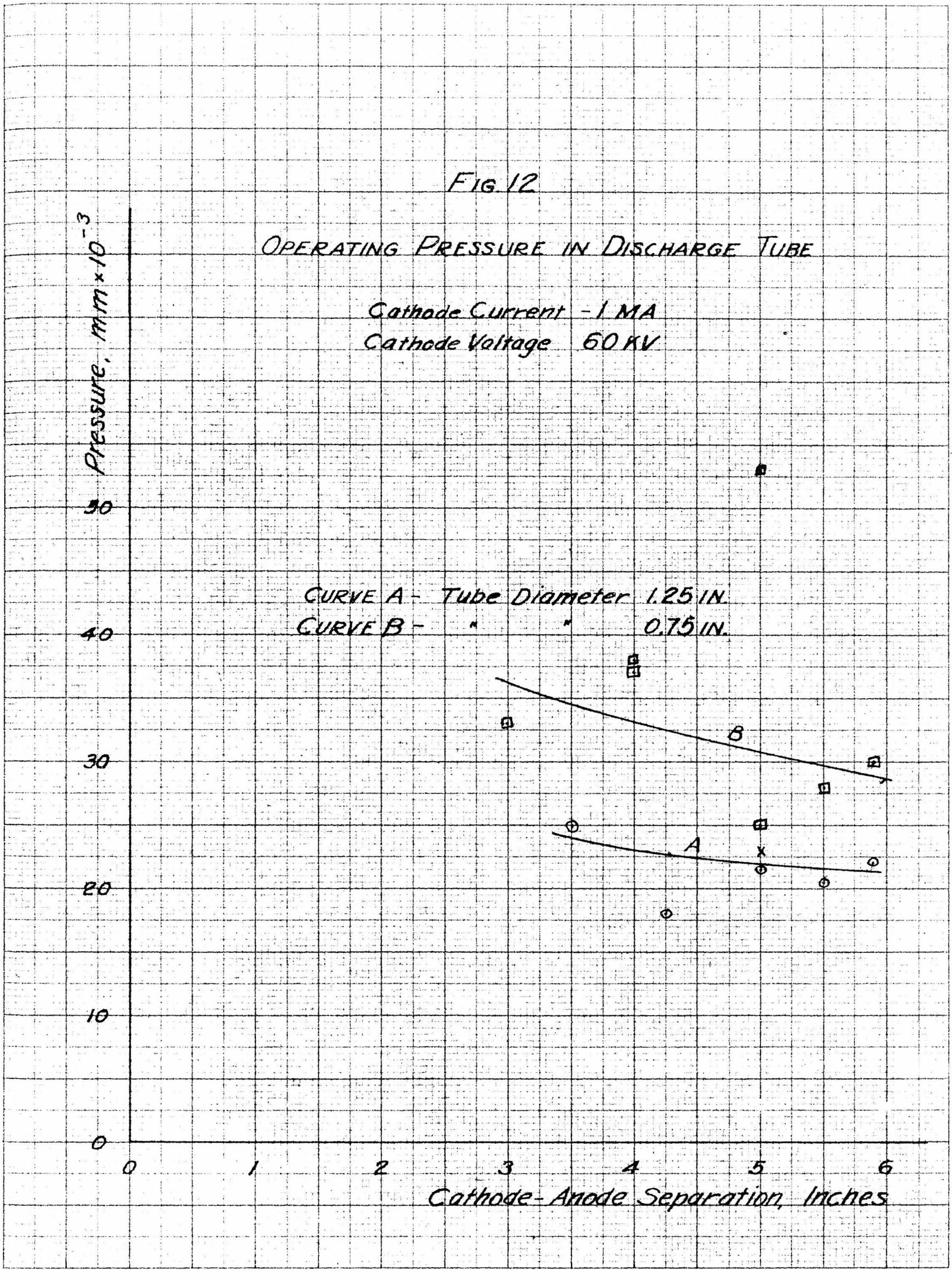


FIG. 12
OPERATING PRESSURE IN DISCHARGE TUBE
Cathode Current - 1 MA
Cathode Voltage 60 KV
CURVE A - Tube Diameter 1.25 IN.
CURVE B - " " 0.75 IN.
Pressure, mm × 10^{-3}
Cathode-Anode Separation, Inches
A
B
0
10
20
30
40
50
0
1
2
3
4
5
6

markedly decreased the unsteadiness due to corona. Undoubtedly better operation could be secured with a large upper corona shield which would better equalize the field.

The highest efficiency obtained with this discharge tube is of the order of 1.5 per cent. This is higher than than obtained by von Borries (6) but very much lower than Miller and Robinson (67) were able to get by the use of an auxiliary focusing electrode. Neither of these tubes used a pre-focusing coil around the discharge chamber. Dodd, (32) using a tube with about double the cathode-anode spacing, and a pre-focusing coil, gives efficiencies as high as 42 per cent. Both water jacket connections on this discharge tube are brought out at the lower side, so that a pre-focusing coil can be slipped on over the top of the tube. However, the beam currents that can be obtained with the present arrangement are quite adequate for writing speeds of more than 1800 km. per second, as demonstrated in the section on photography. In regard to steadiness of operation while using the preferred long cathode-anode spacings, it is possible to select and hold any desired discharge current within the range of the cathode meter (5 milliamperes) for a period limited only by the heating of the water tube resistor in series with the cathode. Currents up to 2 milliamperes have been held over several hours with a variation of less than 0.2 milliamperes. This requires extreme care in setting the air leak, as in general the discharge current tends to "creep" slowly either up or down, and the tube attendant usually corrects this tendency about once each minute. A leak which can be adjusted more delicately (such as the porcelain tube leak of Smythe) might prove of considerable use here.

E. Time Sweep Circuits.

In an oscillograph using a Lenard window, extreme care must be taken that the beam is never stationary on the foil. With a beam power of 0.3 watt (60 kv. and 5 microamperes beam current) to be dissipated by the window, it is obvious that the foil would be ruptured in a very short time. Thus, the blocking circuit must be absolutely dependable. This is a more stringent requirement than is necessary with internal photography, as a loss of blocking can only fog the film.

A survey of the literature on cathode ray oscillography shows that there is scarcely any point in instrument design more diversified than that of the blocking and time sweep circuit. These two circuits are so closely associated that they can hardly be considered separately. Of course, instruments in which the exciting voltage is applied to the cathode only during the operating interval require no blocking circuit, but these instruments are in general being replaced by continuously operated tubes which permit steadier operation, better focusing, and less synchronization troubles.

The blocking of the beam is accomplished in one of two ways: either the beam strikes a blocking diaphragm except during the operating period when it is deflected through an opening, or the beam is normally deflected against a stop and allowed to pass undeflected through the blocking chamber during operating. To the first type belong the instruments of Norinder,[69] Finch,[4] and Whipple,[103] to the second type nearly all the instruments developed by the Aachen and Berlin schools, see especially Boekels,[21] and those of Burch and Whelpton,[24] Miller and Robinson,[67] and Smith, Szeghö, and Bradshaw.[88] The present instrument uses the second type of blocking system for two reasons: increased simplicity of construction, and less likelihood of beam distortion during unblocking. With electrostatic beam deflection, equal potential must be applied to both blocking plates to permit unblocking. This arrangement is inherently less subject to beam distortion than one in which the beam must be deflected to be unblocked. The only disadvantage is that failure of the voltage supply to blocking plates would allow unblocking and possible destruction of the foil, This cannot happen with the deflection-type of unblocking system. However, it was felt that this was more than outweighed by the corresponding advantages given.

Electromagnetic blocking and sweeping systems were not attempted because of the greater difficulty of producing and varying large currents as compared with high voltages.

Because of the type of work encountered in this laboratory, it was decided to construct a blocking and sweep circuit which would operate as a result of surges produced in the test apparatus, rather than initiating the surge from the oscillograph (the so-called "arbitrary operation"). The polarity of the initiating surge could not predetermined. The circuits had to be arranged so that an incoming impulse of either polarity would first cause unblocking of the beam, then a time sweep of controlled speed, and finally reblocking before the return sweep of the beam.

The switching operations connected with these three steps must be performed with such speed that mechanical arrangements, such as rotating switches, etc., are used only for repeating phenomena. Modern circuits use either vacuum tubes or spark gaps, or a combination of both. The vacuum tube is more consistent, since the time lag of small gaps is known to be of the order of 10^{-8} to 10^{-7} seconds for non-prestressed gaps, and even longer for these.[15] However, the use of a delay cable has become so general that this is no longer a major item. Vacuum tubes require more attention as to circuit design and operation. Highly insulated filament supplies are required. High voltage tubes (plate potentials of several kilovolts) are expensive. For these reasons, a spark gap circuit was finally used in this instrument. Several vacuum tube circuits were tested during the investigation, but the results only confirmed the points given above.

To show the evolution of this circuit it is advantageous to mention briefly several others. Such a circuit, published by Boekels[21] in 1931, is shown in Figure 13. The blocking electrodes (A_B) and sweep plates (A_T) are connected across the full gap voltage. Normally the sweep plates are grounded through resistors R_4. A surge applied to the deflection plates A_O is coupled by condensers C_K to the gap whihh breaks down, causing the gap voltage of 2 V to appear across A_T. The time constant of the sweep circuit

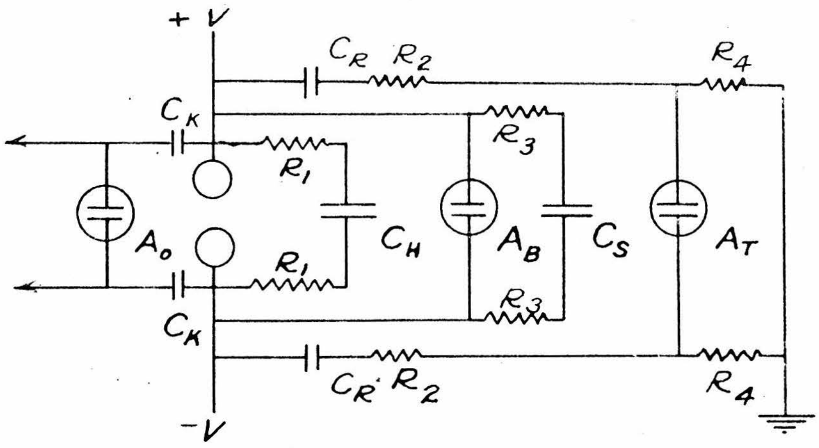


FIG. 13

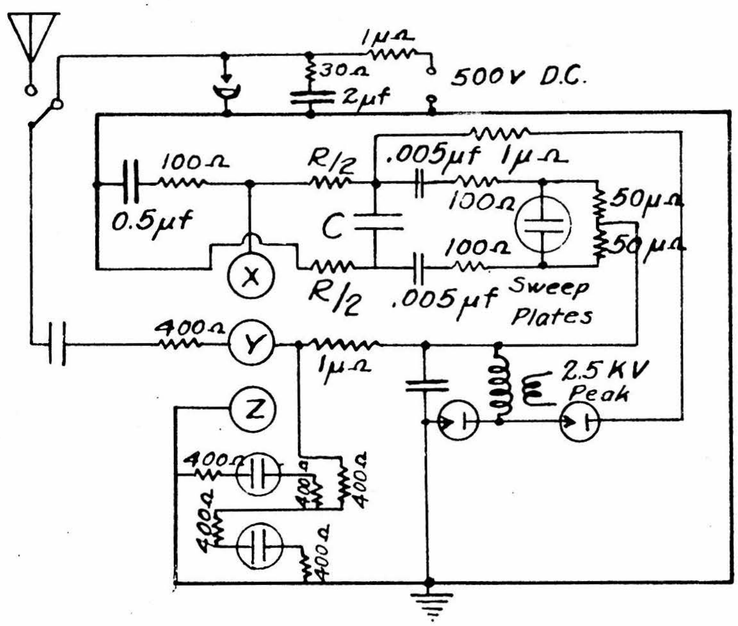


FIG. 14

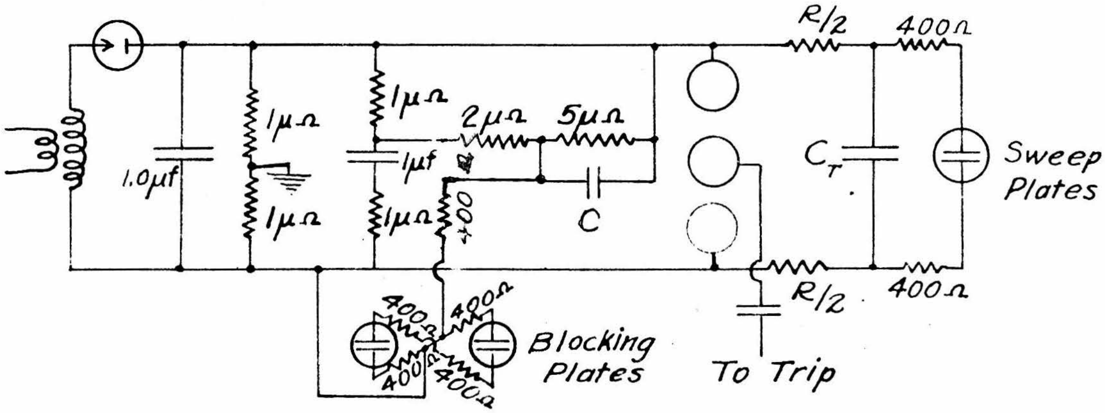


FIG. 15

$(C_R/2 \times 2(R_2 + R_4)$ governs the sweep speed of the beam. The purpose of the heating condenser C_H is to dissipate enough energy across the gap to maintain the discharge as a low voltage arc, although it also suppresses any oscillations in gap voltage due to the oscillations in the applied surge. This latter duty is shared by C_S. In this circuit, as in all time sweep circuits, great pains are taken to suppress spurious oscillations. For this reason, the relative sizes of condensers and resistors are such that all discharges are completely damped and non-oscillatory, and at all points where traveling waves could suffer reflection, damping resistors equal to the line surge impedance are inserted.

One disadvantage of this circuit is that a surge of polarity opposite to that of the gap lowers the gap voltage and will not trip the circuit. This presents no difficulty if the polarity of the surge can be predetermined, but is not permissible if the circuit is to be responsive to all surges. For this reason, the use of triple-sphere gaps has become common. In such circuits, the voltage applied to the middle sphere is halfway between that applied to the outer spheres, and the surge is coupled to the center sphere. Thus, the surge must increase the potential across one gap, and breakdown of this gap applies full voltage across the second gap, breaking it down in turn.

Among the first to use this system were Burch and Whelpton (24) whose circuit is shown in Figure 14. They grounded one sphere of of the triple gap, and used the potential between the middle sphere and ground for the blocking voltage. The sweep plates are charged up to half voltage before operation, but the discharge of time condenser C through the two symmetric resistors R/2 applies across these plates the difference of potential originally across the 0.005 microfarad condensers. The circuit is tripped either by electrostatic pickup of the surge through an antenna, or by oscillations produced by discharging a two microfarad condenser charged to 500 volts.

In both the circuits just described the beam is reblocked before the back sweep by using a charging circuit for the blocking electrodes with shorter time constant than that for the time sweep electrodes. It is possible to use a circuit in which voltage is applied to the blocking plates much more rapidly after the gaps extinguish. Such a circuit is shown in Figure 15, due originally to Boekels,[21] and modified by Mr. R. Howard Griest of this laboratory. Here the outer spheres are symmetrically charged above and below ground. Two one microfarad condensers are used. The first is a heating condenser connected directly across the outer spheres. The second is connected to the gaps through a megohm on each side, and controls the reblocking. Originally small condenser C is uncharged, but when the triple gap breaks down it is charged through 3 megohms, increasing the voltage across the blocking plates in the process. At a certain time, governed by the time constant of this circuit and the voltage necessary to reblock the beam, the voltage across the blocking plates becomes high enough to cause reblocking, regardless of the gap voltage. As soon as the arc goes out, a fraction (in this case, 5/8) of the voltage across the microfarad condenser is applied to the blocking plates, due to the resistance-divider arrangement shown. This insures positive blocking. The sweep voltage is applied to the oscillograph electrodes as shown in Figure 13.

In these three circuits, indicative of modern practice, the difference of potential applied to the sweep plates is zero either at the beginning or end of the cycle. Some auxiliary means must be used to bias the beam to one side. Otherwise, the spot would either begin or end in the middle of the plate. Usually this biasing arrangement is secured by the use of magnetic deflection or a set of auxiliary deflection plates, although Miller and Robinson[(68)] used an ingeneous electrostatic biasing circuit on both time sweep and phenomena plates. All of these methods have the disadvantage that there are two circuits involved in the correct operation of the sweep, so that if either fails to operate, the beam will remain stationary at the center of the plate for an appreciable length of time. As previously discussed, this cannot be tolerated when using a Lenard window. Consequently in the design of the time sweep circuit of this instrument, it was decided to so arrange the circuit that both beginning and end of the sweep would be off the window.

The final circuit and the physical arrangement of the parts are shown in Figures 16 and 29 respectively. It consists of the switching circuits proper and a 6 kv. power pack of conventional

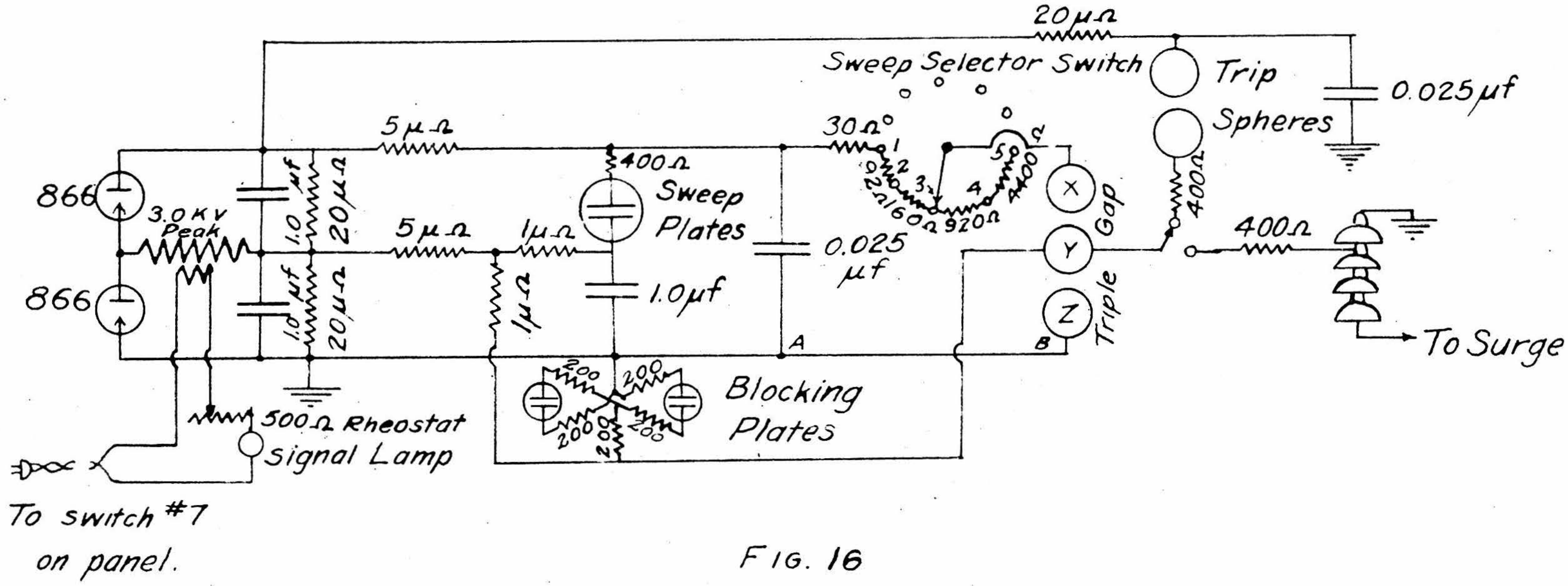


FIG. 16

TIME SWEEP CIRCUIT

voltage-doubler design. The pack is tapped for half voltage, which is applied to the middle sphere of the triple gap. One of the sweep plates is also connected to this center tap through 6 megohms resistance. A 1.0 microfarad condenser is connected between this plate and ground to insure keeping constant potential on this plate at all times. The other plate is connected to the high side of the pack through 5 megohms, and is also connected through a 400-ohm surge resistor to one side of the 0.025 microfarad sweep condenser. This condenser is connected across the outer spheres of the triple gap through the timing resistors. The discharge of the 0.025 microfarad condenser through the timing resistors determines the sweep speed. By means of the selector switch the series resistance can be quickly changed to give a total of 11 different sweep speeds. At present only five are in use, giving sweeping times of 1, 10, 22, 50, and 100 microseconds. The capacity of the timing condenser is low enough that much faster sweep speeds can be used without danger of oscillation. The fastest used in the experiments gave approximately 0.7 microseconds plate exposure, and was not oscillatory. The low capacity of the timing condenser has disadvantages. There is little energy stored in the condenser, so that when high series resistors are used to give slow time sweeps, there is insufficient energy dissipated in the gap to form a low-voltage arc. Instead, a high-voltage glow occurs, the voltage across the condenser does not drop enough for the arc to go out, and the triple gaps are short circuited until the power source is deenergized. This was cured by connecting a 0.1 microfarad heating condenser across the gaps X-Z through two 400-ohm resistors to prevent oscillation. This precaution is necessary when the series resistor in the timing circuit exceeds about 1500 ohms. The blocking plates are cross-connected through surge resistors and are placed directly across the middle gap to ground.

In operation, a surge arcing over the triple gap discharges the blocking plates almost instantly, as their time constant is under 10^{-8} seconds. At the instant the arc occurs there is a difference of potential across the sweep plates of V/2, and the beam is deflected off the window on one side. The discharge of the timing condenser lowers the potential of the high voltage plate until at the end of the discharge it is only a few volts above ground, and the potential difference across the plates is again nearly V/2, but in the opposite direction, so that the beam has been swept off the window in the opposite direction. Thus, neither at the beginning or end of the sweep is the beam on the window. As soon as the arc goes out, both the blocking plates and the sweep plate recharge, but the charging circuit time constant of the blocking plates is so small compared with that of the time sweep circuit (0.0012 second against 0.125 second) that the beam reblocks long before it reaches the window on the back sweep.

Two tripping circuits are used, depending upon whether fully automatic or semi-manual control is desired. For the former, the middle gap is connected through a 400-ohm surge resistor and coupling condenser consisting of an insulator string to the initiating triple gap of the laboratory million-volt Marx surge generator. A single wire stretched near the generator will also trip the circuit. For semi-manual control, the middle gap is connected to a second set of sphere gaps connected across a condenser and charged through a 20-megohm resistor by the full pack voltage. The time constants of all circuits involved are such that the circuits are tripped approximately once each second. This arrangement is used for final adjustment of auxiliary circuits and for focusing. No attempt was made to use this surge for initiating the surge generator.

In operation, this circuit proved to be adequate. The blocking with both sets of plates was complete, and with either set was sufficient so that no perceptible fogging of the film occurred during a half-hour exposure. With the gaps properly adjusted, no return sweeps were found on the oscillograms. Operation was consistent, and such that although the average exposure time of the film (i.e., the time during which the shutter was raised, exposing the window) was around five minutes, no foil was ruined by burning due to the beam. Operating experience with the circuit will be treated later in this paper.

III. Quantitative Tests on Lenard Photography.

Measuring instruments of this class can best be compared by the excellence of the ultimate product --- the film containing the trace of the moving beam. Quantitative measurements on the factors affecting the production of these oscillograms form the only real basis for future design. For these reasons, it is necessary that these factors be determined and their effects measured. This has been carried out in the following analysis.

Little has been reported on quantitative measurements of oscillograms taken through Lenard windows. The most complete account of such tests was published by von Borries[(6)] in 1932. Because of the small amount of data available, some of the previous work has been checked and amplified.

The quantities affecting the production of an oscillogram on film fall naturally in two categories: electrical and photographic. They can be summarized as:-

Electrical:

Charge density in the focused spot.

Spot diameter.

Accelerating voltage applied to beam.

Velocity of spot across the film.

Type of recording (internal, Lenard, etc.)

Photographic:

Type of film used.

Development technique.

Later processes to increase contrast, etc.

Blackening due to beam of electrons.

For any given oscillograph, the accelerating voltage and spot diameter will normally be fixed. The type of recording and the film and photographic processes will then be chosen for convenience and sensitivity. Under these conditions, the maximum velocity of the spot which will produce a satisfactory trace across the film is usually taken as the criterion of performance. Processes to increase contrast are of too varied a nature to be treated here.

A. Beam Analysis.

It would be extremely difficult, if at all possible, to measure the charge density in the beam as it sweeps across the film. For this reason, the current density in the stationary beam is determined, from which the charge density of the spot can be computed at any beam velocity.

Several arrangements were tried in the search for a quick, convenient method of measuring the current distribution in the stationary spot. The final setup is shown in Figure 17. It consisted of a highly insulated collecting cup ("Faraday cage") placed in the center of a square plate used to close the lower end of the oscillograph, and a disc drilled with a series of graduated holes whose centers were equidistant from the center of the disc. This

Fig. 17.

Beam Analysis Apparatus

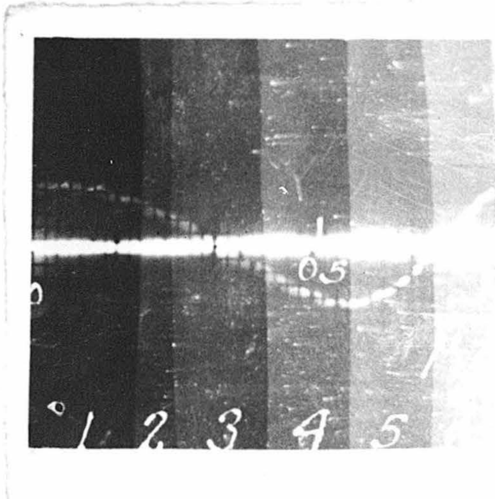


Fig. 24

Oscillogram Developed Progressively in Steps disc was supported by a vertical post so that the lower surface was not over 1/16 inch from the top of the cup. As the disc was rotated, each hole could be centered axially with the cup. The disc was rotated by two bevel gears, one of which was soldered to the disc, and the other of which was fastened on the shaft normally used to rotate the fluorescent-screen shutter. As previously noted, this shaft terminates in a rotatable vacuum joint so that the disc could be turned when the oscillograph was evacuated --- a very obvious necessity. The cup itself resembled a pill box made of brass with a $\frac{1}{4}$ inch hole in the top, and was connected by an insulated lead to one of the deflection plates.

There were two series of holes in the disc. The first consisted of a set with diameters ranging from 0.01 to 0.37 inches. The intervals between hole sizes can be found on Figure 18. The second set comprised five holes of 0.25 inch diameter, four of which were covered with varying thicknesses of cellophane used for measurements on the electronic penetration of cellophane, described in detail in a later section. The disc was coated with a thin layer of willimite and red wax which was carefully scraped away from the edges of the holes.

The technique of measurement was simple. The main plate was attached to the oscillograph, and the instrument evacuated. A beam was then produced, focused to the finest spot possible on the willimite-coated disc over the cup, and the disc rotated until the largest hole was over the opening in the collector. The deflecting plate connected to this cup was connected in series with a 45-volt battery and a microammeter to ground. The meter and battery were carefully insulated on porcelain standoff insulators to reduce leakage currents, which were found to be negligible. After measuring the beam current with the largest diameter diaphragm, the disc was rotated so that measurements could be made with each hole in the set successively limiting the diameter of the part of the beam reaching the cup.

One representative set of readings is reproduced in Figure 18. These readings were taken with cathodes uniformly aged at 1 milliampere cathode current for one-half hour before measurement. The maximum value of collector current is, of course, the total beam current, and these values have been already shown in Figure 9, which was derived from such measurements.

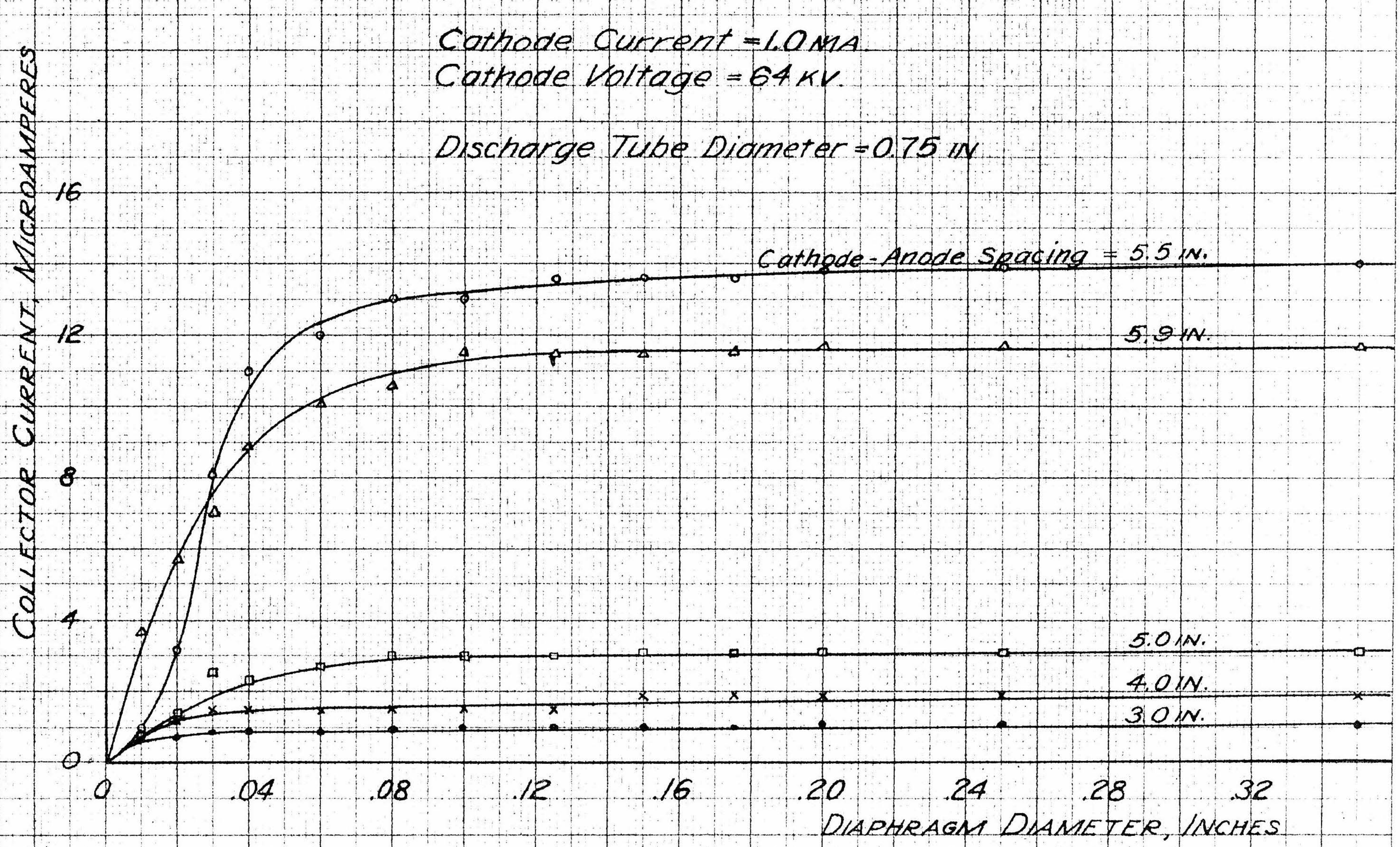
Once having obtained the collector current-diaphragm diameter curves, the current density at any distance from the beam axis can be computed from the formula,

$$j = \frac{1}{10.13 \quad D} \frac{d\,i}{d\,D} \qquad (1)$$

which is derived in Appendix A. In applying this expression to the curves, it is only necessary to determine graphically the slope of the curves at the various diameters. The resultant current density curves computed from Figure 18 are shown in Figure 19.

This experimental setup furnished a very convenient way to obtain quantitatively the effect of changing the dimensions of the discharge tube and the cathode-anode spacing. As a result of

FIG. 18.
TYPICAL BEAM ANALYSIS RECORDS



measurements made with two discharge tube diameters and four cathode-anode spacings, Figures 19 and 20 have been made. Here it is seen that decreasing the discharge tube diameter increased the efficiency of the discharge, but did not have a fosucing effect. This is demonstrated by the fact that the maximum current densities found for equal cathode-anode spacings but varying tube diameters are in direct ratio to the corresponding total beam current in each case. Dicks[31] has also noted an increase in discharge tube efficiency as the effective diameter was decreased. However, in both figures, there is a very definite focusing effect due to the cathode-anode spacing. As the spacing increased, the current density in the core of the beam increased rapidly. This is of especial interest in the case of the 1.25 inch diameter discharge tube, in which the total beam current decreased at spacings greater than 4.5 inches.

This effect has not been previously investigated. It points the interesting conclusion that in this type of discharge tube the design trend should be toward tubes with smaller diameters and increased cathode-anode spacing. There is undoubtedly an optimum value, but it has not been reached in this investigation.

Beam analyses were also made over a range of cathode excitation from 30 to 67 kilovolts. The shape of the curves was quite similar throughout this range, but the maximum current density decreased rapidly as the cathode potential was lowered. The results are plotted in Figure 21. From this figure it is evident that the maximum beam density increases by some power of the voltage between two and three. This is quite different from the results obtained

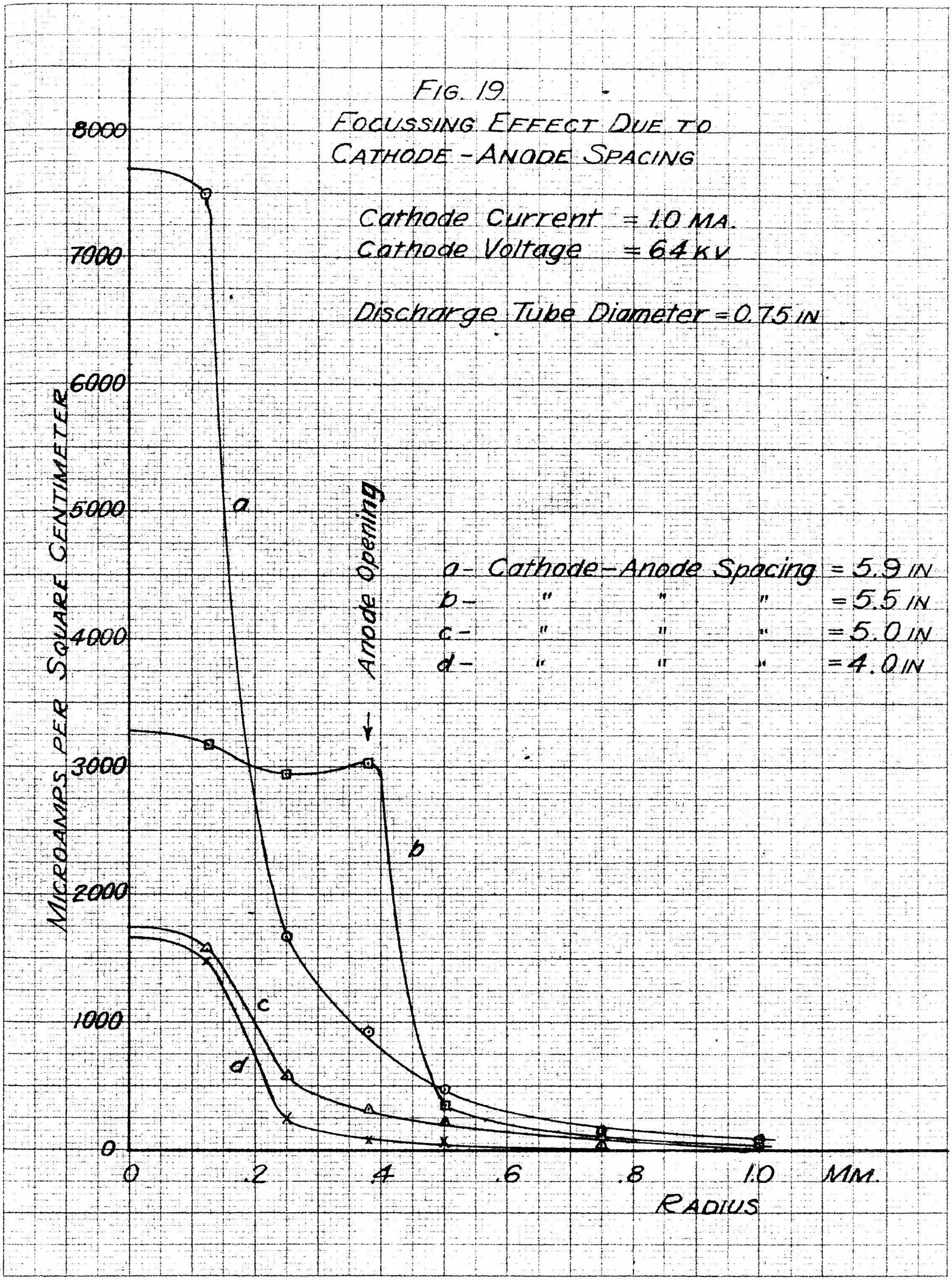


Fig. 19
Focussing Effect Due to
Cathode - Anode Spacing
Cathode Current = 1.0 MA.
Cathode Voltage = 64 KV
Discharge Tube Diameter = 0.75 IN
a- Cathode-Anode Spacing = 5.9 IN
b- " " " = 5.5 IN
c- " " " = 5.0 IN
d- " " " = 4.0 IN
Anode Opening
Microamps per Square Centimeter
8000
7000
6000
5000
4000
3000
2000
1000
0
a
b
c
d
0
.2
.4
.6
.8
1.0
MM.
Radius

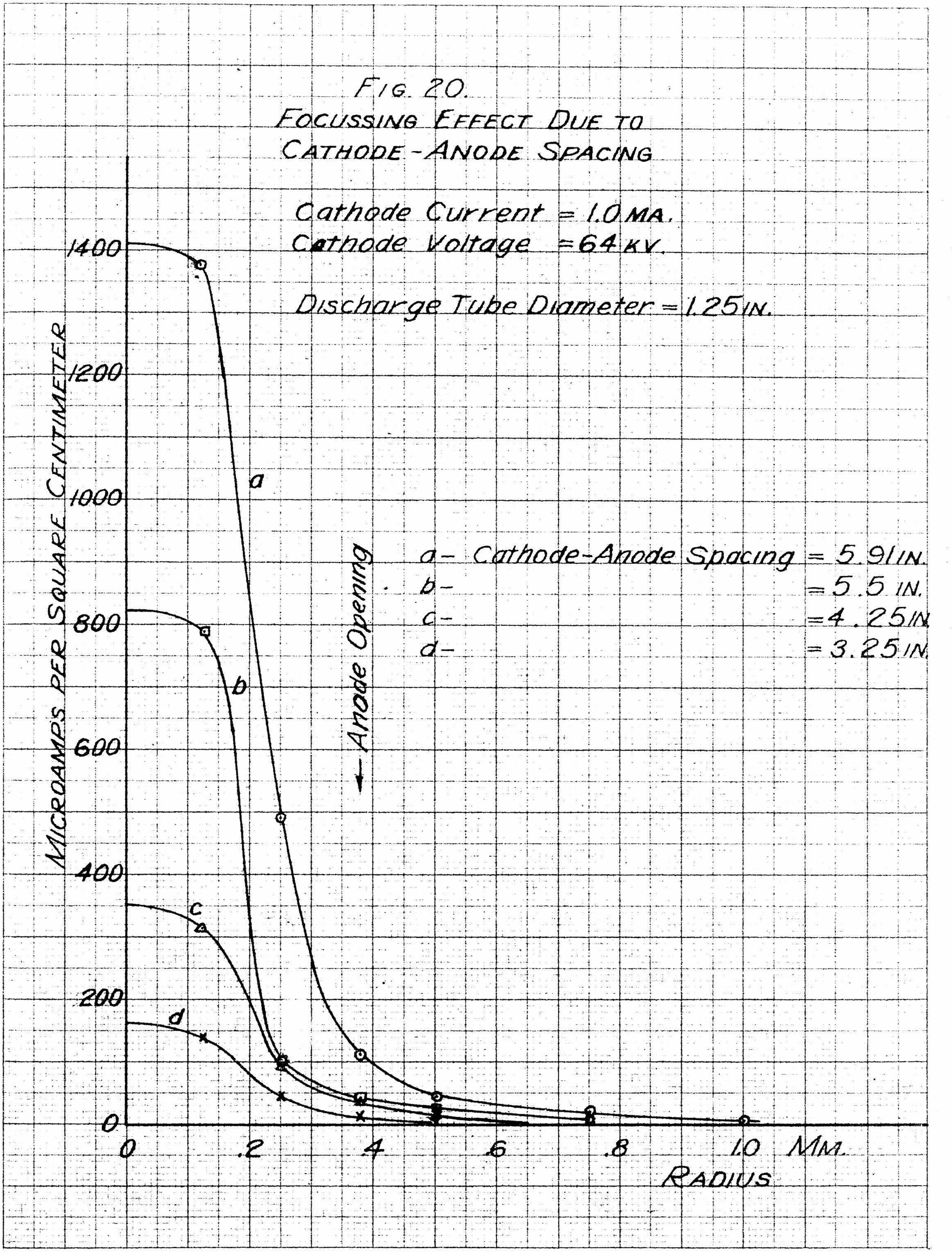
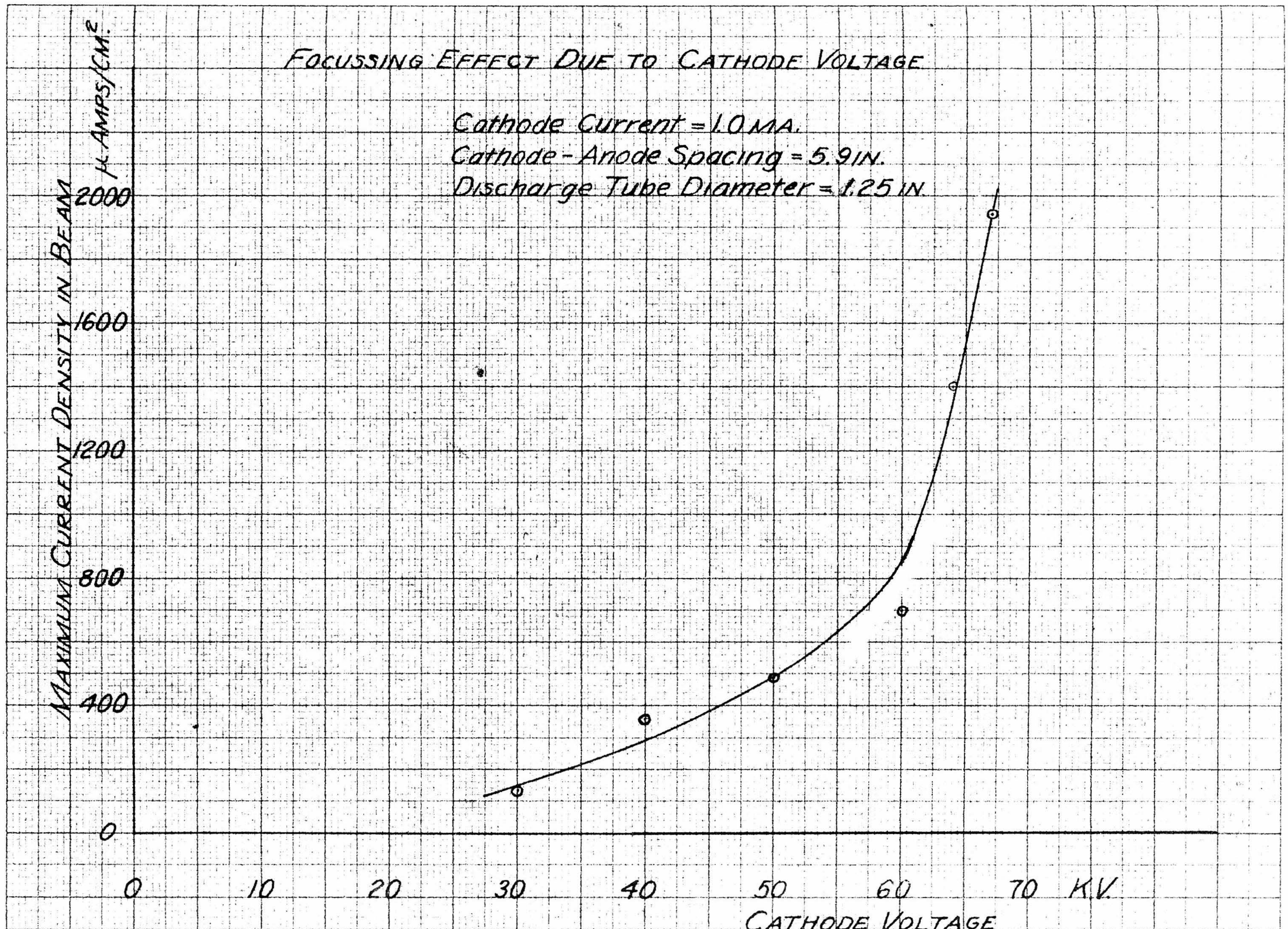


FIG. 20.
FOCUSSING EFFECT DUE TO
CATHODE-ANODE SPACING
Cathode Current = 1.0 MA.
Cathode Voltage = 64 KV.
Discharge Tube Diameter = 1.25 IN.
a- Cathode-Anode Spacing = 5.91 IN.
b- = 5.5 IN.
c- = 4.25 IN.
d- = 3.25 IN.
← Anode Opening
MICROAMPS PER SQUARE CENTIMETER
1400
1200
1000
800
600
400
200
0
.2
.4
.6
.8
1.0
MM.
RADIUS
a
b
c
d



FOCUSSING EFFECT DUE TO CATHODE VOLTAGE
Cathode Current = 1.0 MA.
Cathode - Anode Spacing = 5.9 IN.
Discharge Tube Diameter = 1.25 IN.
MAXIMUM CURRENT DENSITY IN BEAM μ AMPS/CM.²
2000
1600
1200
800
400
0
0
10
20
30
40
50
60
70
K.V.
CATHODE VOLTAGE

FIG. 21.

by von Borries.[6] Working with cathodes which had been used for extended periods (cathode craters of 2 mm. diameter) he shows a nearly linear relationship between maximum current density and cathode voltage. The difference between the two sets of curves must lie in the shape of the cathode surface. In the results given here, the maximum crater diameter was usually less than 1 mm. This would indicate that there is a focusing action of the cathode voltage.

One possible explanation for this phenomenon is that with a plane cathode the electrons are emitted directly toward the bottom of the tube, and with high accelerating voltages there is insufficient time for the electrons to be deflected toward the side walls, also at the anode potential. When the cathode is deeply pitted from positive ion bombardment, electrons are emitted in a diverse "spray" since they are given off normal to the pitted surface. In this case the walls would receive a much greater proportional part of the total current than before, decreasing the maximum current density markedly. This theory would also explain the well known results that the current density is much more uniform in a beam from a highly pitted cathode than from a plane one. In the former case the electrons passing through the anode hole would be those emitted parallel to the tube axis. This would consist of those from the center of the pit and those from the edge. Since the field at the center of the pit is much less than that at the edge, the intensity in the outer part of the resultant beam should increase, while that in the center should decrease. The combined action makes the beam intensity much more uniform than before.

This is well illustrated by the curves of Figure 22. In this figure the beam analysis for a cathode aged 5 minutes at 1.0 ma. and an analysis for the same cathode aged 45 minutes are shown. The core intensity has decreased by a factor of three, while the intensity at the outer edge of the main beam has increased to twice its former value. This results in a fairly uniform beam. The third curve of this figure was taken at a higher voltage, and shows that the relative shape of the curve is unchanged, and that the core intensity has increased only slightly.

Up to this period in the investigation only cathodes with plane ends cut normal to the tube axis had been used. Several other shapes were now prepared and tested to find if there was a best shape. Sharply pointed cathodes gave a slightly higher initial beam density than the plane cathodes, but aged much more rapidly. Beveling the cathode edge did not affect the discharge as long as the beveling was not carried into the crater region. Finally an especially interesting shape was tested. This was a tip in which a thin edge projected roughly 0.10 inch beyond the plane face. The shape of the field close to the emitting area would be expected to concentrate the beam. This was not found to be true. There was an apparent increase in discharge from the cathode edge, judging by the blackening of this region. The cathode is number 6 in Figures 10 and 11.

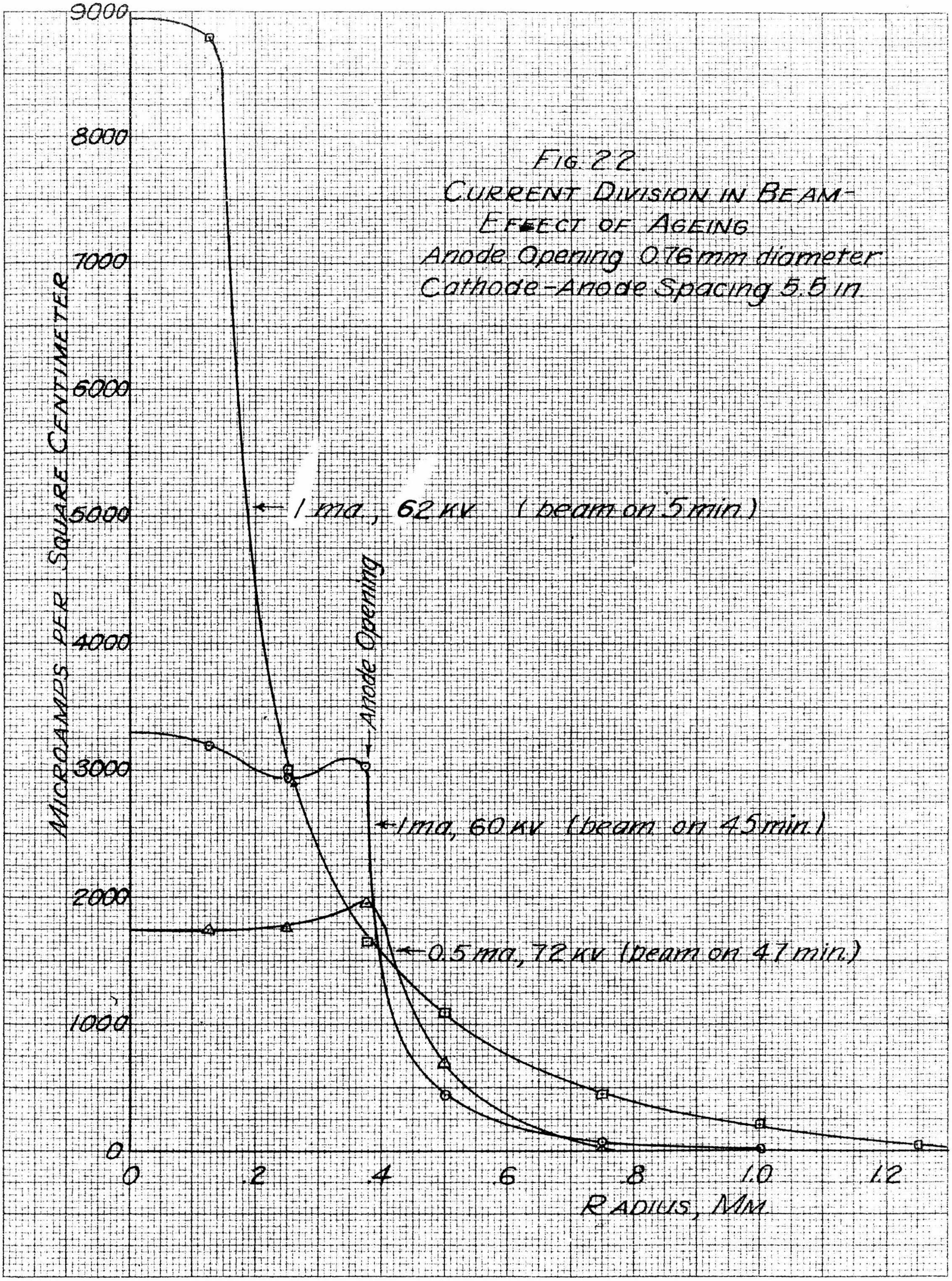


FIG. 22.
CURRENT DIVISION IN BEAM-
EFFECT OF AGEING
Anode Opening 0.76 mm diameter
Cathode-Anode Spacing 5.5 in.
MICROAMPS PER SQUARE CENTIMETER
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1 ma., 62 KV (beam on 5 min)
Anode Opening
1 ma, 60 KV (beam on 45 min.)
0.5 ma, 72 KV (beam on 47 min.)
0
.2
.4
.6
.8
1.0
1.2
RADIUS, MM

B. Absorption of Cathode Rays by Lenard Window.

The penetration of various thin films by cathode rays has been investigated so many times[(2)(6)] that little further work was thought necessary. The beam analysis apparatus was available for a quick convenient check and so was used in the following way. As previously mentioned, the rotating disc of the apparatus had a series of five 0.25 inch holes, of which four were covered with different thicknesses of cellophane. Foils of 0.012 and 0.020 mm. cellophane were available. Accordingly the first hole was covered with a single layer of 0.012 mm. thickness, followed in turn by a single layer of 0.020 mm. over the second hole, two layers of 0.012 mm. on the third, and a layer of 0.012 and one of 0.020 mm. on the fourth. The last was left open as a check. A sensitive d'Arsonval wall type galvanometer was connected in place of the microammeter to the collector cup. The hole in the anode was decreased, and an old cathode was used, so that only very low beam intensities would be obtained. The beam was focused on the collector cup with the disc rotated so that the large open hole was over the cup. Beam currents of the order of 0.25 microampere were used, so that there would be insufficient beam energy to burn the cellophane during the measurement. The holes covered with varying thicknesses of foil were then placed successively over the collector, and the currents recorded. Finally the other open hole was reached and the beam current checked. The results are plotted in Figure 23. The solid lines in that figure are curves reproduced from von Borries[(6)]

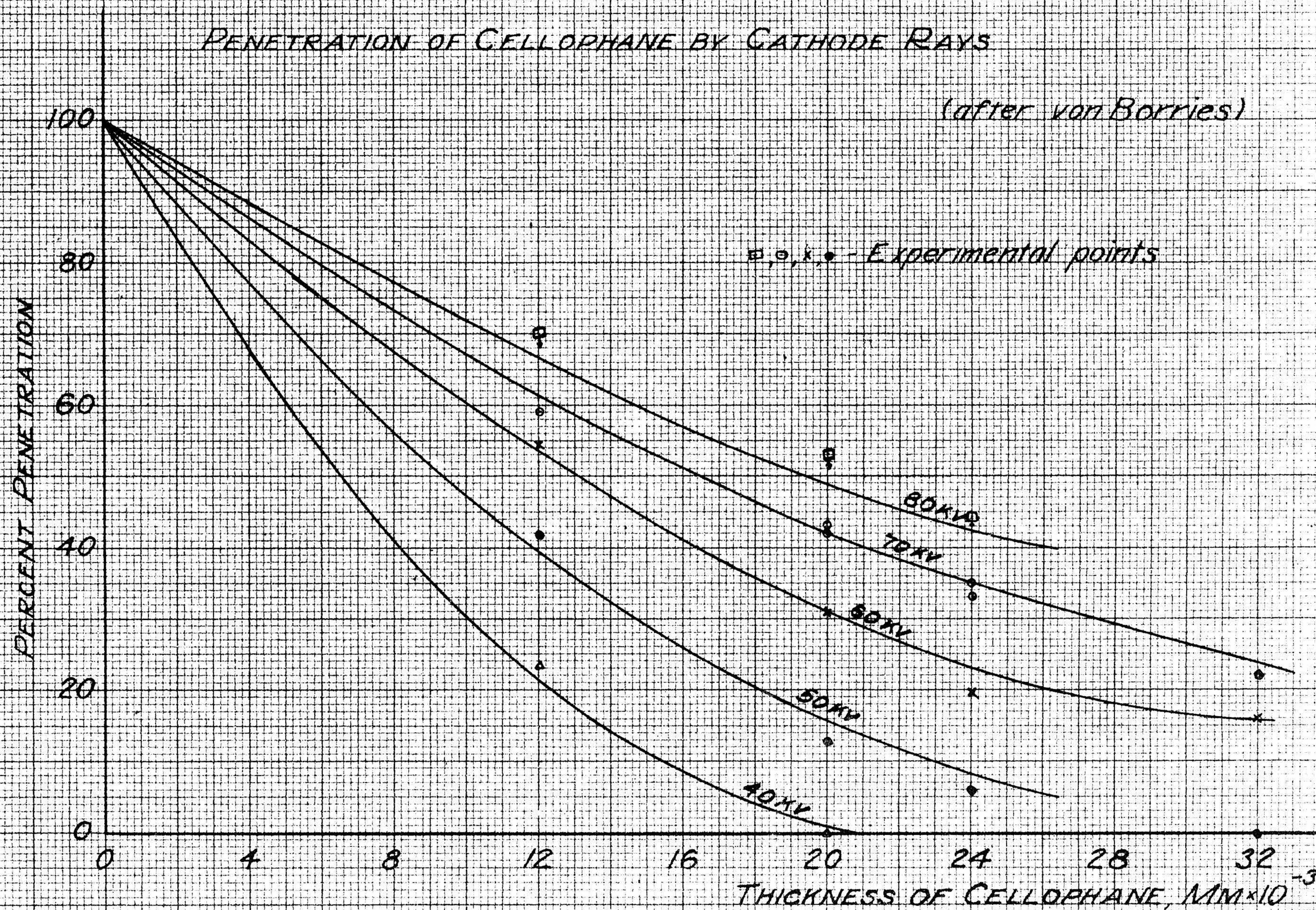

PENETRATION OF CELLOPHANE BY CATHODE RAYS
(after von Borries)
□, ⊖, x, ● - Experimental points
80KV
70KV
60KV
50KV
40KV
PERCENT PENETRATION
100
80
60
40
20
0
0
4
8
12
16
20
24
28
32
THICKNESS OF CELLOPHANE, MM×10⁻³

FIG. 23.

figure 11, and plotted in terms of thickness of cellophane rather than aluminum. The experimental points check the curves within the limit of accuracy with the exception of the values at 80 kv., which are uniformly high. It is quite possible that, even with the precautions taken, the cellophane was slightly damaged during the short exposure period to the beam (around 15 seconds) and that in consequence more current passed through than would normally be the case. It is also possible that the cathode voltage may have been higher than indicated by the sphere-gap readings.

It is evident from this figure that Lenard photography is not well adapted for use at cathode voltages lower than 50 kv. unless very thin cellophane can be used. Above this point the choice of voltage depends upon the maximum writing speed necessary. In general it does not appear necessary to go above 70 kv., as the increase from 70 to say 80 kv. means an increase of the order of 10 to 15 per cent penetration, while an increase from 60 to 70 kv. represents an increase in penetration of the order of 20 to 30 percent. As far as thickness of foil is concerned, the penetration is inversely proportional to the thickness of the film, so that a change from 0.020 mm. to 0.012 mm. cellophane gives nearly twice the penetration. Of course, if internal recording is used, a gain of roughly two to one over the results obtained with external photography through a Lenard window is to be expected.

C. Spot Diameter.

The spot diameter is a function of the anode opening and position of the focusing coil. Busch[25] showed that when using a short focusing coil, the size of the spot when perfectly focused was given by,

$$d_s = \frac{b}{a} d_a \qquad (2)$$

where d_s = diameter of spot

d_a = diameter of anode opening

b = distance from focusing coil to spot

a = distance from focusing coil to anode opening.

With the focusing coil midway between anode opening and film, as in this oscillograph, it is to be expected that the minimum spot diameter would be that of the anode opening (0.76 mm.). Figure 22 shows that this is true only for an old cathode. For a fresh cathode the effective spot diameter is much less than this, due to the focusing in the discharge tube itself. This is probably what von Borries[6] means when he states that the object focused by the coil is the cathode spot when using fresh cathodes, and the anode opening when using old cathodes. MacGregor-Morris[3] states that the maximum spot diameter should be 2 per cent of the maximum deflection for satisfactory recording. This ratio is obtained at a deflection of 3.8 cm. which is well within the scope of this instrument.

It will be noted on a number of the oscillograms shown later in this paper that the maximum spot diameter is seldom as little as 0.76 mm. This is due to dispersion of the beam through the cellophane and air between cellophane and photographic film, and on failing to secure the best possible focus. Ordinarily the focus was checked visually, which was found to be insufficient for best results.

D. Velocity of Spot across the Film.

With a given strength of electron beam, the charge density on any area covered by the moving spot will be inversely proportional to the velocity of the spot. Other conditions being fixed, maximum writing velocity of the spot is determined by the charge density required to produce a usable trace on the film. After this point has been reached, it is necessary to increase the beam voltage or current in order to record higher velocities. This will be discussed further at the conclusion of this section.

The upper limit on recording speed reached by modern investigators is defined by the amount of distortion allowable. This is determined by the finite speed of the beam past the deflection plates. When the transient voltage varies so rapidly that there is a change in deflecting field during the time that an electron passes between the plates, distortion results.

The lower limit to the velocity of the spot in Lenard photography depends on the maximum safe time a beam can rest on the foil without burning it. Several oscillograms were made with the present instrument using sweep times of 0.001 second, with a minimum velocity of the order of 100 meters per second. It should be entirely possible to use recording speeds of a tenth that value without injuring the foil, so that a single cycle of a 50-cycle wave can be recorded.

E. Type of Film Used.

Little was done to find the most sensitive type of film to use in this instrument. Four different kinds of film and one type of sensitive paper were used. Ranged in order of sensitivity, these are:

Eastman Panchromatic
" " Verichrome
" " Process (Nitrate)
" " NC
News Bromide

There was little difference between the first three, so that in choosing the film for later work the factor of convenience was of more importance. Eastman Process films were used because of their decreased sensitivity to light, hence lower fogging, and their excellent mechanical properties due to increased film thickness. It was extremely difficult to use the Panchromatic film without fogging it during exposure, while the Verichrome film was much less convenient to handle. The bromide paper was used only for one test record(reproduced in Figure 48) because of the trouble in making copies of the resultant oscillograms. For ordinary laboratory work when there is no need to secure more than one copy of the oscillogram, this paper could be used to advantage. The upper limit as to speed of recording on bromide paper is not known.

F. Development Technique.

The factors involved in choosing the best development technique were too many to be considered in the scope of this investigation. Hence the type of fixer, and time taken to wash, fix, and rinse were fixed. The usual acid hypo fixer was used, with a fixing time of 20 minutes. This was preceded by a 30-second rinse and followed by a washing period of 15 minutes.

Three developer solutions --- D-11, D-72, and D-19 --- were investigated. These three were chosen as representative of the types of developer most commonly used. The solutions were tested as follows. Stock solutions of each kind were prepared and brought to a uniform temperature of 65°F. Sets of three identical cathode-ray oscillograms were then made with as linear time scale as possible, and with varying sweep speeds. In each case the sine wave from a high voltage high frequency oscillator was used as the deflecting potential. One oscillogram from each set was developed in each type of developer. The films were developed in steps, i.e., the film was lowered a half inch into the developer solution for, say, three minutes, then lowered another half inch for two minutes, and so on. Thus, each developed film consisted of a number of zones which had been developed for different times, so that the background fogging and contrast could be compared. A typical oscillogram treated in this way is shown in Figure 24.

Quantitative measurements of the blackening of the film were made with a transmission densitometer. This consisted of a powerful light source and condensing lens system focused on the film, a photoelectric cell so inclosed that part of the light transmitted through the film could strike the cell, and a galvanometer connected to the cell. The opening in the cell housing was small enough that the effective area of film scanned was 0.02 x 0.04 inches. This was small enough so that the center part of the line could be scanned without introducing error from the streaks on the film caused by the presence of the Lenard window supporting grid.

The measurement of the density of the film is expressed in terms of "blackening" which is defined (cf Knoll,[52] or MacGregor-Morris and Henley)[3] as,

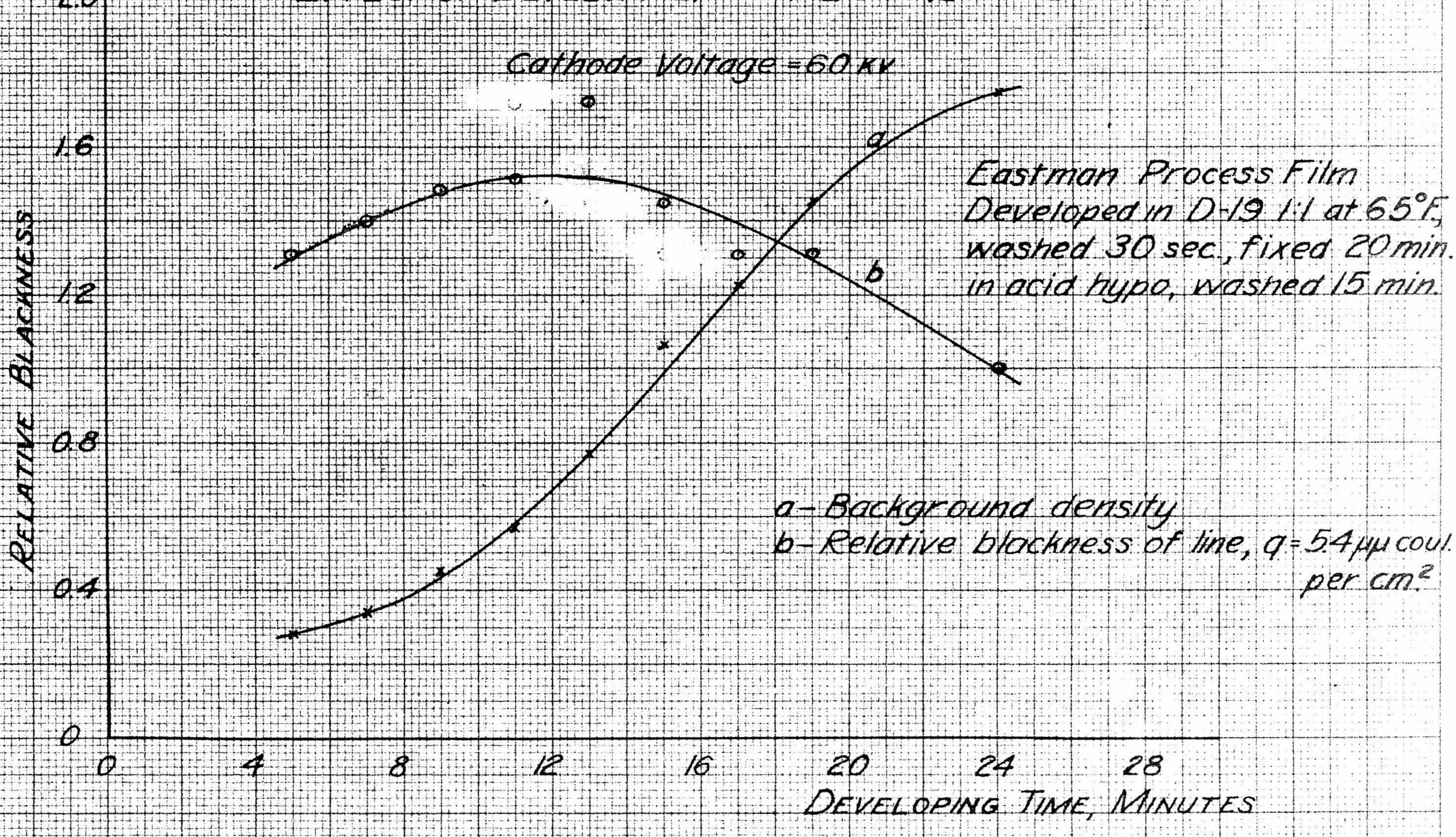
$$B = \log_{10} \frac{\text{light intensity through unexposed film}}{\text{light intensity through blackened film}} \qquad (3)$$

This ratio is equal to the ratio of the corresponding galvanometer readings since the output of the photoelectric cell is directly proportional to the intensity of the incident light over a much wider range than that used in this work.

Figure 25 shows the relation between development time and film blackening for D-19 developer. The background density or fogging, D_0, is plotted in curve a, increasing as the development time is extended. Curve b gives the relative blackening B of the oscillograph trace with respect to the background for one value of charge density. This curve definitely shows that the best contrast between line and background is obtained at a development time of approximately 12 minutes. Beyond this time the background

Fig. 25

Effect of Development Time on Negative Contrast



fog increases faster than the blackness of the line, and the contrast decreases.

The results obtained with D-72 and D-11 were similar to those of Figure 25. Using D-72, the optimum development time is about 13 minutes; for D-11 it is 16 minutes. Neither developer will give as good contrast as the speedier D-19, although the difference is not sufficient to be of importance on any but extremely fast oscillograms. D-19 was used in developing all of the oscillograms described in the following photometric investigations.

G. Blackening Due to Electron Beam.

On the basis of the previous work, it is now possible to investigate the blackening produced by an electron beam sweeping across a sensitized film as a function of the charge density in the beam and the accelerating voltage applied to it. To do this, it is necessary to produce a beam of electrons with known current density and accelerating voltage, sweep the spot across the film at a known velocity, and determine the resultant blackening. The current density in the beam and the spot velocity fix the charge density, so that all perameters are known.

The experimental procedure was as follows. The beam analysis apparatus was attached to the oscillograph, and an analysis made of the current density in a beam from a cathode that had been used for approximately 10 hours. Using the aged cathode insured reasonable constancy in the beam during the tests. Analyses were made at 50, 60, and 70 kv., with corresponding cathode currents of 2, 1, and 0.5 milliamperes. The beam analysis apparatus was then replaced by the Lenard window. As rapidly as possible a series of oscillograms of the sine wave from the high frequency oscillator were taken at the three cathode voltages given. Before and after each oscillogram the beam was deflected into an auxiliary collector cup which had been mounted close to the window, and the total beam current was checked. A range of frequencies from 1000 to 20 kilocycles was used at all available sweep speeds. The focusing was carefully adjusted before each oscillogram, as was the cathode current. It was found that the cathode voltage varied so exactly with the current that it was unnecessary to measure the voltage before each oscillogram. At the end of the series of oscillograms, the beam was again analyzed. The results checked so closely that the mean of the two sets of data was taken as the true beam density for each voltage.

The oscillograms were developed simultaneously in a large tray, constantly agitated so that all had the same effective development time of 9 minutes. They were then rinsed, fixed, and washed according to the data already given. When the films were dry, the transmission photometer was used to determine the blackening of the center of the oscillograph trace with respect to the background for the whole series of oscillograms. At each point scanned by the photometer the spot velocity was then determined, from which the charge density at that point could be found.

The average value of the charge density η for a spot of radius r_s and average current density $\bar{J}$, moving at a velocity v_s is given by,

$$\eta = \bar{j} \frac{d_s}{v_s} \tag{4}$$

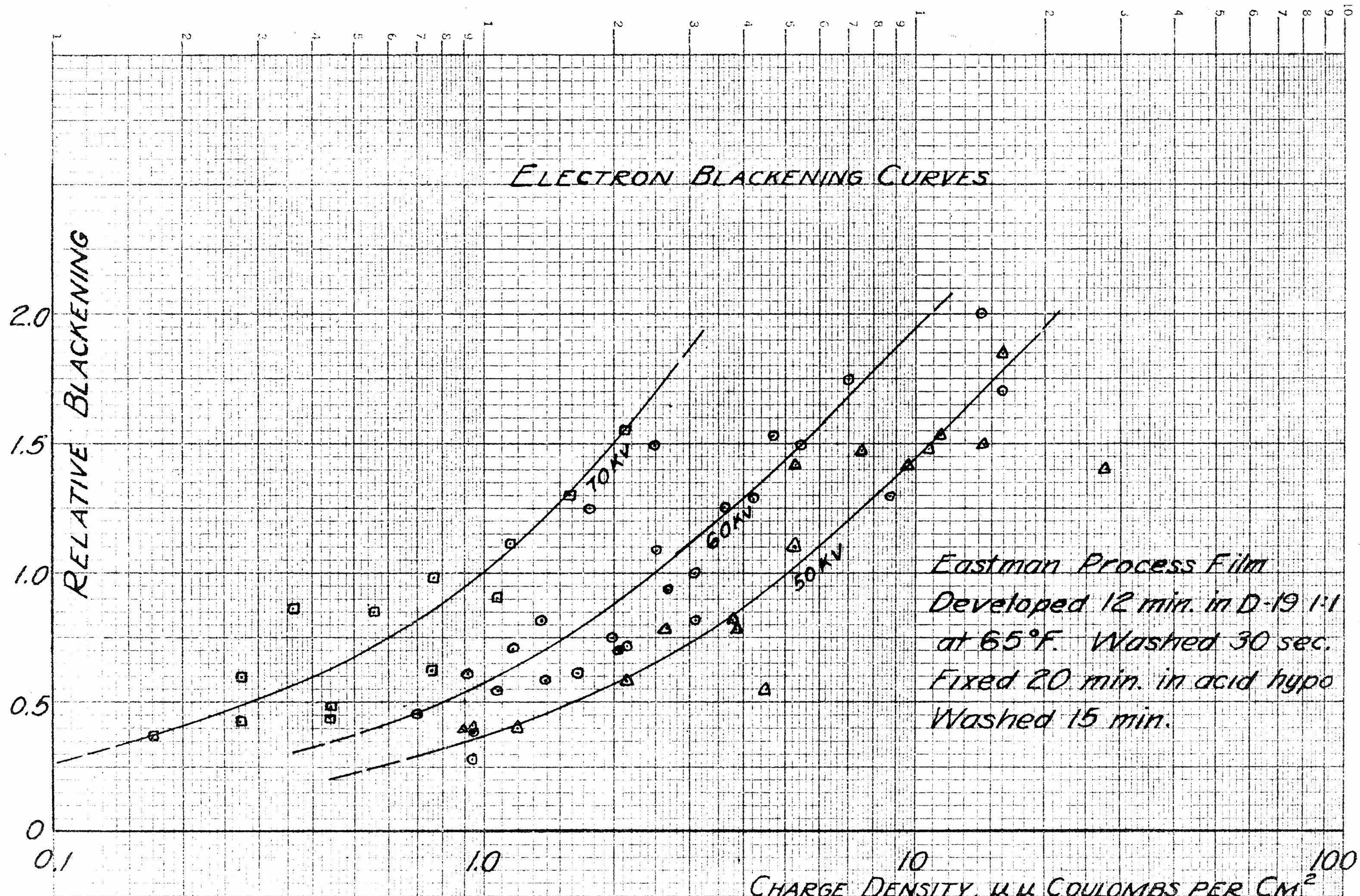
(derived in Appendix B).

In this case the diameter of the spot to be considered is equal to the width of the line scanned by the photometer, namely, 0.02 inch. The average current density in the beam out to 0.02 inch diameter is determined from the beam analysis curve. The velocity of the spot can be calculated from the known frequency of the oscillator for each oscillogram, and the measured displacement of the spot. The method of calculation is too well known to merit description.

Due to the fact that these oscillograms were taken through a Lenard window, the charge density obtained from the formula given above must be multiplied by the per cent penetration of the foil before applying the result to the blackening data. The effect of diffusion of the beam in the foil and in the film of air between foil and negative should also be taken into account. Von Borries[6] has shown that for thin foils, diffusion is negligible. As will be shown later, scattering due to the air film is slight for small separations of foil and negative. Both of these phenomena have been disregarded in the computations.

Figure 26 gives the results of the measurements. It can be shown from this figure that over the major portion of the range of charge density, the relative blackening of the film can be represented by a simple term of the form

$$B = K_v \sqrt{q} \tag{5}$$



ELECTRON BLACKENING CURVES
RELATIVE BLACKENING
2.0
1.5
1.0
0.5
0
0.1
1.0
10
100
CHARGE DENSITY, μμ COULOMBS PER CM²
70 KV
60 KV
50 KV
Eastman Process Film
Developed 12 min. in D-19 1:1
at 65°F. Washed 30 sec.
Fixed 20 min. in acid hypo
Washed 15 min.

FIG. 26

where K_v is a constant depending upon the exciting voltage, and q is the charge density in the writing line. This relationship holds within an error of 10 per cent over the range of densities given in the curves, and gives a rough prediction of the densities to be expected from an oscillogram, knowing the film and photographic process and the charge density. The values of K_v used in the equation are given in Table I.

Table I.

Cathode Voltage	50	60	70
K_v	0.39	0.61	1.01

The form of the curves are similar to those given previously by Becker and Kipphan,[12] von Borries,[6] and others. The magnitudes can be compared only in general, because in all cases a different film and different development techniques were used. The film used in these experiments (Eastman Process Film) is apparently more sensitive to electron blackening than the Agfa-Isocrom Film used by von Borries. He obtained,for example, a blackening of 0.2 at a charge density of 2 micromicrocoulombs and 70 kv. exciting potential. Using Process film and the same exciting potential, the same charge density gave a blackening of 1.5 --- an increase of nearly 7 times. This naturally gives rise to increase in the maximum velocity which can be recorded.

Another point of interest about these curves is the nearly constant increase in blackening obtained with an increase in cathode voltage. Thus, the blackening obtained with a 70 kv. beam is approximately 1.6 times that obtained with a 60 kv. beam at the same beam intensity. The blackening of the 60 kv. beam is 1.56 times that of the 50 kv. beam. This checks the results given by Knoll and von Borries. This again emphasizes the advantage in using high cathode voltages in this type of work.

It is obvious that the curves apply equally well to Lenard photography and internal electron-blackening photography. The writing speeds which can be achieved by the two recording methods can in consequence be compared. For example, a beam of 70 kv. electrons deflected at such a speed that the charge density in the line is 1 micromicrocoulomb per $cm.^2$ will give a line blackening of 1.0 using internal photography. If a 0.020 mm. cellophane Lenard window is used, the penetration will be 42 per cent, so that the charge density on the film will be 0.42 micromicrocoulombs per $cm.^2$ This will give a line blackening of 0.61. The velocity of the beam used with internal photography can be 1.64 times as fast as that used with Lenard photography to give the same blackness of recorded line in this case.

The maximum speed possible to attain with an oscillograph depends upon the requisite contrast between line and background. The minimum relative blackening has been given by Knoll (52) as 0.1. It is interesting to see the maximum velocity which could be obtained using this figure. Unfortunately, relative blackenings of such low magnitude were not encountered, so that the curves of Figure 26 must be extrapolated. By using the constant given in Table I for a 70 kv. beam, a charge density of 0.01 micromicro-coulombs would give a relative blackening of 0.1. Dividing by the per cent penetration through a 0.012 mm. cellophane, the beam charge density must be 0.016 micromicrocoulombs. The maximum current density obtained with a 70 kv. beam was about 600 μ amps./cm.^{2} This beam will give a 0.16 $\mu\mu$ coulomb charge density in the writing line at a velocity of 30,000 km./sec. This is of the order of magnitude obtained by Stekolnikov and Slaschew (91) with fluorescent-screen contact photography, and definitely indicates that the maximum velocity obtained in these tests (around 1800 km./sec.) is far under the possible maximum.

IV. Operation of Instrument.

A. Normal Operation.

This chapter is unusually detailed so that it can serve in part as a manual of operation for the oscillograph. The oscillograph is usually evacuated in about 40 minutes, starting with cold pumps. Most of this time is taken to heat the Apiezon oil in the main and cathode chamber pumps. When the closed tube manometer between main and forepumps registers less than 1 mm., the Pirani vacuum gauge is turned on. The cathode supply is energized when the main chamber vacuum reaches 10^{-4} mm. The needle valve in the cathode chamber is adjusted until the desired beam current is obtained. The beam is then focused by adjusting the focusing coil current, and the coil oriented so that the spot rests in the center of the fluorescent screen shutter. For unipolar surges the rest position can conveniently be moved to top or bottom of the screen to allow for greater deflection. Obviously the shutter must always be down before the beam is produced. A number of sweeps are then observed with the sweep circuit set for manual control. This gives a check on the blocking circuit and on the fineness of the line, and has proved very necessary. The instrument is then ready to use.

Most of the operations given above are controlled from the oscillograph switchboard. This is shown in Figures 2 and 3, and in closeup in Figure 27. In this figure, switches 1 to 6 control respectively the forepump, the heater on the Apiezon pumps, the Pirani gauge, the cathodes of the power pack rectifiers, the light illuminating the inside of the oscillograph table, and the focusing coil. The switch on the semi-manual sweep circuit control is shown at 7. The auxiliary pair of sphere gaps, and the condensers and resistors used in this circuit are inclosed in the metal shield immediately above. The high voltage switch on the power pack is shown at 8 with the switch terminals above it. To the left of the switch is the focusing rheostat 9. The two Pirani meters are shown at 10 and 12. Rheostat 13 controls the amount of current flowing to a Wheatstone bridge forming the gauge. Opposite arms of this bridge consist of 7-inch lengths of 0.003 inch diameter platinum wire placed in a container off the main chamber. The other two arms are external resistors, one of which is variable, so that the bridge can be balanced. The current across the middle of the bridge, measured by the 0-2 milliammeter 10, is zero at 10^{-4} mm. of mercury. The bridge current measured by the 0-100 milliammeter 12 is held at 90 milliamperes. 11 is a shunt switch halving the sensitivity of meter 10. The variable resistor used in balancing the bridge is located behind the switchboard between the two meters. The ground on the entire oscillograph system is brought out to a terminal 14 at the left end of the switchboard, directly above a 110-volt inlet plug.

Much of the remaining control apparatus is shown in Figure 28. The current in discharge tube 2 is read on meter 1 and controlled

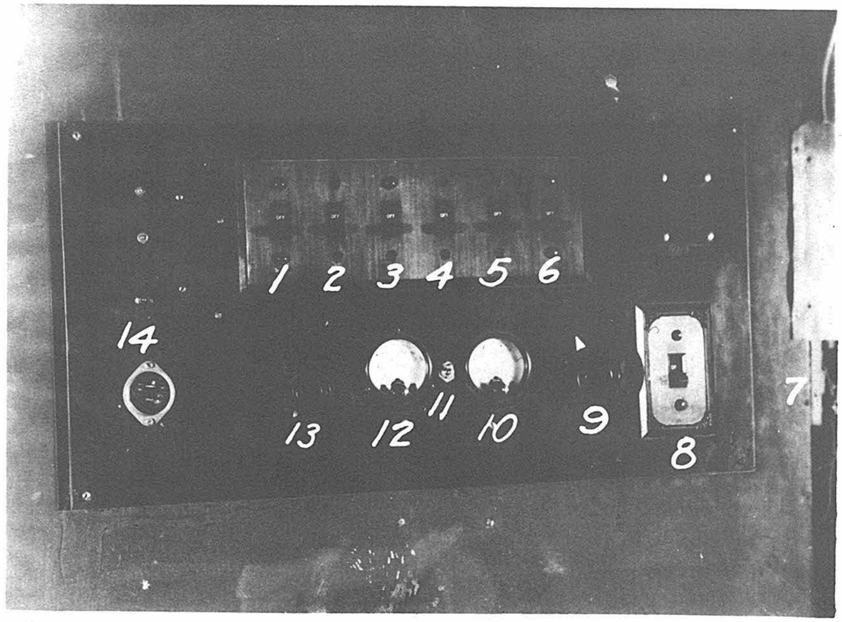


Fig. 27

Oscillograph Switchboard

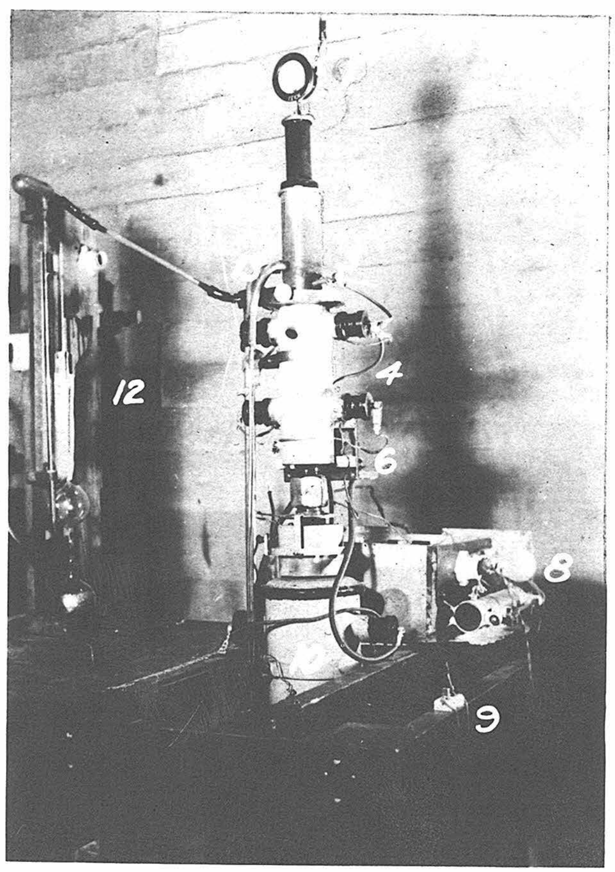


Fig. 28

Closeup of

Instrument

by needle valve 3. The blocking electrodes 4 and time sweep electrodes 10 are connected to the time sweep circuit 6. The 5000 volt power pack 8 is just below the sweep circuit. Switch 9 is in series with the primary of the high voltage cathode supply transformer. The McLeod gauge 12 is not a permanent part of the apparatus. Cooling water to the discharge chamber is circulated through the two tubes 13. The tripping lead to the sweep circuit can be seen at 11.

The details of the time sweep circuit can be more plainly seen in Figure 29. The triple gap, adjustable timing switch, etc. are evident. Normally this is all inclosed in the shield can shown at the left so that there is little coupling with stray fields. This is a necessary precaution.

The technique used in taking surge oscillograms is simple. The sweep circuit is connected for automatic tripping from the iniating sphere of the surge generator, as described in Part II of this paper. The operator then focuses the beam, energizes the blocking circuit, and opens the shutter. He then keeps strict attention of the cathode current, altering the needle valve if there is any variation. The surge generator operator is at absolute liberty to initiate the surge at any convenient time. After the surge has occurred, the oscillograph operator closes the shutter. Usually, a timing wave and a zero line are also put on the film.

B. Typical Oscillograms.

In taking the surge oscillograms shown in this paper, a

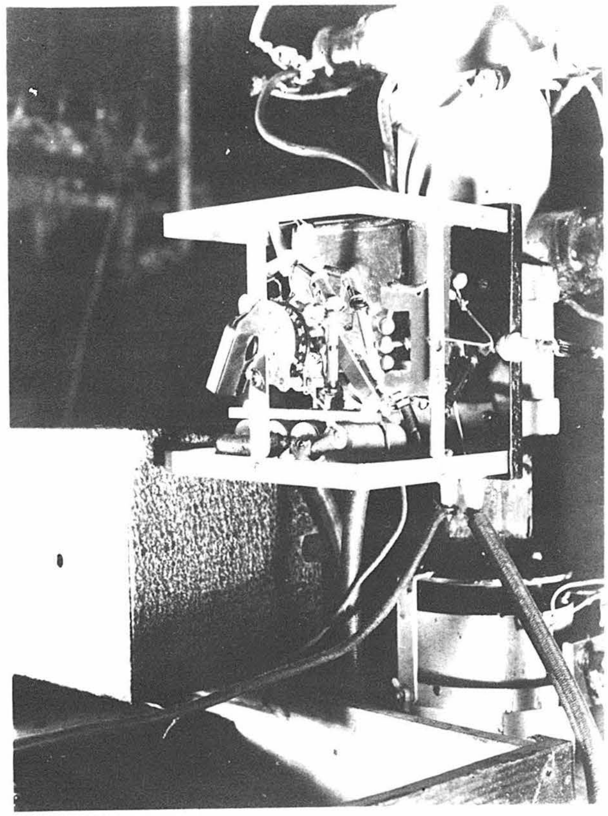


Fig. 29

Time-Sweep Apparatus

resistance voltage divider was used. This consisted of a number of identical sections of micarta card wound non-inductively with two copper wires, and connected in series. Each four cards were immersed in oil in micarta tubular cases, and were identical with those described by Benedict.[16] The total resistance is 10,000 ohms. The lower end of the potentiometer was connected to a 100 foot length of delay cable leading to the oscillograph. To prevent reflection, the cable was grounded at the oscillograph end through its surge impedance. The proper value of resistance to be used to suppress all oscillation was found by trial. The series of oscillograms, Figures 30, 31, 32, and 33, show the effect of various terminating resistors on the spurious oscillation on the head of the wave. The cable impedance is obviously about 120 ohms. These and the following oscillograms are not as clear as the originals, due to inherent difficulties in reproduction.

All four of the oscillograms were taken with a 40 microsecond sweep. Other sweeps are shown in Figures 34, 35, 36, and 37. The first shows the usual $1\frac{1}{2}$-40 microsecond wave, taken with a 100 microsecond sweep. Figure 35 shows a 3-26 microsecond wave taken with a 26 microsecond sweep. This surge was impressed on the ungrounded sphere of the 100 cm. sphere gap, and shows a very decided 1400 kilocycle oscillation on the wave front. This is a customary phenomena[24] when working with sphere gaps, and is usually suppressed by the insertion of damping resistors. In this case, since the aim was to determine the ability of the oscillograph to record such transient phenomena, no such suppression was attempted.

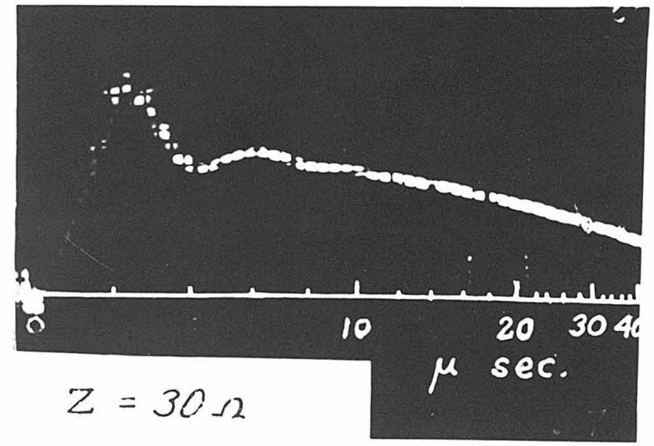


Fig. 30

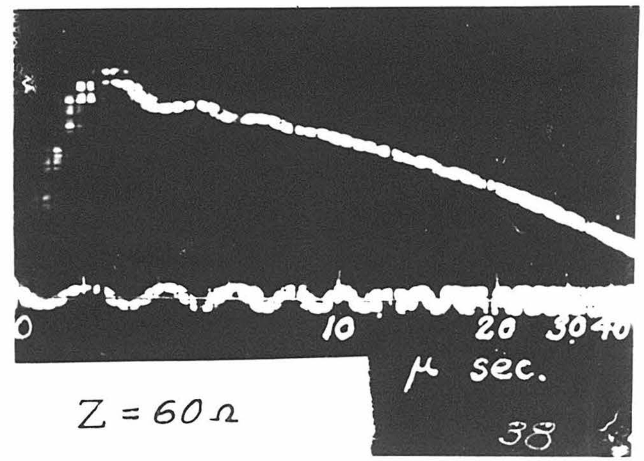


Fig. 31

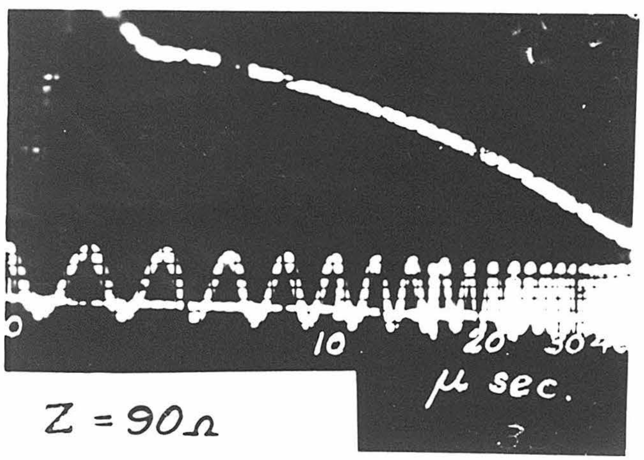


Fig. 32

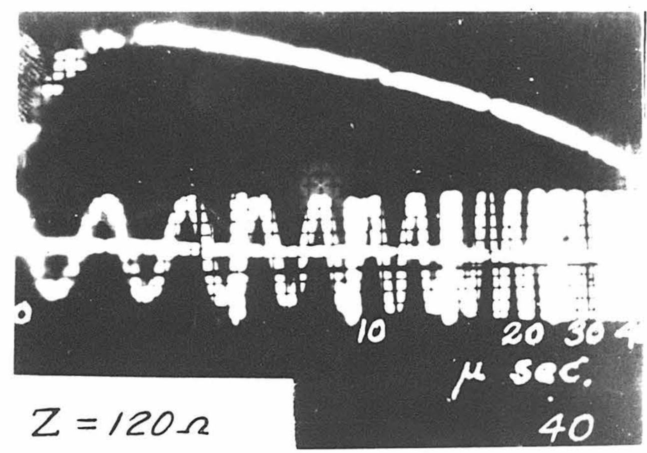


Fig. 33

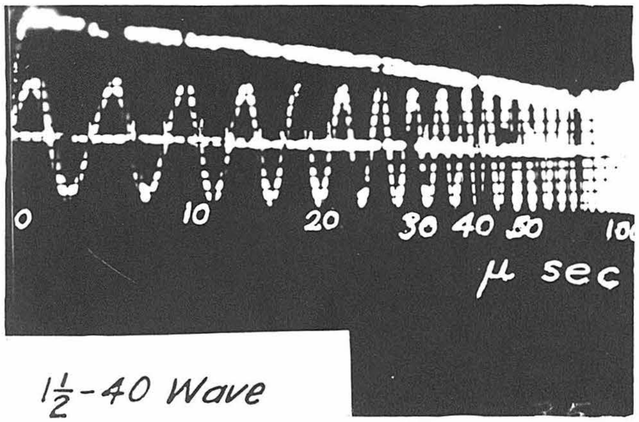


Fig. 34

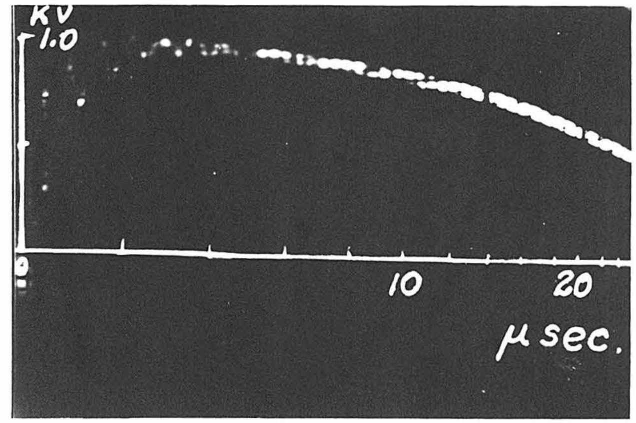


Fig. 35

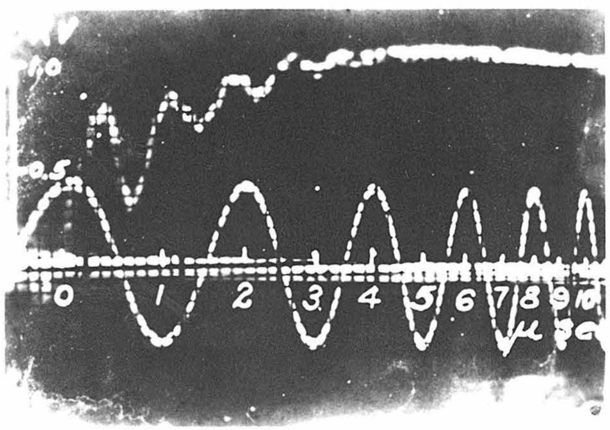


Fig. 36

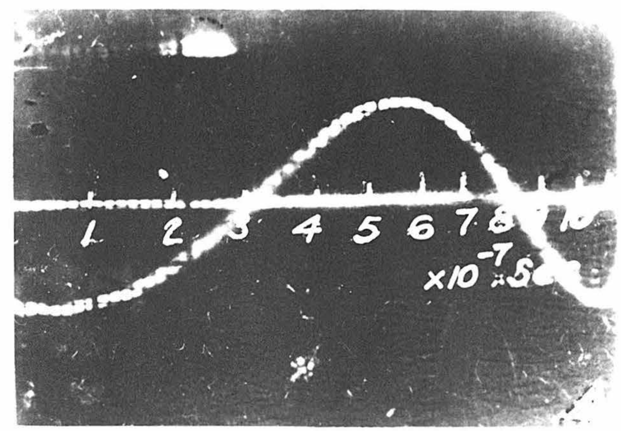


Fig. 37

Figure 36 was taken immediately after Figure 35 and with a faster sweep --- 12 microseconds --- to show the oscillations on the front of the wave more clearly. As can be seen from this oscillogram, oscillations on the wave front can now be easily analysed.

Figure 37 is an oscillogram of a one megacycle sine wave from the oscillator, taken with the fastest sweep normally used on the oscillograph --- 1 microsecond. This oscillogram proves that there is no oscillation in the sweep circuit, even with the lowest sweep resistance employed.

Usually the exponential time sweep shown in these records is decidedly advantageous, especially in studying surge phenomena. Occasionally it is of importance to use a more linear time sweep. There are numerous arrangements which will accomplish this purpose. Probably the most popular arrangement is to use only the first third or half of the discharge voltage of a condenser to drive the beam, so that only the linear portion of the discharge is utilized. In this particular case, such a setup would have required a voltage source double that available. A possible alternative consisted of connecting a suitable inductance in series with the discharge condenser and resistor. By using an inductance which would just render the circuit oscillatory, the condenser voltage is a highly damped sinusoidal wave, hence after the first few microseconds is linear for a considerable part of the discharge. Due to the oscillatory nature of the discharge, the beam will oscillate about the final deflected position at one side of the instrument. If the discharge voltage is sufficiently high, this oscillation will take place off the film, just as the initial nonlinear section will be off the film on the opposite side. This arrangement gives a much greater linear section than can be obtained with a simple condenser discharge circuit of the same voltage.

Such a circuit was constructed for the oscillograph. This was a circuit exactly similar to that shown in Figure 16 except that an inductance was connected between points A-B. The capacity of the surge condenser was 1 microfarad, and the inductance used depended upon the discharge resistance. The inductance was chosen to be just high enough to render the circuit oscillatory.

A single sweep of this circuit is shown in Figure 38. The sine wave has a frequency of 500 kc. It is evident from the oscillogram that both the first 6 and the last 10 microseconds of the first sweep are useless. However, there is a usable region between these limits of 24 microseconds in which the sweep is linear within a (measured) limit of 10 per cent error. By raising the supply voltage 25 per cent, the linear sweep would have been extended over the entire film. Incidentally, the sweep voltage used in this picture was 2500 volts. Thus, with the full pack voltage of 5000 volts, linear time sweeps can be easily made.

There are two disadvantages with this method. In the first place, there is inherent distortion during the first and last sections of the sweep, so that if the phenomena to be studied reaches the oscillograph deflection plates before the initial period is over, it will appear distorted, or, if the sweep voltage is high enough to eliminate the nonlinear portion of the sweep,

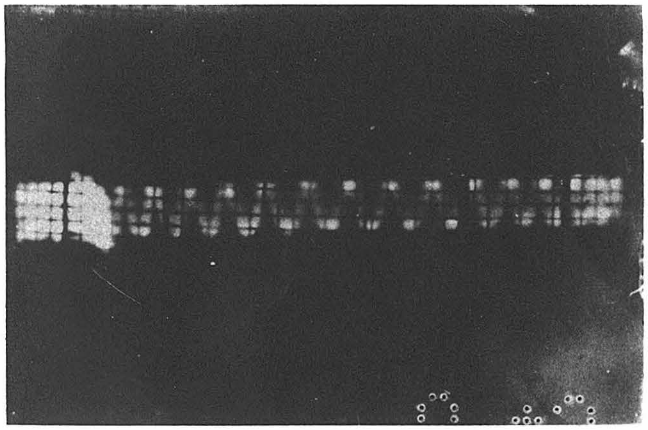


Fig. 38

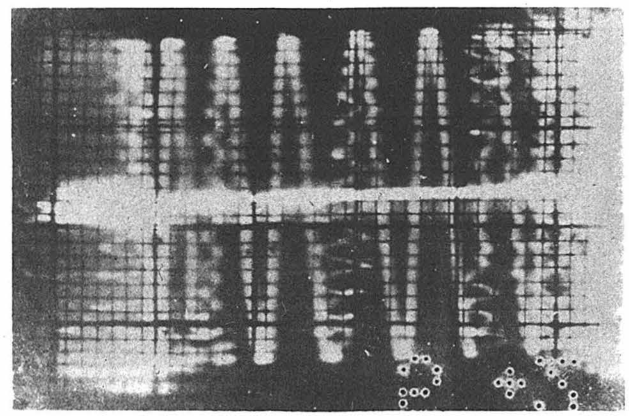


Fig. 39

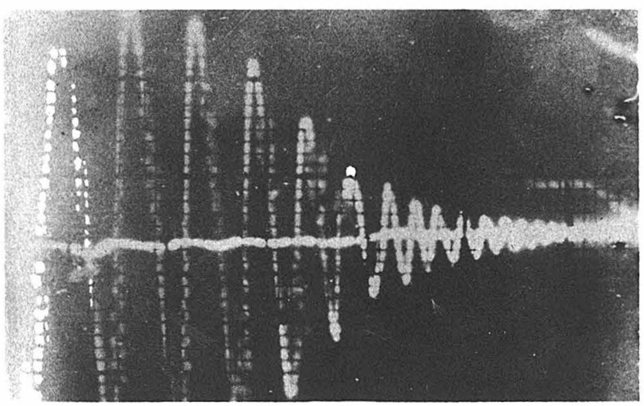


Fig. 40

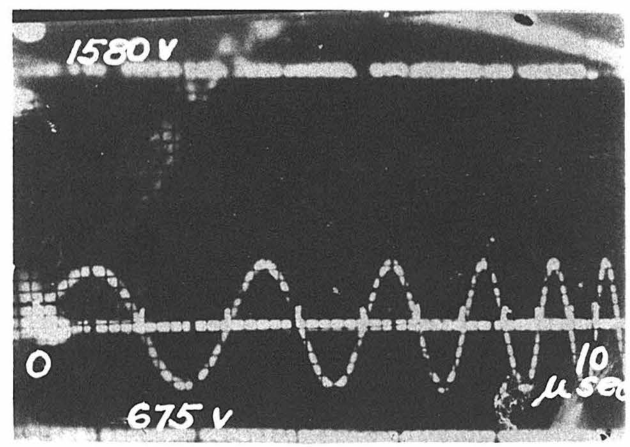


Fig. 41

will not be recorded at all. Usually this difficulty is not important in circumstances where such a sweep is necessary. The second disadvantage is that there is an upper limit to the sweeping speed. When the discharge resistance is decreased, to permit faster sweeps, there comes a point at which it is insufficient to damp out the oscillations generated in the inductance by the self-capacity of the coil. When this point is reached, these oscillations are generated and impressed on the sweep plates so that there is a secondary, high frequency oscillation in the sweep. This phenomena is well illustrated in Figure 39. The impressed sine wave is a 900 kc. wave, thus the sweep time is of the order of 10 microseconds. There is a horizontal oscillation, due to the high frequency generated in the inductance. This is a recurrant, damped, 23 megacycle wave.

Obviously more discharge resistance would cure this difficulty. If a smaller condenser is used, the discharge resistor will be increased proportionately for the same time sweep. At the same time the linearizing inductance is also decreased, so that the amount of resistance needed to damp local oscillations is decreased. Thus, use of a low capacitance time sweep circuit facilitates ease in securing rapid, linear time sweeps. For this reason, the final time sweep circuit used on the oscillograph (cf Figure 16) was designed with a low sweep capacitance. Unfortunately, there was no time to investigate the maximum sweep speed which could be obtained with a linear sweep.

A further point of interest about Figure 39 is that the spurious oscillations were recorded at the fastest writing velocity actually obtained on an oscillogram. Thus, the 23 megacycle oscillations shown in the center of the picture were recorded at an average velocity of 460 km. per second, and a maximum velocity of 900 km. per second. Those shown in the left of the picture were of much greater amplitude. The highest computed velocity is 1800 km. per second. This is of the order of magnitude obtained by previous investigators.(6)(37)(3)

There is another way in which oscillations can occur on the time sweep plates. This is due to coupling between the sweep plates and oscillatory circuits adjacent the plates. This occurred in Figure 40. The deflection plates were loosely coupled to a resonant circuit (output circuit of the high frequency oscillator) tuned to one megacycle. The major oscillation shown in this oscillogram was produced by shock exciting the resonant circuit by discharging the time sweep circuit. However, a much higher frequency oscillation (around 32 megacycles) was present on the time sweep plates. This may be due to coupling between the sweep plates and some oscillating circuit, possibly the coupling coil of the high frequency oscillator, which was oscillating at a frequency determined by its inductance and self-capacity. An oscillation of this frequency could not have been generated in the time sweep circuit itself, due to insufficient inductance.

Under certain conditions oscillations in the blocking circuit have been obtained. This was the cause of the four vertical lines spaced at odd intervals across the zero line in Figure 33. Probably the blocking voltage oscillated at a relatively low frequency, so that these vertical lines are due to the beam unblocking for very short periods on the return sweep in recording the timing wave. Placing 200-ohm resistors in series with the blocking plates effectively suppressed this oscillation.

For effective operation of the oscillograph, it must be very carefully calibrated as to voltage deflection. It has been shown (104) that if an origin-shifting magnetic field is used, or if there is coupling between the mutually perpendicular sets of deflecting plates, the deflection "constant" will vary with the position of the origin and voltage applied to the plates not under calibration. In this oscillograph the coupling between sets of plates is extremely small, due to the grounded shield between them. This is demonstrated in Figure 41. Two calibrating lines were recorded on the film by applying known voltages (measured with an electrostatic voltmeter) to the deflection plates. The lines are parallel to the zero line throughout, showing that the varying voltage applied to the sweep plates has not affected the field of the deflection plates. A number of similar records taken with the zero axis displaced varying amounts by the focusing coil have shown that there is a very slight correction to be applied if the axis is shifted more than half a centimeter. This correction amounts to less than 6 per cent on any record.

The same figure shows another type of distortion which was occasionally encountered. The first part of the surge recorded on this oscillogram appears very indistinct, and the beam appears poorly focused. However, the last part of the wave, and the other lines are well focused. The cause is distortion due to poor unblocking. The voltage on the blocking system did not drop sufficiently for the beam to pass through the blocking diaphragms without striking the side walls. This scatters the beam and produces secondary electrons. Moving the triple gap spheres connected across the blocking circuit closer together decreased the initial arc drop and cured the difficulty.

Figures 42, 43, and 44 are illustrations of surge flashover on the laboratory 100-centimeter spheres. The first shows flashover on the head of the wave, followed by the customary oscillatory discharge, in this case at 180 kc. frequency. The recorded voltage did not drop off to zero at the instant of flashover. This discrepancy is probably due to the fact that the voltage divider was not connected directly across the spheres, but was connected to them through a 20-foot length of No. 28 wire, so that line drop and reflection distorted the correct picture. The second shows two flashovers on the tail of the wave, and shows identity of reproduction which gives confidence in the ability of the instrument to record correctly the phenomena impressed on the terminals. It should be added that the zero was shifted between the two records. Figure 44 shows the head of the same type of flashover taken with a faster sweep, giving a much better picture of the rapid voltage fluctuations.

Figure 45 shows the effect of the separation of the film from the Lenard window. This oscillogram was made with the left

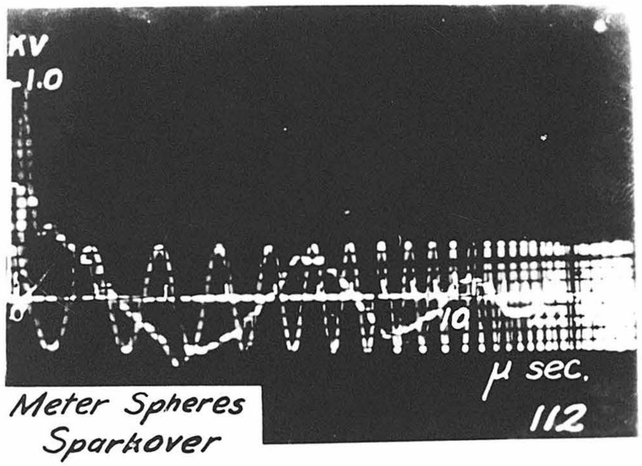


Fig. 42

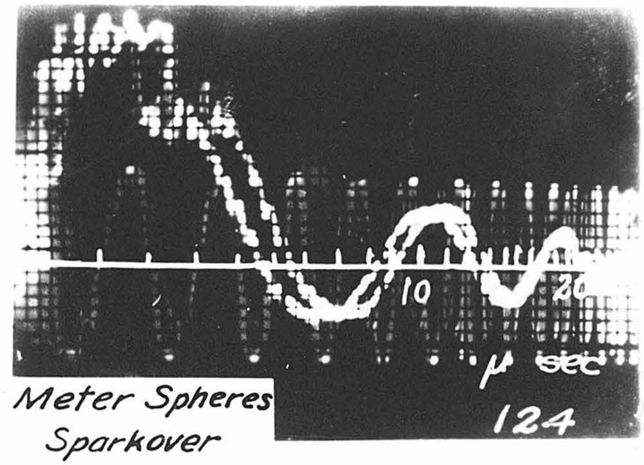


Fig. 43

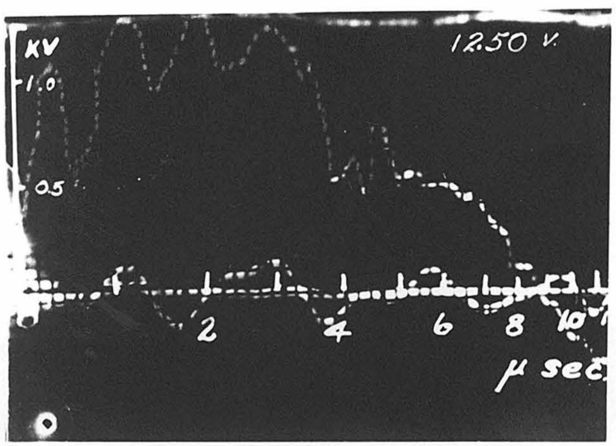


Fig. 44

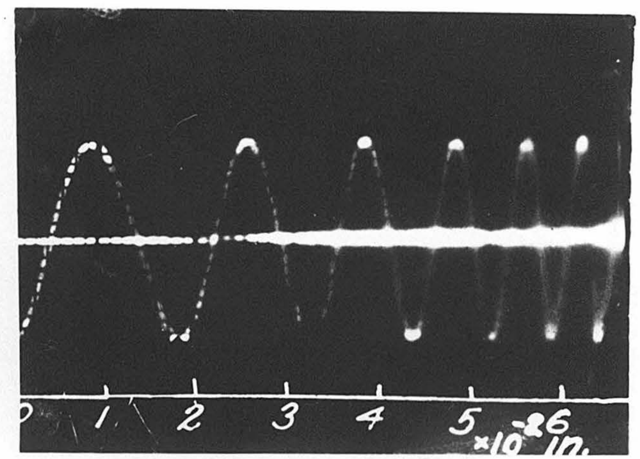


Fig. 45

edge of the negative pressed against the foil and with the right separated about 0.067 inches from it. It is quite evident that at separations greater than approximately 0.025 inches the line sharpness is poor.

The delay time of the cable and Marx generator gaps was determined by removing the terminating impedance on the cable, tripping the generator as before, and tripping the oscillograph simultaneously. Figure 46 shows the resulting oscillogram. Unfortunately, the megacycle timing wave was applied with the cable still attached to the surge generator, and the coupling between cable and oscillator was sufficient to distort the wave badly. Two surges were recorded, with the zero shifted to the right approximately half an inch between recordings. The delay time is almost exactly one microsecond.

The effect of thickness of Lenard windows on the beam penetration is shown graphically in Figure 47. Here a 500 kilocycle wave has been taken through four thicknesses of cellophane. These are, from left to right: 0.032, 0.044, 0.024, and 0.012 mm. It is evident that no beam penetrated the thickest foil, and that the 0.012 mm. window is quite superior to the 0.024 mm. window.

Figure 48 is the one oscillogram taken on News Bromide. This is merely a voltage calibration, showing equal and opposite voltages applied to the deflection plates. Quite readable lines are produced.

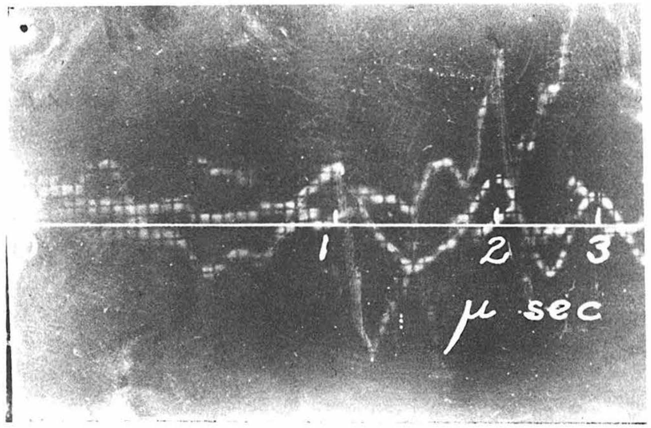


Fig. 46

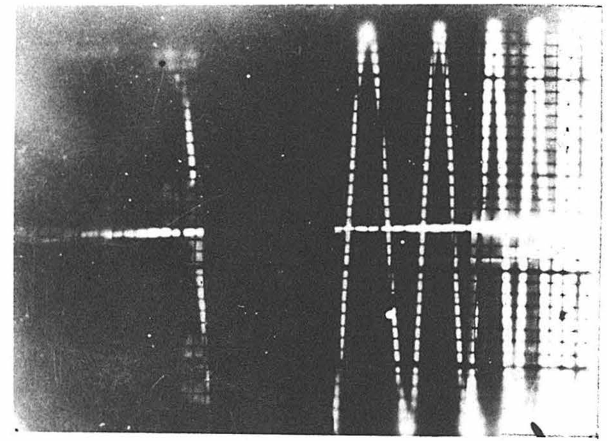


Fig. 47

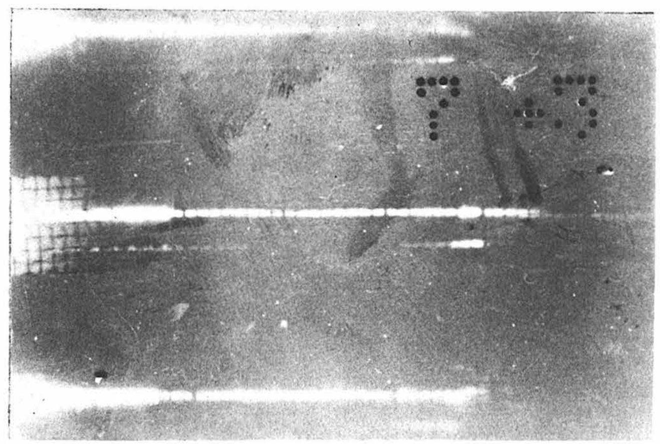


Fig. 48

V. Conclusions.

General.

1. The type of oscillograph described in this paper is well suited for continuous routine surge testing or other similar transient analysis.

2. The maximum writing velocity using Lenard photography exceeds 1800 km./sec., and is calculated to be of the order of 30,000 km./sec.

Discharge Tube.

3. Admitting air into the discharge tube near the anode opening improves the focus and centers the discharge.

4. There is a definite focusing action due to the cathode-anode spacing. As the tube diameter is decreased, the optimum spacing increases.

5. There is also a focusing effect due to the cathode potential. Increasing the voltage increases the current density in the spot.

6. The shape of the cathode tip is not of importance as long as the crater area is normal to the tube axis.

7. The air pressure in the discharge chamber decreases slowly with increased cathode-anode spacings (at constant discharge current). Over the range from 3 to 6 inches spacing the pressure

is of the order of 2 to 4 x 10^{-2} mm. of mercury.

8. Decreasing the diameter of the discharge tube from 1.25 inches to 0.75 inches increased the efficiency of the tube to three times its initial value.

Beam Analysis.

9. The current density in the main body of the beam decreases rapidly from a maximum at the center when a fresh cathode surface is used. In the beam from a pitted cathode the density is nearly constant out to the effective diameter of the spot.

10. The effective diameter of the spot is considerably less than that given by Busch's equation (25) when a new cathode is used. The expression is correct for the diameter of the beam from a pitted cathode.

Lenard Photography.

11. Results of measurements on penetration of cellophane by cathode rays check closely against those of previous investigators. (6) The penetration is inversely proportional to the thickness of the foil, and varies with cathode voltage V according to the expression $P = A(1 - e^{-bV})$ where A and b are constants depending on the foil thickness.

12. Over the range of densities encountered, the blackening of a film by cathode rays as a function of charge density q follows the empirical formula $B = K\sqrt{q}$, for a given cathode voltage. The blackening varies exponentially with the cathode voltage.

13. The minimum cathode voltage for successful operation with Lenard photography is approximately 50 kv.

Appendix A.

Current Density in Beam from Analysis Measurements.

The current division in the beam is assumed to be uniform in azimuth. Successively smaller diaphragms are interposed before the collector, intercepting all the current in the beam except that passing through the diaphragms. By changing diaphragm diameters by an amount Δd centimeters, a change in collector current Δi is observed. The average current density in this zone is

$$\bar{J} = \frac{\Delta i}{\pi D \frac{\Delta d}{2}} \quad \text{amperes per cm.}^2$$

By plotting the collector currents as a function of the diaphragm diameter, and drawing a smooth curve through the points, it is possible to pass to the limit in the above expression, giving the current density j as a function of the diameter as:

$$j(D) = \frac{2}{\pi D} \frac{\partial i}{\partial d} \quad \text{amperes per cm.}^2$$

In this case it was convenient to express the diaphragm diameter in inches, giving:

$$j(D) = \frac{2}{\pi D \, 2.54^2} \frac{\partial i}{\partial D}$$

$$= \frac{1}{10.13 \, D} \frac{\partial i}{\partial D} \quad \text{amperes per cm.}^2$$

Appendix B.

Charge Density in Writing Line.

Consider a center zone of the writing spot, with an effective diameter d_s, traveling at a velocity v_s over the film. The average current density in the beam over the area defined by d_s is $\bar{j}$, determined from beam analysis measurements. The charge density η in the writing line is given by

$$\eta = \frac{q}{A}$$

$$q = i\,\Delta t$$

$$i = \frac{\pi d_s^2}{4}\,\bar{j}$$

$$\Delta t = \frac{d_s}{v_s}$$

$$A = \frac{\pi d_s^2}{4}$$

Thus,

$$\eta = \frac{\frac{\pi d_s^2}{4}\,\bar{j}\,\frac{d_s}{v_s}}{\frac{\pi d_s^2}{4}}$$

$$= \bar{j}\,\frac{d_s}{v_s} \qquad \text{coulombs per cm.}^2$$

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