# A STUDY OF VACUUM SWITCH ARC PHENOMENA
# WITH THE
# CATHODE RAY OSCILLOGRAPH

THESIS

by

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## SUMMARY

This thesis describes the results of an investigation of the arc and glow discharges occuring between the contacts of a vacuum switch when an alternating current is interrupted. The investigation was made by taking cathode ray oscillograms of current vs. time, voltage vs. time, and voltage vs. current. Circuit voltages of 2200, 15,000, and 30,000 volts and currents of from 0.4 to 14.0 amperes r.m.s. at both lagging and leading power factors were employed. At different times, both aluminum and copper switch contacts were used.

The function of the arc in acting as an electrical "shock absorber," preventing inductive voltage surges from being set up by the switching operation, is discussed, and tabulated results are given, showing that a rather loose connection exists between the current at which the arc extinguishes and the maximum value of the induced voltage surge, but that the average arc extinction current and also the average induced voltage surge are both quite definitely lower for aluminum contacts than for copper ones. Previous switching experience indicates that the voltage surges are much higher when tungsten contacts are used. From these facts the theory is advanced that the arc extinction current and the voltage surge depend upon the vaporization temperature of the contact metal and the use of magnesium or zinc is suggested.

The voltage-current oscillograms indicate a storage of energy in the discharge itself and a subsequent release occuring in some cases several times while the discharge lasts. No explanation has as yet been found for this surprising result, but it seems to be authentic, since every effort to eliminate it was unsuccessful. If this result may be regarded as a true one, radical changes must be made in the accepted arc theory.

# INTRODUCTION

The investigation, described in this thesis, of the arc and glow phenomena which take place when two metallic electrodes, carrying an alternating current at moderately high voltage, are separated in a vacuum was undertaken as a part of the Vacuum Switch research program which is being conducted in the Million Volt Laboratory at the California Institute of Technology.

Preliminary tests[1] followed by more exhaustive ones at higher currents and voltageshave proved the soundness of the fundamental idea of breaking an electric current in a vacuum. Currents as high as fifteen thousand amperes at fourteen thousand volts and two thousand amperes at ninety thousand volts have been successfully broken by a vacuum switch having relatively small physical dimensions. In all the tests made it has been the kva capacity of the power source rather than failure of the vacuum switch which has set the upper limit of voltage and current reached.

When the vacuum switch has been evacuated to below the maximum operating pressure (about $10^{-3}$ mm. of Hg.) and the contacts have been properly outgassed, the alternating current is invariably broken in the first half cycle with a small momentary arc.

It should be borne in mind that in studying this arc it is not desired to eliminate it, for the arc acts as an electrical shock absorber, preventing voltage shocks from being transmitted to the system by the switching operation. Assuming that the switch is opened at some point of the current wave other than the zero point, the presence of the arc allows the current to continue to flow, gradually decreasing to a value near zero on the sine wave. If there were no arc and the current dropped to zero immediately upon opening the contacts, the enormous rate of change of current with time, acting through the inductance of the circuit, would cause very high voltages to be induced. High voltage surges of this kind have a very detrimental effect on the system, causing flashover and puncture of insulation. If the arc could be made to continue until the current reached zero instead of extinguishing shortly before, ideal switch operation with no line voltage surges would result. As a matter of fact, however, the arc form of discharge does not continue to zero current but changes to a glow form when the current falls below a certain minimum value, as will be explained in more detail later. It was with the idea of studying this transition and the hope of finding means of eliminating in the vacuum switch the voltage surges which accompany it in all kinds of switches that this research was begun.

Owing to the late arrival of the cathode ray oscillograph used in this work and the time delay involved in making it operate satisfactorily and in making certain changes necessary to adapt it to the work, the investigation may by no means be regarded as finished. If the results so far obtained may be relied upon, phenomena have been uncovered which cannot be explained by the accepted arc theory and which certainly deserve further attention.

## THEORY

Fundamentally, the electrical discharge characteristics for electrodes in all different kinds of gases and vapors and at all pressures ranging from a fraction of a millimeter of mercury to atmospheric or higher seem to be quite similar. With suitable changes in scale and relative proportions the curve given by Compton[2] and shown in fig. 1 might be adjusted to fit any of these conditions. In the vacuum switch the medium in which the discharge occurs is principally vaporized metal from the electrodes. Examining this curve we see that three types of discharge are recognized: corona, glow, and arc.

Corona discharge occurs when the gas or vapor medium is ionized for only a part of the distance between electrodes. With this type of discharge relatively high applied voltages cause only relatively small currents (field currents) to flow. If the voltage is raised, however, ionization progresses in a cumulative manner and the current rises at an ever increasing rate until a point of instability, A, is reached at which the current continues to increase even though no further increase in voltage is made. At this point the discharge changes from corona to glow.

In the glow form of discharge the gas or vapor is ionized for the whole of the distance between the electrodes and the current is carried by the positive ions and electrons coming from the gas or vapor with the exception of a few electrons which are emitted from the cathode by a photoelectric effect or by a secondary emission effect resulting from positive ion bombardment of the cathode. As may be seen from the portion AB of the curve, the glow discharge has a negative resistance characteristic, that is, the voltage decreases as the current is increased. To maintain this form of discharge the current must be limited by external resistance or reactance in the circuit.

The arc form of discharge is distinguished from the glow by the presence of a bright spot on the cathode, commonly called the "cathode spot." This spot seems to be a very abundant source of electrons. These electrons produce positive ions by collision with the gas molecules,which, having a slower velocity than the electrons, build up a positive space charge, which in turn allows the saturation current to flow from the cathode spot and across the space between electrodes with very little potential drop. This is illustrated in the curve in fig. 1 by the closeness with which the arc characteristic CD approaches the ordinate axis. This potential drop is scarcely greater than the minimum ionizing potential of the gas or vapor involved and usually ranges in the neighborhood of from ten to thirty volts. J. H. Hamilton(3) has found the potential drop to vary from ten to twenty five volts in the case of vacuum switch arcs for copper, aluminum, and tungsten electrodes.

Concerning the mechanism of the electron emission from the cathode, two theories have been proposed: thermionic emission, and the pulling of electrons from the cathode by a high field at its surface. J. J. Thompson(4) and Stark(5) first suggested the former theory and Langmuir(6) the latter one. K. T. Compton(2) believes that either kind of emission may take place and in many cases a combination of the two occurs.

The transition from glow to arc discharge or vice-versa seems to be more or less erratic. As indicated by the portion TB of the curve, the glow form of discharge may sometimes persist into higher currents even though the same current could be carried at a much lower voltage by the arc form of discharge. Conversely, as indicated by the portion TC, the arc may continue to hang on even though the current is reduced below the value at the transition point T at which the discharge should normally change to the glow form. The whole transition region is one of great instability and one in which oscillations commonly occur.

# APPARATUS

## A. THE CATHODE RAY OSCILLOGRAPH.

The cathode ray oscillograph is a very suitable instrument for investigating electric arc and glow discharge phenomena because of its ability to follow the extremely rapid variations of voltage and current that occur. Frequencies of the order of one hundred million cycles per second have been recorded with this device. The upper limit of frequency which it is possible to record is set by the sensitivity of the photographic film rather than by any inertia effect of the cathode ray.

The oscillograph used in this research was a General Electric Company development detailed description of which may be found elsewhere[7]. In general, it may be said that it is of the Dufour cold cathode type arranged to have the photographic film inside the vacuum chamber so that the cathode ray impinges directly upon it. This increases its sensitivity over the Braun type of oscillograph many fold. Fig. 2 shows the essential parts of the instrument. For descriptive purposes they may be divided into three parts: the cathode tube, the deflecting tube, and the film bell. The cathode tube shown at the left hand end in the figure is made of glass and contains the flat aluminum disk cathode. The deflecting tube, also made of glass, contains the electrostatic deflecting plates and is supported inside a metal cylinder which has holes cut in it to allow electromagnetic deflecting coils to be placed about the tube. Between the cathode tube and the deflecting tube are mounted two pinholes which limit the cathode ray discharge to a narrow beam. Both these tubes are contained in a box lined with sheet copper for the purpose of electrostatic shielding. Connections to the deflecting plates and coils are made through bushings in the back of the box. The film bell is made entirely of metal and has an end plate which may be removed for the purpose of changing the film which is contained in a metal film box quite similar to that of an ordinary camera. The film used is standard 4" x 5" camera roll film on which six exposures may be made before it is necessary to let air into the vacuum chanber and reload. Pumps are provided with the oscillograph which are capable of evacuating the chamber to the working pressure in about fifteen minutes. The cathode ray trace may be observed visually through a port hole in the side of the film bell on a flourescent screen which is swung in front of the film.

The circuit provided for exciting the cathode is shown in fig. 3a. The cathode is connected through a steadying resistance of 60,000 ohms to a small X-ray type transformer the secondary voltage of which may be varied from 30 kv. max. to 65 kv. max. by adjusting a rheostat in the primary circuit. Also included in the primary circuit is a synchronous switch which completes the circuit during only one-half cycle in every twenty cycles. It is intended that the operating switch be closed while the synchronous switch makes one contact and then be opened again before the next contact is made. Thus the cathode is excited by a negative half sine wave of potential.

The sweep coil is intended to provide a time axis for the oscillograms by causing the cathode beam to sweep horizontally across the film under the influence of the varying magnetic field which it sets up. The sweep coil is connected through a reactance to the same alternating current source that supplies the cathode transformer. Since the sweep coil circuit is almost purely reactive, the current in it and hence the magnetic field of the sweep coil lags the voltage by nearly ninety degrees and hence is passing through zero when the cathode voltage is near its maximum. For a short period near this time the cathode voltage is practically constant and the magnetic field of the sweep coil is varying through zero at a practically uniform rate, so that a working combination of constant cathode voltage and linear time axis is obtained.

This system, however, has two distinct disadvantages which render it entirely unsuitable for recording the vacuum switch arc characteristics. First, the maximum length of time during which a transient may be recorded is but a small fraction of a half cycle, whereas it was desired to record phenomena occurring over one or two complete cycles. Second, only transients may be recorded which occur during the part of the cycle that the voltage is near its crest. This second disadvantage might have been overcome by using some kind of a voltage phase shifting device capable of supplying sufficient current to operate the oscillograph; but no such device was available. Another method would consist in operating the oscillograph from a different phase of a three-phase source. This method, however, does not cover the complete cycle and attempts to use it were without encouraging results.

To overcome the above described troubles it was decided to excite the cathode from a steady, high voltage, direct current source. This kind of excitation was obtained by making the circuit changes illustrated in fig. 3b. The synchronous switch was eliminated and the high voltage from the transformer rectified by means of a kenetron, using a 0.02 mfd. condenser for smoothing. The sweep coil circuit was also changed as shown in the same figure. A pair of contacts were mounted on the vacuum switch operating lever and arranged to close the circuit connecting a 24 v. storage battery in series with the sweep coil and the reactance when the vacuum switch was opened. The initial part of the transient exponential building-up current of the reactance provided a practically uniform time rate of change of current for the sweep coil. In order to move the starting position of the cathode spot from the center to the left hand edge of the film a small steady direct current (bias current) was sent through the sweep coil from the bias current circuit shown in the figure.

The above described system gave excellent results and was used in taking practically all the oscillograms. Its only drawback lies in the fact that the life of the cathode was very materially shortened owing to the greatly increased time of voltage application. This trouble was completely compensated for by designing and constructing a new cathode tube in which the cathode may be readily renewed. For a description of this tube see the appendix.

Three kinds of oscillograms were taken: voltage-time, current-time, and voltage-current. For the voltage-current oscillograms some means of preventing the film from being blackened by the repeated retracing of the voltage and current axes by the sine current wave before the switch was opened and the sine voltage wave afterward was desired. This was accomplished by the "electron shutter" whose circuit is shown in fig. 3c. This "shutter" consisted of a coil wound on a cardboard tube which was attached to the cathode tube opposite the first pinhole as may be seen in fig. 2. The coil was connected to a 6 v. storage battery through a double set of contacts mounted on the operating lever of the vacuum switch. These contacts were so arranged that the shutter circuit was closed when the vacuum switch was in either the open or closed position, but was open during the time the switch was in the process of opening. The magnetic field set up by a current flowing in the shutter coil would deflect the cathode ray as it passed through the first pinhole so that it completely missed the second and so would not reach the film. Thus it is easily seen that the cathode ray would strike the film only during the time the vacuum switch was opening and so trace out the arc characteristic without needless retracing of the voltage and current axes.

B. THE VACUUM SWITCH.

The vacuum switch used was quite similar in construction to one used by F. C. Lindvall in previous work and described in his thesis[8]. Briefly, as shown in fig. 4, it consisted of a glass bulb into which two copper rods carrying the current were brought through the medium of copper to glass seals. One of the rods was rigidly mounted while the other was connected by a flexible copper bellows in such a way that it could be moved longitudinally from outside the vacuum chamber, causing the contacts mounted on the inside ends of the rods to be pressed together or separated. Motion was transmitted to the movable rod by a transverse operating lever. Manual operation was accomplished by means of an insulating rod which could be attached to this lever. For automatic operation the vacuum switch was arranged to be pulled open by a steel coil spring attached to the operating lever. The switch was held in the closed position against the tension of the spring by a toggle catch which could be tripped by an electric solenoid. The solenoid was energized from a direct current source through a synchronous switch which could be adjusted to open the vacuum switch at any desired point on the current wave.

Both copper and aluminum contacts were used in the switch, the area of contact in each case being 0.03 sq. in.

The switch chamber was evacuated through a liquid air trap by a two stage mercury diffusion pump backed by a rotary oil fore pump. The degree of vacuum was determined by an ionization gauge constructed from a type 201 A tungsten filament radio vacuum tube and sealed into the pump tube as shown in fig. 4. Assuming the calibration for this type of gauge obtained by Lindvall[8] to be correct, the pressure in the switch during the investigation ranged from 5 to 10 x $10^{-5}$ millimeters of mercury. No attempt was made to determine the variations in the characteristics with residual gas pressure.

C. THE VACUUM SWITCH POWER CIRCUITS.

Oscillograms were taken at three different voltages: 15,000, 30,000, and 2200. The 15,000 volt circuit consisted of a 15,000/110-220 10 kva. distribution transformer, the high voltage side of which was short-circuited by the vacuum switch. The current was limited on the low voltage side by an iron grid resistor or a water barrel rheostat. This circuit is shown diagramatically by fig. 5a. As may be seen, the oscillograph current deflections were obtained by passing all the current through the oscillograph current coil, while voltage deflections were obtained by connecting one pair of the electrostatic deflection plates across a portion near the grounded end of a 300,000 ohm multiplier resistance connected across the vacuum switch terminals. This multiplier resistance consisted of fifteen 20,000 ohm carborundum rods mounted on a wooden board and connected in a zig-zag manner to reduce the inductance. A condenser multiplier was tried before adopting the resistance but the combination of the condenser with the vacuum switch arc and the inductance of the leads formed an oscillating circuit the oscillations of which completely masked the arc characteristic. For some work the current coil was placed between the vacuum switch and ground as shown in fig. 5b. This was done to prevent the charging current of the transformer capacitance to ground and the current taken by the multiplier resistance from flowing in the current coil.

The 30,000 volt circuit was similar to the 15,000 volt circuit except that two identical transformers were used with their high voltage coils connected in series. This circuit is shown in fig. 5c.

No attempt was made to vary the power factor of either the 15,000 v. or the 30,000 v. circuits. The power factor as measured on the input side of the transformer was approximately 0.70 lag for the 15,000 volt circuit and 0.60 lag for the 30,000 volt circuit.

The 2200 volt circuit consisted of a 550 kva. induction regulator, 15,000/0-3000 volts, connected through the vacuum switch to a 50 kva. 2200/110-220 volt transformer which was loaded on the low voltage side as shown in fig. 5d. Inductive loads of power factors ranging from 0.06 to unity could be obtained by applying a load consisting of various combinations of reactance and resistance. Leading power factor loads were obtained by stepping the voltage up to 7500 volts by means of a 10 kva 15,000/110-220 volt transformer working at half voltage and connecting static condensers. A change in the position of the ground from that used in the 15,000 and 30,000 volt circuits was necessary owing to the fact that it was not possible to remove the ground connection from the regulator.

The magnitude of the currents interrupted varied from 0.4 to 14 amperes r.m.s. Larger currents were not used owing to the limitations of the laboratory equipment. It was realized that these currents were far below the maximum which the switch was capable of breaking but this was not deemed to be of great importance in this more or less preliminary work since it was the phenomena occurring when the arc extinguishes that we were interested in and this takes place just before the current wave passes through zero. The work may have some additional practical interest owing to the fact that these currents are of the order of magnitude of exciting currents of transformers or charging currents to bus structures and short unloaded transmission lines. Queerly enough, the interruption of these kinds of currents has been found, in the case of oil circuit breakers, to cause the arc to persist for a longer time and to cause worse voltage surges than do currents of full load magnitude. Because of this fact they have been called "sticky currents" by circuit breaker design and test men.

## RESULTS

The following data sheets were prepared mainly for the purpose of determining what conclusions could be drawn as to the connection between the value of current at which the arc extinguishes and the maximum value of the induced voltage surge, together with the variation of these quantities with contact material, circuit voltage, and power factor. On account of the meager quantity of the data and its great variability no very accurate conclusions may be drawn, but at least some interesting trends are indicated.

The prefix CU to an oscillogram number indicates that it was taken with copper contacts in the switch, while AL indicates that aluminum contacts were used. The 100 series is for oscillograms of voltage as ordinate against time as abscissa. The 200 series is for current as ordinate against time as abscissa. The 300 series is for voltage as ordinate against current as abscissa.

Table I shows a variation of the arc extinction current for copper contacts of from 0.8 to 3.7 amperes, with the average at 2.5. The maximum value of the voltage transient varies from 19 to something over 48 kv., the maximum of the 15 kv. sine wave voltage being 21 kv. In a general way it may be said that low values of arc extinction current are accompanied by low values of transient induced voltage and vice-versa, although several exceptions occur.

Table II shows the corresponding values for aluminum contacts. In this case the arc extinction current is lower, varying from 0.6 to 2.0 amperes with the average at 1.2. The maximum value of the transient induced voltage is also lower, varying from 6 kv. to something greater than 34 kv.

Table III shows the values obtained for copper contacts on the 2200 volt and the 30 kv. circuits. It appears that for the 2200 volt circuit the arc extinction current is higher than for the 15 kv. while the ratio of the maximum value of the transient induced voltage to the maximum value of the sine wave voltage is also higher. For the 30 kv. circuit the arc extinction current is slightly higher than for the 15 kv. circuit but the ratio of transient to sine wave voltage is lower.

Figure 6 is a current-time oscillogram for copper contacts. It illustrated very well the rapid rate at which the current falls off after the arc has extinguished. A twenty thousand cycle timing wave is shown traced on the same film for comparison. Figure 7 is also a current-time oscillogram but for aluminum contacts. The current in this case was only 0.8 ampere r.m.s. or 1.1 amperes max., which is slightly below the average value at which the arc extinguishes for aluminum contacts.

Figure 8 is a voltage-time oscillogram for aluminum contacts. It shows the transient voltage "kick" at the time the arc extinguishes and also another voltage that occured earlier, perhaps at the time the contacts first separate, indicating a condition of glow discharge existing before the arc formed. Figure 9 is a similar oscillogram for copper contacts. Some of the voltage-time oscillograms obtained do not show this earlier voltage.

Figures 10 and 11 are oscillograms for copper contacts taken with voltage ordinates and current abscissas. If the "electron shutter" had not been used the sine wave alternating current flowing through the vacuum switch before opening would cause the cathode ray spot to retrace itself in a horizontal line across the film once every half cycle. Similarly, the sine wave voltage across the switch after the circuit has been completely opened would cause the cathode ray spot to retrace a vertical line bisecting the current trace at right angles. While the arc and glow discharges are taking place, the voltage-current characteristic for them will be traced having the above described voltage and current lines as axes. The "electron shutter" prevents blackening of the film by preventing the spot from tracing over axes more than once.

In fig. 10 the trace begins off the right hand edge of the film before the contacts separate. It travels across the film from right to left breaking into some form of glow discharge when the current has descended to about one ampere. This discharge has a voltage first in one direction and then in the other before the current has reached zero. The glow discharge continues with oscillations while the current goes through zero and increases in the opposite direction, the voltage remaining in the same direction. At some value of current so high as to be off the film the discharge changes to an arc, in which form it may be seen coming back on the film at the left hand edge. The arc continues until the current has fallen to 0.8 ampere at which value the arc extinguishes and a voltage is induced having a maximum value of 19 kv.

Since the power factor of the circuit is 0.70 lag the transformer voltage at this time is in the opposite direction and so the trace reverses and after making a saw-toothed figure starts tracing the vertical axis. No explanation of the saw-toothed figure has been found; it appears in the same form in all the voltage-current oscillograms taken on the 15 kv. circuit, for both copper and aluminum contacts. The form of the figure was different when the 2200 volt and the 30 kv. circuits were switched as may be seen in figures 12, 13, 14, and 15.

It is hard to conceive of energy being stored by any kind of discharge in the vacuum switch, but, if the oscillograms may be trusted, this is what occurs, because in figure 10 the product of volts and amperes changes sign no less than three times. Figure 11 is similar to figure 10 and was taken under the same conditions. It may be analyzed in the same way that figure 10 has been and exhibits the same phenomenon of apparent energy storage although the glow and arc discharges do not take place in the same way nor at the same values of voltage and current.

It was thought for a long time that this effect was due to some extraneous cause and much effort was expended in trying to eliminate it. The leads to the oscillograph were made short and separated as far as possible, various kinds of shielding were tried, the small inductance of the voltage multiplier circuit was varied, capacitance was placed across the switch, different current coils were used, different measuring circuits such as shown in figure 5a and 5b were tried, all without finding any indication that the effect was other than a true one. Interaction between the voltage and current measuring circuits is ruled out by the fact that the current-time and voltage-time oscillograms may be combined to form a voltage-current oscillogram which is of the same form as the ones obtained.

Figures 12, 13, and 14 are voltage-current oscillograms taken on the 2200 volt circuit. In the oscillogram of figure 12 the power factor was 0.17 leading, in that of figure 13 it was 0.06 lagging, while in that of figure 14 it was unity. Figure 15 was taken on the 30 kv. circuit. These all show the same effect of apparent energy storage, in the 2200 volt circuit oscillograms particularly the voltage oscillated on both sides of the zero axis while the current was continuously of the same sign. The horizontal tail-like traces in figures 12 and 13 connecting with the vertical trace made by the voltage after the circuit was cleared have no significance, they were caused by bouncing of the "electron shutter" contacts.

TABLE I

Values for the current at which the arc extinguishes and for the maximum value of the induced voltage transient obtained by measurement of the oscillograms.

Copper Contacts. Circuit Voltage = 15 kv. rms. or 21 kv. max.
Power Factor = 0.70 lag.

| Oscillogram number | Minimum arc current amperes | Maximum of voltage transient kilovolts | Remarks |
|---|---|---|---|
| CU-101 | | 24 | |
| CU-102 | | 23 | |
| CU-103 | | 33 | |
| CU-201 | 3.1 | | |
| CU-202 | 3.7 | | |
| CU-203 | 3.5 | | |
| CU-301 | 3.2 | >29 | |
| CU-302 | 3.2 | >27 | |
| CU-303 | 3.1 | >35 | |
| CU-304 | 2.6 | >35 | |
| CU-305 | 1.8 | >35 | |
| CU-306 | 3.6 | >35 | |
| CU-307 | 0.8 | 19 | |
| CU-308 | 2.2 | 37 | Oscillations |
| CU-309 | 2.2 | 40 | " |
| CU-313 | 2.3 | 35 | " |
| CU-314 | 1.0 | 21 | |
| CU-315 | 1.4 | 38 | |
| CU-316 | 2.5 | >48 | Oscillations |
| CU-317 | 2.1 | >46 | " |
| CU-318 | 2.3 | 22 | " |
| | Average 2.5 | | |

TABLE II

Values for the current at which the arc extinguishes and for the maximum value of the induced voltage transient obtained by measurement of the oscillograms.

Aluminum Contacts. Circuit Voltage = 15 kv. rms. or 21 kv. max.
Power Factor = 0.70 lag.

| Oscillogram number | Minimum arc current amperes | Maximum of voltage transient kilovolts | Remarks |
|---|---|---|---|
| AL-101 | | 31 | |
| AL-102 | | 25 | |
| AL-103 | | 6 | |
| AL-201 | 0.9 | | 0.8 amp. rms. |
| AL-202 | 1.2 | | 1.4 " " |
| AL-203 | 1.0 | | 2.6 " " |
| AL-204 | 1.1 | | 4.5 " " |
| AL-205 | 1.1 | | 6.0 " " |
| AL-206 | 0.7 | | 120° } Synch. Switch Position |
| AL-207 | 0.6 | | 110° |
| AL-208 | 1.0 | | 100° |
| AL-209 | 1.0 | | 90° |
| AL-210 | 0.8 | | 80° |
| AL-211 | 1.0 | | 70° |
| AL-301 | 1.2 | 21 | |
| AL-302 | 1.6 | 23 | |
| AL-303 | 2.0 | $>27$ | |
| AL-304 | 1.4 | $>34$ | |
| AL-306 | 1.6 | 15 | |
| AL-307 | 1.4 | 13 | |
| AL-309 | 2.1 | 28 | |
| AL-313 | 1.5 | 28 | |
| | Average 1.2 | | |

TABLE III

Values for the current at which the arc is extinguished and for the maximum value of the induced voltage transient obtained by measurement of the oscillograms.

2200 volt circuit (see figure 5d) 3.1 kv. max. Copper Contacts.

| Oscillogram number | Minimum arc current amperes | Maximum of voltage transient kilovolts | Remarks | | |
|---|---|---|---|---|---|
| CU-323 | 2.8 | 5.1 | Very Large Oscillations 10.4 amp. 17% Lead | | |
| CU-327 | >3.5 | >9.7 | Oscillations | 5.8 amp. | 6% Lag |
| CU-328 | 4.1 | 8.0 | " | " | " |
| CU-329 | >2.3 | >8.7 | " | " | " |
| CU-330 | >3.3 | >6.4 | " | " | " |

30 kv. circuit (see figure 5e) 42.5 kv. max. Copper Contacts.

| Oscillogram number | Minimum arc current amperes | Maximum of voltage transient kilovolts | Remarks | |
|---|---|---|---|---|
| CU-331 | 1.2 | >48.0 | 3.53 amps. | 60.3% Lag |
| CU-332 | 1.2 | 46.2 | " | " |
| CU-333 | 2.7 | >53.4 | " | " |
| CU-336 | 4.4 | 55.0 | " | " |
| CU-337 | 2.9 | >53.8 | " | " |
| CU-338 | 3.8 | >57.1 | " | " |
| CU-339 | 3.7 | >55.3 | " | " |
| CU-340 | 2.5 | >54.0 | " | " |
| CU-341 | 3.1 | 42.5 | " | " |
| | Average 2.8 | | | |

## DISCUSSION OF RESULTS AND

## SUGGESTIONS FOR FURTHER RESEARCH

The data given in the tables seems to indicate rather definitely that the transient voltage surges caused by switching with aluminum contacts are less severe than those caused by switching with copper contacts. Although no cathode ray oscillograms have as yet been taken with tungsten contacts, previous switching experience with tungsten indicates that the voltage surges are much worse than for either the copper or aluminum. Since the data given in the tables indicates that low arc extinction currents are, in general, accompanied by low voltage surges, and since the arc conduction is believed to take place in atmosphere of vaporized contact metal it might be expected that the arc would persist to lower currents, with correspondingly lower voltage surges if the vaporization temperature of the contact metal were lower. Aluminum, with a vaporization temperature of 2000° C. causes less severe surges than copper, which has a vaporization temperature of 2200° C. Tungsten, with a vaporization temperature of 3700° C. is known to cause very severe surges. It seems only reasonable to expect that some metal with a low vaporization point such as Magnesium (1100°) or Zinc (930°) should cause but very mild voltage surges, perhaps no greater than the maximum of the circuit voltage. Magnesium would have the added advantage of a strong "getter" action when arced which would improve the vacuum. In future oscillographic work these two metals should surely be investigated as contact materials.

A good explanation of the apparent energy storage in the glow discharge has not yet been found. It is well known that the glow part of the discharge characteristic has a negative slope, (see figure I) and this has the effect of a negative resistance, but to the author's knowledge no one has ever before obtained evidence that the negative slope continues across the axes in the way indicated by the oscillograms of figures 10, 11, 12, 13, 14, and 15. If the effect is a false one and is due to some extraneous cause, then further work should result in finding this out. On the other hand, if the effect is a true one, then certainly more work should be done to find out more about it. This work should include investigation of the phenomena for higher switch currents, and more investigation of the effect of power factor and higher voltages, besides the use of contacts made of other metals, as described in the last paragraph.

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## APPENDIX

### A NEW DESIGN OF CATHODE TUBE

As has been stated earlier in this thesis, (see APPARATUS, CATHODE RAY OSCILLOGRAPH) the use of steady high voltage direct current for exciting the cathode, replacing the single half-cycle voltage pulse source supplied with the oscillograph, caused a marked shortening of the life of the cathode. Since the list price on new cathode tubes is two hundred dollars, and getting a new tube also involved the time delay of sending to the factory, it seemed advisable to devise some means of renewing the cathode more quickly and cheaply.

Aging of the cathode consists in the formation of a thick, black film coating on its polished surface. This coating starts at the center and slowly spreads toward the edges, sometimes forming rather pretty colored and shaded rings. This coating quite definitely interferes with the electron emission because the intensity of the cathode ray trace on the flourescent screen fades and finally the trace disappears altogether when the coating covers a considerable portion of the surface of the cathode.

When voltage is applied to the cathode a thin pencil of ionization appears to start from the center of its surface and proceed along the axis of the cathode tube. Undoubtedly the electronic charge on the walls of the tube is the cause of the discharge concentrating along the axis in this manner. This pencil of ionization is probably made up of both electrons and positive ions moving in opposite directions. The electrons form the cathode ray while the positive ions strike the cathode surface and knock out more electrons from it. If the residual gas were pure and contained no foreign matter, such as stopcock grease vapor, little or no damage to the cathode would result. Atoms of carbon from the stopcock grease, however, stick to the surface of the cathode when they strike and eventually build up the black coating.

In order to make an old cathode operative again it is necessary to remove the accumulated film coating. This cannot be readily accomplished in the original cathode tube because the only opening into the tube is a 3/8" hole in which the brass tube carrying the two pinholes is mounted. Cutting open the tube and sealing it together again after the cathode has been cleaned causes irregularities in the glass tube wall which interfere with the action of the electron charge thereon in concentrating the discharge.

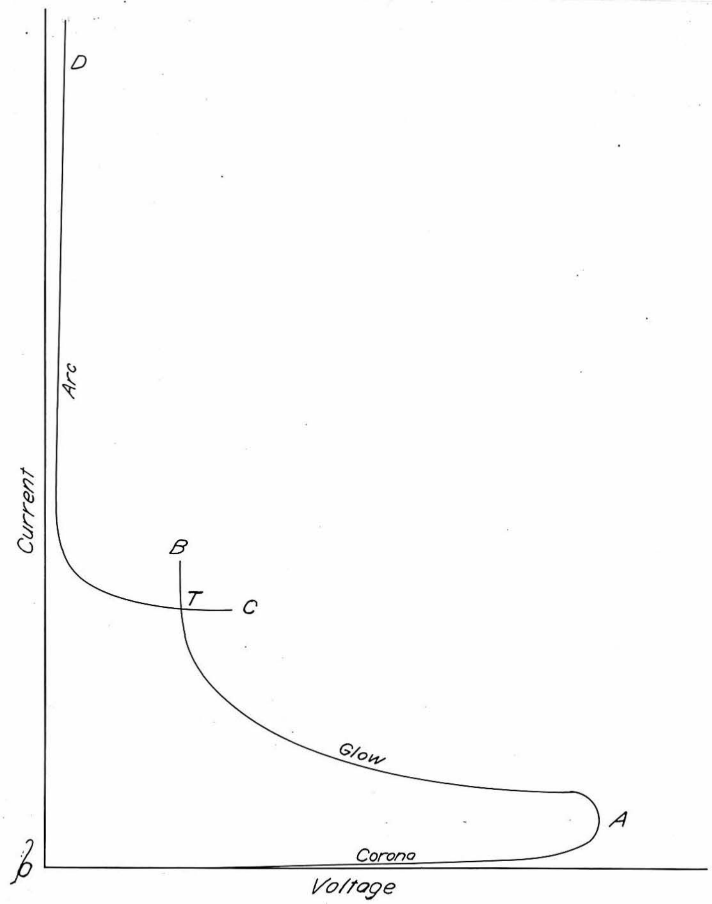
A new cathode tube was then designed and constructed which seemed to solve the problem quite satisfactorily. This tube is shown in figure 16 together with the old tube for comparison. It is seen that the copper to glass seal which joins the glass tube to the metal supporting flange in the old tube has been replaced by a ground joint in the new one. This joint may be readily pulled apart allowing the cathode to be removed by a special tool which is thrust down the tube.

The film coating may be removed by rubbing the cathode surface on a piece of very fine emery paper laid on a sheet of plate glass and dampened with alcohol. The cathode may then be repolished by buffing with Vienna Lime and Jeweler's Rouge.

The new cathode tube seemed to have only one bad feature; owing to the presence of another greased joint in the tube itself the cathode blackened at a faster rate than in the case of the original tube. This feature caused no great amount of trouble since it was a simple matter to clean the cathode every time air was let in to change the film, if it was thought necessary. To carry the improvement a step farther, however, and eliminate even this trouble, still another cathode tube was designed and it is expected that it will be constructed in the near future.

A drawing of this latest cathode tube is appended. It is seen that the ground joint has been eliminated by reverting to a copper to glass seal, but one of larger diameter than was used in the original tube. The assembly consisting of the pinhole tube marked (2) in the drawing and its supporting plug (3) may be removed after the flange coupling has been taken apart, leaving a hole of sufficient size to allow the cathode to be unscrewed and removed by the tool also shown in the drawing.

Another new feature is the tube marked (11). This tube is to be connected through a needle valve to the rough vacuum line. It will be noticed that the pinholes form the only opening between the cathode tube and the rest of the vacuum chamber through which air may flow to equalize the pressure. If the vacuum in the film bell and deflecting tube is made as good as the pumps will produce, the vacuum in the cathode tube may be softened to the proper degree by opening the needle valve slightly allowing a small amount of gas to flow in under the influence of the slightly higher pressure in the forevacuum line. By properly adjusting the needle valve the inflow through it may be made to just balance the outflow through the pinholes, and thus the proper vacuum for the cathode discharge will be maintained continuously. If this can be accomplished one of the chief operating problems, that of maintaining just the proper vacuum, will be solved. It is also believed that having a harder vacuum in the deflecting tube and the film bell will result in sharper oscillograph traces since less collisions will occur between the electrons in the cathode ray and the air molecules in the vacuum chamber.



GENERAL GAS DISCHARGE CHARACTERISTIC

Figure 1.

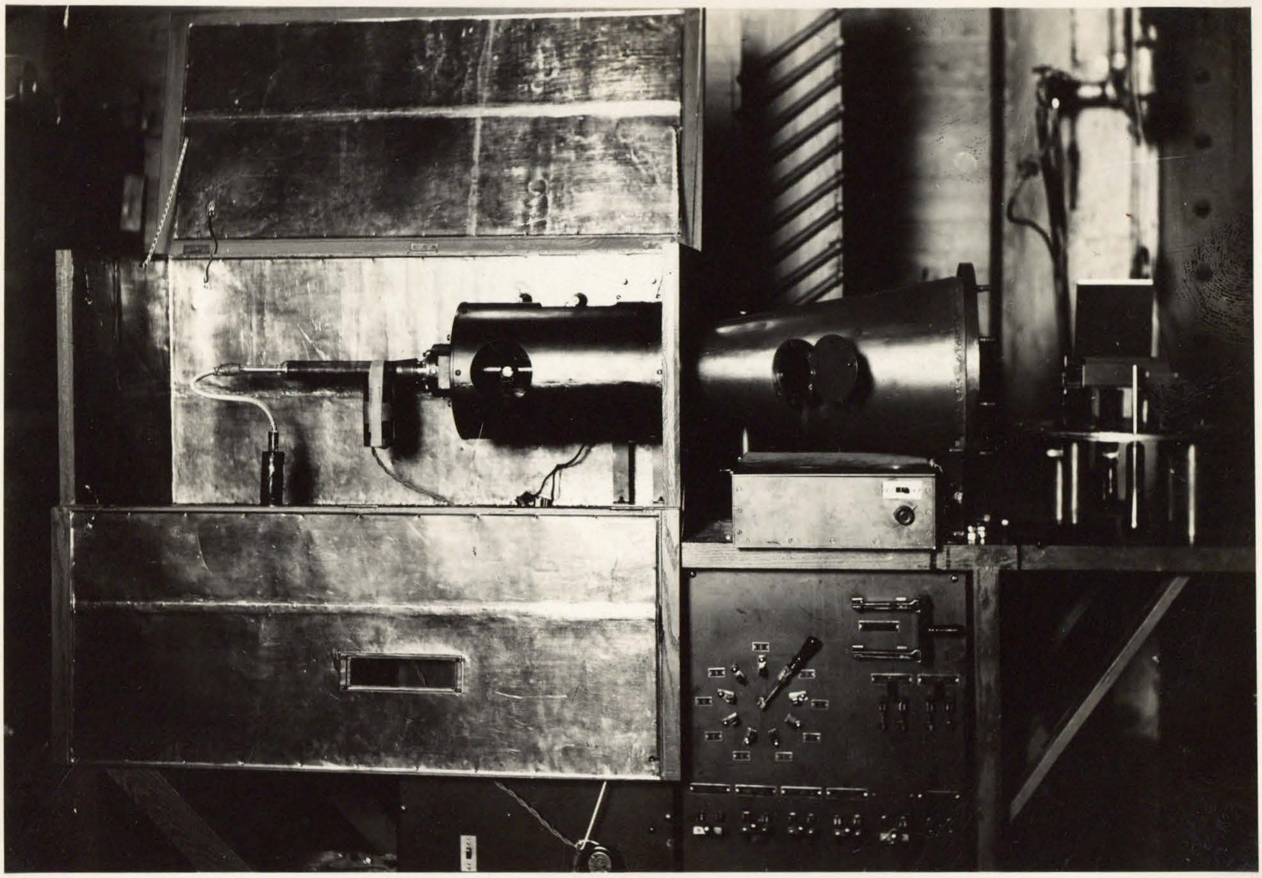


Figure 2.

THE CATHODE RAY OSCILLOGRAPH.

after p. 7

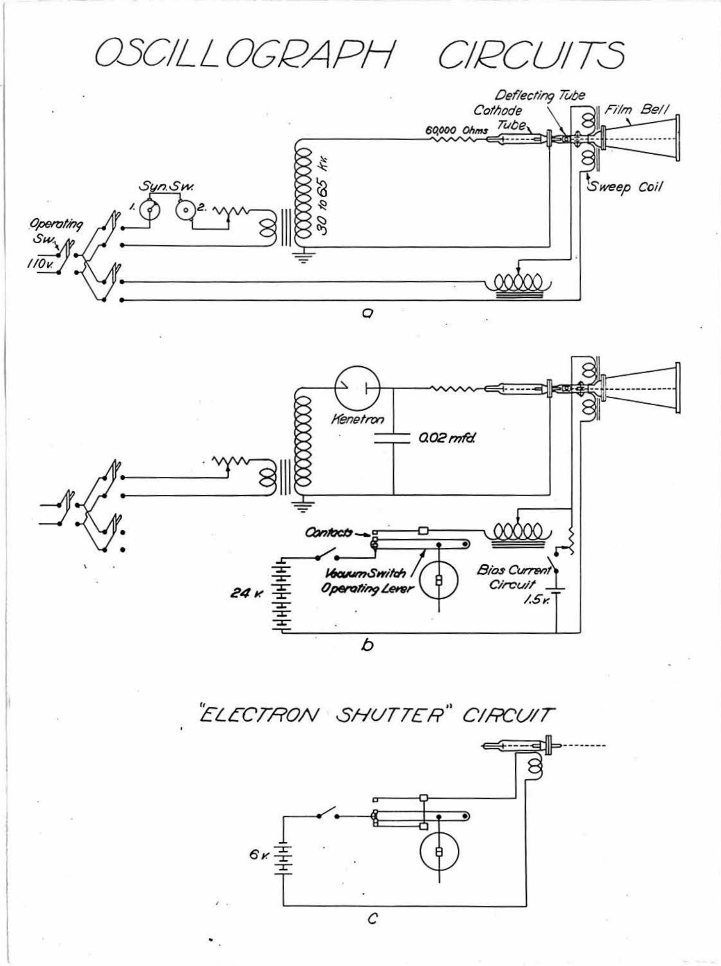



Figure 3.

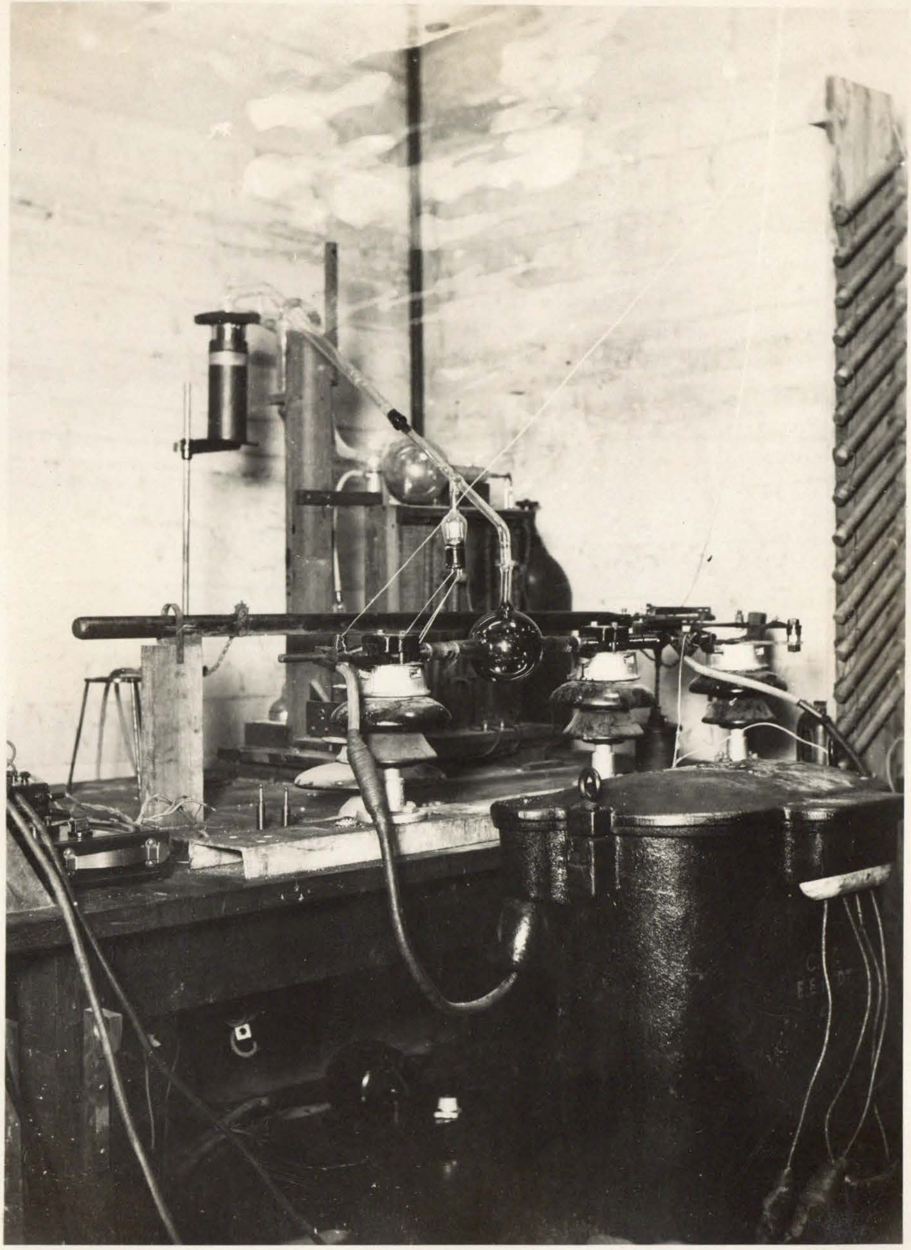


Figure 4.

THE VACUUM SWITCH

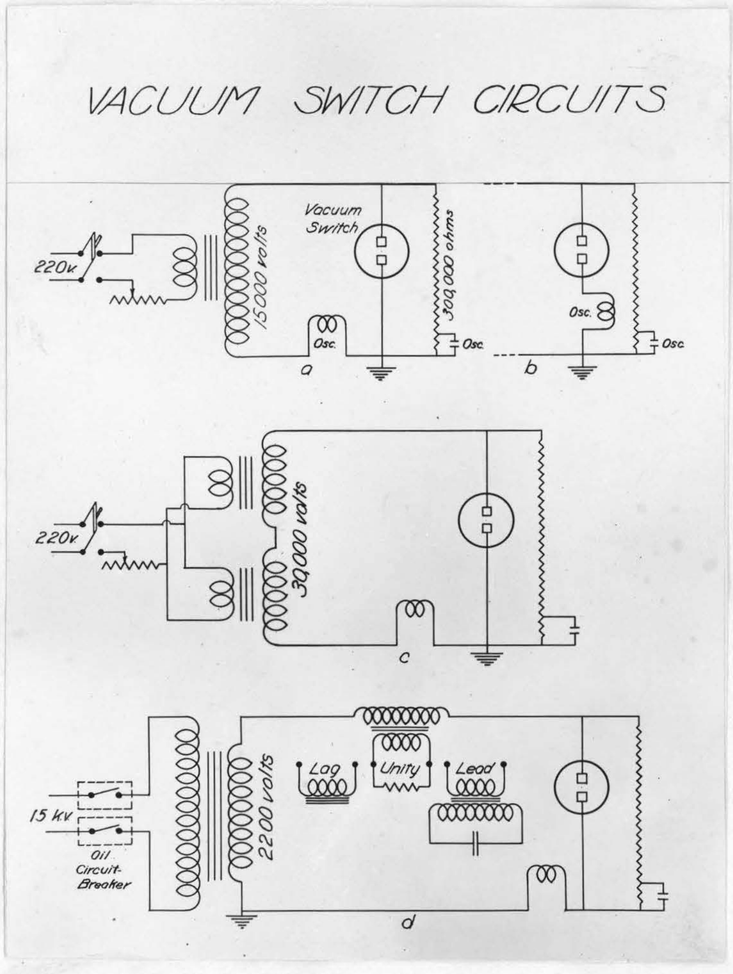

VACUUM SWITCH CIRCUITS
Vacuum Switch
220v
15000 volts
30,000 ohms
Osc.
a
b
220v
30,000 volts
c
Lag
Unity
Lead
15 kv
Oil Circuit-Breaker
2200 volts
d

Figure 5


Figure 6.


Figure 7.


Figure 8.

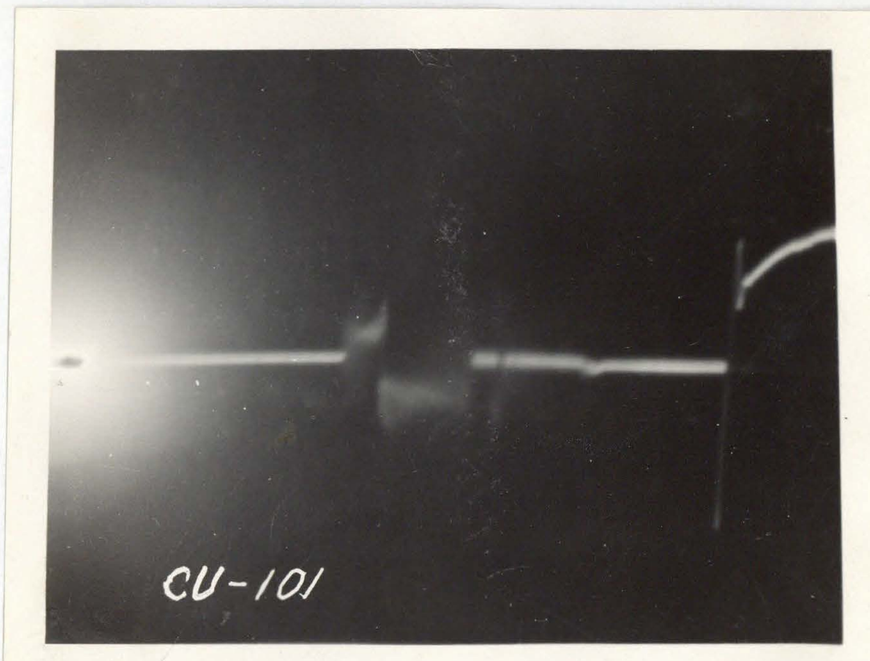



Figure 9.

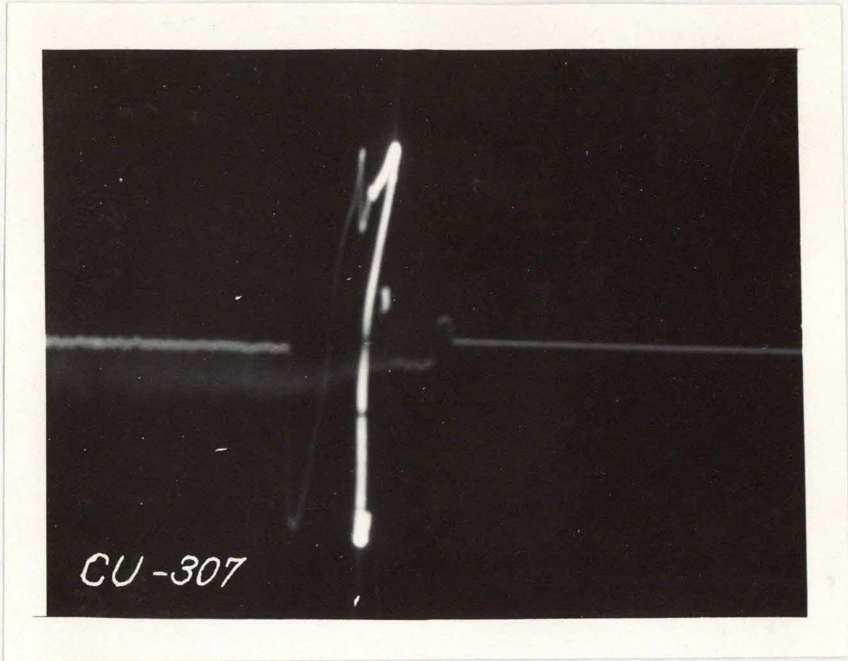



Figure 10.


Figure 11.


Figure 12.


Figure 13.


Figure 14.

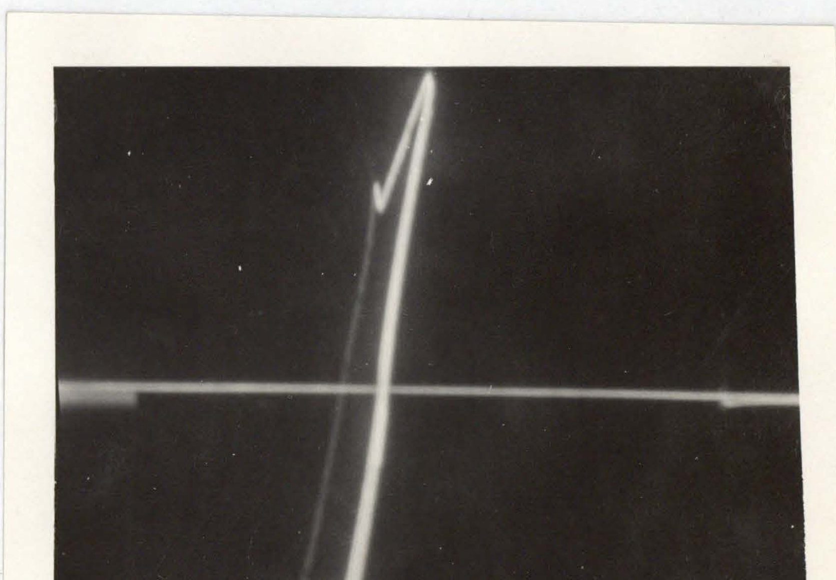



Figure 15.

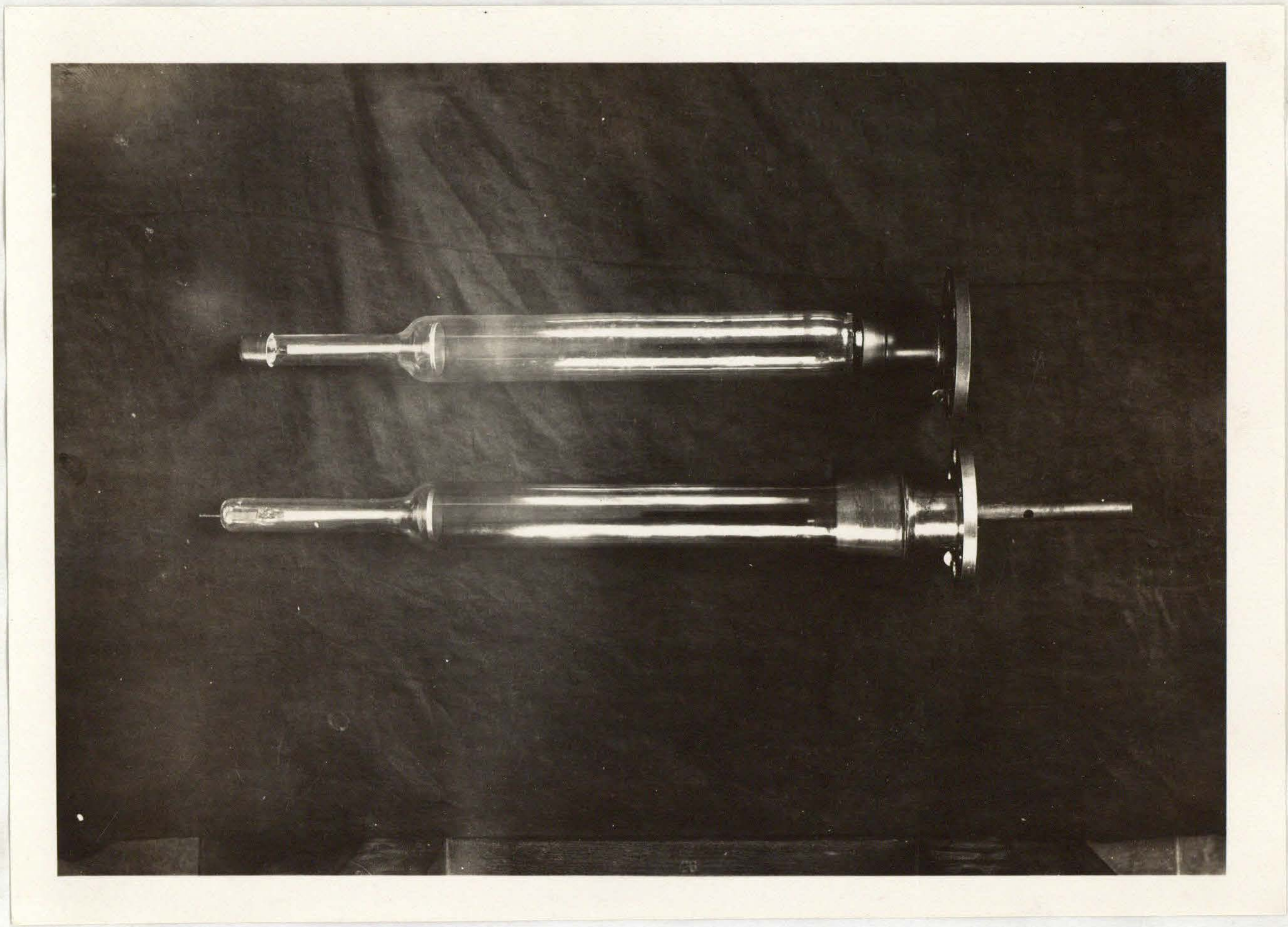
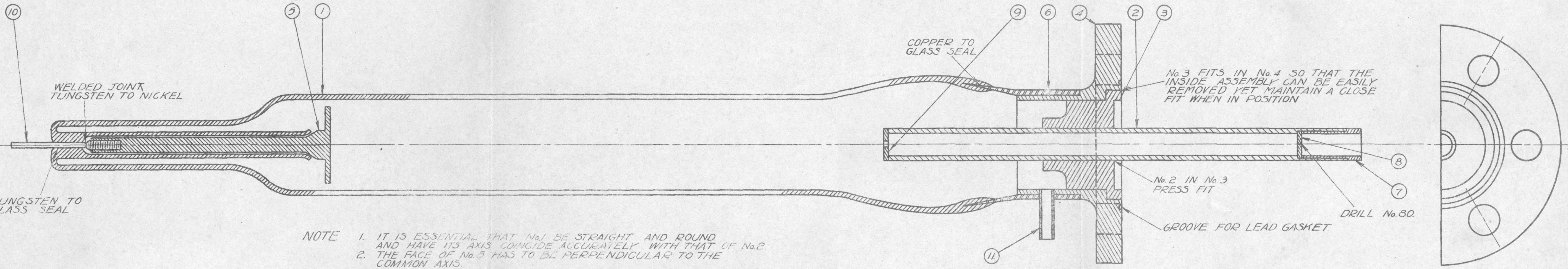


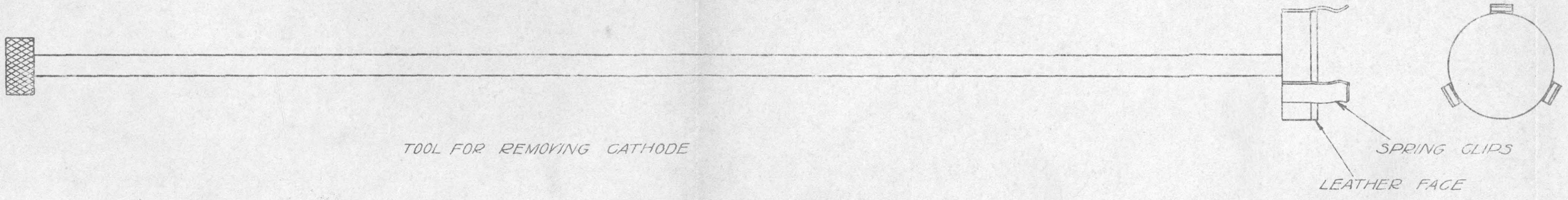
Figure 16.

THE CATHODE TUBES.

# CATHODE TUBE




NOTE
1. IT IS ESSENTIAL THAT No.1 BE STRAIGHT AND ROUND AND HAVE ITS AXIS COINCIDE ACCURATELY WITH THAT OF No.2.
2. THE FACE OF No.5 HAS TO BE PERPENDICULAR TO THE COMMON AXIS.




TOOL FOR REMOVING CATHODE

| No | MATERIAL |
|---|---|
| 1 | G-702P GLASS |
| 2 | BRASS TUBING |
| 3 | STEEL |
| 4 | STEEL |
| 5 | ALUMINUM |
| 6 | COPPER |
| 7 | BRASS |
| 8 | BRASS |
| 9 | BRASS |
| 10 | TUNGSTEN AND NICKEL |
| 11 | COPPER TUBING |