STUDY OF ELECTRIC TRANSIENTS IN THE VACUUM SWITCH BY MEANS OF THE CATHODE RAY OSCILLOGRAPH

Thesis By

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In Partial Fulfillment of the Requirements for the

Degree Of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

1931

SUMMARY

The opening of an electric circuit by means of a vacuum switch is a complex performance which is analysed into a sequence of stages according to the phenomena involved. First, the voltage difference between the opening contacts will increase more rapidly than the electrode spacing, producing successive discharges, which physically are field currents. If the energy delivered is sufficient, an arc is formed; if not, the transients persist for a time. The arc, if formed, continues until a minimum current is reached, when the current suddenly drops to zero. Immediately before and just after this drop occurs, the current is unsteady, many surges being superimposed on the otherwise simple characteristic. The sudden drop to zero current induces a damped sinusoidal voltage oscillation of appreciable magnitude in the external circuit. Such an oscillation of small magnitude follows the field currents when the interrupted current is too small to form an arc. As can be seen, the circuit is normally cleared in the first half cycle.

Hayward's work disclosed, but left incomplete, the question of an apparent power storage in the arc. This thesis presents considerable new data from which it appears we may conclude that there is no storage of energy in an arc such as appeared to be the case. While several hypotheses may explain why Hayward's results were not duplicated, it is probable that his current measurement was erroneous, due to a time lag in his current coil deflections.

While the equipment available did not permit the determination of the kva. limit of the vacuum switch, the tests made indicated that it will handle its tasks well.

INTRODUCTION

For a number of years the investigation of the vacuum switch has been carried on at the Institute. Professor Sorensen recognized the acute necessity for a better solution to the switching problem and suggested a vacuum switch. The vacuum technique already developed by Dr. Millikan opened the way for a joint attack by the forces of Physics and Engineering. A short account of the work of the men who have already contributed to the undertaking is in order.

In 1927 H. E. Mendenhall presented a thesis on "The Interruption of Electric Circuits in Vacuo." He discussed the experiences with the first vacuum switches. These switches performed the tasks given them with great success. Within the limits of the tests they indicated that the vacuum switch would open a short circuit in the first half cycle without excessive voltage surges. It was found that the switch would fail a number of times when first evacuated, but that these failures cleaned the gas from the metal and left the switch ready to operate.

F. C. Lindvall presented a thesis in 1928 covering his investigation of "Contact Behavior and Gas Phenomena in a Vacuum Switch." He observed that in operation there is both a releasing of gas and a "getter" action, or absorbing of gas. The release of gas increased with both current and voltage. The switch would operate satisfactorily with pressures from 10^{-3} mm. of mercury to the lowest possible. Copper was found to give the best operating characteristics. Severe heating of the contacts did not prevent the switch from opening the circuit.

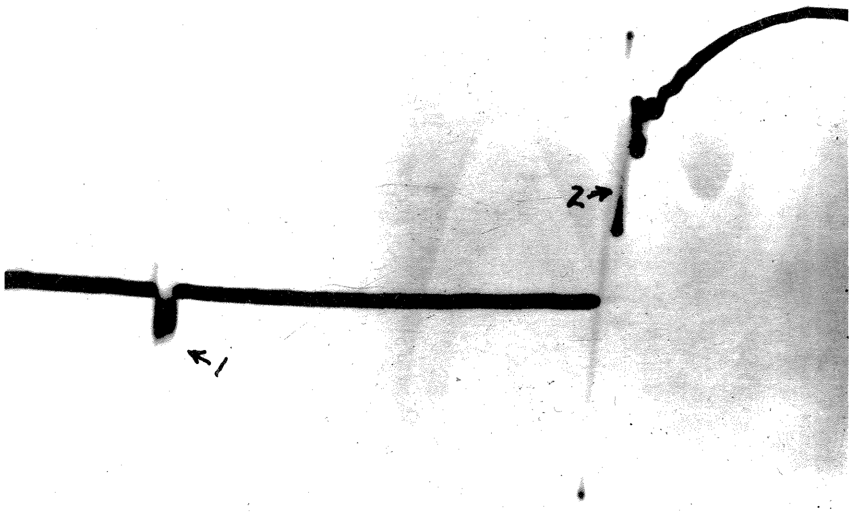
J. H. Hamilton also presented his thesis in 1928. He worked with a special circuit which enabled him to measure arc voltages, even where voltages many times those measured would suddenly be applied to his apparatus. The arc voltage was found to be between 10 and 25 volts for high currents, but much higher for very small currents.

The latest work follows more directly the work of C. D. Hayward, whose thesis was submitted in 1929. He found a rough agreement between the value of current at which the arc went out and the voltage surge induced. He also found that aluminum contacts gave a lower extinction current and lower surge voltages than copper. The most surprising results he gave were oscillograms showing voltage reversals with current maintained in a constant direction, a result which meant that the vacuum switch stored energy in a form available for return to the line.

It was thought highly desirable to check the arc storage phenomena found by Hayward and to further investigate the different properties of the vacuum switch by means of the cathode-ray oscillograph. The results obtained are given as a series of oscillograms with a description for each, together with an analysis of the phenomena found. The analysis is a running narrative which will occupy the top of the page above the oscillogram and description. It will be preceded by a key to the oscillograms.

KEY TO OSCILLOGRAMS

With each oscillogram certain data are given; the number, the coordinates, the transformer used, the effective short circuit amperes through the switch, and the approximate time required by the beam to cross the film. In the example below, the serial number is 9-4, meaning the ninth picture of the fourth dozen. The "V-t" means that ordinates correspond to volts, the abscissae to time.



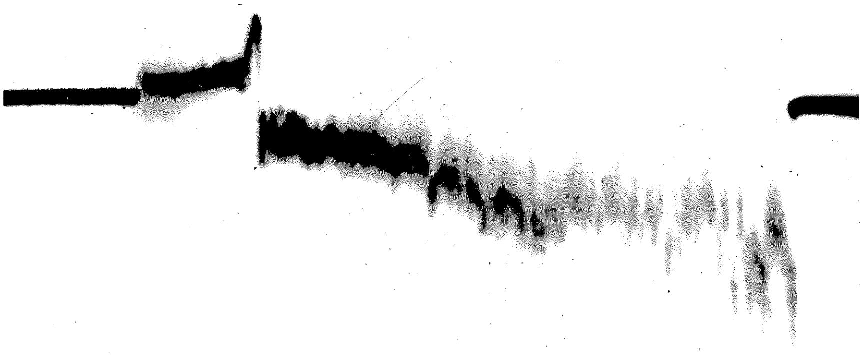
9-4
V-t
15 kv.
5.7 amps
.02 sec.

9-4

Following from left to right can be seen the zero voltage for short circuit, the short 1st transient at (1), the almost zero arc voltage, and the oscillations of the 2nd transient which damp out, revealing the fundamental 50 cycle open circuit voltage. This oscillogram is typical of a large number of oscillograms, both in this thesis, and in that of Dr. Hayward.

ANALYSIS OF THE FIRST TRANSIENT

While an arc, once established, may reasonably be expected to continue for a time, it is evident that there must be some auxiliary mechanism to initiate the arc. The question properly arises, what is this mechanism in a vacuum arc? There is reason to believe that field currents pass while the contacts



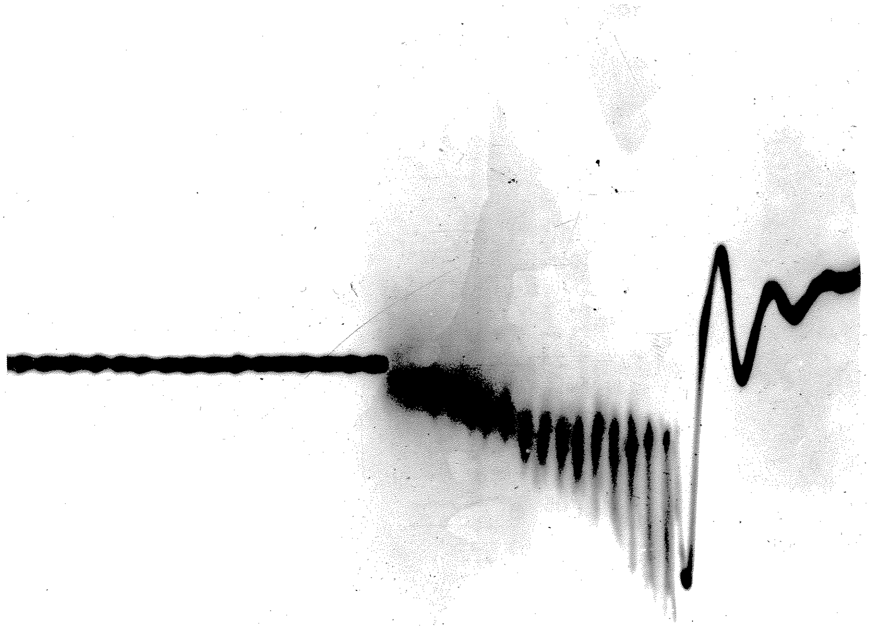
2-7
V-t
15 kv.
5.7 amps
.006 sec.

2-7

This is another example of the 1st transient which begins on the opening of the switch contacts and lasts until the arc strikes. The beam has travelled faster here than in 9-4 and some idea of the frequency of these oscillations may be gained. The voltage reversal came before there was time to either establish an arc or gain an electrode spacing sufficient to prevent field currents. Maximum of the 15 kv. wave would probably come at the edge of the film.

are first separating. With a high voltage, the currents need not be large to give sufficient power to vaporize a bit of the contacts and then ionize this vapor to form an arc. On the other hand it is perfectly reasonable that this power should prove insufficient to serve the purpose, and that no arc should occur.

The results indicate that the field current is not a single discharge, but a large number of short surges with rapidly



5-7

V-t

15 kv.

4.3 amps

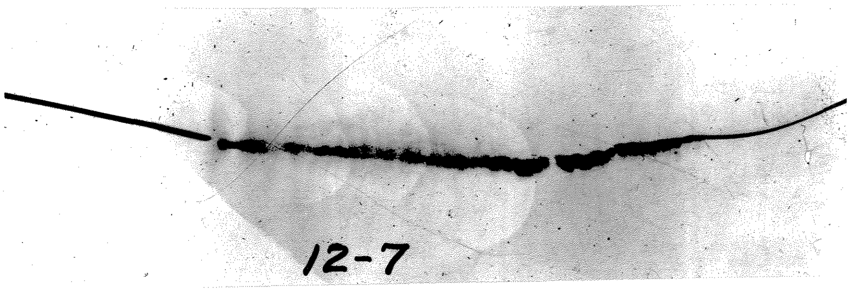
.008 sec.

5-7

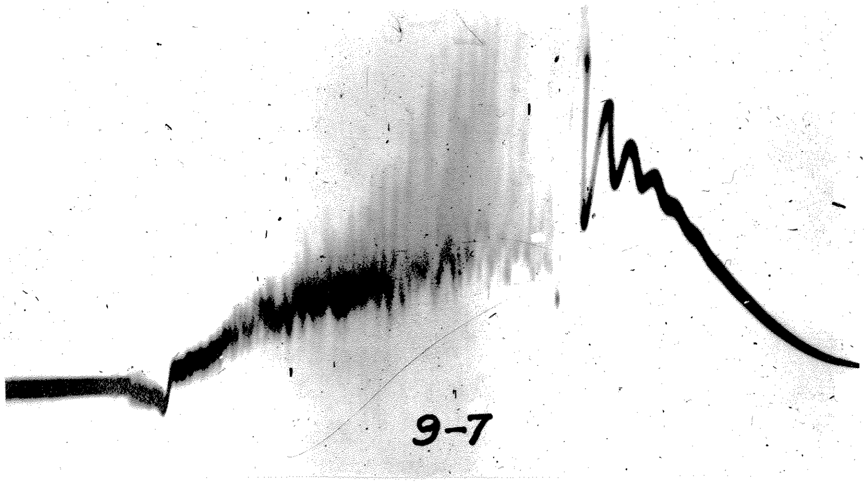
This is an example of a 1st transient which led directly into a second transient and open circuit without an intermediate arc. The duration of the 1st transient was enough to allow a contact separation too great to be broken down by the reversed voltage. The spots seen during zero voltage indicate that the oscillograph vacuum was too hard. The bars in the transient part are due to this same effect, not to any characteristic of the transient.

changing voltage requiring an appreciable time before enough energy has been produced to form an arc. Should the current and voltage of the switch tend to reverse too soon after the contacts separate, field currents will begin to travel in the opposite direction, if the gradient established in that direction is sufficient. Cases will be shown both of failure to give field currents after reversal and of such currents which will lead to an arc, or will finally cease. These transients sometimes last as much as a half cycle.

Previous experimenters on the vacuum switch had noticed



12-7 I-t



9-7 V-t

Both:

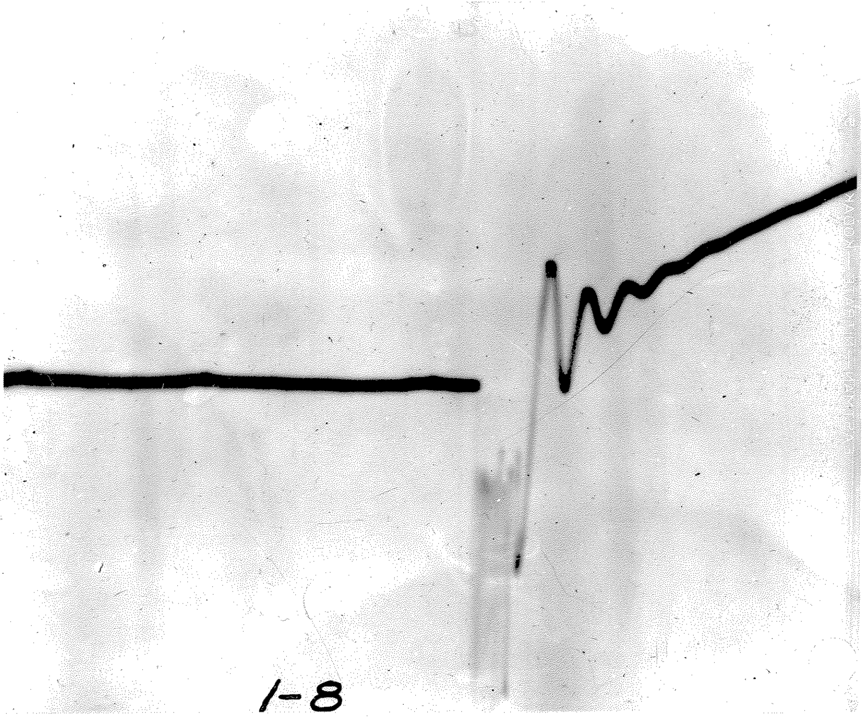
15 kv.

4.3 amps

.01 sec.

Two oscillograms taken within a short period are presented here for comparison. They represent the case of opening with 1st and 2nd transients, but without an arc.

that there were surges which occurred during switching. These surges at times would blow elements and fuses in magnetic oscillographs. Insulated pieces of metal would build up voltages to ground sufficient to give wicked sounding sparks. The switches used in these experiments certainly would give discharges with considerable voltages, particularly when using the 15 kv. transformer, between the high potential lead and a wire binding it to an insulator. Shielding and grounding of all possible con-

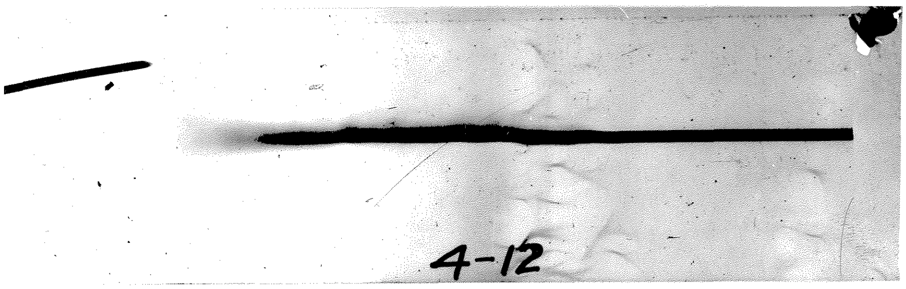


1-8
V-t
15 kv.
4.3 amps
.0005 sec.

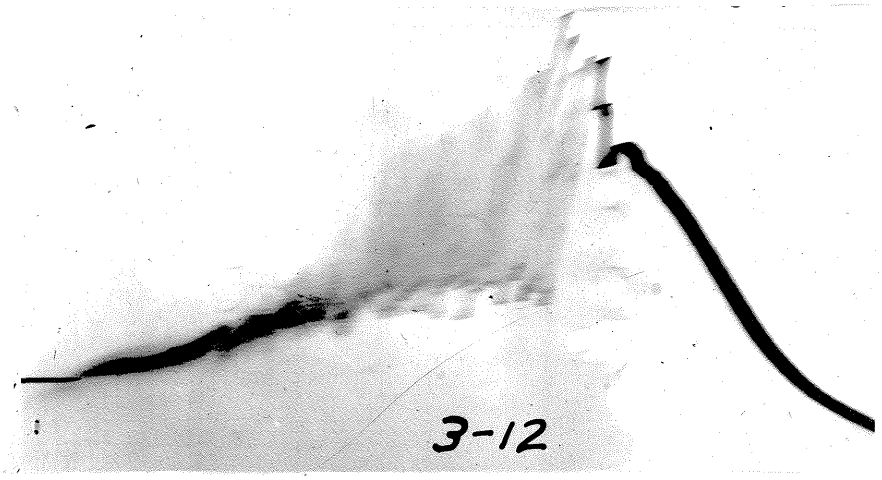
This is another case of a 1st transient leading to a 2nd transient and open circuit. In this case and several others it is probably that the favorable timing of the contact separation was the reason for the lack of an arc. Cases will be presented in which this is not the reason.

ductors usually makes it possible to continue to make measurements, but these measurements must be more doubtful than before.

Although the voltage oscillations which result from the sudden extinction of the arc, i.e., the 2nd transient, were the ones previously looked upon with most apprehension and interest, the author soon decided that the cause of all of the sparks around the vacuum switch was the 1st transient. Briefly, the reasons for this were (1) the frequency was much higher than that of the 2nd transient, (2) such sparks were observed



4-12 I-t



3-12 V-t

Both:

15 kv.

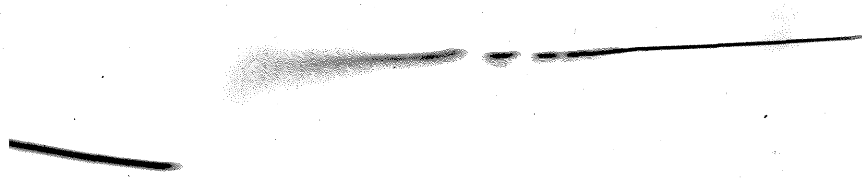
.41 amps.

.01 sec.

The current oscillogram shows that the current broke suddenly, but that transient currents occur with the transient voltages. These are typical of the transients which occur when the current through the switch is limited to a low valve. The print 3-12 has a cathode spot elliptical in shape.

on closing as well as on opening the switch (3) although small in magnitude, there were real current pulsations of high frequency during the 1st transient. Another phenomena caused by these transients was the glowing of the gas in the gas reservoir between the mercury diffusion pump and the oil pump.

To get a rough check on the gradients in the switch a test was devised to determine the rate of opening of the con-



2-12

I-t

15 kv.

.41 amps

.01 sec.

2-12

This is a picture of the current as it occurs during a transient. This picture was taken immediately before 3-12, and the conditions were the same. Apparently the current was interrupted at about its maximum which, however, was too small to give rise to an arc.

tacts. If 110 v. are placed on a potential element of the magnetic oscillograph, the vacuum switch will interrupt that voltage, and the magnetic oscillograph will record the exact time the switch contacts separate. If in addition the contacts on the switch lever arm (see Sheet 3) are connected to a storage battery they will give records of the times that the switch lever arm reached chosen points. Since these contacts can be varied, an analysis of switch position with time can be made. The results of four oscillograms are given on Sheet 1.

This test showed that there would be gradients sufficient to give field currents for at least 0.0001 seconds and probably 0.001 seconds or more. The roughness of contacts must enter into such an estimate, reducing the gradient many fold.

The basis of the gradients necessary for field currents is the work of Millikan and his co-workers. The reader is referred to the following articles:

Millikan, R. A. and Eycing, C. F., "Laws Governing the Pulling of Electrons from Metals by Strong Electric Fields." Phys. Rev. 27, p. 51, 1926.

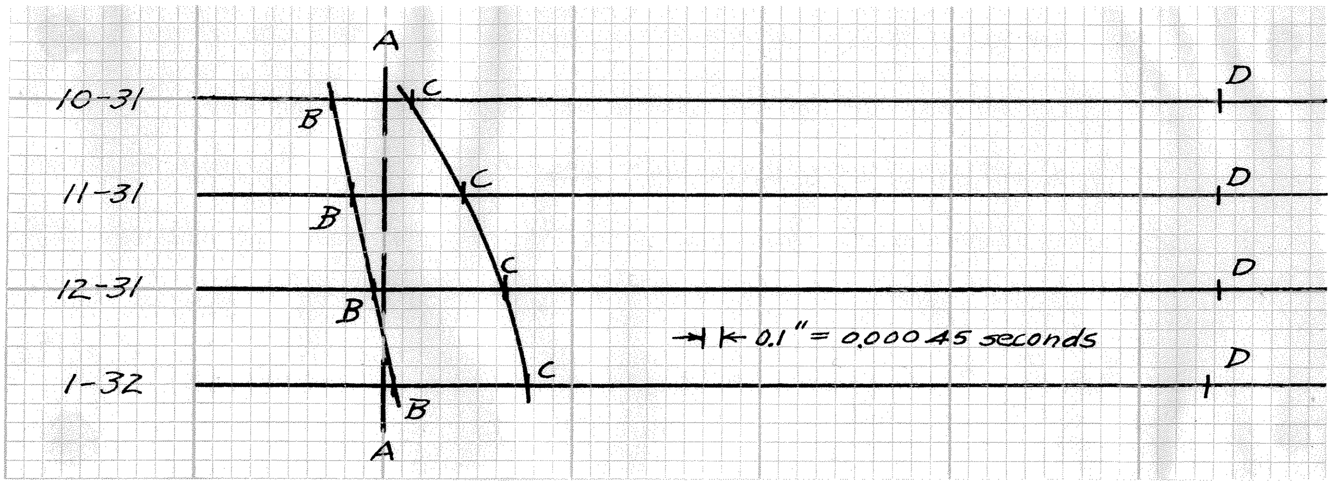
Lauritsen, C. C. and R. A. Millikan, on field currents, Phys. Rev. 33, April 1929.

There were several reasons for believing these currents to be field currents rather than any other type of discharge.

MAGNETIC

OSCILLOGRAM SHEET 1.

NOS.



Distance proportional to time as on oscillogram

Event A - Opening of Vacuum Switch Contacts

B - Closing of 12 v. on Sweep Circuit

C - Opening of Short on Resistance

D - One cycle after A; AD = .02 sec.

Point of lever arm pulling switch contacts apart has moved .0025" further at event B and .0044" further at event C in each succeeding oscillogram. See Sheet 3.

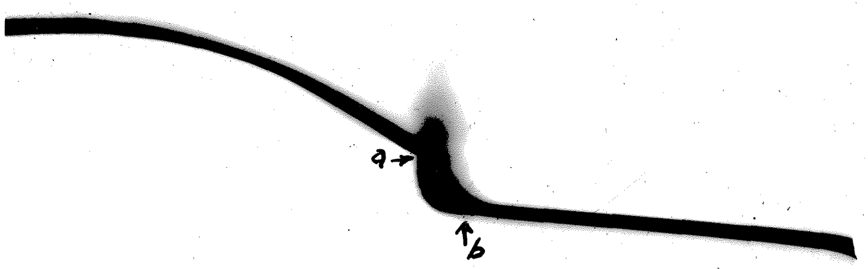
Results:

At time of separation contacts have average velocity of .005 in. = .013 cm. per .001 sec.

For parallel plates with .013 cm. separation, 52,000 volts gives 4 x 10^6 volts per cm.

Oscillograms taken between Cathode Ray oscillograms 12-18 and 1-19. Spring tension not necessarily equal to tension for all C. R. oscillograms, but reasonably typical.

One of the principal reasons was that, as already mentioned, on closing the switch, the external disturbances were the same as on opening. Since the gas pressure was between 2 and 5×10^{-5} mm. of mercury, there could be no discharge on closing until field currents occurred. The gradients available were sufficient to make field currents the most reasonable answer. (See Sheet I) Furthermore, it was unlikely that there



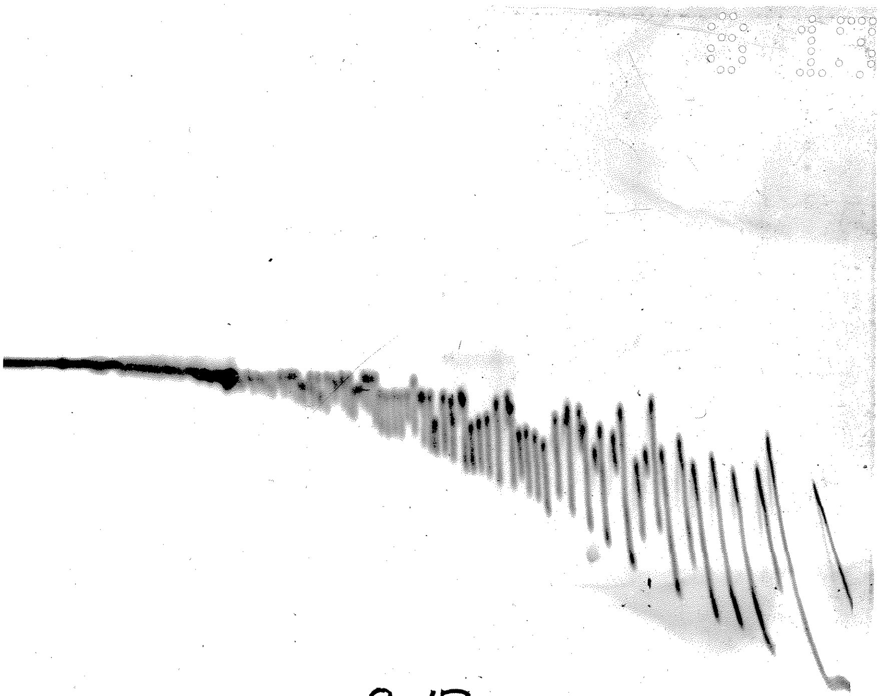
3-13
I-t
15 kv.
.15 amps
.005 sec.

3-13

The current was interrupted fairly near zero. There was no arc, since the current was too low, but transient currents passed for a period. The average value of current, as it might be measured on an oscillograph which would not respond to above 10,000 cycles would presumably give a fairly gradual current decay, although the falling current can be seen by this picture to consist of many short lived impulses of sizeable magnitude.

should be sufficient ions in the space between the electrodes to support a glow discharge if an arc was never formed. After an arc has boiled off some vapor, it might reasonably turn into a glow discharge for a time.

To obtain further evidence on its nature, the wave shape and frequency of the 1st transient were examined. It was

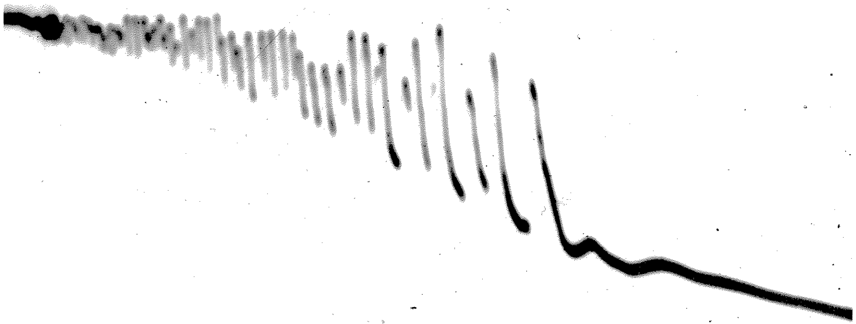


8-13
V-t
15 kv.
.13 amps
.0015 sec.

8-13

A faster sweep was used to get an idea of the wave shape and frequency of the 1st transient. A test with an oscillator showed the timing to be linear. It can be seen that the transient is approximately of the type obtained when a voltage with a limited rate of increase continually succeeds in breaking down some dielectric, the breakdown causing the voltage to fall much faster than it rose, and each breakdown requiring a higher voltage than the preceeding one.

found that the 1st transient consists of a series of cycles of voltage rises followed by sudden drops; the rises being slower than the drops. At first the rise only goes to a small voltage, but later it rises to a higher and higher value. Since the voltage each time drops to zero or almost zero, the later rises take longer, as do the drops. Finally the voltage does not drop, but goes into the damped sinusoidal oscillation typical of the second transient. The rising curves appear to



9-13
V-t
15 kv.
.13 amps
.0015 sec.

9-13

This picture differs from 8-13 only in that it was timed a trifle later. A very small oscillation after the last breakdown represents all of the 2nd transient which occurred in this case. The switch is of course open at the left of the picture. A small knot at the start of the trace was caused by jumping of the timing contacts.

be of logarithmic form. The last cycles had a period corresponding to about 2- kilocycles, the first cycles being much shorter. The current had repeated, sudden surges, corresponding roughly to the voltage surges. It is very probable that the voltage rose under the influence of the external circuit; the gradient caused a train of electrons to suddenly pass, and this in turn caused the voltage to drop.

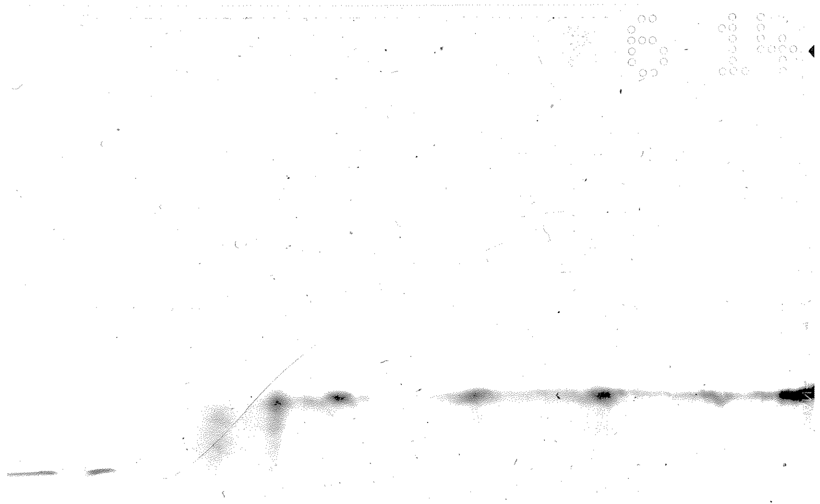
3-14
I-t
15 kv.
.13 amps
.0005 sec.

3-14

There are two exposures on this film, but one, the straight line, failed to bring the transient on to the film. The other shows how the current behaved under circumstances similar to 8 and 9-13. One can hardly escape the conclusion that the voltage drops on 9-13 are due to the current transients which the picture shows. Again the sweep contacts jumped, causing overlapping of the trace.

If the current during these transients were a repeating function of voltage, the function might be found on I-V pictures if the spot retraced the curve enough times. Since the total time of this transient is usually short, and the I-V curve is different for each cycle, the trace is almost lost in I-V oscillograms. Another difficulty in simple I-V oscillograms is that the I-V curve for the 1st transient might combine with a possible curve for the 2nd transient.

For a time certain oscillograms, principally 4-13



6-14

I-t

15 kv.

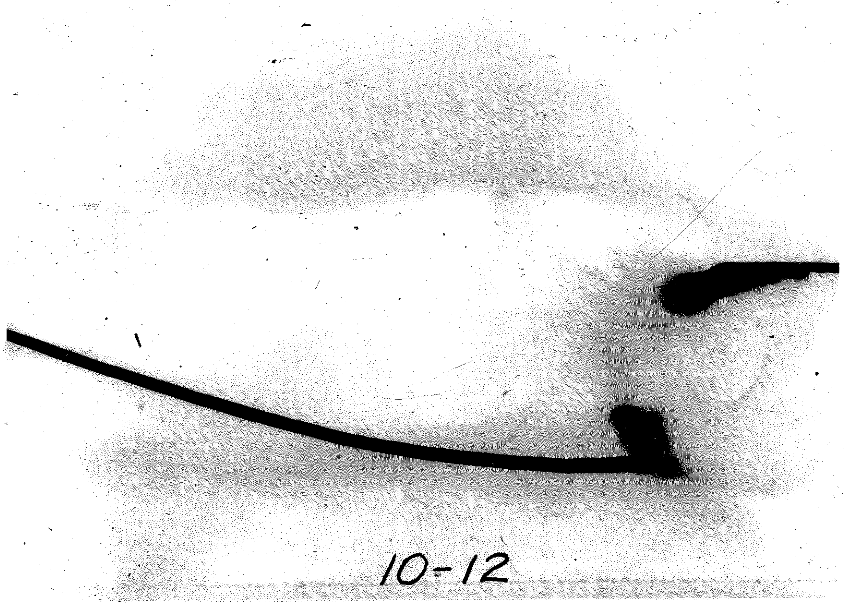
.13 amps

.0003 sec.

6-14

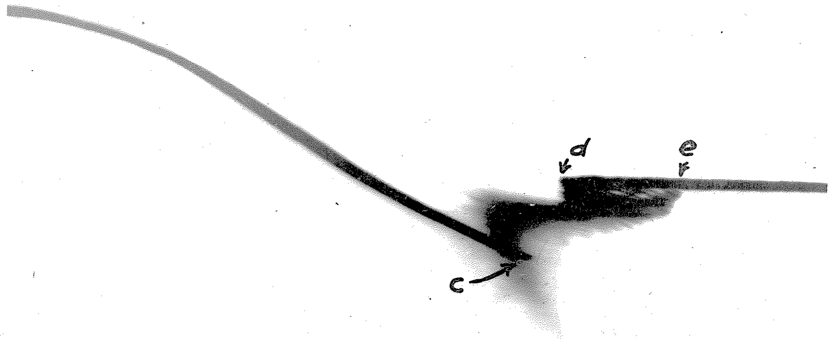
This again gives an idea of what the current does just after the contacts are separated, if the limiting resistance in the transformer primary has held the short circuit to a value too small for an arc to form.

seemed to give voltage oscillations with current continuing in one direction, but more careful examination makes possible an alternative explanation. In other cases the trace indicated the current and voltage had the same direction. While not proved, it is very probable that no power is returned from the 1st transient to the circuit.



10-12
I-t, V
15 kv.
.34 amps
.01 sec.

If the reader will recall how in I-t oscillograms such as 3-13, the current drops to zero except for a short transient, it will be clear that if horizontal deflections due to voltage are superimposed on the slow time deflections, the result will alter the I-t picture only in the transient period, and perhaps extend the zero current line. When there is a short circuit or a steady arc, the voltage will have no effect, and when the current is zero, voltage oscillations will be confined to a straight line, namely, the x axis. This is such a picture.



4-13

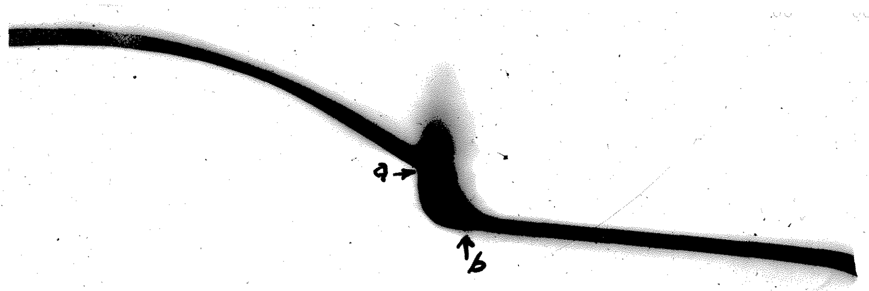
4-13 I-t,v

Both:

15 kv.

.15 amps

.0005 sec.

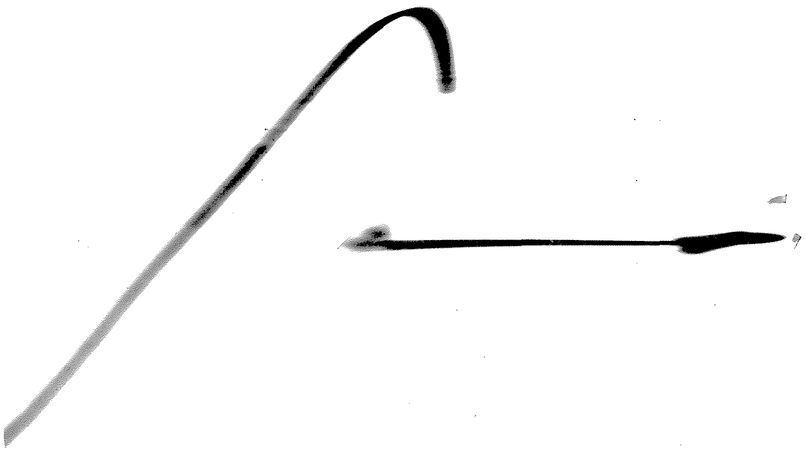


3-13

3-13 I-t

The upper picture was taken using the same scheme as 10-12. The lower was the I-t record of which the upper was supposed to be a modification. If the transients were confined to the interval a b, the record of transients would be almost independent of time. At first glance 4-13 seems to prove that voltage oscillations occur with the current constantly above the axis, point d corresponding to point b. It will be seen, however, that the interruption of the current, c, occurred at a different part of the cycle from a, and therefore could be expected to last longer.

(Continued on next page.)



11-11

I-t, V

15 kv.

.72 amps

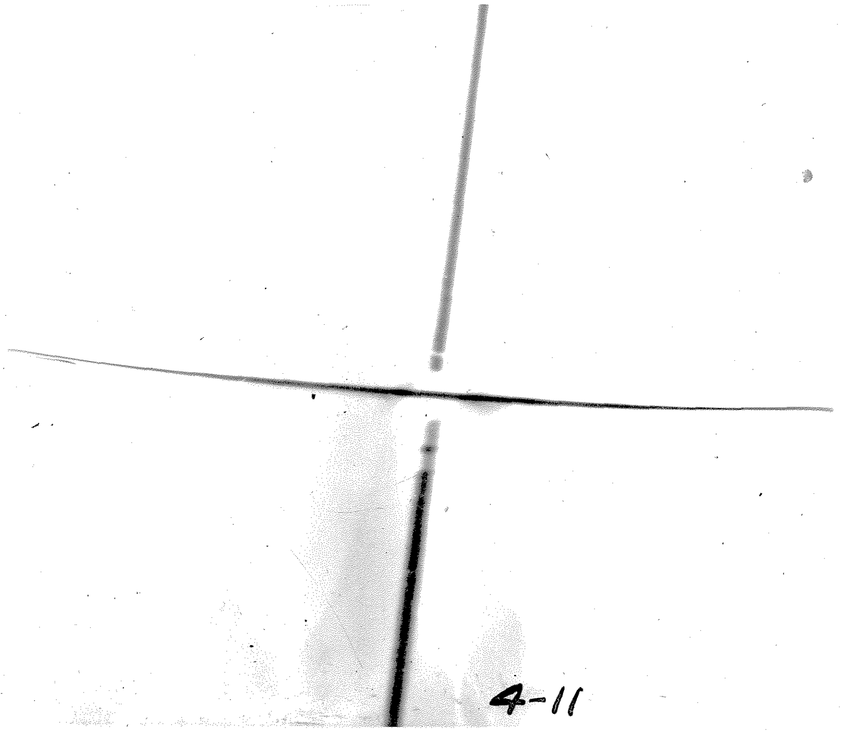
.015 sec.

11-11

The scheme of this picture is the same as that of 10-12. The chances are that the time displacement had a bit of distortion to give the poor sine wave. The lack of voltage oscillations while the current falls to zero, indeed the lack of any trace which might be seen, indicates either that they do not occur or that they are extremely rapid.

(Continued from previous page.)

Probably the transient would have extended to e rather than d, had the voltage deflections been omitted. Voltage contrary to current represented by points to the right of the corresponding point of an I-t curve has, therefore, an ambiguous status.



4-11

I-V

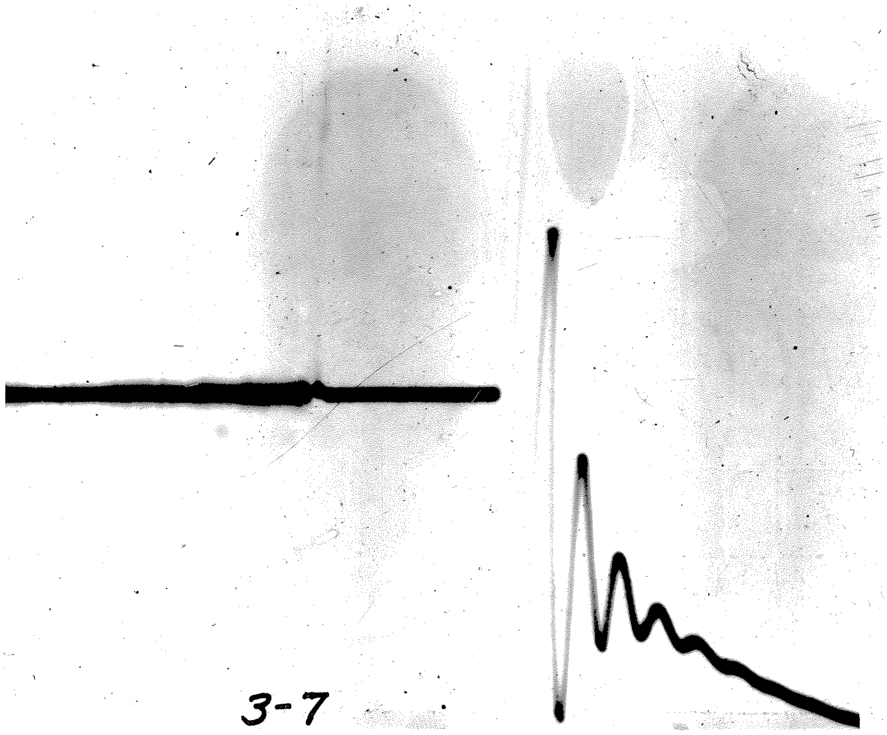
2.3 kv.

45 amps

Here again the simple cross is the whole of the true trace. The drop from a little current to zero was so rapid that it left a blank. The two faint lines parallel to the current oscillation were probably due to either a doubling of the spot, or more likely, a trace due to current when the cathode voltage was low before the electron shutter took effect. The slight separation of the two parts on the right hand end of the voltage swing is probably within the reproduceable accuracy of the instrument. Presumably the switch contacts separated just after a zero current, or so little before that the arc restruck in the opposite direction, the current jumping the small values quickly. This caused the gap around zero current. Of Course, the electron shutter could have caused the same effect.

ANALYSIS OF THE SECOND TRANSIENT

It is not necessary to use a cathode ray oscillograph to show that there are voltage oscillations after the arc is extinguished. The earliest work on the vacuum switch with a magnetic oscillograph showed that there were oscillations of considerable magnitude and fairly high frequency, although of lesser magnitude than in the case of oil circuit breakers.

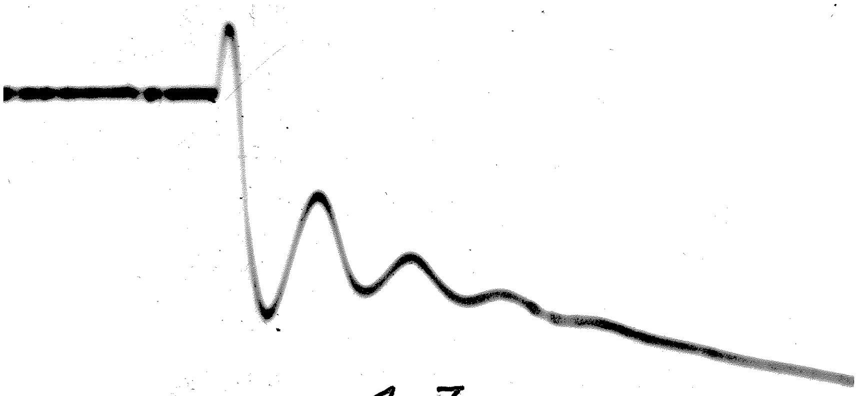


3-7
V-t
15 kv.
5.7 amps
.01 sec.

This is a good example of the second transient which follows the arc. The frequency figures out to be about 2500 cycles per second. The sinusoidal form of the wave and its rapid, but not critical, damping, are evident. The fuzziness and break in the arc voltage are probably caused by instability of the arc and will be discussed later. If the reader will refer back to 9-4 he will see the first example of the second transient.

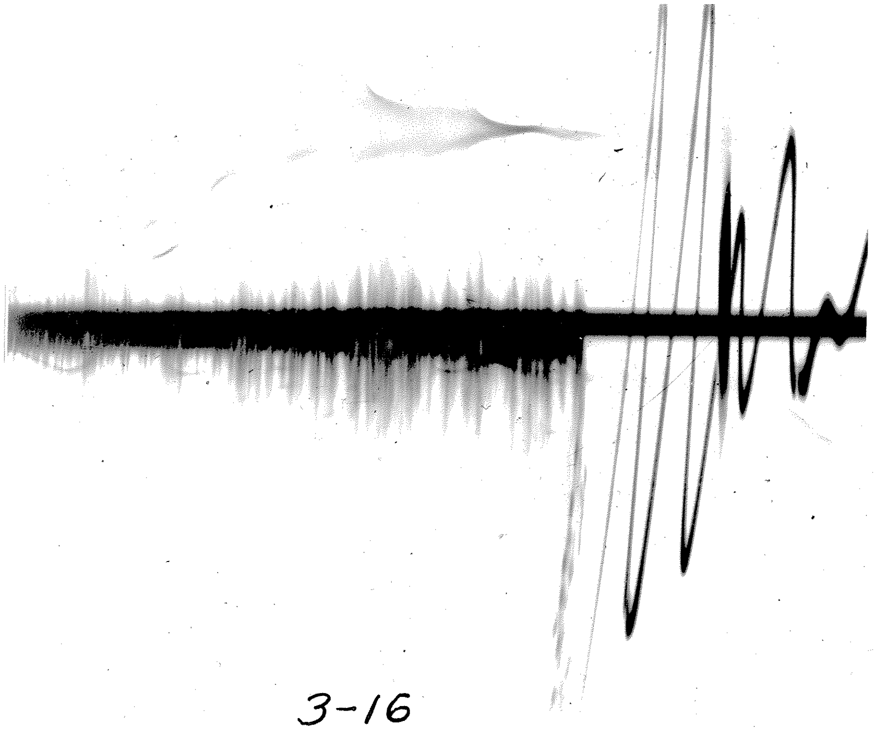
The cathode ray oscillograph has done two things however; (1) it has given faster and more conclusive pictures showing that these oscillations are damped sinusoidal waves; and (2) it has shown what the current time curve is for this phenomena. The current is found to decrease on a smooth sine curve, to have short jumps from this position, and to drop from a value of a few amperes to zero within a very short time, probably less than a microsecond. Sometimes short pulses occurred after this, but in general the current was zero. The transformer used, with its inductance and capacity could be expected to set up oscil-

4-7
V-t
15 kv.
5.7 amps
.005 sec.



4-7

The shape of the second transient stands out still more clearly here than in 3-7.



3-16

V-t

2.3 kv.

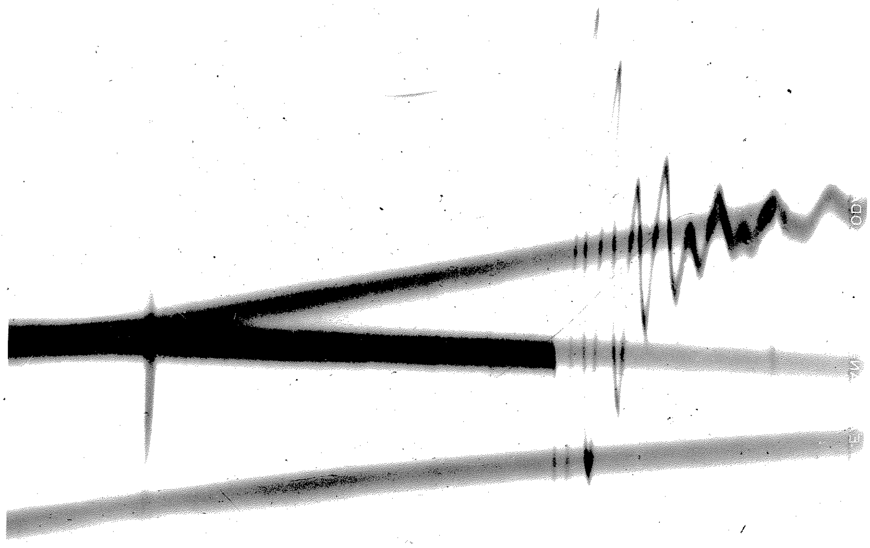
29 amps.

.0007 sec.

3-16

At the left of this picture is an example of the 2nd transient in the 2.3 kv. circuit. The phenomena at the right and center of the picture will be discussed later. The vertical streak at about the center of the 2nd transient was caused by the shutter over the film holder being slightly open, allowing this streak of light to enter. It is present in oscillograms 7-15 to 6-17. The second transient here is more complicated than simply a single frequency wave, possibly due to two circuits oscillating simultaneously.

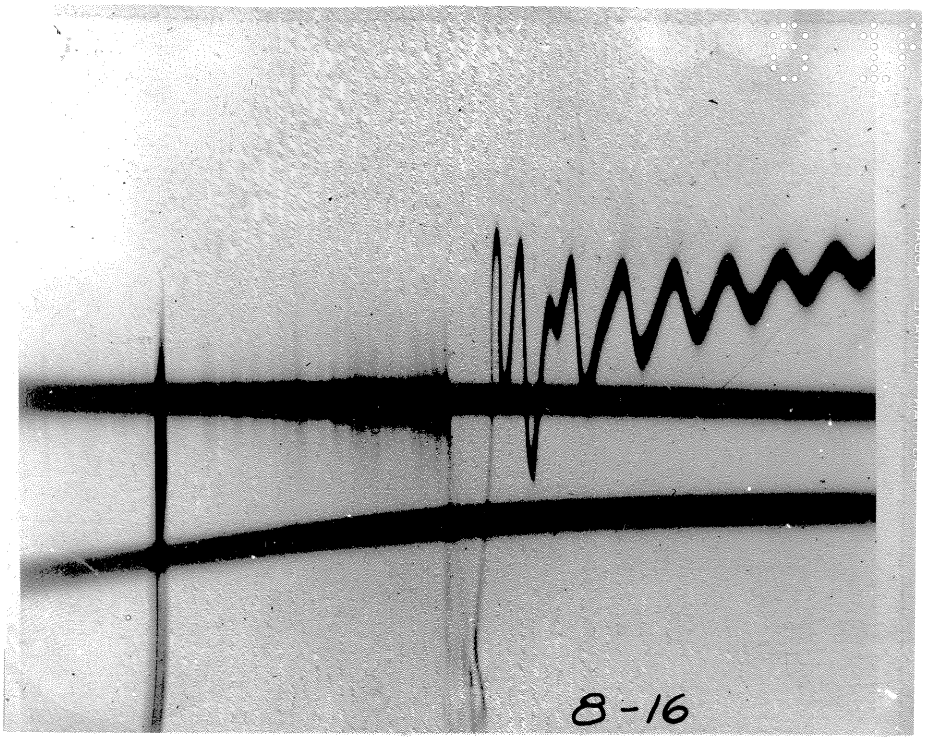
lations when the current is so sharply cut off. These would be sinusoidal and damped. Wellman traced the damping to the potentiometer. With the 2.3 kv. transformer complex oscillations with more than one frequency were found. The external circuit certainly determines the nature of these oscillations, the switch determining only the decay of current. It is possible for the voltage to rise to a point where field currents will occur, and at this point the effect is different from the normal 2nd transient.



10-16
V-t
2.3 kv.
32 amps
.001 sec.

10-16

This is another example of the 2nd transient. The other three lines are due to the beam crossing the film under the influence of the 50 cycle sweep coil, once at zero and twice at open circuit voltage.



8-16

V-t

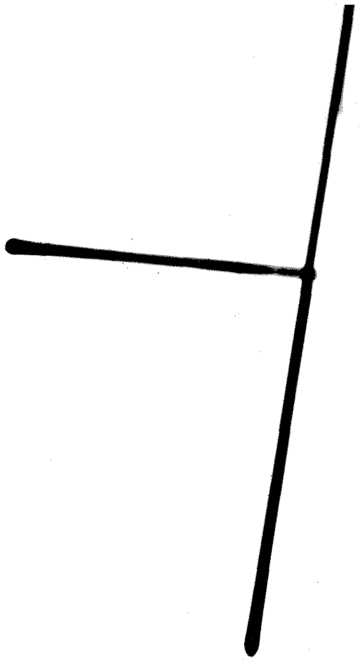
2.3 kv.

32 amps

.001 sec.

Here is a second transient under the same conditions as 3-16, but with a comparatively small amplitude. Again more than a single frequency is present.

While the case of current-voltage traces for the 1st transient have been discussed, there remains the case of the 2nd transient. All simple I-V pictures gave negative results, showing only a simple cross. This is consistent with the finding that the 1st transient would spread out so it would be too faint and with the fact that the current-time traces showed that the current cut off abruptly, reaching zero in a fraction of the period of the voltage oscillation.



9-10

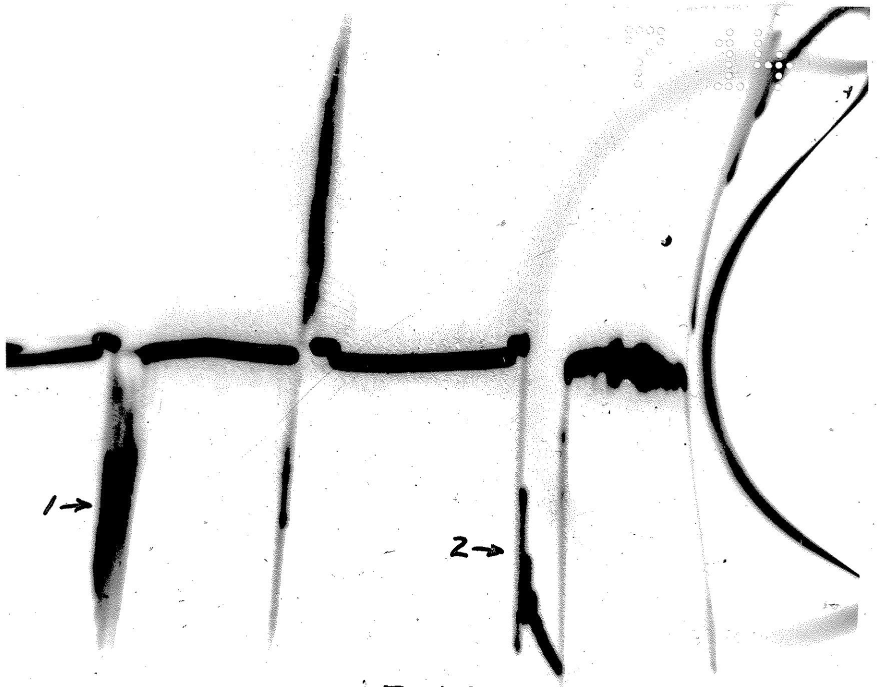
I-V

2.3 kv.

5.1 amps

9-10

A number of simple I-V oscillograms were taken to see if anything but the simple crossed lines representing current alternations with zero voltage, and voltage alternations with zero current could be found. The only thing found was the little trace where the spot came on the film from the influence of the electron shutter.



7-14

7-14

V-t

15 kv.

8 amps

.04 sec.

This oscillogram was taken under unusual conditions. The switch was placed with contacts slightly open, voltage applied, and the switch opened in the usual manner. The switch struck of its own accord. The transients marked (1) correspond to 1st transients, and like the 1st transient of 2-7 lead to an arc. The straight lines are low arc voltage traces. A characteristic 2nd transient can be seen building up, (2), but a voltage was evidently reached which broke down the electrode spacing. The timing device gave a peculiar appearance to the last part of the trace, but apparently the switch really became open before the beam left the film. The cause of the small steps of almost zero voltage is not known, although it may reasonably be glow voltage. These steps or jumps come at the beginning and end of every other half cycle, both in this picture and in another taken at the same time. The ellipse in the background belongs to the large family of eccentricities of the cathode ray.

ANALYSIS OF ARC EXTINCTION

Probably the consideration in the vacuum switch which attracts the most attention is the phenomena of arc extinction. Since the actual change from arc to not arc occurs so rapidly, it is necessary to consider what happens before and after.

5-9

V-t

15 kv.

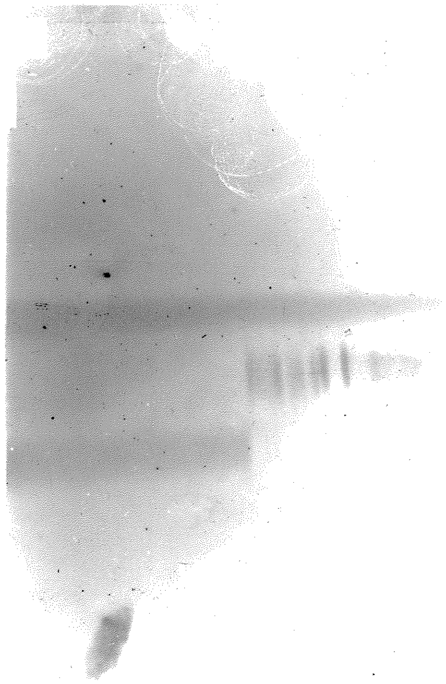
5.7 amps

0.015 sec.

5-9

Two exposures were made here, one of the switch opening transients, and one 20 cycles later of the open circuit voltage existing then. The point which is of interest here is that while the arc voltage is constant and low a good deal of the time, there are both small variations from zero, or fuzziness, and a few large magnitude kicks, indicating that the arc is not completely stable. The small step at the end of the arc is similar to that seen in 7-14, and may be a glow voltage.

Hamilton found the steady arc voltage to be around 15 volts. Some of his pictures show events during the arc period which were aside from the regular arc conditions. An examination of many of the cathode ray pictures of the arc reveals that although the arc voltage is usually a straight constant line, there will be bumps, or even traces extending far from zero.



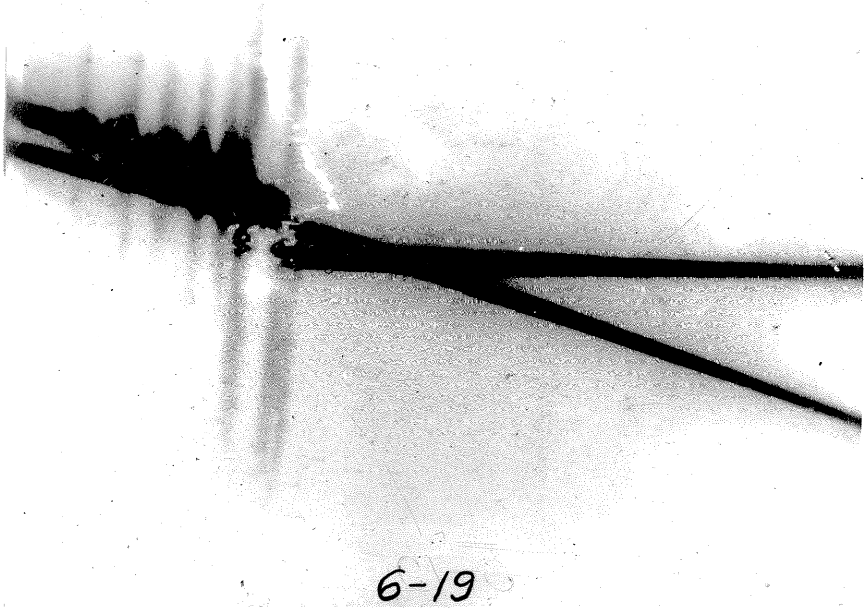
7-17
I-t
2.3 kv.
18 amps
.00026 sec.

7-17

Here is another example of the current cut off. The picture is interesting because of the holes in the current trace after the cut off, and because it is the fastest picture obtained of this type. With only 260 microseconds for 4.5 inches of film, no measurable distance can be detected for the time of current fall, indicating that it takes less than one microsecond, although no minimum is indicated.

A general fuzziness is often observable.

It was found possible to synchronize the timing to the current extinction. When this was done it was discovered that the current had many apparent discontinuities both before and after the arc extinction. These repeated so many times that it was hardly possible to doubt them. They lead to the conclusion that the arc is not stable, but tends to go out before it reaches the actual current of extinction. More important



6-19

6-19

I-t

2.3 kv.

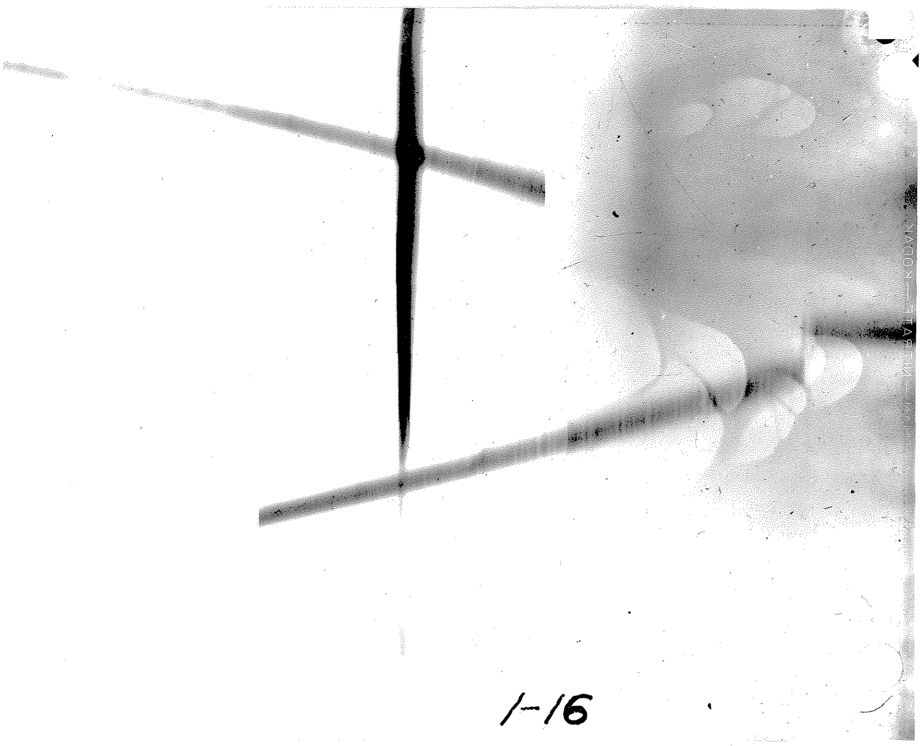
22 amps

.001 sec.

Two crossings of the film are seen here. The straight, even line is interesting for showing that the shunt gives perfect current recording for the region near zero current. The trace to both sides of the main trace is evidence that the current oscillates unsteadily, even reversing, during the critical period of arc extinction.

still was the fact that there were seen to be pulses which oscillated with a great enough amplitude so that there was a current of direction opposite to the normal current.

The voltage curve accompanying these current curves showed very rapid surges corresponding to the current surges. These would exist in short intervals between steady arc voltage. When the arc finally went out it meant that these voltage pulses did not return to zero but went to high values, until finally the fine tooth structure gave way to the comparatively smooth trace



1-16

I-t

2.3 kv.

27.0 amps.

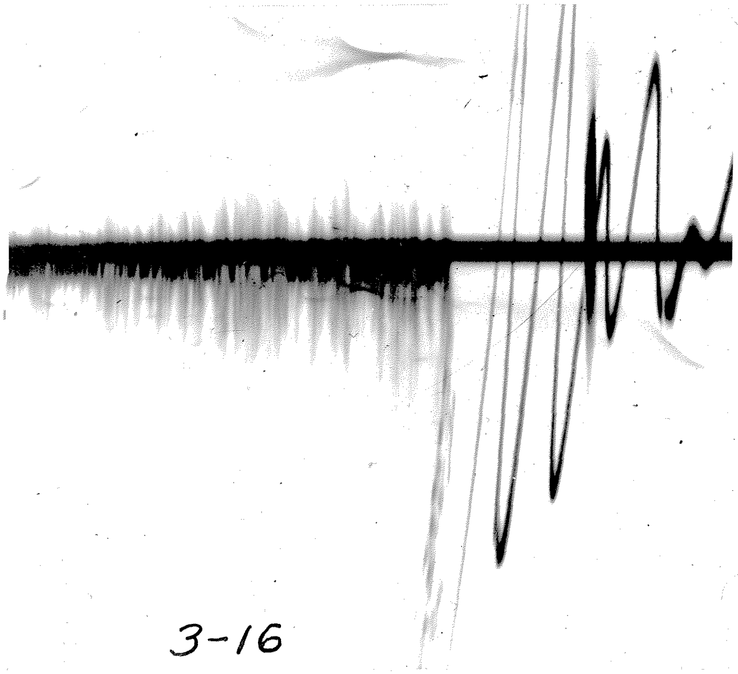
Although partly double exposed, this picture is of interest because it shows a current trace which starts from a perfectly smooth curve and gradually comes to have more and more empty spaces, or gaps, in its trace.

of the 2nd transient.

If, on the other hand, we go back, we find that about 500 microseconds before the arc goes out these pulses were less frequent, and still earlier they were not to be found.

2-16

2-16
I-t
2.3 kv.
29 amps
.0007 sec.



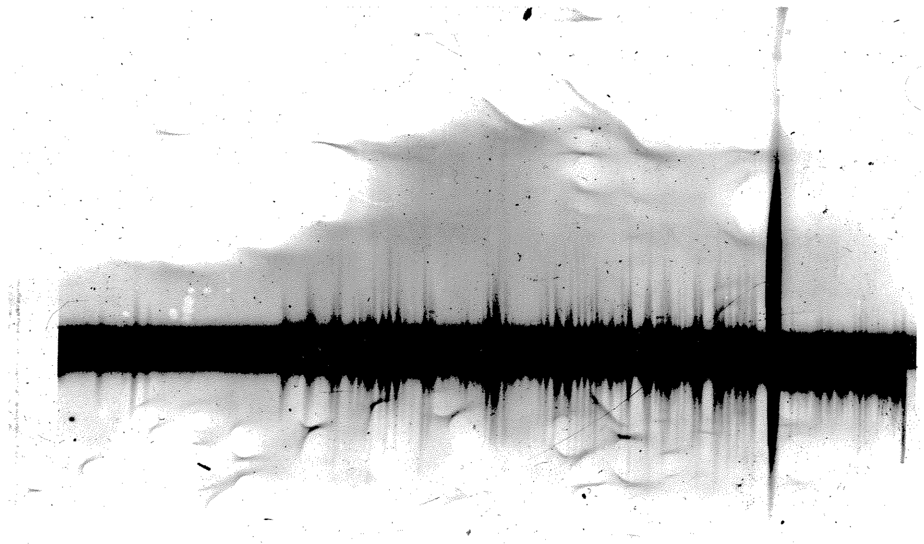
3-16

3-16
V-t
Same kv,
amps, time,
as 2-16

It is interesting to consider what voltages accompany the currents just shown. Comment is hardly needed except to point out that the first rise to the high voltage taking the beam from the picture corresponds to the time of current extinction. Since these pictures are consecutive rather than simultaneous, the timing coordination is not exact.

This indicates that the surges were the result of the arc condition rather than of any oscillations initiated at the beginning of the arc by the outside circuit.

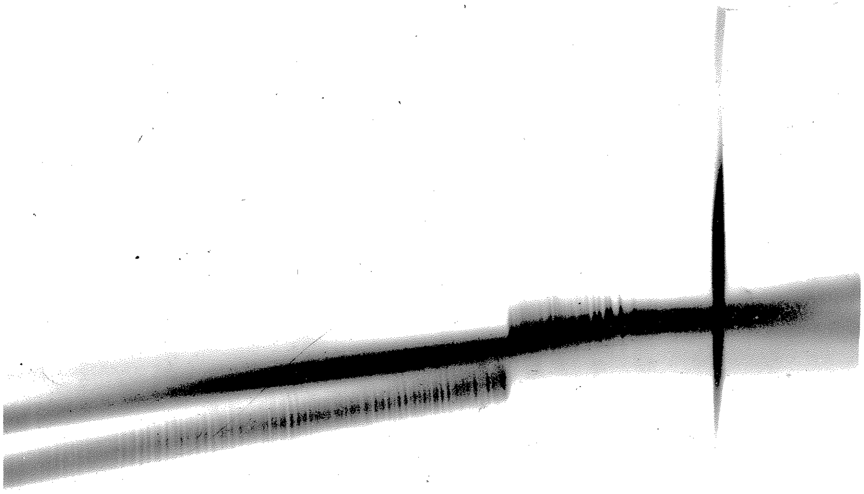
If the supply of electrons from the cathode is obtained by the field currents resulting from the positive ion space charge, as is demonstrated by S. S. MacKeown in the Phys. Rev. of August 15, 1929, these surges may reasonably be the manifestations of changes in the position and charge in that space charge. Equilibrium in the arc is necessarily a dynamic equilibrium and if there is any change in one factor, say



4-16
V-t
2.3 kv.
29 amps.
.0007 sec.

4-16

This oscillogram is a companion to the last one, differing only in the timing. The beginning of the second transient is seen at the extreme right, hence the body of the picture just precedes that of 3-16. Compare the thickness of voltage transients on the left and on the right.



5-16

I-t

2.3 kv.

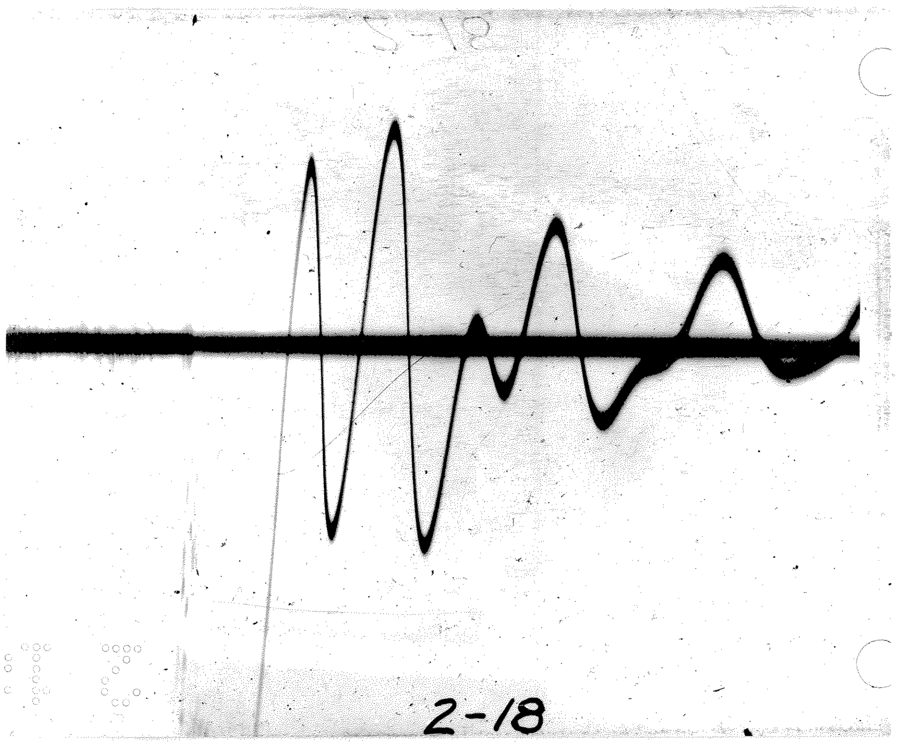
29 amps

.0007 sec.

5-16

This oscillogram is similar to 2-16. Over two lines cross the film, but the interesting one stands out. The object of showing this picture is that the cloudiness above the zero current position and following the current cut off gives a hint of where the beam is during the time represented by the open spaces. While the cathode ray at times is a dotted line rather than a continuous line, it would hardly be expected to repeatedly become broken up at this particular point, while being a continuous line before and after. For this reason it is believed that the open spaces really are caused by sudden surges of current.

the supply of positive ions, the result may be decreased electron emission. A voltage would build up until the emission was increased. The chances are that even in a steady arc there are such changes, but the rapidity is too great to measure. As the current approaches the cut off value, the changes in the arc would probably start and show effects be-



2-18

V-t

2.3 kv.

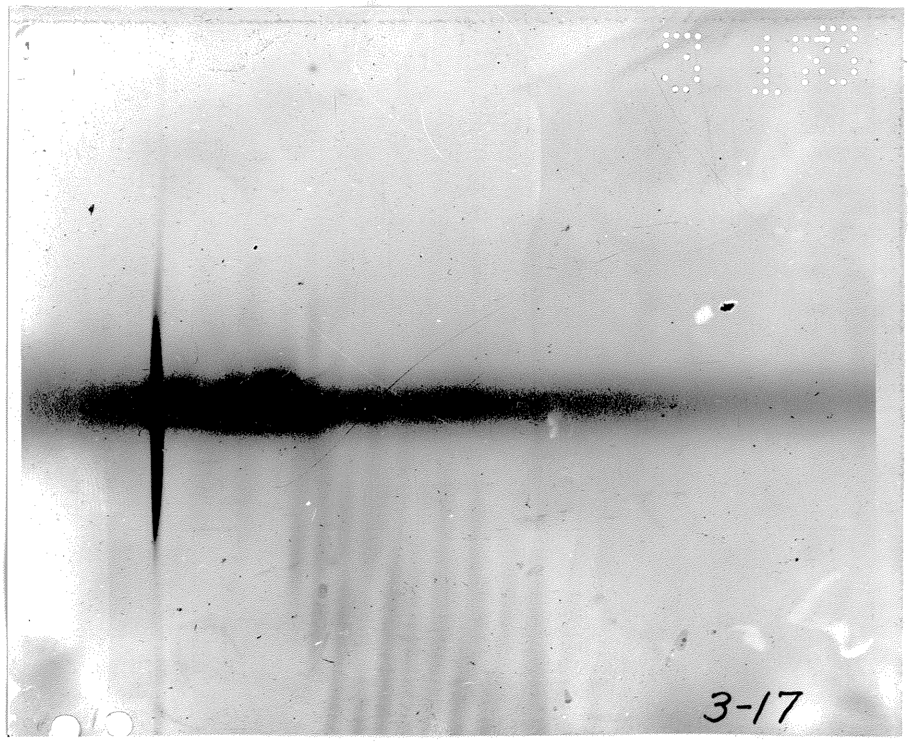
22 amps

.00026 sec.

This is the most rapid picture of V-t at the period of arc extinction which has reasonable clarity. The intermittent transients during arcing, the peculiar transient while the voltage is rising, and the well defined 2nd transient are of interest. The reader will find another example of the transient of the first voltage rise to high values by referring back to 8-16.

fore, as well as right at the time the arc goes out.

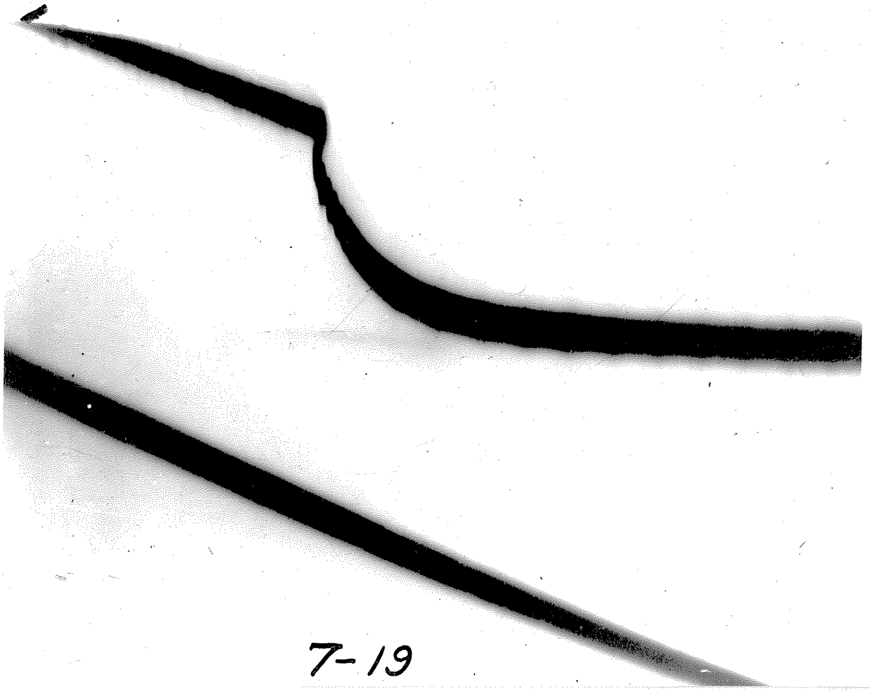
In application, the vacuum switch depends upon changing the conditions between the electrodes rapidly enough from ionization to perfect insulation. No limits have yet been found to the rate of decay of the arc condition. It is worth noting that the problem of deionization and the problem of getting a large enough space free of ions to prevent field currents, become the same problem if the extinction of the arc means physically the decrease of the cathode gradient by the decay of the positive space charge.



3-17
V-t
2.3 kv.
15 amps
.00010 sec.

This is more rapid than 2-18. It is believed that the vertical traces are the rising voltages of arc extinction. They are about three microseconds apart.

On comparing and combining these results with Hayward's, the conclusion that he reached that there were voltage oscillations with current continuing in the same direction is found to be extremely doubtful. There are four possible places in which the error might have arisen. In the first place, if the D. C. excitation is not given around five cycles



7-19
I-t
2.3 kv.
5 amps
.001 sec.

In order to compare the records of the current coil and the current shunt as regards the arc decay, several pictures were taken. This one was taken with a thirty turn coil carrying the 5 amperes, the deflections being due to the magnetic field of the coil. The 30 turns were outside turns of the two coils of 50 turns each, the other turns simply being left open circuited.

to build up before letting the beam on the film, there may be traces with low voltage excitation. Frequently the zero position as well as the sensitivity changes with voltage, so that he may have, as the author has, obtained regular 50 cycle oscillations which were separated due to the gradual shift of the zero position. The method of cathode excitation he used makes this quite possible. The second possibility is that his carbon rod potentiometer may have behaved irregularly, as the sparks along its surface under operation indicated. The

10-19
I-t
2.3 kv.
5 amps.
0.001 sec.

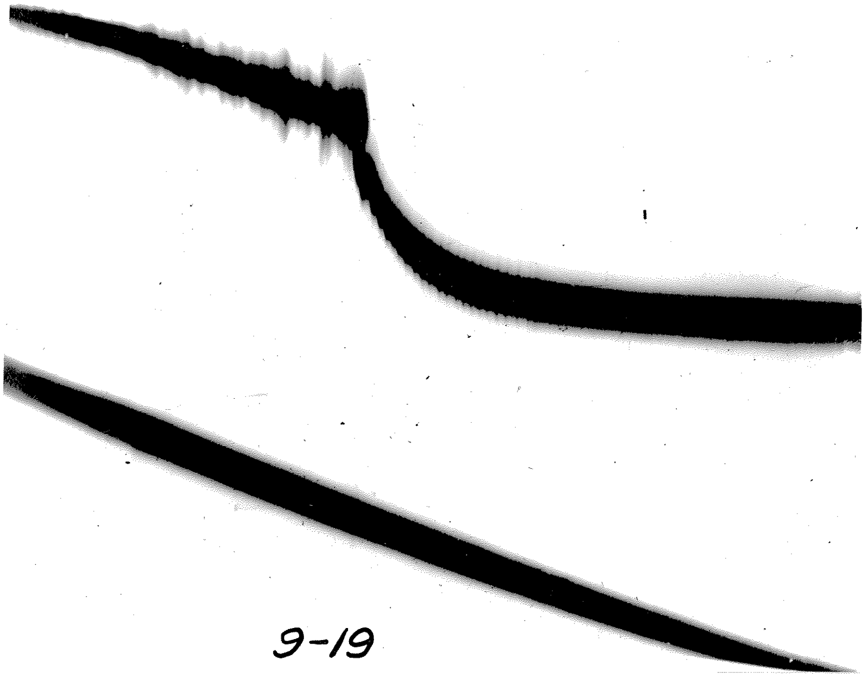
10-19

The conditions of this picture were the same as those of 7-19 except that the current deflections were caused by the water shunt voltages, the current coil being shorted and grounded.

third possibility is that the current coil might have had a sufficient choking action to smooth out the sudden drop of current, with the result that the voltage oscillations occurring in reality after zero current was reached might still come before the apparent current curve had reached zero. Fourthly, metal such as the deflection plates or the caps on their leads might have given eddy currents in the field of the current coil which lasted after the current in the coil fell to zero.

All of the cases in Hayward's thesis occurred at the time of arc extinction. The results presented here all show (1) that the time between the end of the normal arc and zero current was extremely short, too short to allow anything but the shortest trace to be visible, and (2) that all sinusoidal waves were comparatively slow. The crux of the whole matter is that in his Fig. 6, the current makes a gradual bend to get to zero while in all of these pictures it makes a right angle, with no rounding of the corner.

SOME UNEXPLAINED CASES



9-19

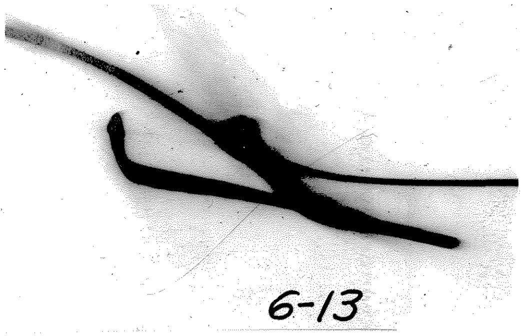
I-t

2.3

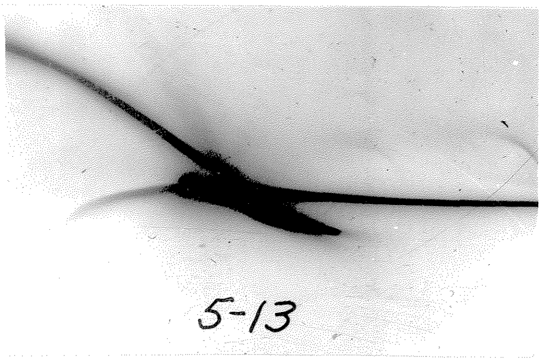
5 amps

.001 sec.

The same as 10-19 except current coil connected to high side of shunt.



6-13



5-13

Both: I-t, V 15 kv. 0.15 amps .005 sec.

The scheme here is the same as in the case of 10-12. The only clue to explain them is that the half dozen oscillograms preceding these had had double and triple cathode spots, besides behaving queerly in general.

ACCOUNT OF EXPERIMENTAL WORK

The tangible results of this research are in the form of oscillograms. The most important are the cathode ray oscillograms, the magnetic oscillograph being an auxiliary used only at the end of the work. The cathode ray oscillograph gives a spot which varies greatly in its intensity, sharpness, and uniformity. These qualities are obvious, but not so obvious are some of the tricks of these rays. It has been found that the zero position sometimes varies with voltage. With high vacuum the spot varies periodically in size with time, so that when displaced regularly it consists of alternate heavy and light portions, which became dots when carried to the extreme. The spot is often elliptical instead of circular. Most disconcerting is its occasional habit of becoming double or more complicated. In all oscillograms the cathode is excited by direct or constant voltage which is brought suddenly to a low value by discharging the condensers of the rectifier by a synchronously short circuited gap.

The deflections of the spot are obtained by placing voltage on either a horizontal pair of plates or a vertical pair, or by magnetic fields. An electron shutter is used consistently in the pictures. It simply sets up a field which is sufficient to keep the ray from the film while a synchronous switch is closed. Many times the trace of the ray can be seen as it changes from the position dictated by the electron shutter to the position determined by the other factors.

Whenever deflections proportional to time are wished, they are obtained from the magnetic field of the sweep coil. The sweep coil is furnished current from (1) the 50 cycle, 110 v. circuit of the oscillograph, (2) a 5 cycle, 11 volt alternator connected to the synchronous switches, (3) the same alternator running faster to give 15 cycles, (4) a storage battery, which gives a current varying exponentially with time. A bias shifts the zero to one side of the film. In all films the time deflection is practically proportional to the first power of time. With the 50 cycle sweep several crossings of the film will be seen. The calibrated oscillator in the oscillograph was used intermittently to find the speeds.

A potentiometer was used for a voltage divider to give deflections proportional to voltage. For deflections proportional to current, water shunts were usually used, so that the voltage to the deflector plates would give the current. Some oscillograms were taken with a wire shunt. A few were taken using a coil of wire to give a magnetic field, as Hayward did. These will be specially marked.

In making prints the negatives have been turned so as to use the emulsion side and give time from left to right.

About the middle of August, 1930, the old vacuum switch, which was of the same design as used by Lindvall, Hamilton, and Hayward, broke up. The last picture with the old switch was 4-7. A new switch was built and put in operation on September 2nd. A picture of it is given in the Apparatus section. It was simply a glass cylinder placed between two steel plates with rubber gaskets covered with shellac for seals. It pumped down when first put in operation and behaved well afterwards. Some trouble was experienced with arcs puncturing the glass tubing during the gas discharges that always occur when first outgassing the switch. The trouble was due to having put the pumping connection on the high voltage end. An electrode was placed inside the vacuum, so that any unusual discharges would be conducted to ground through a safe path. This switch behaved about the same as the other as far as appearances were concerned except that green fluorescence due to electron currents often appeared on the glass cylinder when voltage was applied, although no other discharge might be taking place. When it became necessary to take this switch apart, it took but three-quarters of an hour to take it apart and reassemble; and in another hour and three-quarters the vacuum was better than 10^{-4} mm., of mercury. Practically every picture was taken with the vacuum better than 10^{-4} mm.

Many negatives were darkened and marked as a result of standing several months in the High Voltage Laboratory where

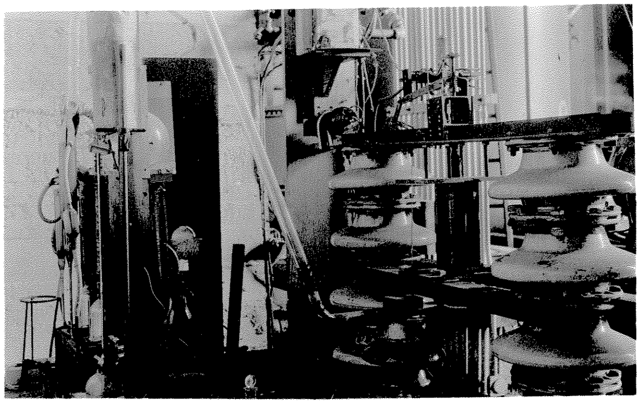
Dr. Lauritsen was working with very high voltage x-rays.

Oscillograms up to and including 8-10 were taken with the potentiometer measuring the voltage across the switch and the current shunt. The connections were changed so that pictures after that had the potentiometer measuring simply the switch voltage, and the current shunt measured switch current and potentiometer current. The latter was completely negligible.

ACKNOWLEDGEMENT

The author desires to acknowledge the aid given to the project by a number of people. He is particularly grateful to Edson Lee, who devoted the whole of the Summer of 1930 and his research time through the Fall to this work. William Clancy has often contributed his skill and practice in glass-blowing to constructing and repairing the vacuum switch and the cathode ray oscillograph. Julius Pearson has helped by constructing the metal parts of the new cathode tube for the oscillograph, and giving aid and advice in various other matters. Needless to say, Professor Sorensen continues to be the inspirer of all this work. Professor Mackeowen and F. C. Lindvall have often produced new ideas in the discussions we have had together.

IX - APPARATUS



The Second Vacuum Switch

1. Vacuum Switch
    1. First Switch
       (same as Hayward's)
    2. Second Switch
    3. McLeod Gauge

2. Power Supply

.1 22 v., open delta transformer

.2 15 kv. transformer: 1 o; G. E. 2245092, Type H, Form G, 230/115 to 15,000; 50 cycles; 10 kva.

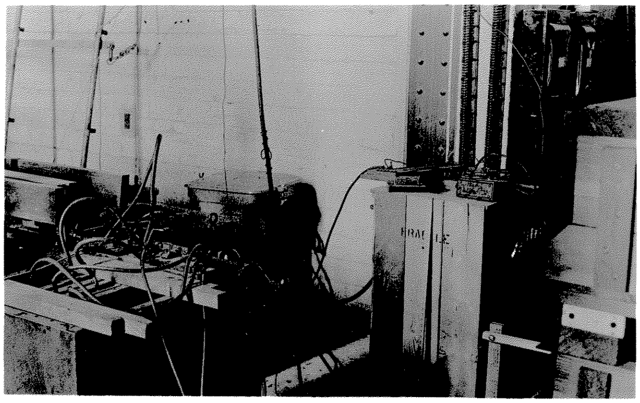
.3 2.3 kv. transformer: 1 o; Westinghouse: 1608090, type S, style 316596; 230 to 2300; 50 cycles; 25 kva.

.4 Iron Grids

.41 and .42 each .175 ohms.

.5 Water barrels 2.51 and 2.52

.6 Ammeters, Weston
Model 155, Ranges
.750, 2.0, 5,
10, 15, 25, 50,
75.



The 15 kv. and the 2300 volt transformers, a water barrel and meters.

3. CATHODE RAY OSCILLOGRAPH

.1 Cathode tube

.2 Vacuum system

.21 Reservoir

.22 Capillary

.23 Vacuum gauge

.3 Fluorescent screens

.4 Cathode Excitation

.41 Kenotron

.411 Filament Transformer

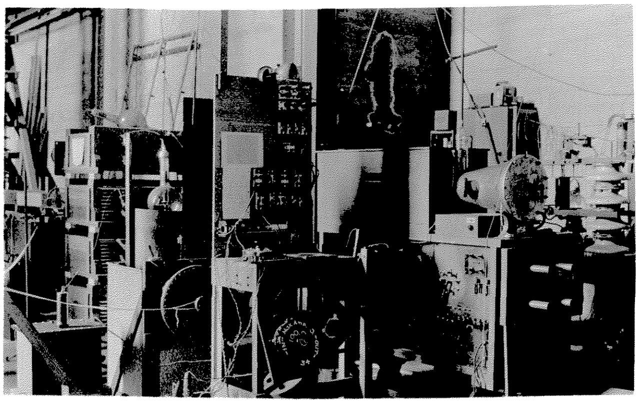
.412 Filament Rheostat

.42 Condenser

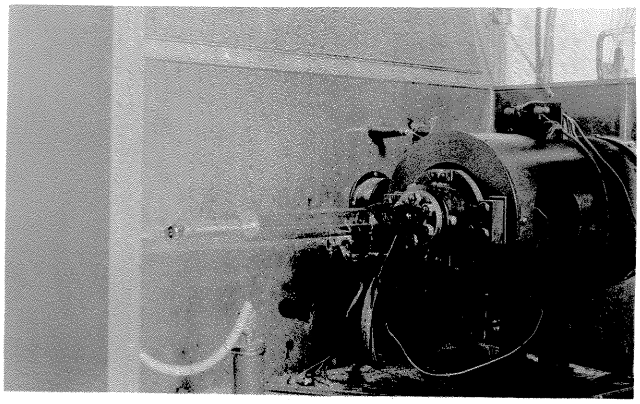
Transformer Primary

.43 Limiting Resistance

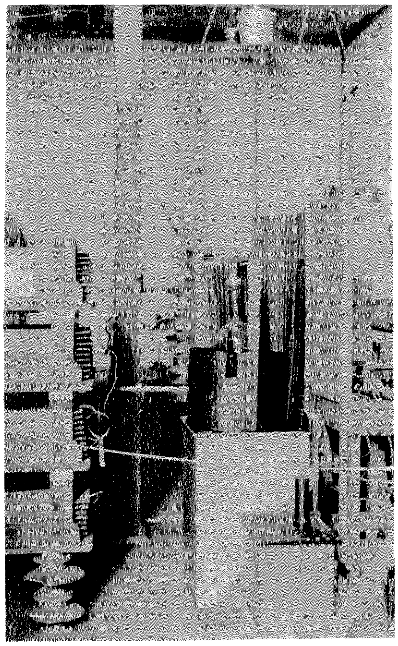
20 ohms, 18 amps, taps 1-61



Cathode Ray Oscillograph



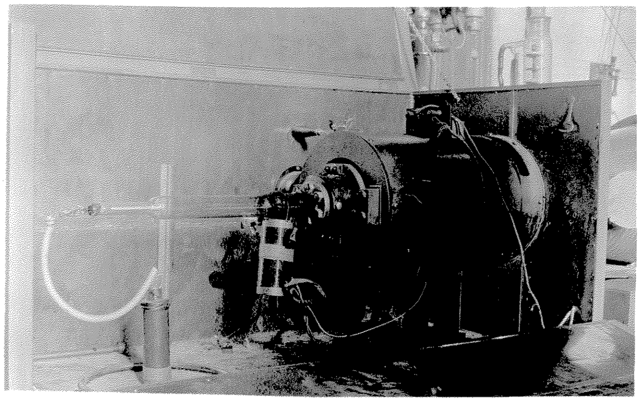
Cathode Tube showing Vacuum Connections



Kenotron, Condenser and Transformer

3.5 Electron Shutter

Air coil, 150 turns,
24 enameled wire,
5 cm. diameter; 9 cm.
length.



Cathode Tube with
Electron Shutter in
Place

3.6 Sweep Coil System

.61 Coil

.62 Limiting impedance

.621 Reactor (built into oscillograph)

.622 Resistance 0-1760 ohms

.63 5 cycle alternator

Rated 110 volts, 50 cycles 1500 revolutions per minute

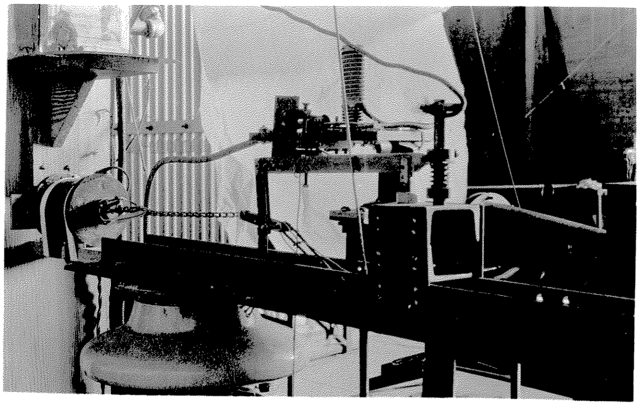
Run 11 volts, 5 cycles, 150 revolutions per minute
to 10-15 on 1/1/31.
33 volts, 15 cycles, 450 r.p.m. after 1-16, 1/5/31

.64 Switch lever Contacts

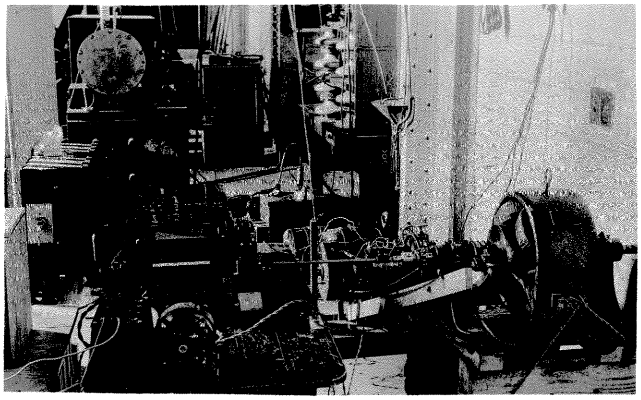
.65 Series and Parallel Spot Shifters

.651 Resistances

.652 Batteries



Switch Lever Contacts
And Switch Trip
Mechanism



The 5 Cycle Alternator,
Magnetic Oscillograph, etc.

3.7 Oscillator

3.8 Synchronous Contacts

.81 Discharge gap for
    Cathode Excitation

3.9 Voltage and Current
    Measuring Devices.

- .91 Potentiometer
- .92 Current Coil
- .93 Wire Shunts
- .94 Water Shunts

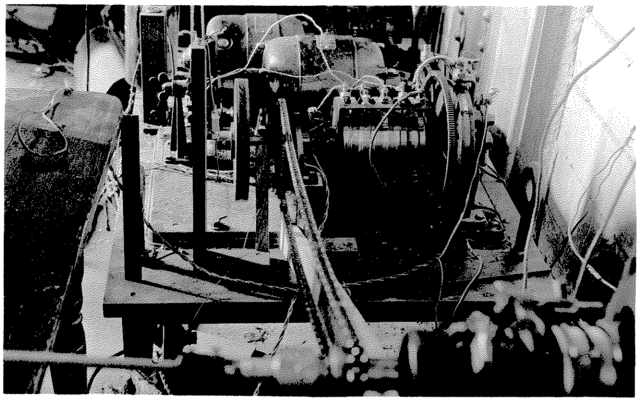
4.0 Magnetic Oscillograph

.1 Potentiometer

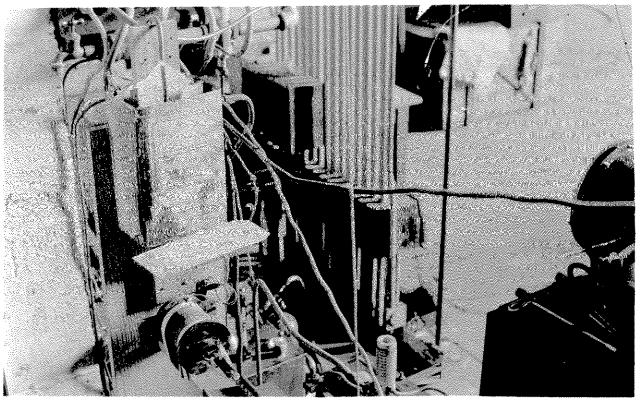
.2 Amplifier

.3 Synchronous Drive

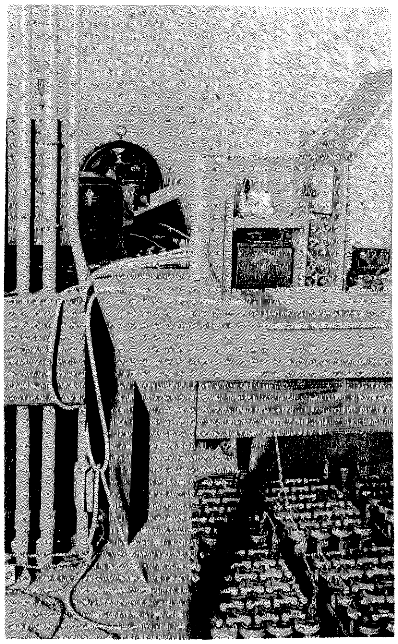
.4 Trip device



Synchronous Contacts

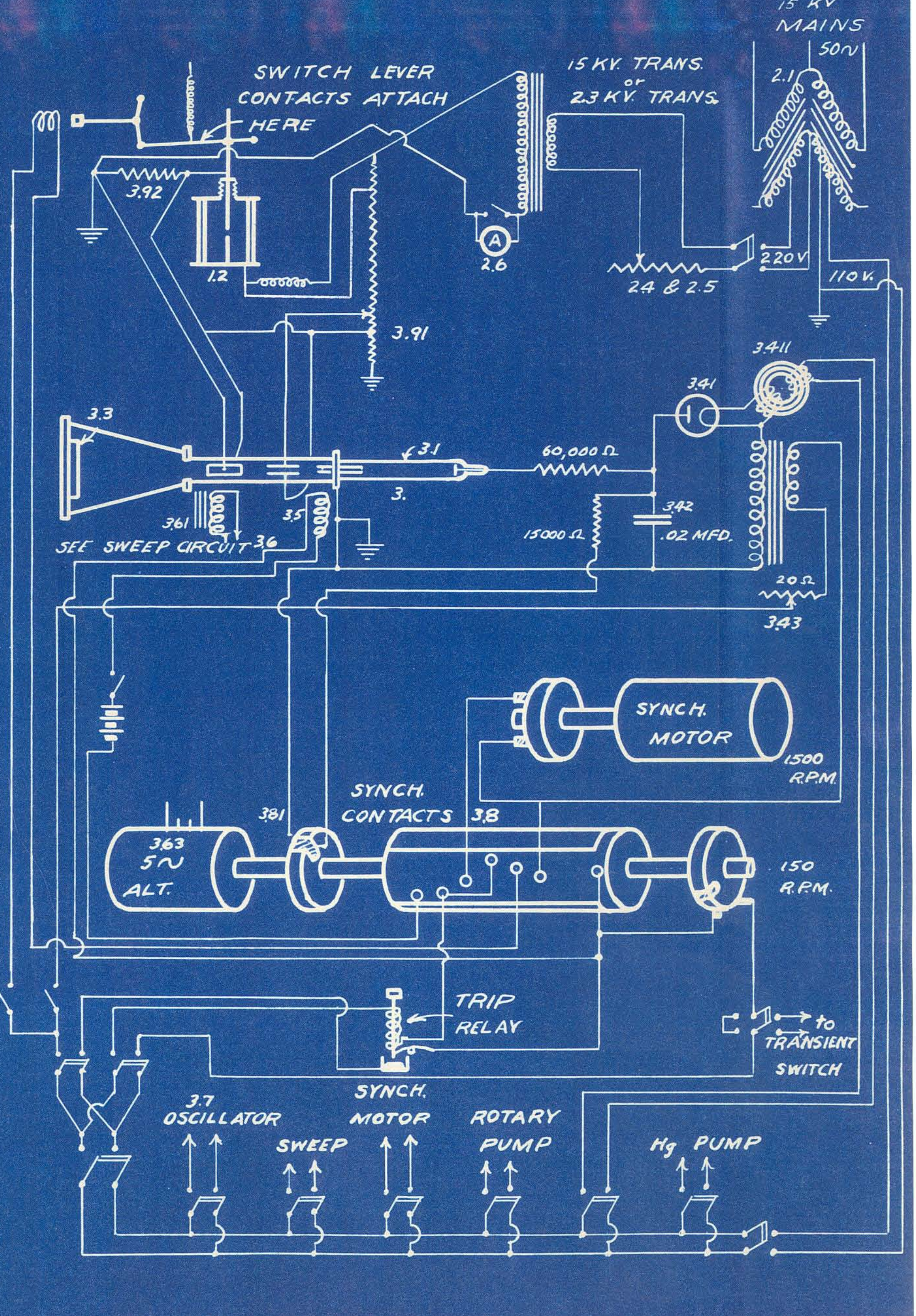


Current Water Shunt

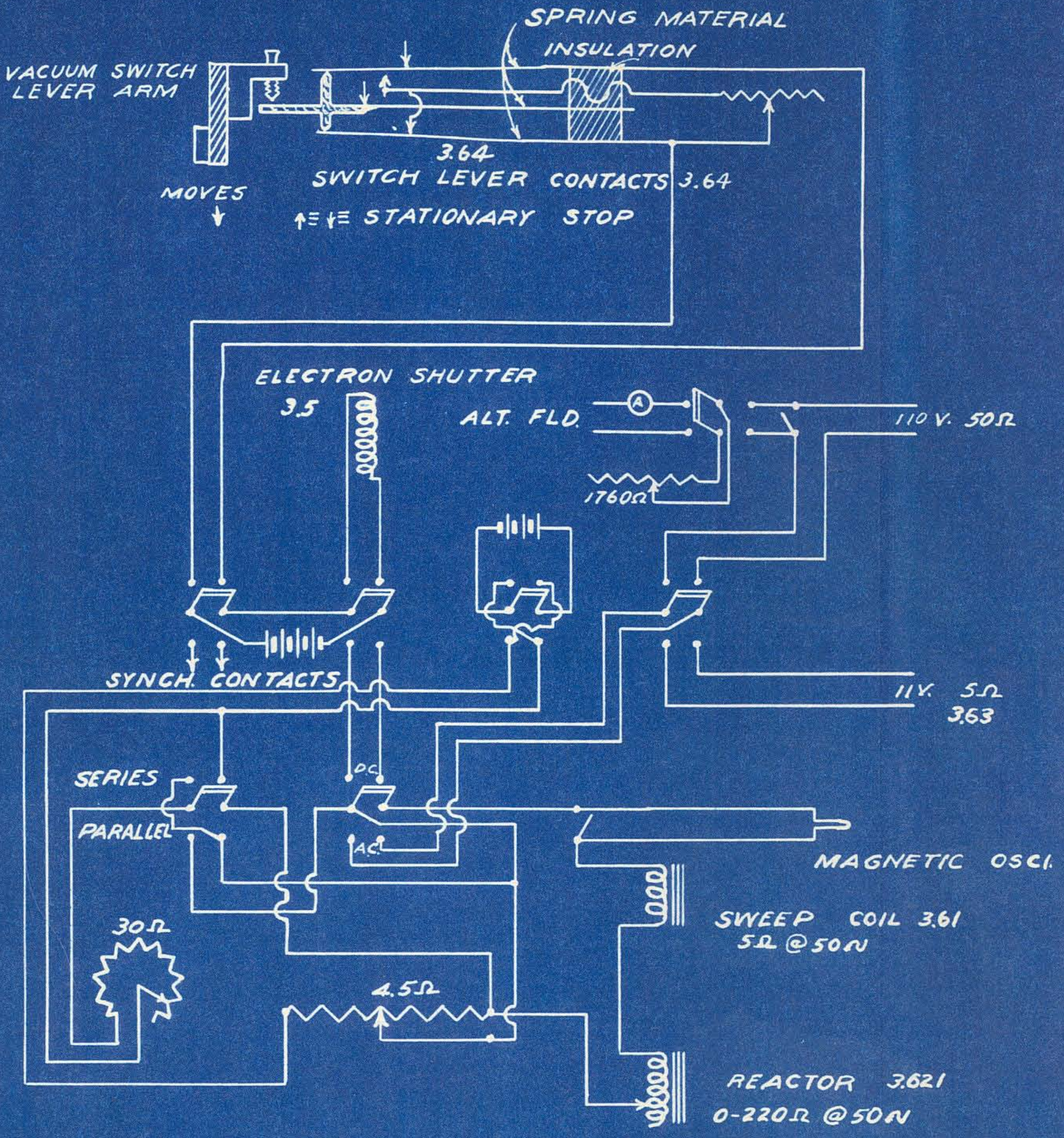


Amplifier for Magnetic Oscillograph

WIRING DIAGRAM

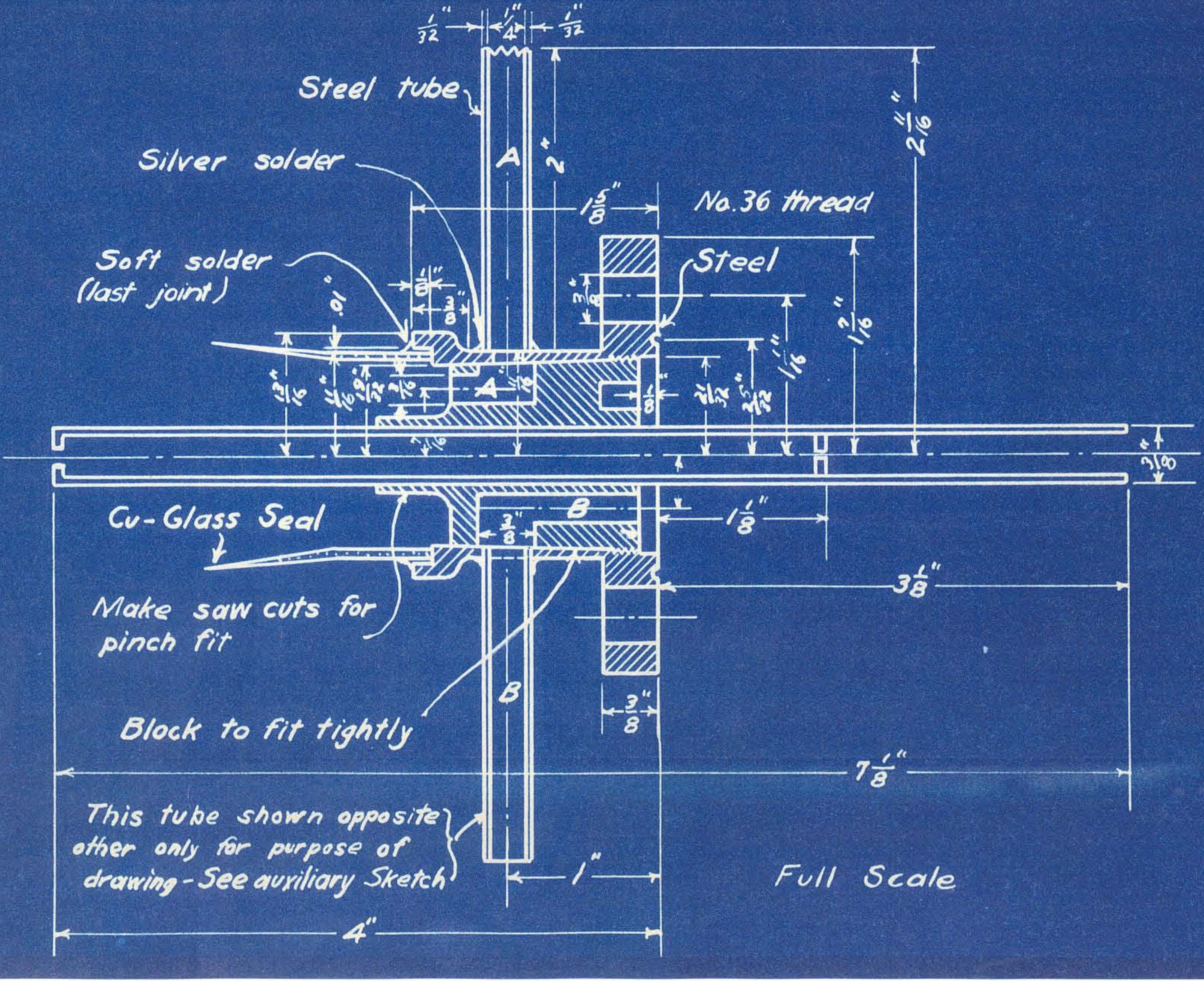


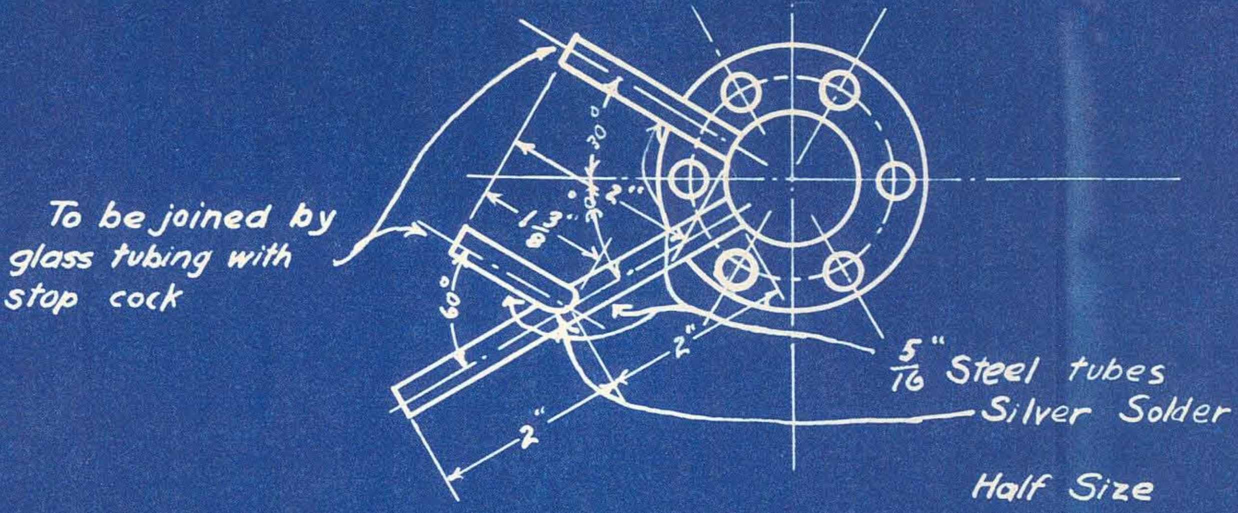
WIRING DIAGRAM
SWEEP CIRCUIT 3.6



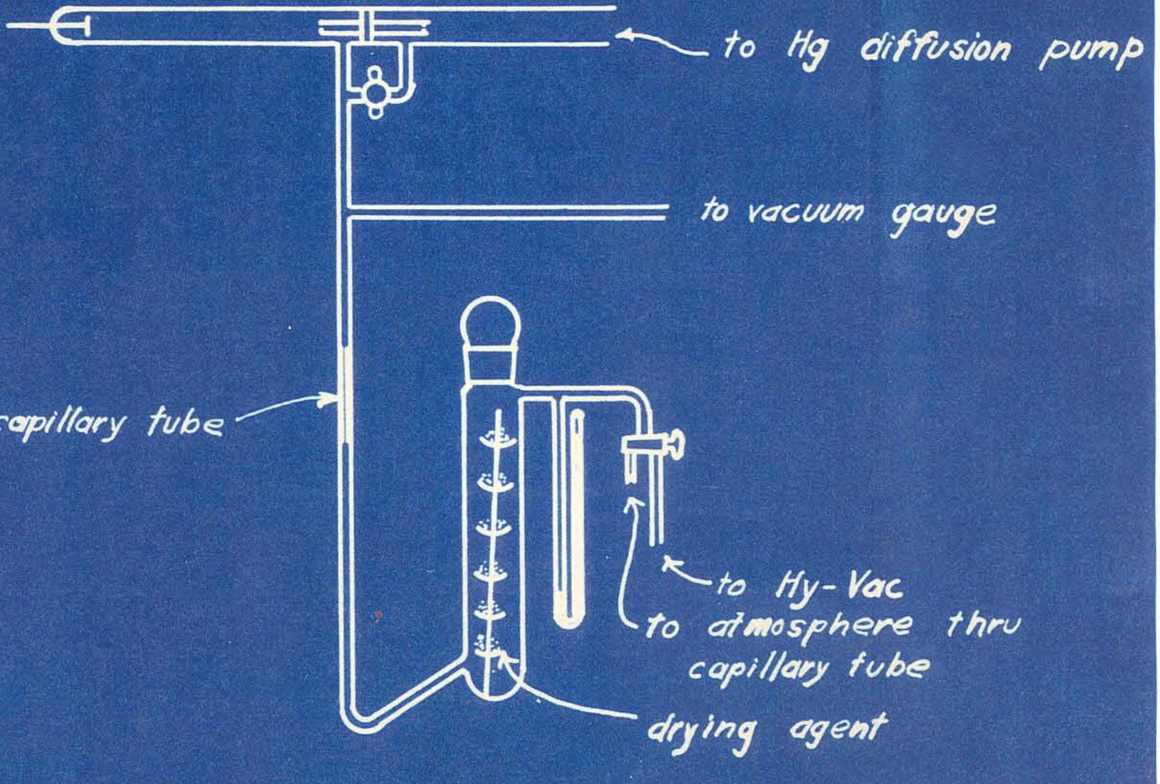
END PIECE FOR CATHODE TUBE FOR G.E. CATHODE RAY OSCILLOGRAPH

SHEET 4





END VIEW OF END PIECE
FOR CATHODE TUBE



CATHODE TUBE PRESSURE SYSTEM