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A STUDY OF THE EFFECT OF SPACE CHARGE
ON THE DIELECTRIC AND CONDUCTIVE
PROPERTIES OF AN INSULATING FLUID

GENE F. SULLIVAN

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Gene F. Sullivan

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ON THE DIELECTRIC AND CONDUCTIVE PROPERTIES
OF AN INSULATING FLUID

by

Gene F. Sullivan
//
Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ELECTRICAL ENGINEERING

United States Naval Postgraduate School
Monterey, California

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ELECTRICAL ENGINEERING

from the

United States Naval Postgraduate School

ABSTRACT

The effect of the space charge on the properties of an insulating fluid were studied under flowing and static conditions by comparison of the current and space potential distribution for various voltages applied to parallel plates in the fluid. The static test showed a building up of space charge which (1) reduced the current over the first 15 to 30 minutes to a final value of $1/2$ to $1/5$ of the initial current, (2) caused the potential distribution to be non-linear, and (3) increased the bound charge on the plates. The test with just measurable flow showed the space charge and its effects were virtually eliminated. The experimental data also permitted estimates of the amount of space charge and the charge mobility.

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1. Introduction.

The conductivity of insulating fluids has long been recognized as ionic in nature, but nevertheless is anomalous in character, i.e., not subject to exact expression by empirical laws /5/. When these fluids are subjected to a constant potential, the current is high at first and then slowly decreases to a final value after a half hour or more. This characteristic is common to all liquid dielectrics. Even the most highly refined insulating oils (with conductivities as low as 10^{-18} mho per cubic centimeter) still show this phenomenon although both the initial and final currents are greatly reduced. In fact, this phenomenon only tends to disappear as the conductivity is increased to about the value of electrolytic fluids.

J. B. Whitehead and his associates at Johns Hopkins University in the late 1920's and early 1930's investigated this current-time relationship in a number of such fluids and waxes. Three types of behavior were subjected to a series of tests and were found to be closely related; (1) the so called "d-c cleanup", or reduction of a-c dielectric loss following the application of a d-c potential for a long period of time, (2) the current time relationship, and (3) the non-uniform potential distribution due to the accumulation of space charge /6/. Another interesting behavior which was observed was that, on reversing the potential after steady state had been established, the current was at first low, then rises sharply to a peak value, and finally decreased to a value equal to what it had been in the opposite direction.

When in the steady state, the current-voltage relationship in a pure insulating liquid is very similar to that of gases, e.g., diodes. This suggests that the ionization theory developed for gases might be applied to the study of conduction phenomena in liquids. Non-uniform potential

distribution and space charges are found in gases and are in accord with ionization theory. The ionization theory, however, can not be used to explain the peak current common to insulating liquids following the reversal of potential. This can be explained by the "sluggish ion" theory /1/. Ion mobility for insulating fluids has been determined by various methods to be of the order of 10^{-4} cm./sec./volt/cm., which corresponds to the mobilities of ions in electrolytic solutions. In the neutral state some ions exist, and some of these ions attract to themselves a cloud or shell of neutral molecules. When a potential of less than 3000 volts/cm. is applied, there will be a motion of these large "sluggish ions" and any newly formed ions. As the ions arrive at the electrodes, some of the old ions will retain enough of the neutral molecule envelope to insulate the ion and prevent discharge. Thus the space charge begins to accumulate. After steady state has been established, the newly formed ions account for practically all the current. On reversal of the potential, these ions also account for the initial current, while the peak current is due to the later arrival of the "sluggish ions" which have shed their shells /1/. The results of these tests are in complete accord with this theory.

This thesis is a report of further study of some of the properties of an insulating fluid, as extended to include the case where the fluid is in motion. A considerable portion of the laboratory work involved reproducing the results of Whitehead and Minor /1/, This also allowed time to solve any instrumentation problems that arose and permitted a check on the results obtained from this part of the test. A major difficulty was the determination of the potential distribution using floating point methods /7/ for the case of the static test. It was believed that the use of electrostatic voltmeters would minimize the current drain from the probe so that the

potential measured would actually be that at the point probed. This method worked quite well for the case of the flowing liquid, but was very inaccurate for the static case. (The measured voltage varied erratically with time, even when the current measurement indicated steady state had been established.)

While the conductivity of a highly refined insulating oil is quite low, the degree of purity, or the amount of contamination (moisture or sludge), may increase its conductivity a thousand fold. This is not the case for an electrolytic fluid /3/. In these tests it was found that the conductivity changed very little during the first period of test when no flow was involved, but increased about 30 fold due to contamination the first day that the fluid was pumped.

In conducting the tests, a potential of 500 to 3000 volts was applied to the test cell (essentially a parallel plate, oil filled capacitor). Current versus time, and potential distribution were determined for the cases of (1) the static fluid and (2) the flowing fluid. Short time (RC) transients were shorted out as only the long time effects were of interest here. Charge mobility was deduced by reversing the applied potential and observing the time of the peak current (due to the space charge). The amount of space charge and its effect on the dielectric properties of the material was deduced by determining the change in the amount of the bound charge on the plates for the flow and no-flow conditions.

The author wishes to express his appreciation to Professor O. H. Polk of the United States Naval Postgraduate School, whose assistance and advice largely made possible the completion of this project. Appreciation is also extended to the personnel of the electrical engineering laboratory and machine shop for their assistance in modifying and installing the test equipment.

2. Equipment and Measurements.

The general arrangement of the test equipment is shown in Fig. 1 and Fig. 2. The 30 kilovolt source (in cabinet to the right) was available, but was not used during these tests.

(a) Test Tank.

The test tank, shown in Fig. 3, was fabricated using one inch and one-half inch lucite panels and measures 32x8x10 inches. The plates were two sets of 8x10x1/8 inch brass plates separated one-half inch. Fixed test probes were inserted 0.20 inch and 0.12 inch from one electrode, one being between each set of plates. This was to permit determination of the potential distribution at four points (by exchanging the high and ground terminals). The probe itself was a single 1/16 inch brass rod. The two sets of plates permitted two selections of plate length in the direction of flow, yet were close enough together to act effectively as one set of plates when connected in parallel. Fittings were attached to each end of the tank to permit pumping the oil through the tank and between the plates.

(b) Insulating Fluid.

The insulating fluid was a typical high grade transformer insulating oil, specifically, Shell DIALA OIL AX. Typical data supplied by the company as follows: Viscosity, 0.09 poise; Specific gravity, 0.872; pour point, -70°F; Dielectric Strength, 35KV/cm. Initially the actual conductivity was about 10^{-15} mhos per cubic centimeter.

(c) Potential Source.

The source used was designed as a high voltage supply system for the Navy Model TAJ-12 radio equipment. The unit shown in Fig. 2 behind the pump, consists of a DC motor driving the generator and its separate

exciter. Name plate data is as follows:

Motor	115 volts	31 amps.	1780 RPM
Exciter	250 volts	1.0 amps	1780 RPM
Generator	3000 volts	4 amps.	1780 RPM

Sensitive voltage control was obtained by rheostat adjustment of both the exciter and generator fields (Fig. 4). A 0.36 microfarad smoothing capacitor was included to reduced high frequency ripple.

(d) Pumping System.

The pumping system, consisting of a size 2 Waterbury speed gear, an adjustable speed motor, and an orifice flow meter, is shown in Fig. 2. The pump was rated at 870 RPM and a maximum pressure of 1600psi. The motor was a General Electric BTA, adjustable speed, 225 volt, 3 phase, 60 cycle, AC motor. At 800 RPM, it was rated at 2.5 horsepower and 14 amperes. The flow meter was mounted vertically instead of horizontally, and for this reason the velocity measurements were not considered to be exact. However, since the velocity was known to be non-linear in the test tank, only the average velocity could be determined in any case. The flow meter consists of a one inch orifice in a two inch pipe and a mercury manometer. For all tests, the velocity was such that less than one inch of mercury differential was measured. The derivation of the equation for flow velocity is outlined in Appendix I.

(e) Voltage Measurements.

Three Sensitive Research Company electrostatic voltmeters were used for high voltage measurements. Source voltage was measured with a model ESH set to the 5000 volt scale. Probe measurements and all voltages less than 1000 volts were determined using two model ESD's, with 1000 and 3000 volt scales. Insulation resistance for all models was about 10^{15} ohms with capacitance varying from 22 to 50 micromicrofarads. All had a

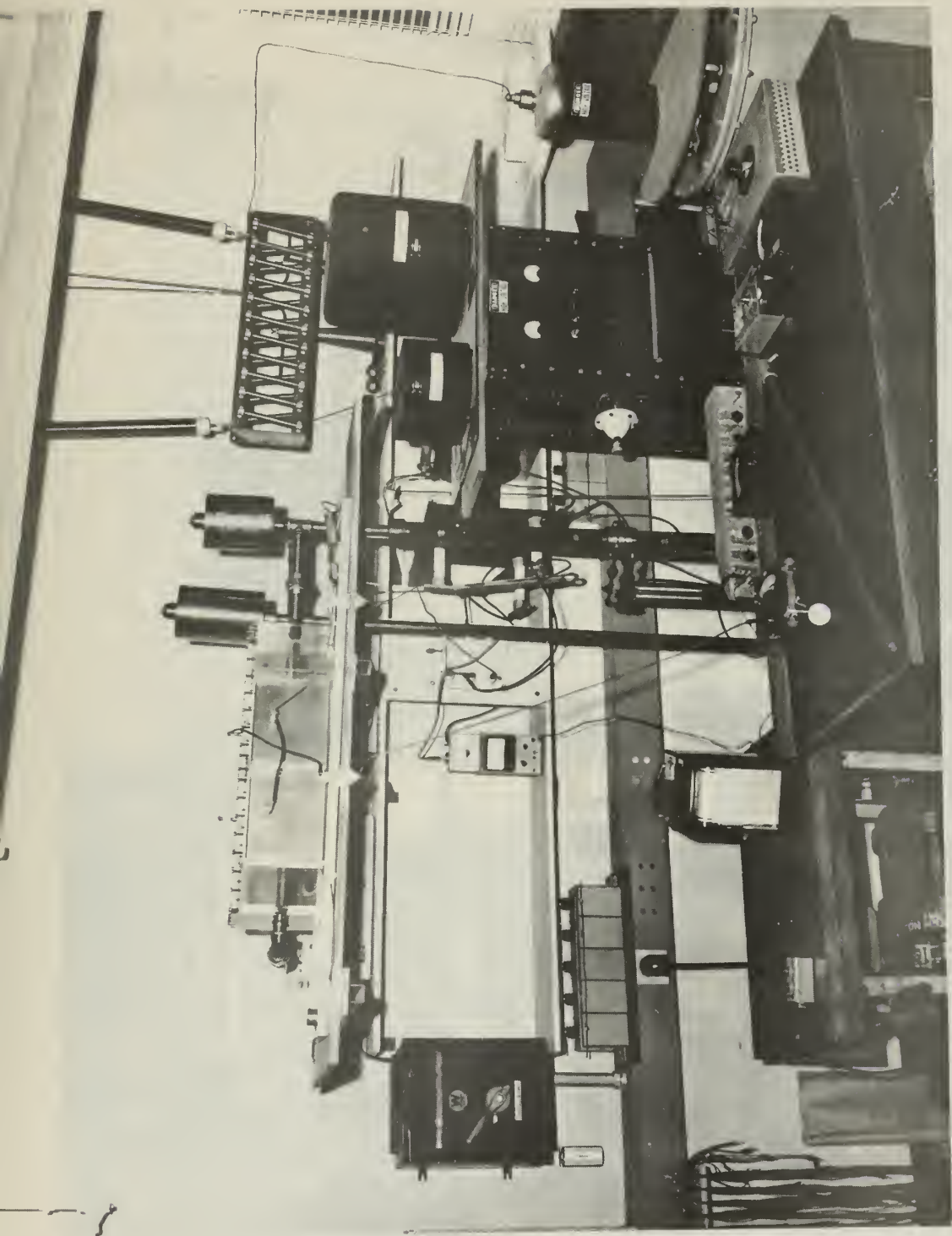


Fig. 1. General arrangement of laboratory equipment.



Fig. 2. Laboratory equipment showing pumping system.

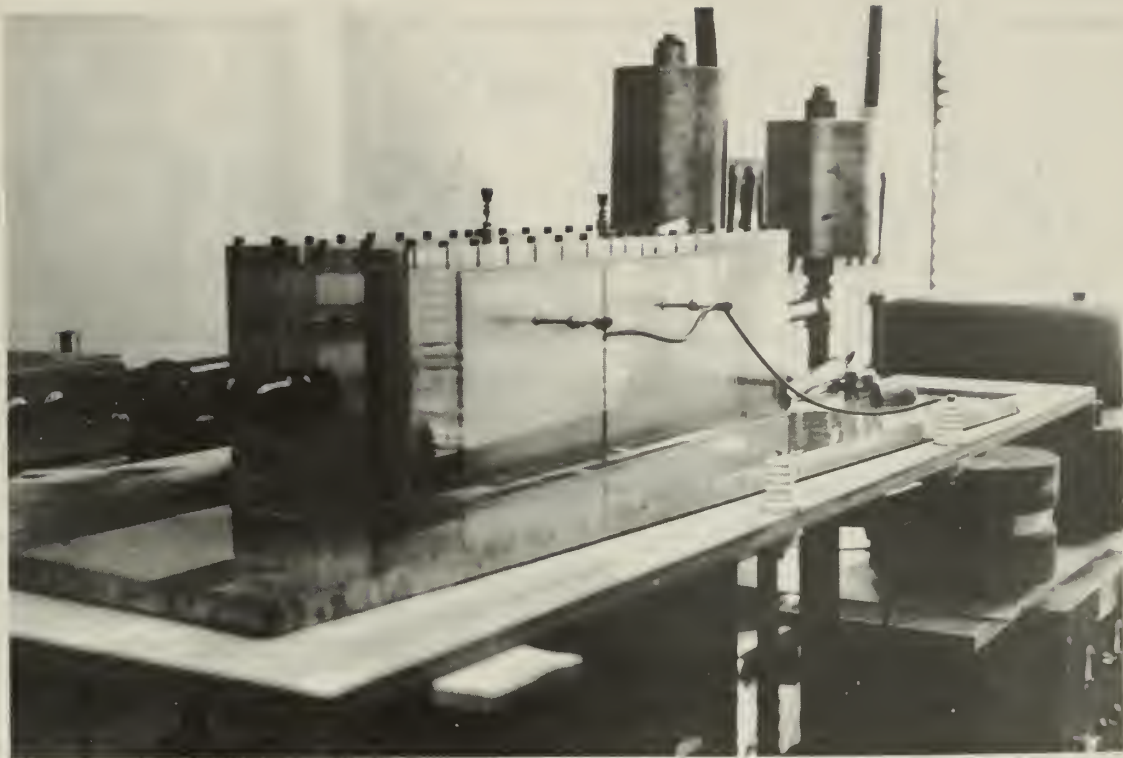


Fig. 3. Test tank.

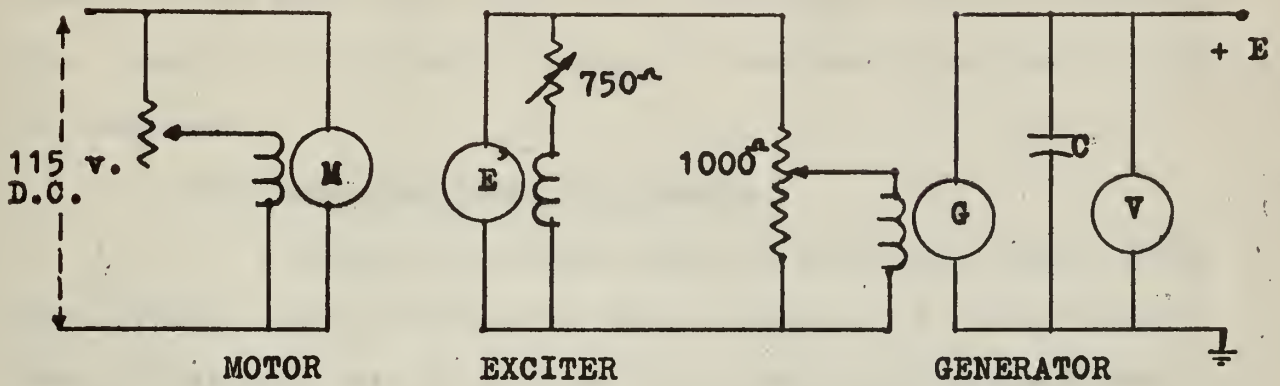


Fig. 4. Schematic diagram of 3000 volt generator.

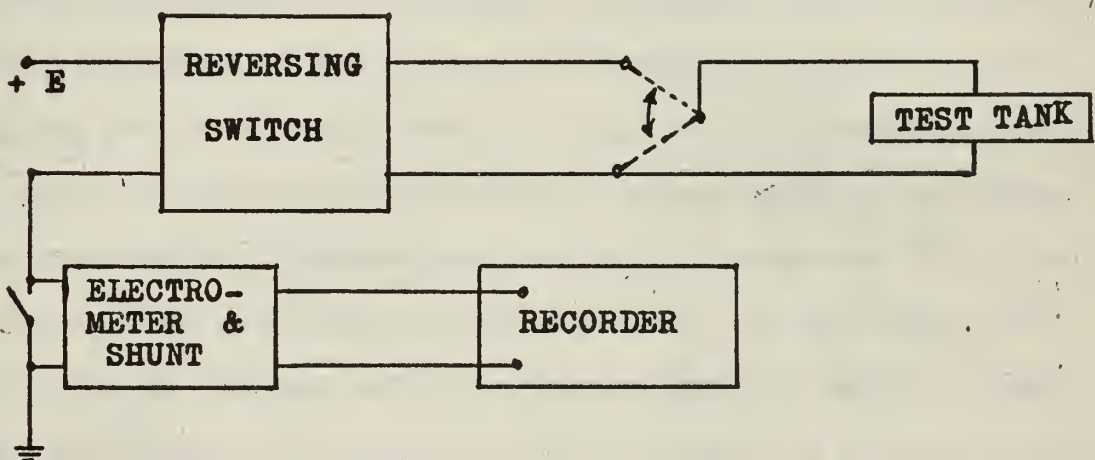


Fig. 5. Schematic diagram of test circuit.

period of about three seconds and an accuracy of one percent. Use of the electrostatic voltmeter for measurement of probe potential proved unsatisfactory for the case of the static oil, as the results were not reproducible. However for the flowing oil tests the measurements were reproducible and consistent.

(f) Current Measurement and Recorder.

A Keithley electrometer Model 210 with decade current shunt Model 2008 was used to determine current by essentially a voltage measurement. It was found that the meter was just under critically damped when using the 8 and 20 volt scales with the appropriate shunt multiplier, and these scales were used so that stray currents would not cause undesirable oscillations. This arrangement permitted measurement of currents as low as 10^{-14} ampere. The output amplifier of the electrometer was used to drive an Esterline-Angus 1.0 milliampere direct writing balanced recorder. This circuit was adjusted so that full scale deflection on the electrometer delivered 0.8 milliampere to the recorder. Swinging time was one second for full scale deflection for the recorder, and although not determined, was considerably less for the electrometer. In all cases the shunt was shorted for an instant when the source potential was applied to the system or the polarity was reversed, to prevent overloading the electrometer during the instantaneous surge of capacitor charging current. The electrometer was connected from the reversing switch to ground so that the current through the shunt was always in the same direction even though the potential applied to the test tank was reversed. See the schematic diagram in Fig. 5. Recorder chart speeds from 3/4 inch per hour to 12 inches per minute were available.

3. Procedure.

Laboratory procedure was divided into two phases as follows:

Phase 1---Familiarization with the equipment and the conductivity and dielectric properties of the fluid to the extent of making numerous trial runs to establish the basic techniques and time between runs necessary to obtain consistent results. Most of these runs were made with the fluid not flowing.

Phase 2---Collection of data for the following conditions for potentials of 500, 1000, 1500, 2000, 2500, and 3000 volts: (1) current vs. time for the static oil, (2) current vs. time for the transition from the static to the flowing condition, (3) current vs. time for the transition from the flowing to the static condition, (4) current vs. time for potential reversal for both conditions, and (5) potential distribution for both conditions.

In general, all runs required a matter of 15 to 20 minutes to reach a value reasonably near steady state. Small changes occurred over the next hour but the values determined after about 20 minutes were always within five percent of the actual steady state value. For the case of the runs involving the static fluid, considerable differences in results occurred if consecutive runs were made closer than four hours apart. However, when flow was involved, only a matter of a few minutes was required to reach the original neutral state. As previously stated, the electrometer was always shorted for a period of about one second when applying or reversing the potential.

4. Results.

In general the results obtained for the static case were compatible with those reported by Whitehead and Minor /1/. Two differences were noted and both involve potential reversal current behavior. On reversing the potential, the initial current was in all cases higher than the steady state current before reversal but slightly less than the initial charging current. For the higher potentials there were two peaks in the current-time curve when the potential was reversed, indicating ions of two different mobilities (Fig. 24). Using the time of the peak current to compute the ion mobility, Fig. 7 shows this effect. These data were collected before the sample became contaminated due to the pumping. Afterwards the second peak came much later and a mobility of 2×10^{-5} cm./sec./volt/cm. was calculated. This corroborates the report by Whitehead and Minor /1/ that for a less pure oil the ion mobility is lower.

The minimum velocity of flow required to affect the results was less than the minimum measureable velocity for these tests. (On the orifice flow meter used, 0.1 inch of mercury differential was equivalent to about 3cm./sec. velocity between the plates). In general velocities higher than this minimum only affected the transient times (current during the transient from static to flowing condition or vice versa) and affected steady state current only slightly. For the higher velocities a noticeable amount of bubbles was evident, and hence velocities greater than 10 cm./sec. were not used. For all data runs the flow rate was held constant at about 5 cm./sec.

The current during the transition from the static to the flowing condition showed an interesting effect. The current dropped very sharply at first, sometimes even going negative, and then rose to a value somewhat higher than the steady state value for the static condition. (See Fig. 20

through 22.) For the higher potentials there was some overshoot in reaching steady state, but in all cases, steady state was established in 30 to 60 seconds. The time of the negative peak (minimum current) varied inversely with the potential and the final fluid velocity. For the higher velocities, the drop was sharper and the minimum value was lower, but the time involved was also proportionally less. The area between this current curve and the linear rise to the steady state value represents the change in the bound charge on the plates. This area was very nearly constant at about 20×10^{-8} coulombs for all values of potential and fluid velocity, and is believed to be a measure of the space charge that had been established in the static oil. Table I lists the actual values determined for each applied potential along with the theoretical bound charge assuming the test tank to be an oil capacitor with a dielectric constant of 2.3.

Steady state conductivity versus applied voltage has been plotted in Fig. 6. Note that for the flowing fluid the conductivity changed very little with applied voltage, indicating that the space charge (or saturation effect) has been practically eliminated.

When the potential was reversed with the oil flowing the current is constant for the first one or two minutes at about twice the steady state value, and then drops sharply at first and then more slowly to the value it had been before reversal. (See Fig. 9, 11, 13, 15.) The charging current curve with flow (Fig. 23) is very similar except that the initial constant value lasts for only a few seconds, the time of the constant initial value being proportional to the plate length in the direction of flow.

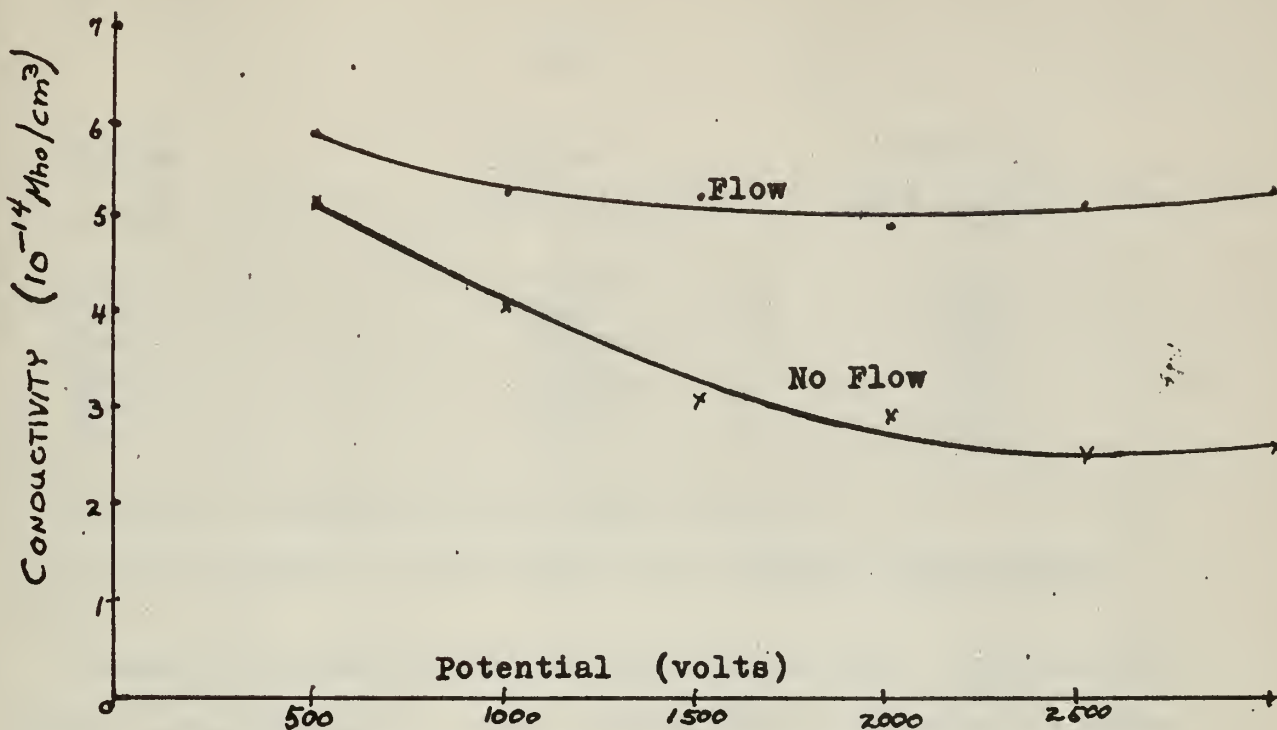


Fig. 6. Conductivity vs. Potential.

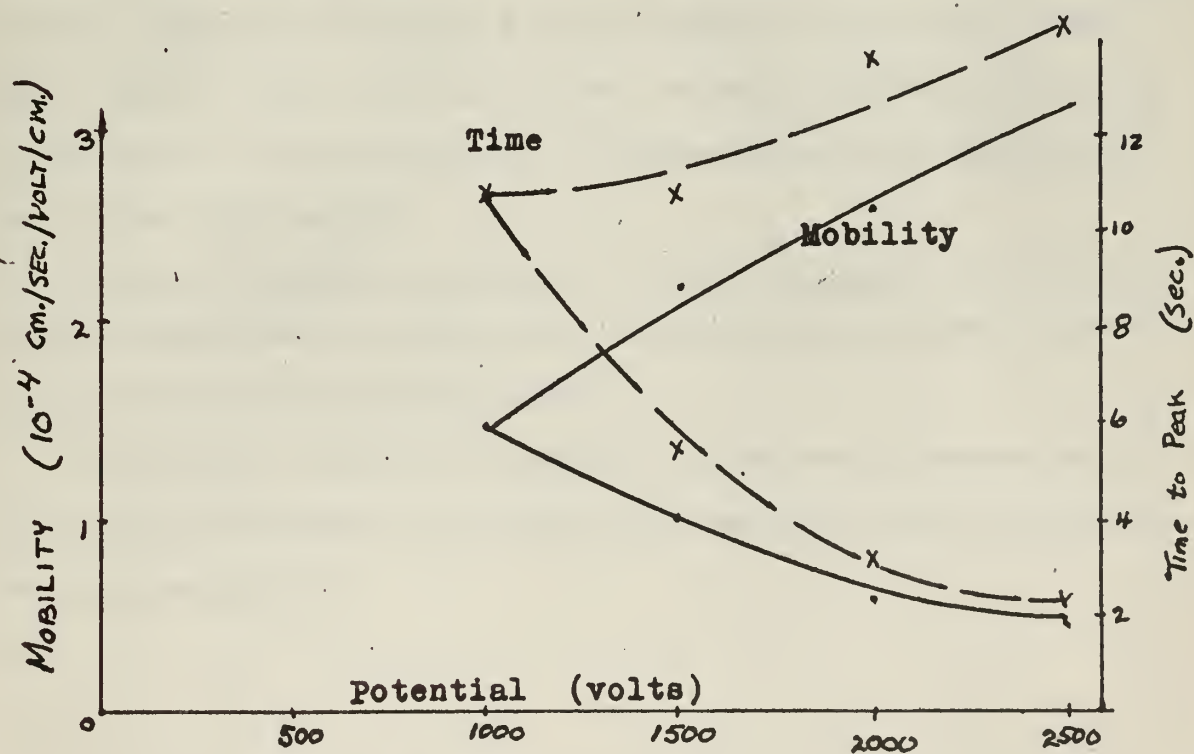


Fig. 7. Time of peak current on potential reversal and Ion Mobility vs. Potential.

TABLE I

Applied	Column I	Column II
Voltage	10^{-8} Coulomb	10^{-8} Coulomb
520	8.25	19.1
1000	16.5	21.6
1500	24.75	15.8
2000	33.0	19.1
2500	41.25	21.9
3000	49.5	17.0

Column I: Theoretical bound charge--- $Q = C V$.

Column II: Change in bound charge due to removal of space charge.

During the transition from the flowing to the static condition, the current increased sharply at first and then began to decrease in a manner similar to the static charging current. In fact, if the static charging current curve could be described as some function of time, $i(t)$, then apart from the initial rise, the current following this transition could be described as $i(t+b)$, where b is a constant depending on the potential and initial fluid velocity.

While the potential distribution is quite non-linear for the static fluid, it was found to be linear for the flowing fluid, within the limits of the accuracy of the equipment used.

The current time curves, reproduced from the actual recorder tapes, are included in Appendix II for each of the tests described in phase 2 of the procedure section.

5. Discussion.

In general, the conduction phenomena in insulating oil can be described as follows:

In the neutral state, even highly purified insulating liquids show some conductivity, though it be small, due to the presence of ions. These ions may be produced by any one of a number of reactions or effects, e.g., inherent dissociation, traces of impurities, radioactive influences or cosmic rays /1/. In the neutral state an equilibrium is established when the rate of dissociation is equal to the rate of recombination. Some of these ions attract to themselves a cloud of neutral molecules thus becoming large and sluggish. When the potential gradient is not too high, these ions carry their surrounding cloud of neutral molecules with them as they move under the influence of the field. As their velocity increases, they may be expected to shed some or all of the surrounding cloud. For the higher potential gradients, these large ions will reach higher velocities sooner and thus the probability of shedding the neutral molecules is increased. Another possibility at the lower potentials is that a positive and a negative ion may be drawn together but yet may not recombine due to the intervening cloud, thus forming a very large polarized "molecule" or aggregate /8/.

When a potential is applied, and the potential gradient is 3000 volts/cm. or less, the freshly formed ions and the large sluggish ions will move towards the electrodes, the freshly formed ions having the higher velocity because of their smaller masses. As the ions move from the central region the rate of recombination will be decreased, and thus more new ions become available. Because the fresh ions have higher velocities, they will reach the electrode first and will account for the initial current. As the current due to these ions begins to drop (being limited by the rate of dissociation) some of the sluggish ions will have shed part of their cloud of

molecules and begin to arrive at the electrodes. Some of these ions will be discharged, but some will have retained enough of their neutral envelope to prevent complete arrival or to "insulate" it from discharge. Space charge will therefore begin to accumulate near the electrodes due partially to the large sluggish ions and partially to the drift of the freshly formed ions towards the electrodes (following the similiar behavior in gases). As the space charges progressively accumulate, the potential gradient increases in the vicinity of the electrodes and decreases in the central region. This results in a saturation effect, as in gases, with the associated decrease in current. (In gases the time to establish the space charge is not nearly so long). As the gradient in the central region decreases, the rate of removal of the newly formed ions is decreased and hence the recombination rate is increased. Thus the steady state current is due to the rate of dissociation minus the rate of recombination. Another effect of the space charge is to increase the amount of bound charge on the plates. This acts in a similar manner to the polarization effect to increase the dielectric property of the fluid.

On reversal of the potential the space charge acts to increase the potential gradient in the central region just as it had acted to reduce the gradient before the reversal. This causes the rate of removal of the newly formed ions from the central region to increase, thus decreasing the recombination rate and accounting for the current immediately following the reversal being higher than the previous steady state current. Initially there is a charge (Q) on the plate due to the geometric effect ($Q = CV$) and an opposite charge (Q') due to the space charge which has not yet moved away. Thus initially there is a bound charge on the plate that is less than there would have been had the space charge not been present. The current maintains

initial value until the ions which had made up the space charge begin moving into the central region. At this stage several effects interact, and the result depends on the potential applied. The potential gradient in the central region begins to decrease, the rate of recombinations increases, and the current increases to establish the proper bound charge on the plates. This might have caused a decrease in the current, but since none was observed during these tests, it was assumed either that these effects canceled or else accounted for the initial rise in the current. During this movement between the electrodes, most of the large sluggish ions shed their neutral cloud and are discharged on arrival at the electrodes. The ones that are not discharged start the accumulation of space charge and increase the bound charge on the plates, thus having the same effect on the current as if they had been discharged. The arrival of these ions thus account for the peak current on the reversal. For the higher potentials, two peaks were observed, indicating that the ions were of two different types or masses, thus having different mean velocities and mobilities. After this peak is passed, the charging phenomena that occurred after the initial application of voltage repeats itself (Figs. 16 and 17).

Before discussing the conduction phenomena in oil flowing between the plates, a few preliminary remarks concerning the flow are appropriate. The flow between the plates was laminar, having a Reynolds number of less than 2000 for average velocities less than 10 cm./sec. Flow rates having velocities higher than this were not used because there were bubbles formed in the piping which seemed to affect the results. For laminar flow, the velocity distribution is parabolic in shape with the velocity at the center equal to twice the average velocity. Defining the direction of flow as the y direction, the direction from the positive plate to the grounded plate as the x

direction, and the midpoint between the plates at the entrance to the plates as the origin, then the flow velocity distribution can be expressed as:

$$\dot{y} = 2 V (1 - 4 x^2/d^2)$$

where V is the average flow velocity. For the collection of test data, V was held constant at 5 cm./sec., except to note the effect of the velocity. Applying one of the results of the test (that the potential distribution was linear with the oil in motion), the velocity of ion drift towards the electrodes when a potential is applied can be expressed as follows:

$$\dot{x} = \frac{E}{d} u$$

where E is the applied potential and u is the ion mobility.

One would expect that the drift of the ions towards the electrodes would still affect the linearity of the potential distribution as is the case in gases. Since the potential distribution was determined to be linear in these tests, this can only be reconciled if a slight amount of non-linearity (within the accuracy limits of the test procedure and equipment) is assumed. However, since the nonlinearity is small, the gradient is essentially a constant and the assumption previously introduced is still valid. Further basis for believing that the potential distribution is more nearly linear is that the space charge due to the large sluggish ions has been removed by the flowing oil as shown by the dip in the current during the transient from the static to the flowing condition. This will be discussed in more detail later.

In the neutral state with the oil in motion, ions exist in the oil under an equilibrium condition just as in the static case. There is less probability, however, that the sluggish ions can exist because the fluid friction would tend to dislodge any of the loosely bound neutral molecules

that may be attracted to an ion. All the ions and molecules have a velocity (\dot{y}) as described above, depending on their position between the plates. When a potential is applied, the ions all act as newly formed ions and move towards the electrodes with a constant drift velocity in the x direction. If any of the sluggish ions do exist, the number that will contribute to a space charge is limited since they are continuously being removed from the test tank by the flowing oil. Assuming a mobility of 3×10^{-4} c./sec./volt/cm. (which was previously determined in the static test), the magnitudes of the two velocities would be as follows for 1000 volts:

$$\begin{aligned}\dot{y} &= 10 \left(1 - 4x^2/d^2\right) \text{ cm./sec.} \\ \dot{x} &= 0.237 \text{ cm./sec.}\end{aligned}$$

At the instant the potential is applied, the ions will be about equally distributed through the fluid. Thus initially, ions will move towards the electrodes from the whole region between the plates. Afterwards most of the new ions will come from the central region because of the higher probability of recombination in the regions nearer the electrodes. The y dimension of the test cell was about 50 cm. Thus for the above example, an ion formed at (0,0) will reach the electrode at $y = 18$ cm., and those formed in the central region but at y greater than 32 cm. actually miss the plates. Thus one would expect the steady state conductivity to be less than the initial conductivity since a greater percentage of the ions that start towards the plates in the first few seconds arrive there than for any other equal time interval (Fig. 23).

The duration of the constant initial charging current was found to vary directly with the y dimension and inversely with the average flow velocity. However the duration of this current on reversal of the potential was a much longer time (one to two minutes as compared to about 20 seconds). This is

an indication of the time required to establish the new equilibrium condition of dissociation and recombination in the central region. In the case of the potential reversal, this time is delayed due to ions reversing their direction of drift and passing completely through the central region. Although there are ions passing through the central region during the initial charge, the intensity is much less, and more or less maintains the neutral state equilibrium, rather than upsetting the one that had been established before the potential reversal. Thus a (longer) time is required before the current begins to fall than for the initial charge.

If after steady state has been established the flow is stopped, the current will rise since now all the ions will reach the electrodes and none will miss as had been the case with flow. However the current will not rise as high as the value of the initial charging current for the static case. This is because there already exist a small amount of "space charge" due to the drift of the ions towards the electrodes when the fluid was in motion. Since the fluid is not now in motion, there will be a tendency for the sluggish ions to be formed and to contribute to the space charge. It is these ions that will make up the larger part of the space charge and account primarily for the space charge effect which causes the non-linear potential distribution, the slowly decreasing charging current, and the increase in the bound charge on the plates.

The latter effect was the cause of the negative dip in the current during the transient from the static to the flowing condition. When the fluid was put in motion, the sluggish ions were removed from between the plates and the excess charges on the plates were freed, thus giving the observed reduction of current until charge equilibrium had been re-established. In the cases where the current actually became negative, the plates were actually supplying charges (current) to the generator. Thus the time interval of

this current minus the value the current would have been (had the generator had to supply all the current through the oil) represents the space charge which has been removed by the flowing oil. For analysis this latter current was assumed to rise linearly to a point tangent to the actual curve near the steady state value. Using graphical methods and this technique, the values listed in Table I were obtained. The probable error in the results due to this method is at least ten percent. The fact that these values are essentially constant with potential indicates that the space charge reaches a saturation value at steady state that is independent of voltage.

6. Conclusions.

The results of these tests lead to the following conclusions which add new understanding to the space charge effect and the conduction phenomena in insulating fluids:

a. The "sluggish ion" theory was substantiated for static insulating fluids.

b. The sluggish ions are essentially non-existent in a flowing insulating fluid.

c. The minimum velocity of fluid flow necessary to remove the space charge was not determined due to the lower limit of the flow meter used. However, at velocities as low as 3 cm./sec., the conclusions stated herein apply.

d. The amount of space charge in a static insulating fluid is essentially invariant with voltage. For the test cell used the space charge was found to be constant at 2×10^{-7} coulombs or 1.5×10^{-10} coulombs per cubic centimeter.

e. The potential distribution is essentially linear in a flowing insulating fluid. Although test methods prohibited verification of the exact non-linearity of the potential distribution in the static fluid, the fact that it was NOT linear was verified. For the flowing oil, the potential distribution was linear within two percent (which was considered to be within the limits of the test equipment).

f. The conductivity of a static insulating fluid is due to two types of ions having different mobilities. One mobility is about 3×10^{-6} cm./sec./volt/cm., and the other is about 5×10^{-7} cm./sec./volt/cm. The results indicate that the mobility of the faster ion increases with potential, while that of the slower decreases. If the sample becomes contaminated, the

lower mobility may be reduced as much as one order of magnitude.

g. The conductivity of the flowing fluid was essentially constant with potential and at a somewhat higher value than that of the static fluid since the flowing fluid is not space charge limited.

7. Recommendations.

If the properties of insulating fluids are to be investigated further using test methods similar to those used for these tests, the following is recommended:

a. A flow meter should be chosen which permits investigation of lower flow rates. The meter, if of a pressure differential type, should be installed in a horizontal section of piping and should be between the pump and the test tank in any case.

b. Higher potential gradients should be investigated.

c. Some type of filter should be included in the system to maintain a uniform purity in the sample during the test.

d. A switching arrangement such as that used by Whitehead and Minor /1/ should be used so that short time effects may be investigated.

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APPENDIX I

DERIVATION OF FLOW VELOCITY

The derivation of the flow rate of the fluid between the plates is outlined below, starting with the general energy equation for the fluid as it passes through the orifice.

$$1. \quad \frac{P_1}{w} + \frac{V_1^2}{2g} + h_1 = \frac{P_2}{w} + \frac{V_2^2}{2g} + h_2$$

Where point 1 is the entrance to the orifice

point 2 is the exit from the orifice

P is the pressure

V is the velocity

h is the static head ($h_1 \neq h_2$ due to the vertical pipe.)

w is the specific weight of the oil.

$$2. \quad Q = V_1 A_1 = V_2 A_2$$

Where A is the cross section area at the point.

$$3. \quad \frac{P_1 - P_2}{w} = (h_2 - h_1) + \frac{w_m - w}{w} h$$

Where h is the differential height of mercury in the manometer /10/.

$$4. \quad \text{Let } B = \frac{D_2}{D_1}, \text{ and the ratio of the actual to the ideal flow rate be}$$

the product CxE , Where C and E are figures of merit for the orifice depending on the Reynolds number of the flow through the orifice and the geometry respectively.

$$5. \quad Q_{\text{act}} = \frac{C E A_2}{\sqrt{1 - B^4}} \sqrt{2 g h \frac{w_m - w}{w}}$$

6. Keeping the dimensions in the CGS system

$$g = 980.7 \text{ cm./sec./sec.}$$

$$w_m = 13.56 \text{ gm./cm.}^3$$

$$w = .870 \text{ gm./cm.}^3$$

$$\frac{E}{\sqrt{1 - B^4}} = 0.15 \quad (\text{from table II /9/.)}$$

C = 1.2 as a first approximation.

7. For h = 0.25 inch = 0.625 cm.

$$V_2 = \frac{Q}{A_2} = 24.25 \text{ cm./sec.}$$

8. Now the Reynolds number of the orifice is defined as

$$N_r = \frac{w V_2 D_2}{\mu}$$

where the viscosity $\mu = 0.1$ poise (gm./cm./sec.) and

$$D_2 = 1.0 \text{ inch} = 2.54 \text{ cm.}$$

Thus $N_r = 535$ and

$$C = 1.2$$

9. Now for the flow through the test cell between the plates

$$V = \frac{Q}{A} = \frac{V_2 A_2}{A}$$
$$= 4.77 \text{ cm./sec.}$$

remembering that the plates were 8 inches high and 1/2 inch apart.

10. For the range of velocities used in these tests, C may be considered constant at 1.2, and hence for h in inches,

$$V = 9.5 \sqrt{h} \text{ cm./sec.}$$

11. To determine the Reynolds number for the flow between the plates, replace D in the above equation by the cross section area divided by the parameter of the cross section. Thus

$$N_r = 50 \sqrt{h}$$

and the flow is laminar for all tests.

APPENDIX II

This appendix is a compilation of representative current versus time data collected during these tests. Except for Fig. 24, these data are presented as it was collected, i.e., on the recorder tapes. Because of the length of the tapes the steady state values are not shown on many of the curves, however the actual value was used in determining the points for the curve in Fig. 6.

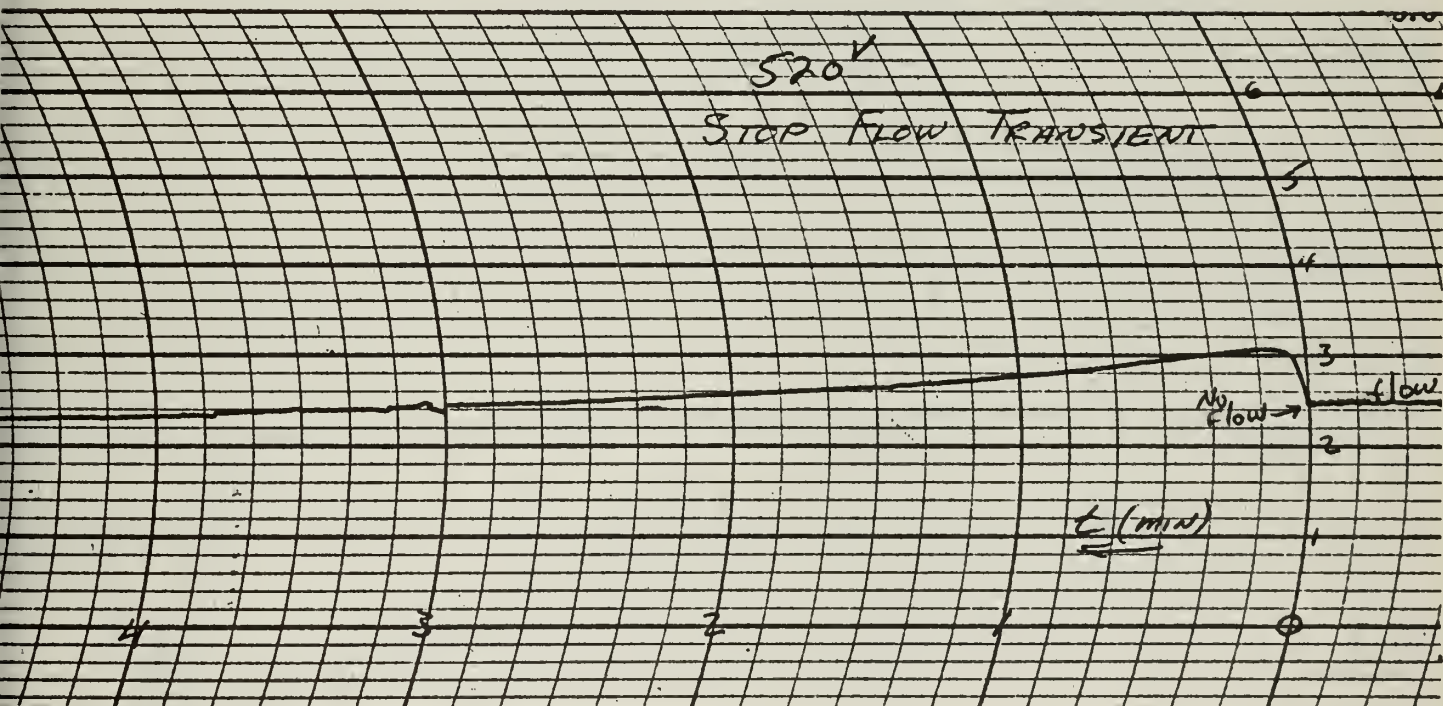
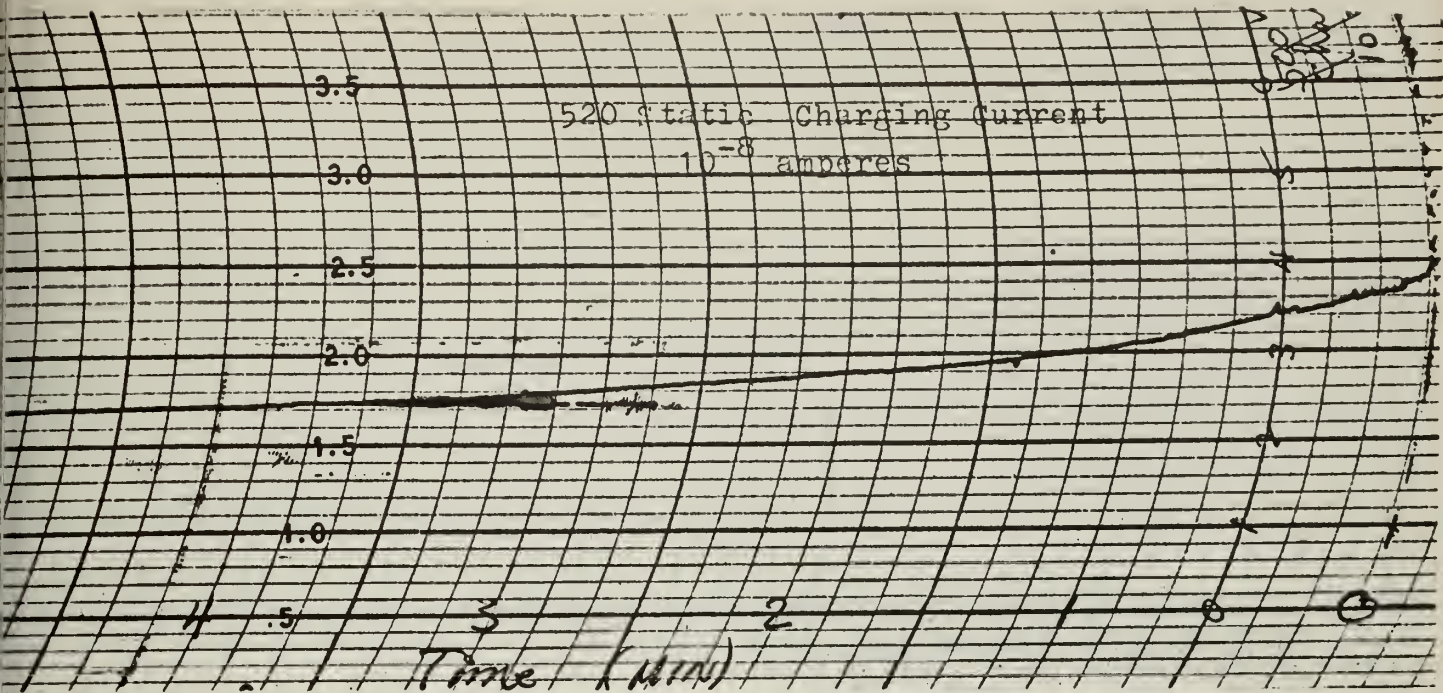


Fig. 8. Current vs. Time recorder tapes for 520 volts static charge and stop flow transient.

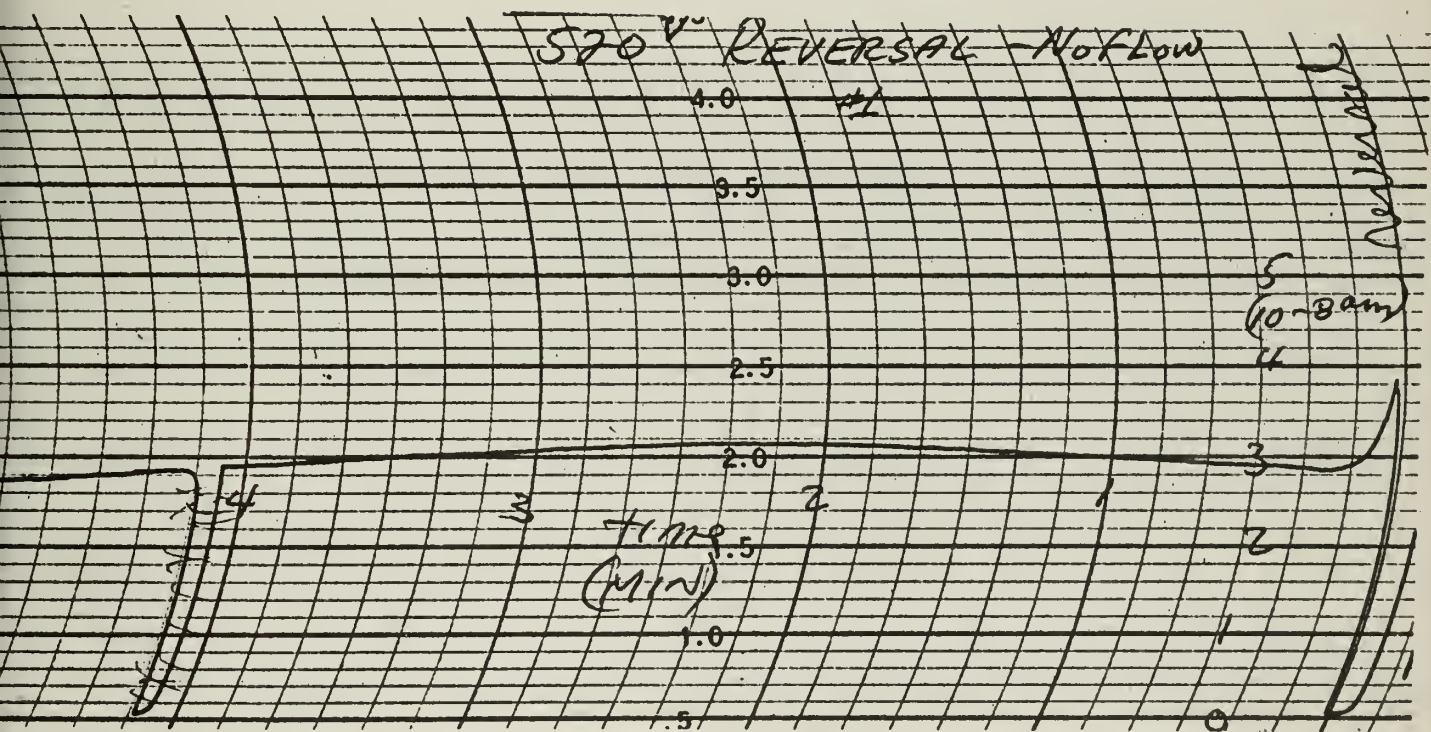
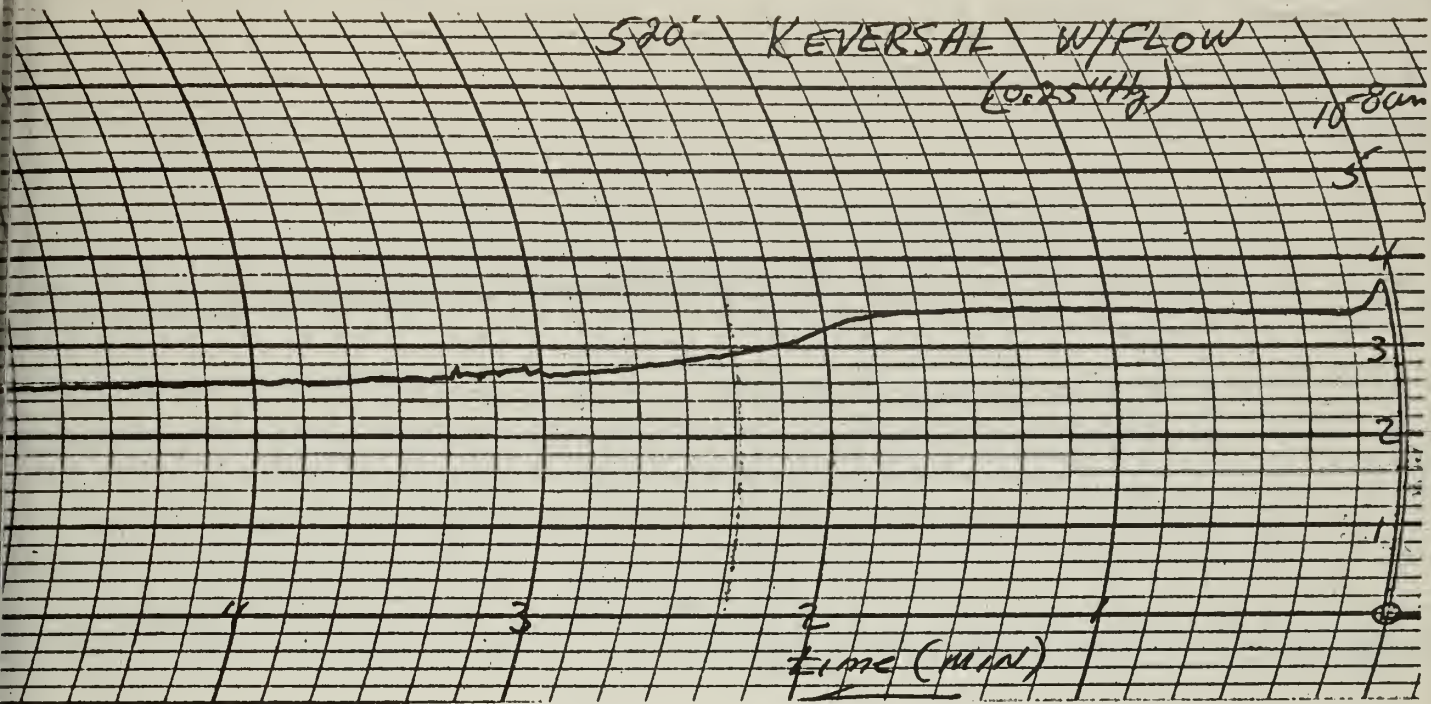
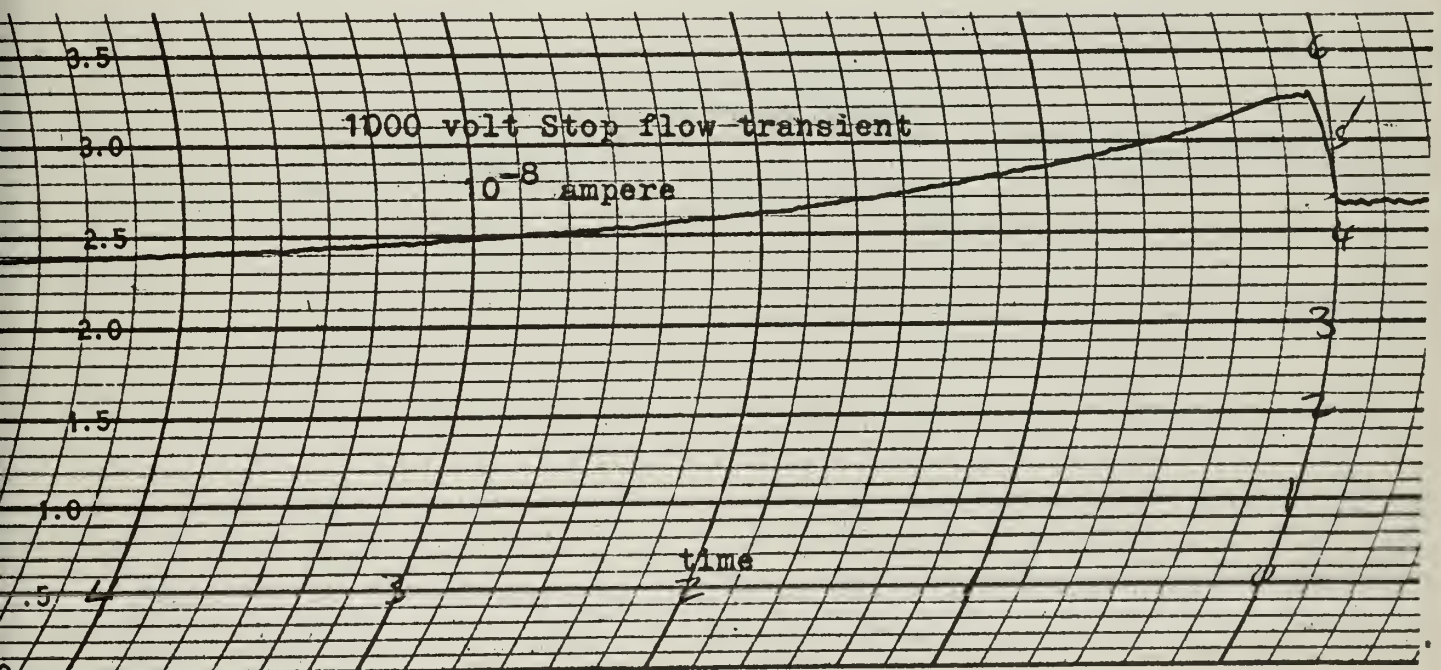
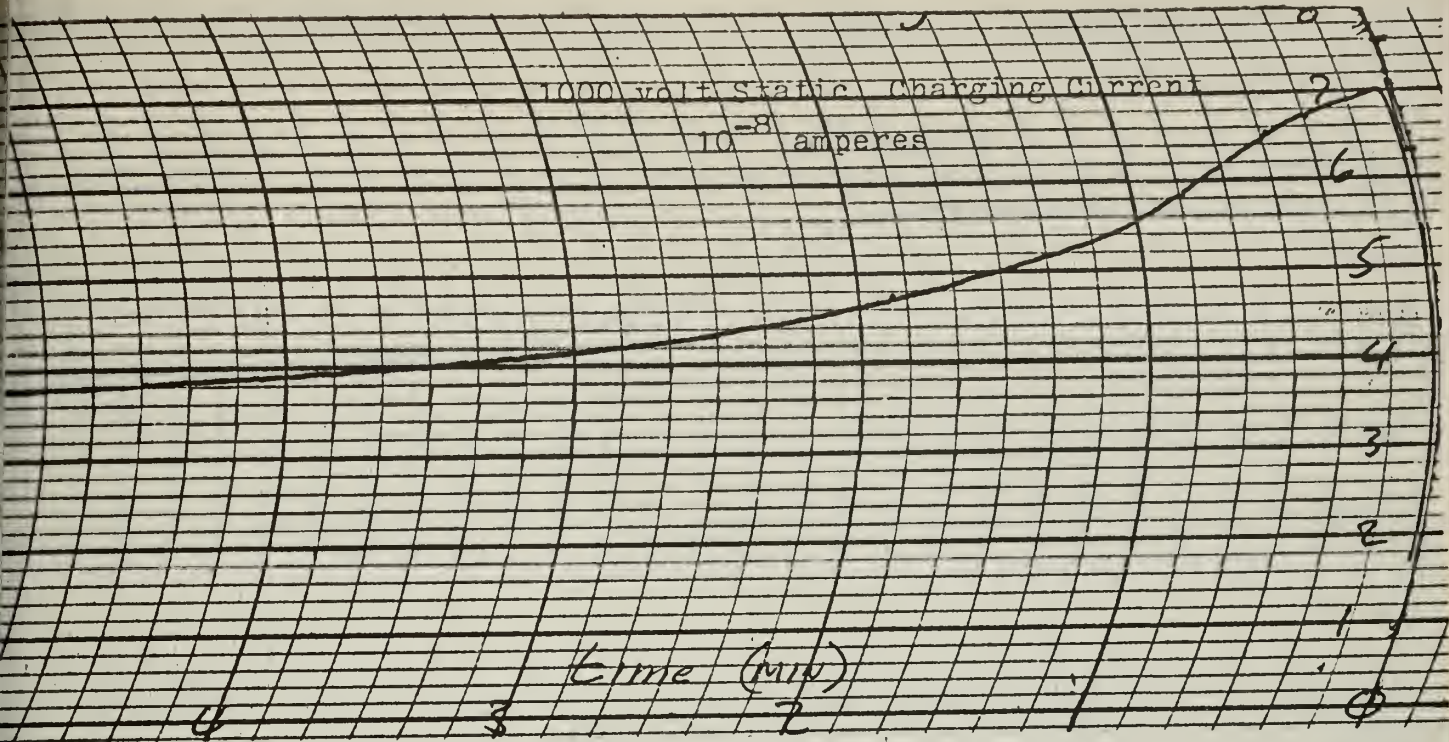


Fig. 9. Current vs. Time recorder tapes for 520 volts potential reversal with and without flow.



- Fig. 10. Current vs. Time recorder tapes for 1000 volts static charge and stop flow transient.

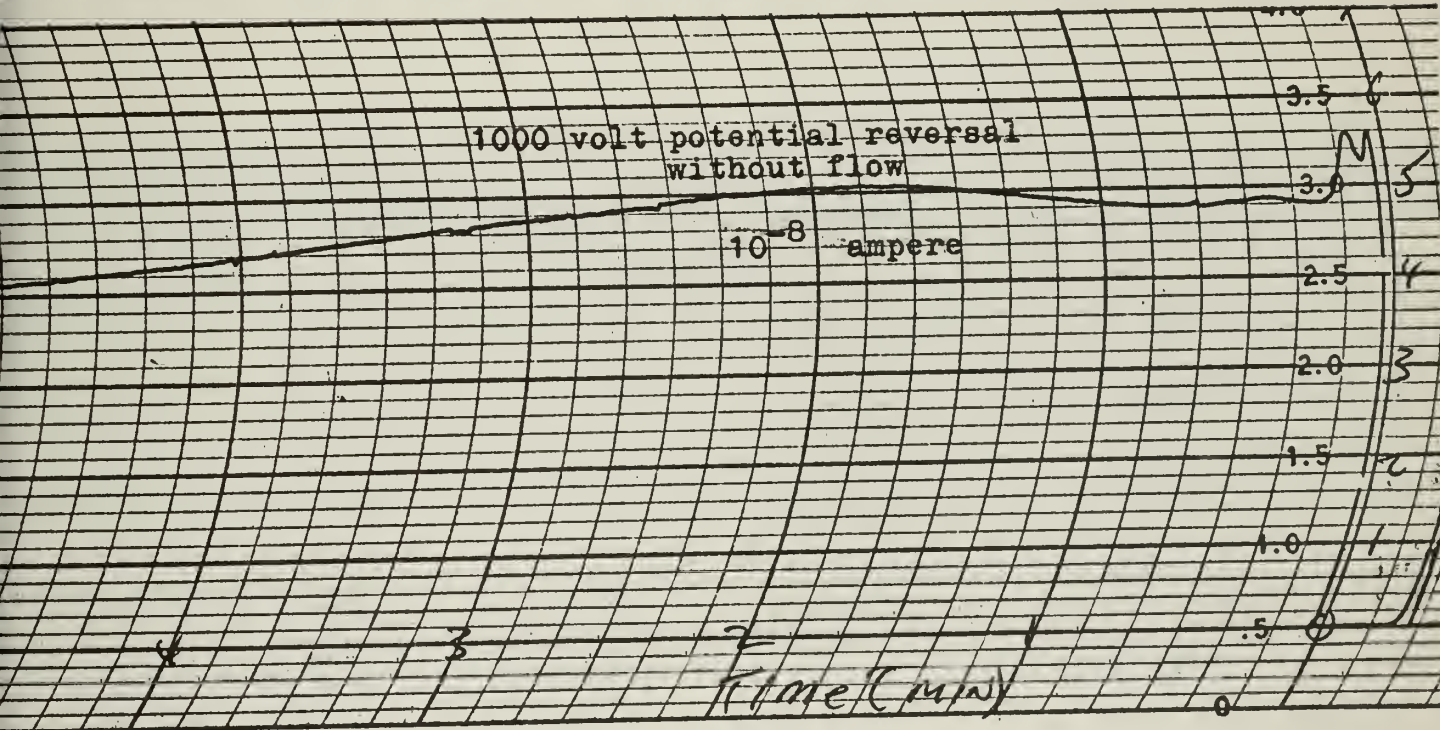
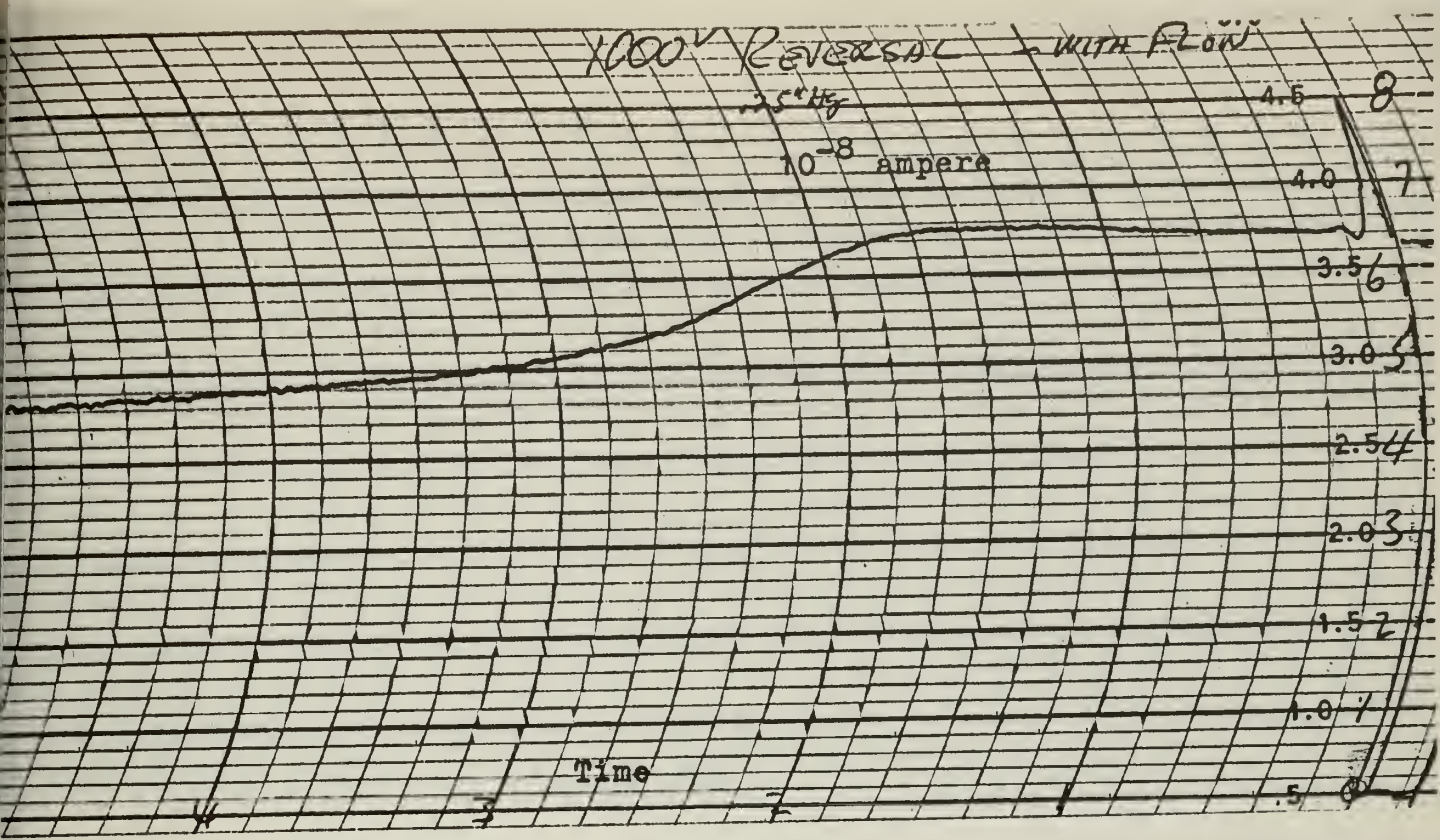


Fig. 11. Current vs. Time recorder tapes for 1000 volts potential reversal with and without flow

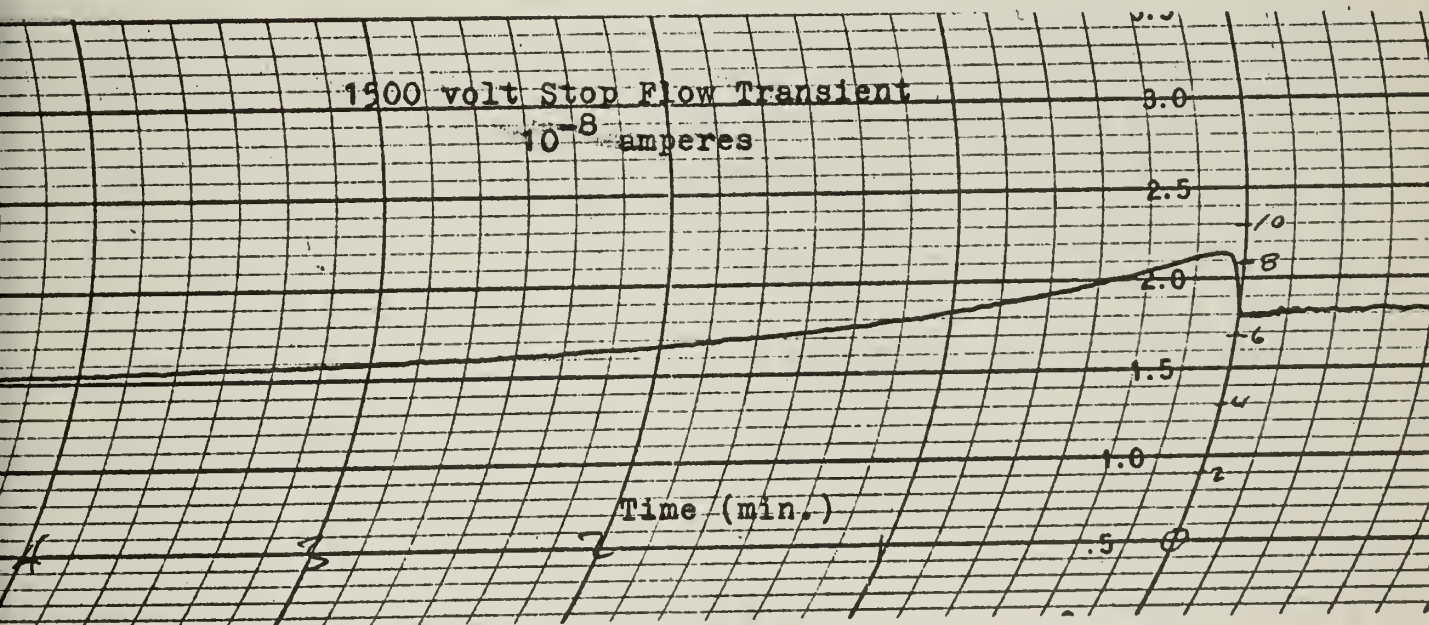
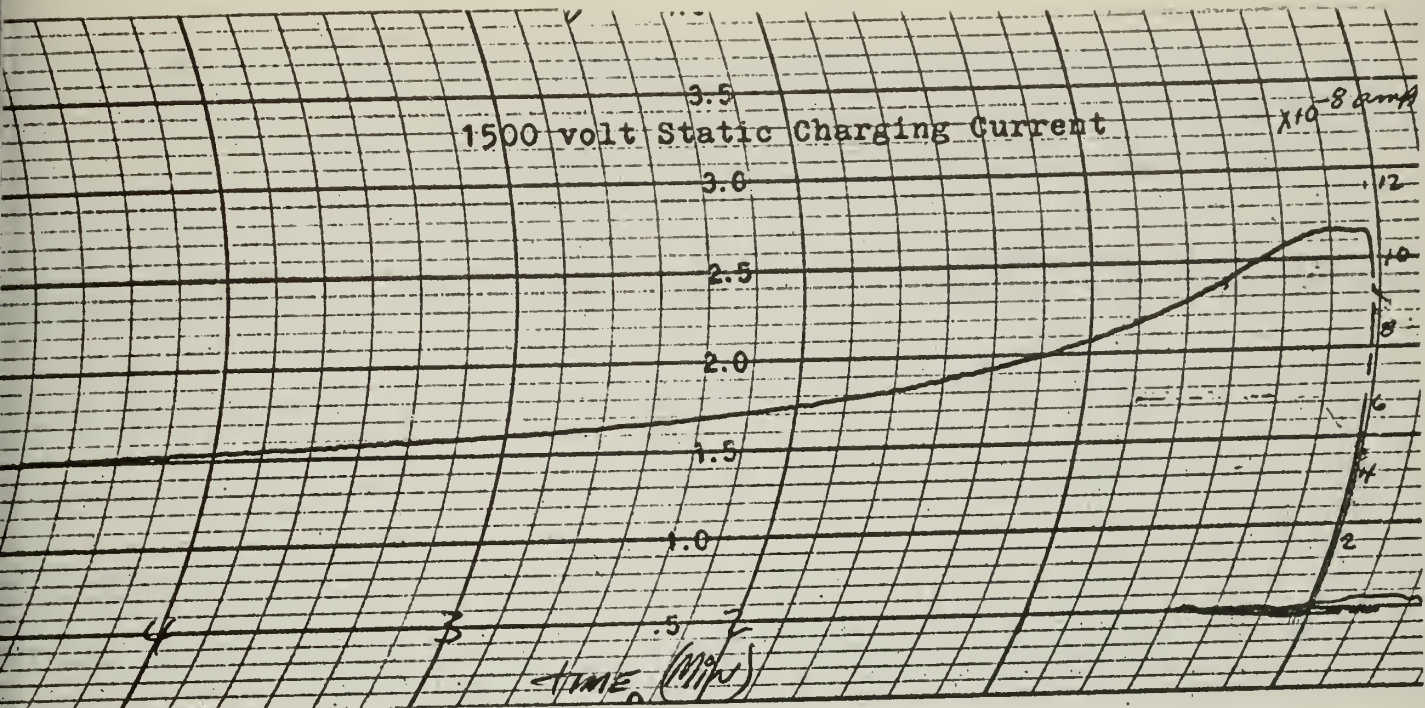


Fig. 12. Current vs. Time recorder tapes for 1500 volts static charge and stop flow transient.

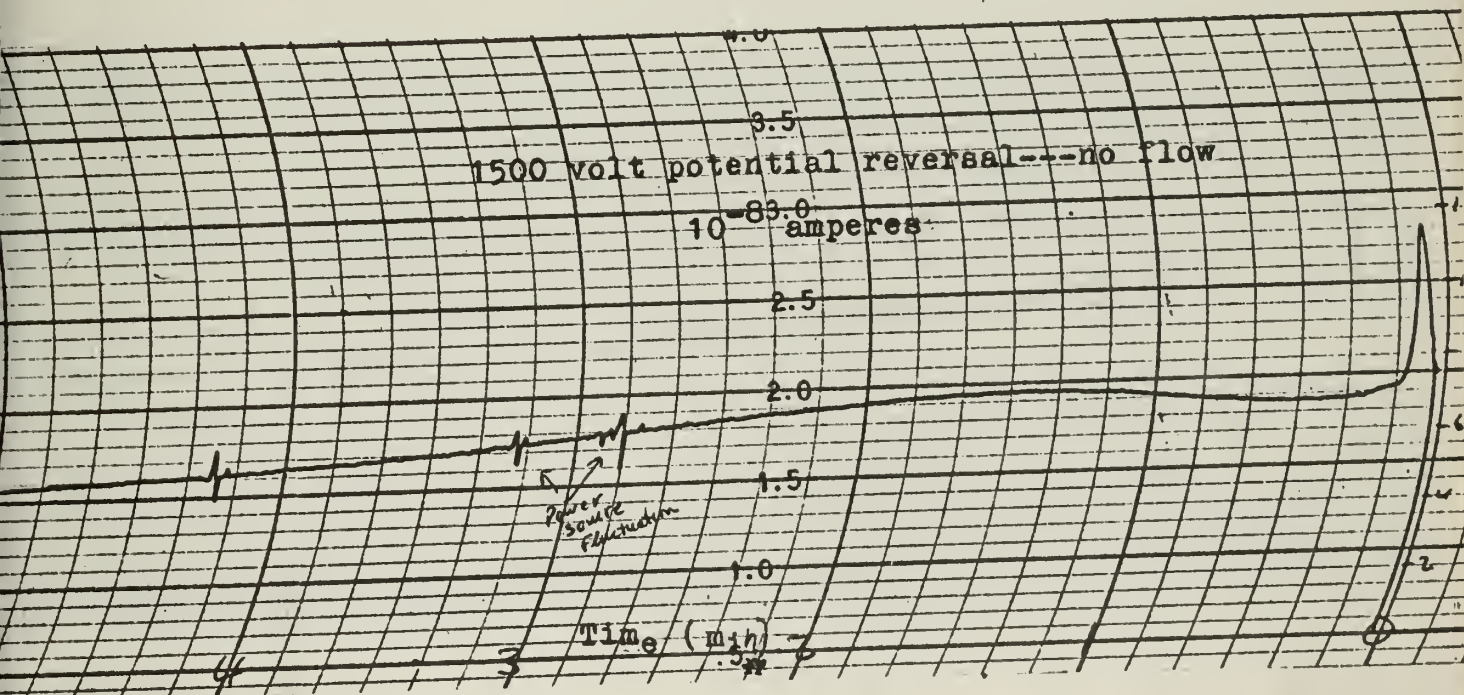
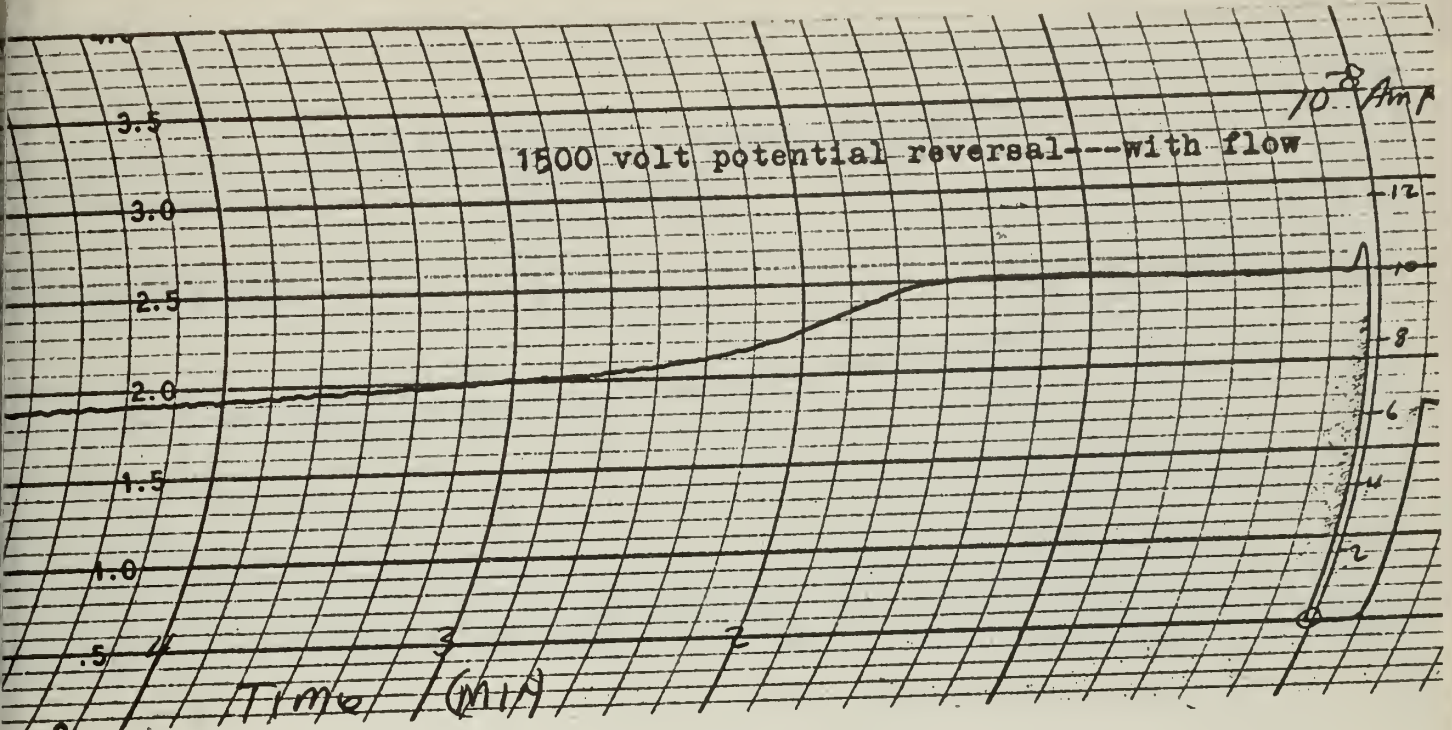
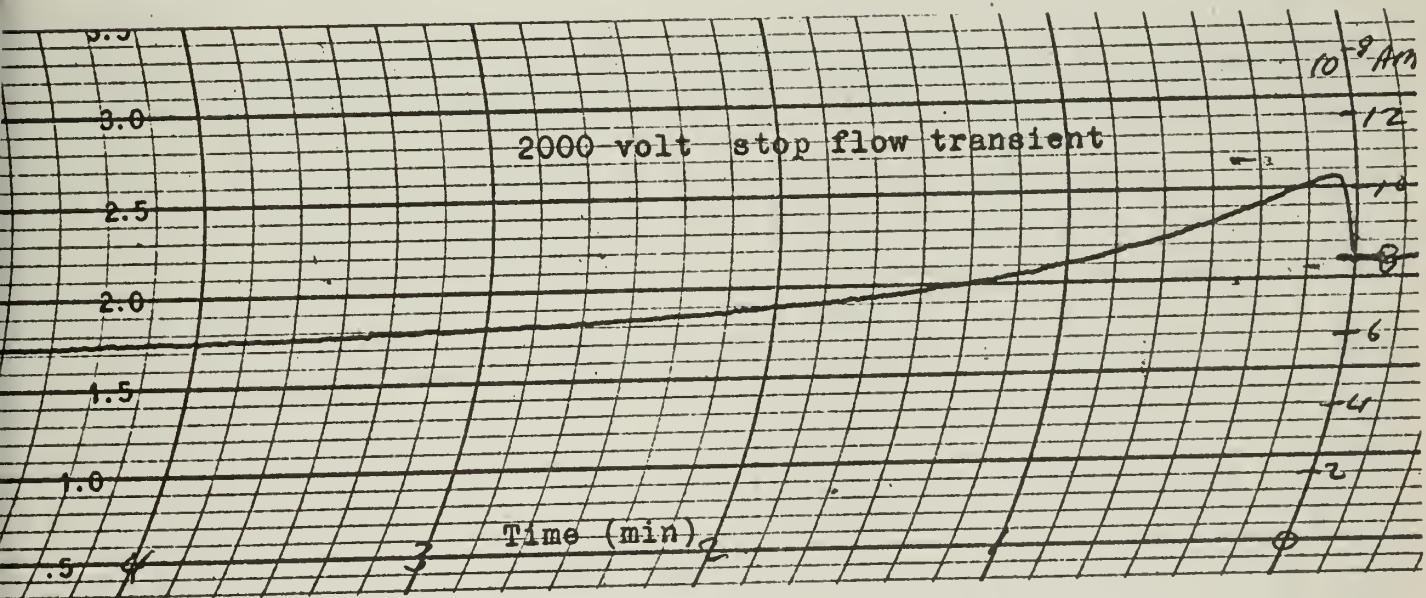
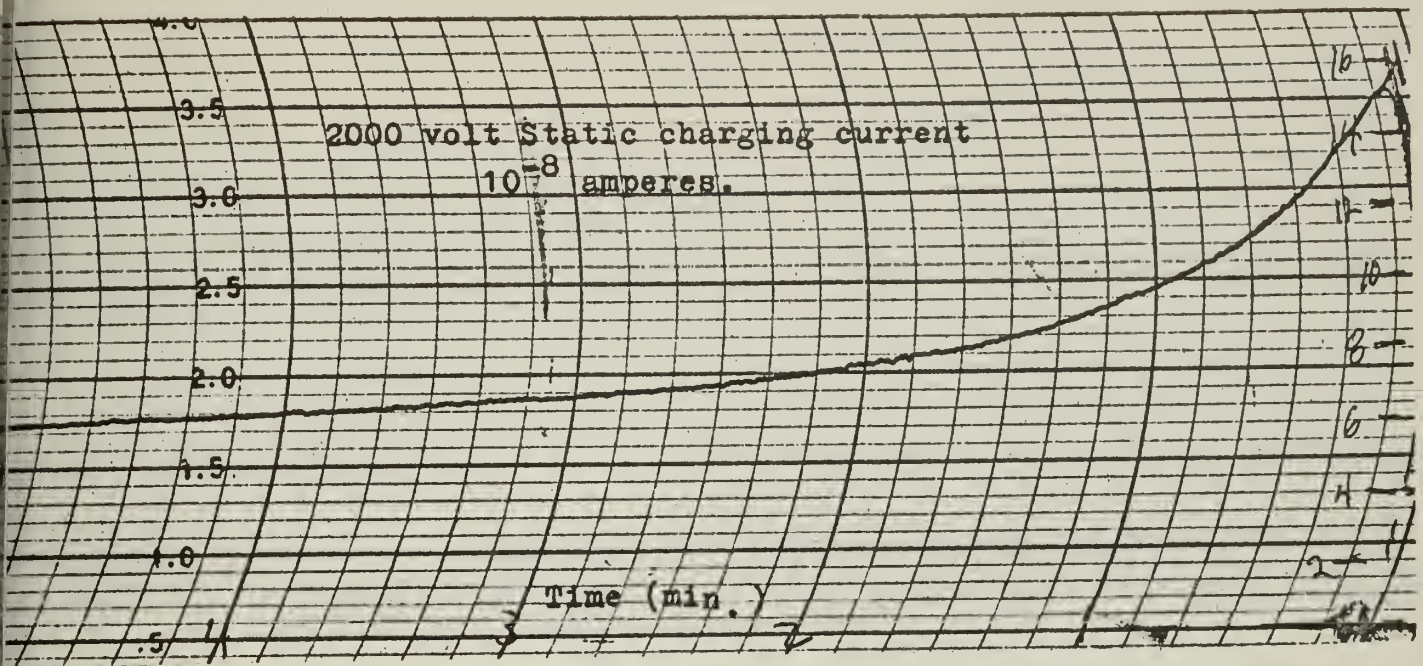


Fig. 13. Current vs. Time recorder tapes for 1500 volts potential reversal with and without flow.



- Fig. 14. Current vs. Time recorder tapes for 2000 volts static charge and stop flow transient.

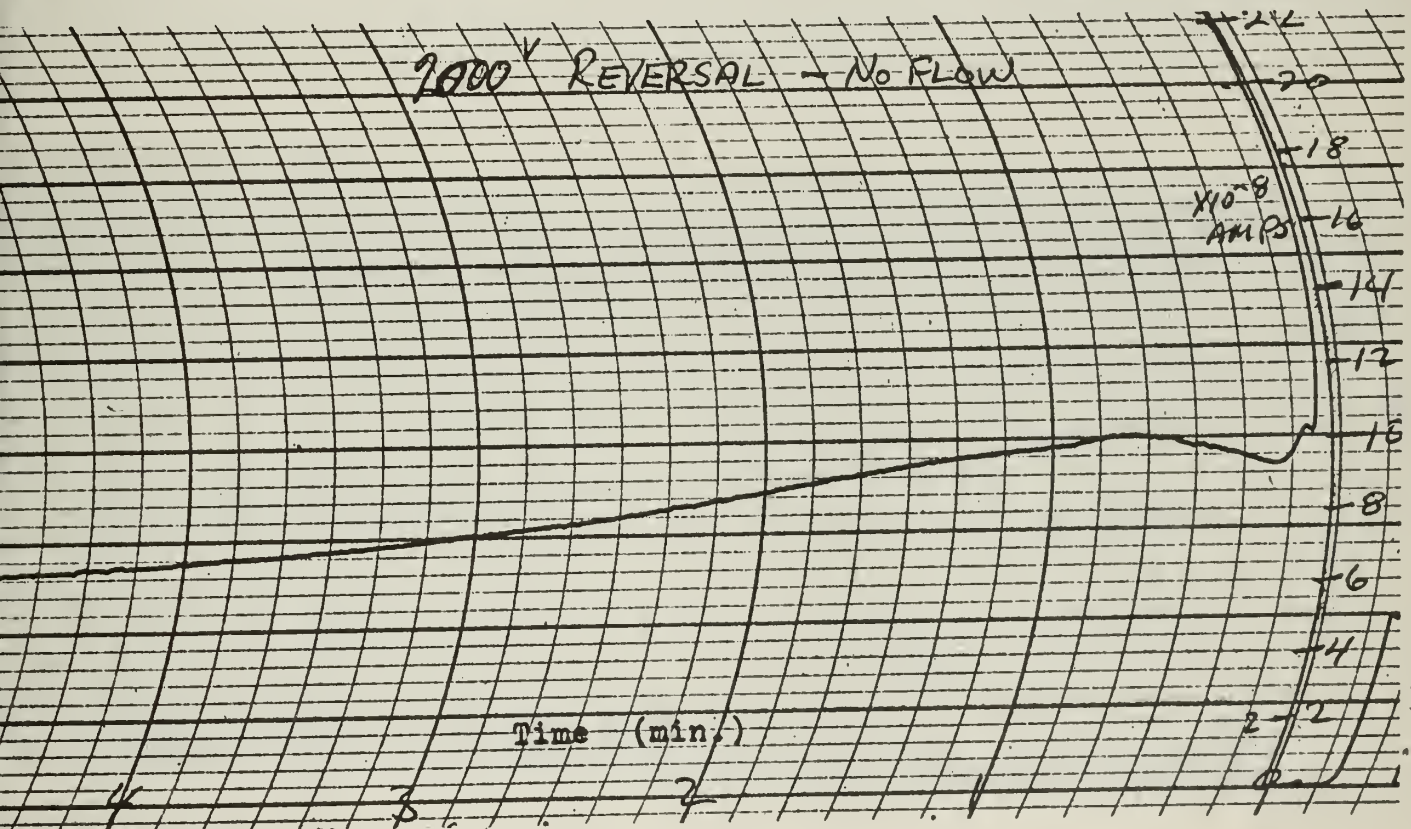
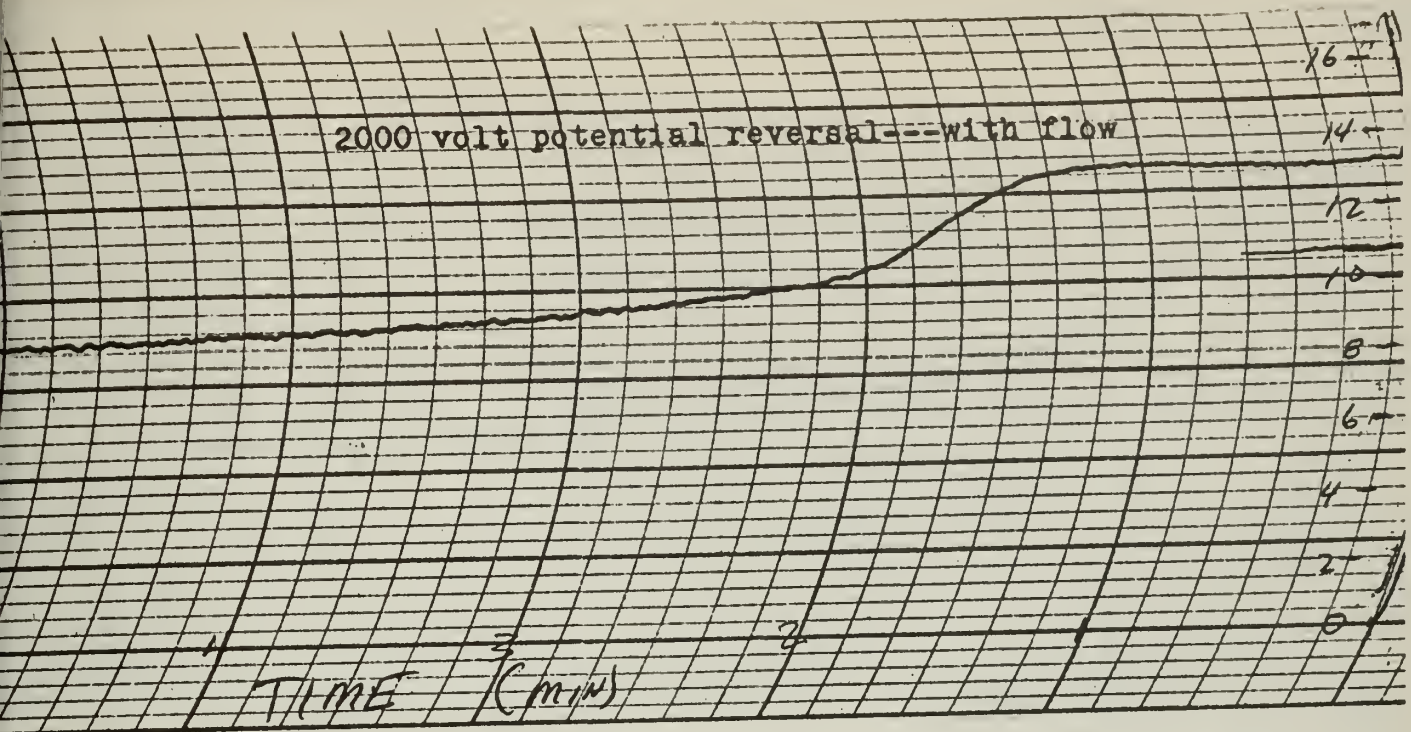


Fig. 15. Current vs. Time recorder tapes for 2000 volts potential reversal with and without flow.

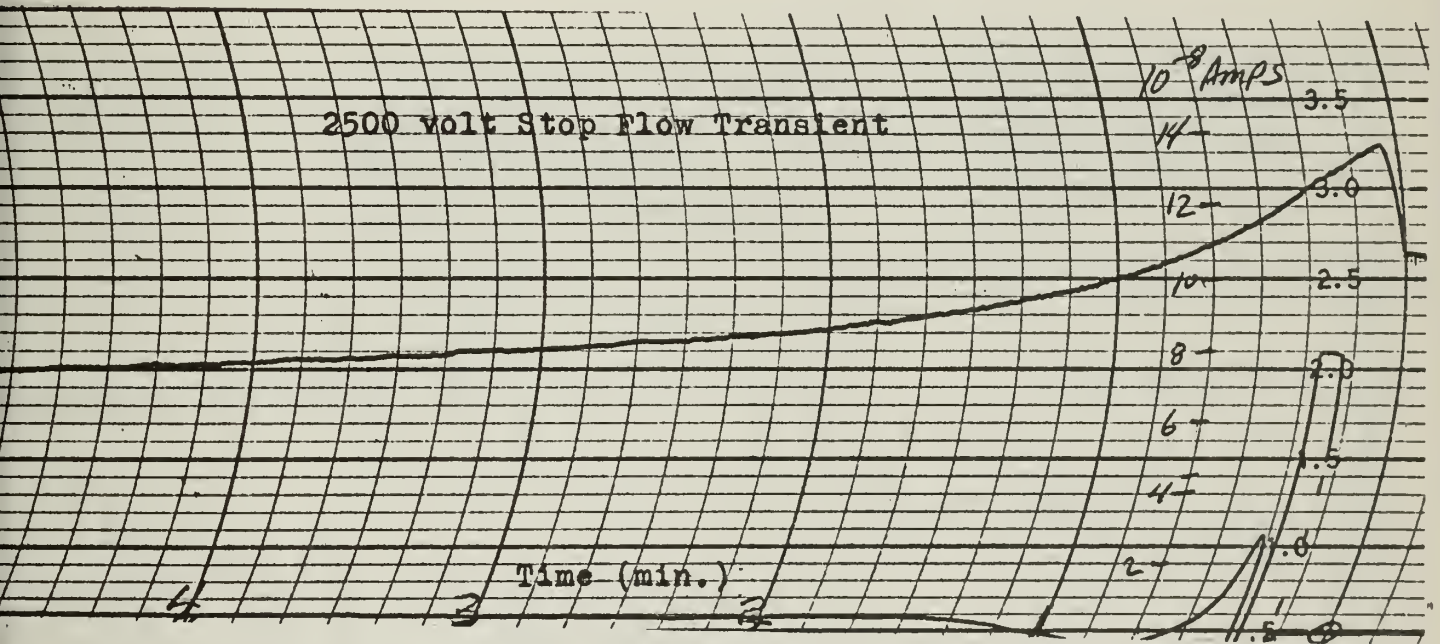
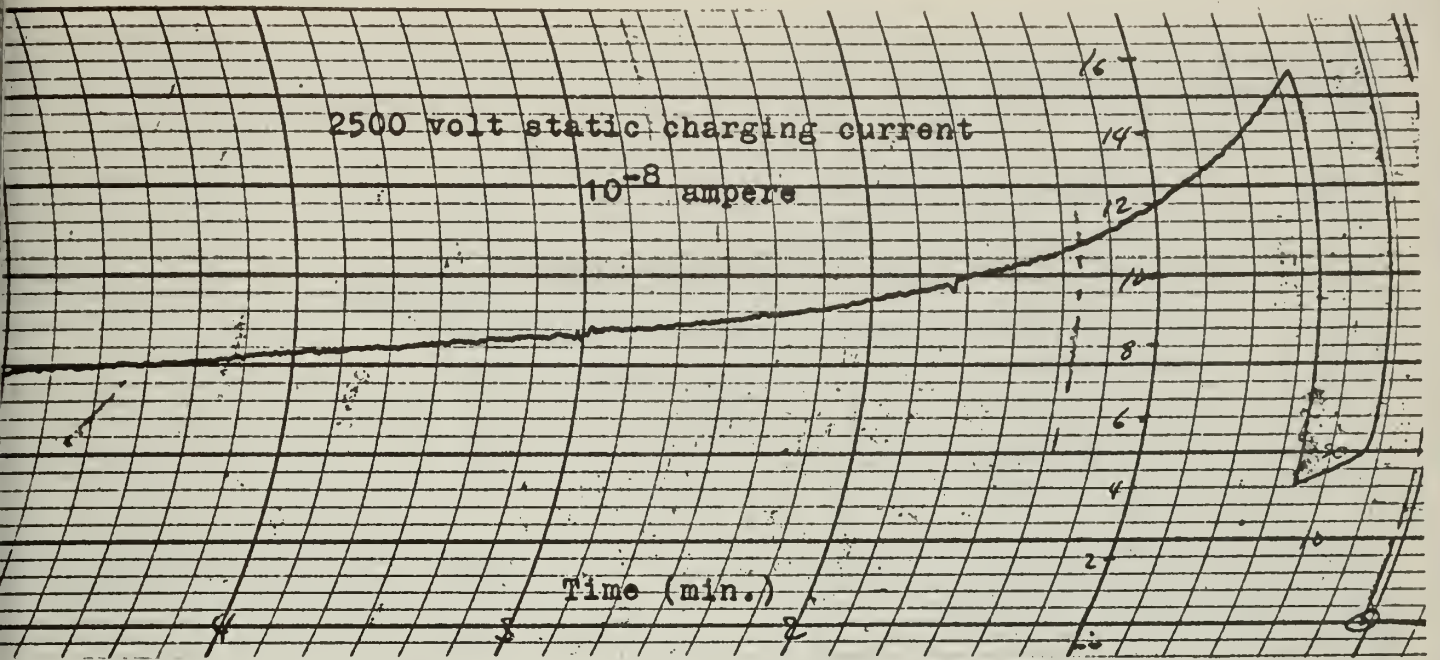


Fig. 16. Current vs. Time recorder tapes for 2500 volts static charge and stop flow transient.

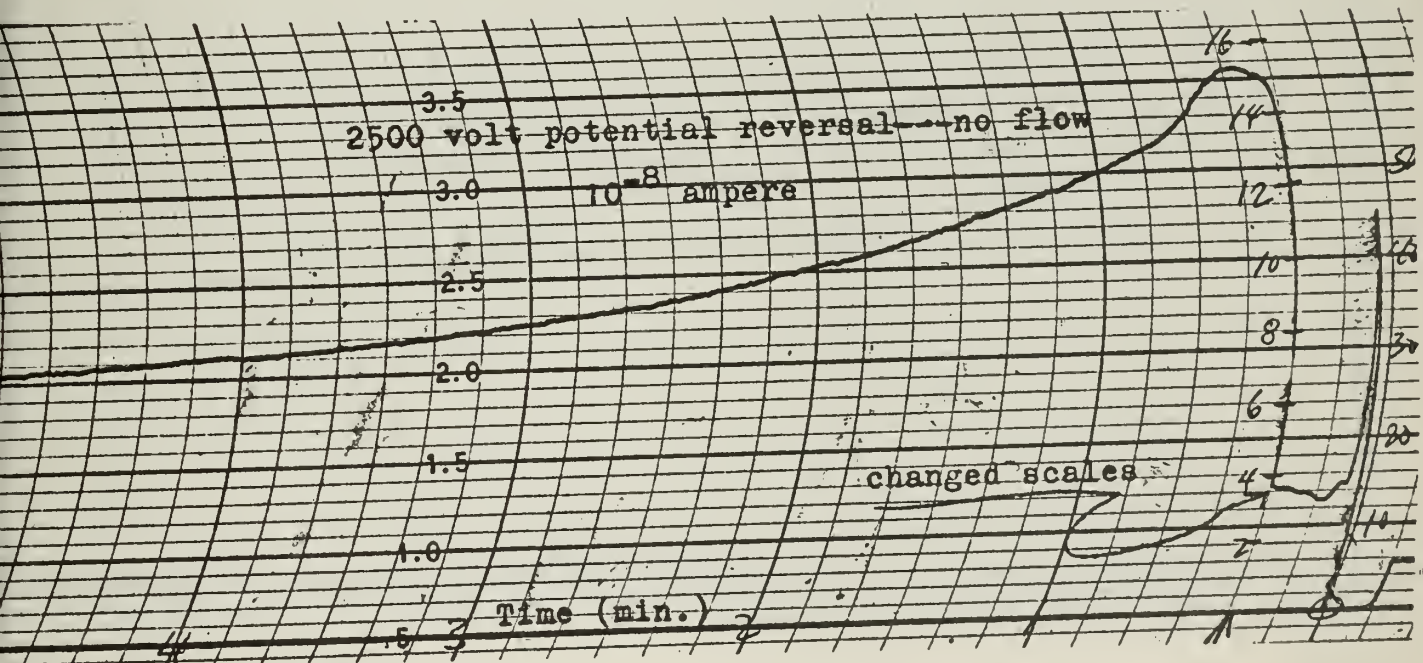
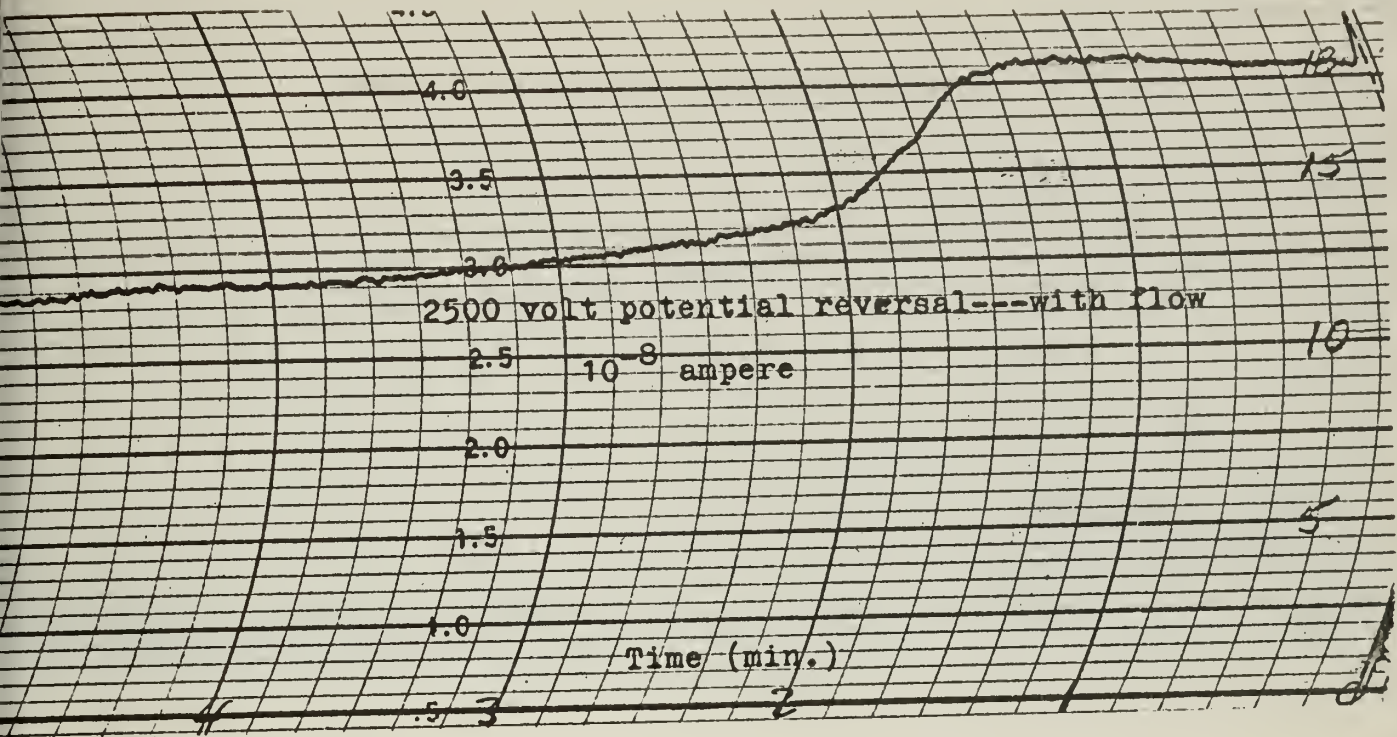


Fig. 17. Current vs. Time recorder tapes for 2500 volts potential reversal with and without flow.

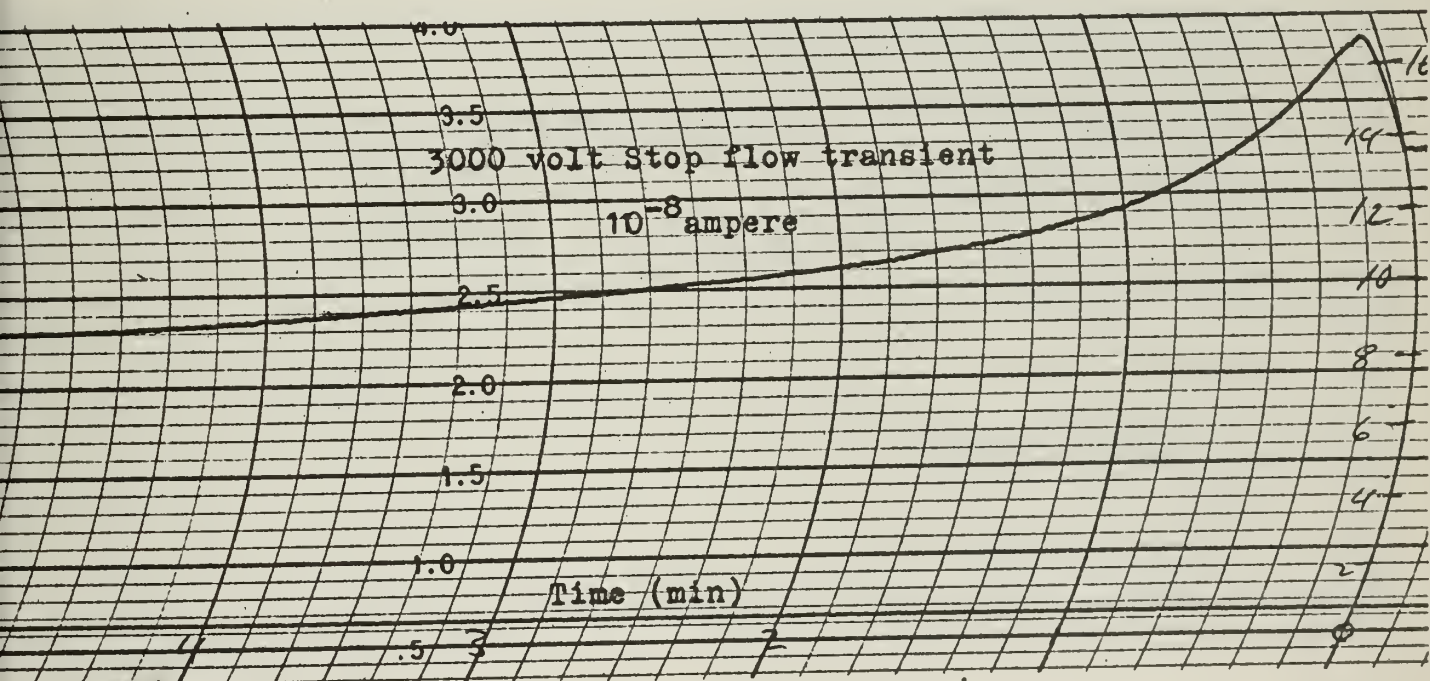
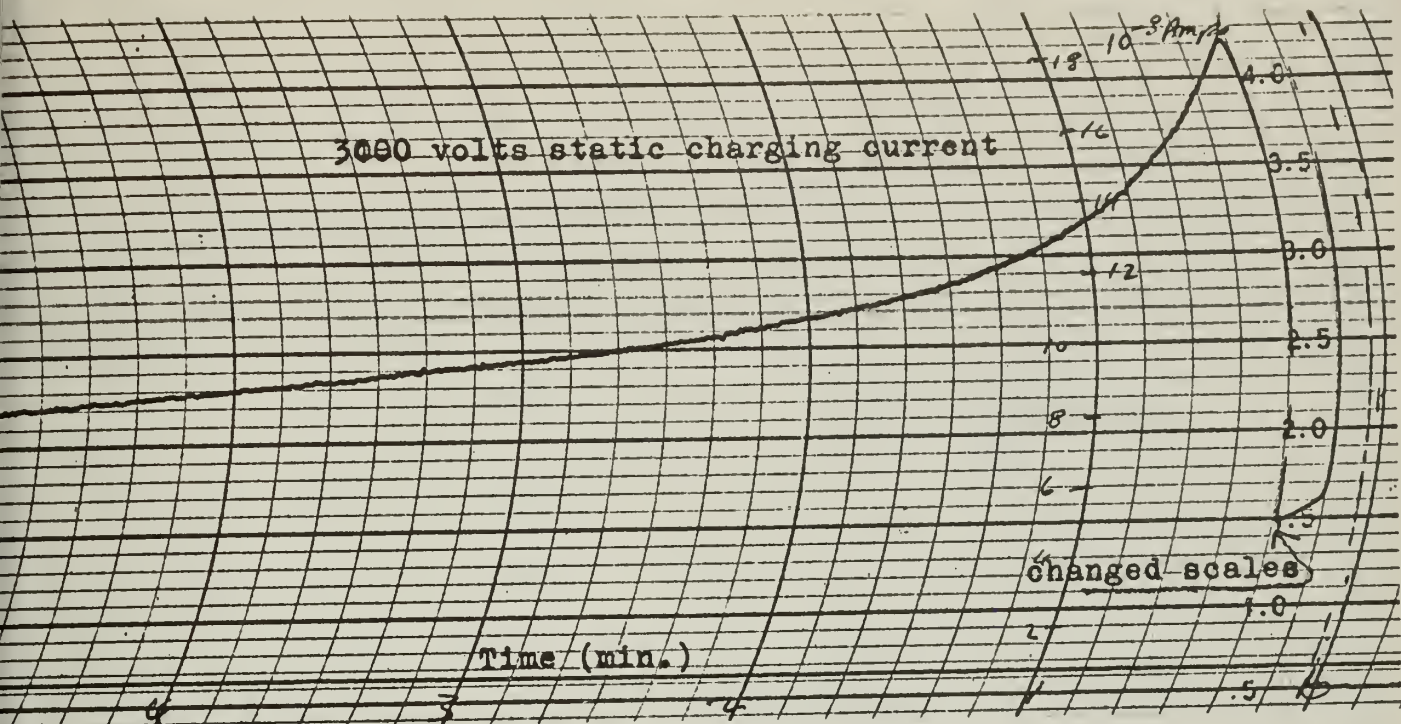


Fig. 18. Current vs. Time recorder tapes for 3000 volts static charge and stop flow transient.

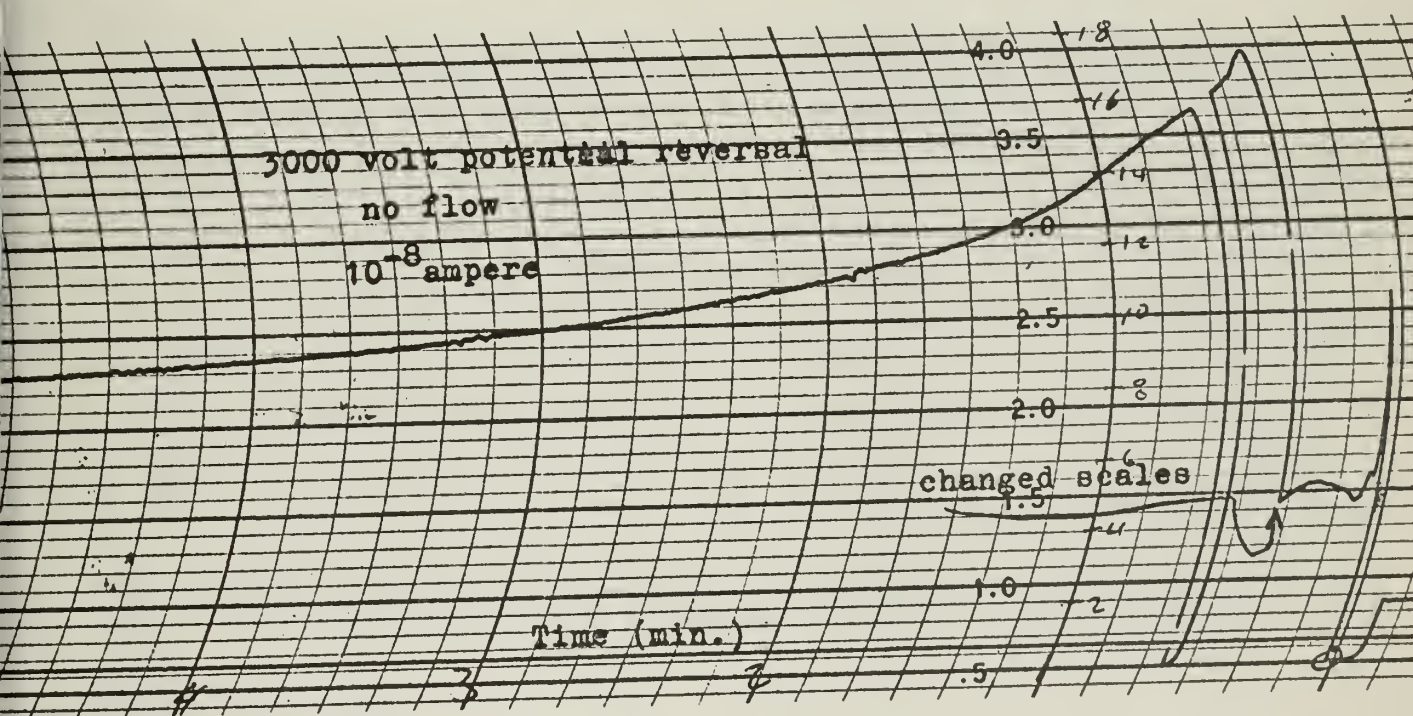
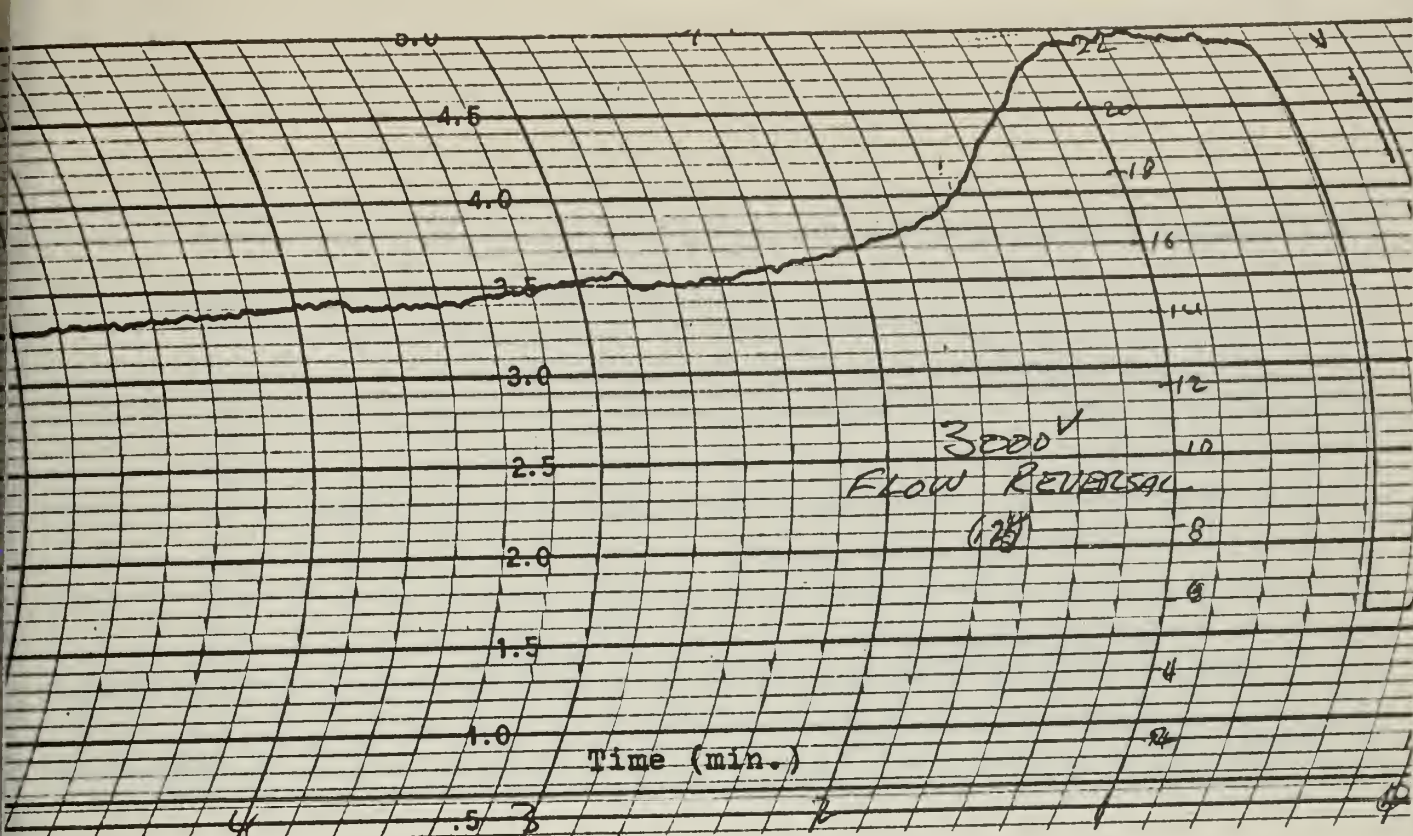


Fig. 19. Current vs. Time recorder tapes for 3000 volts potential reversal with and without flow.

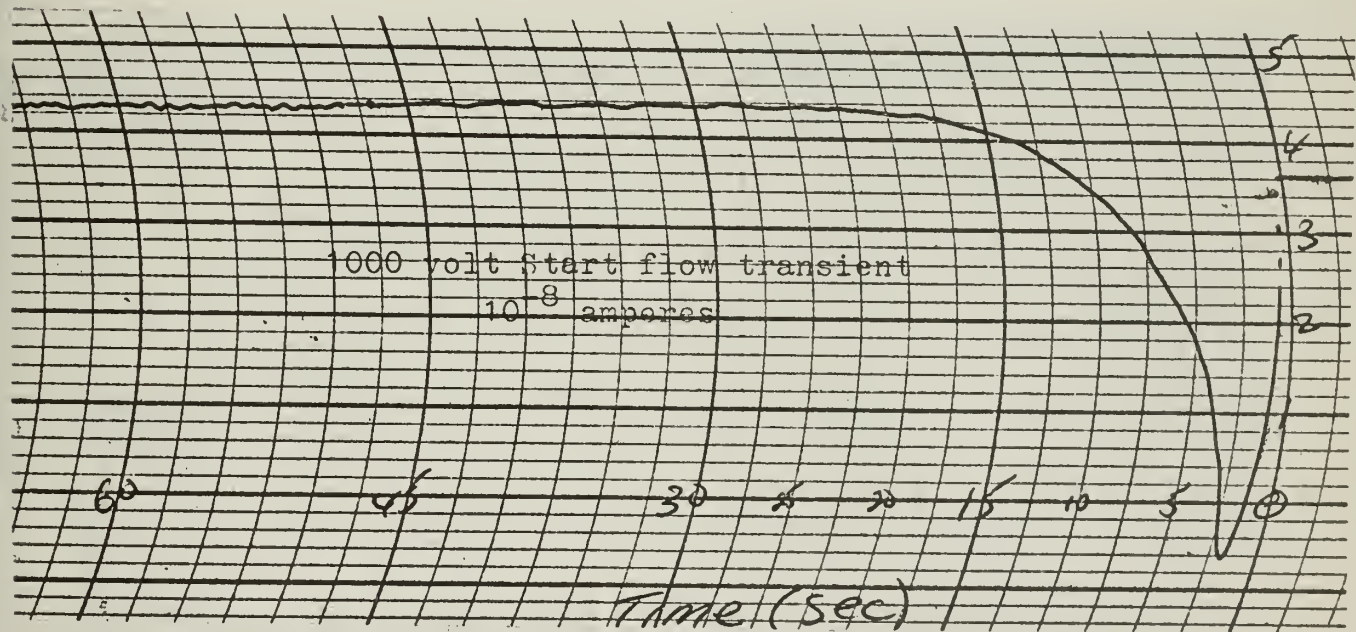
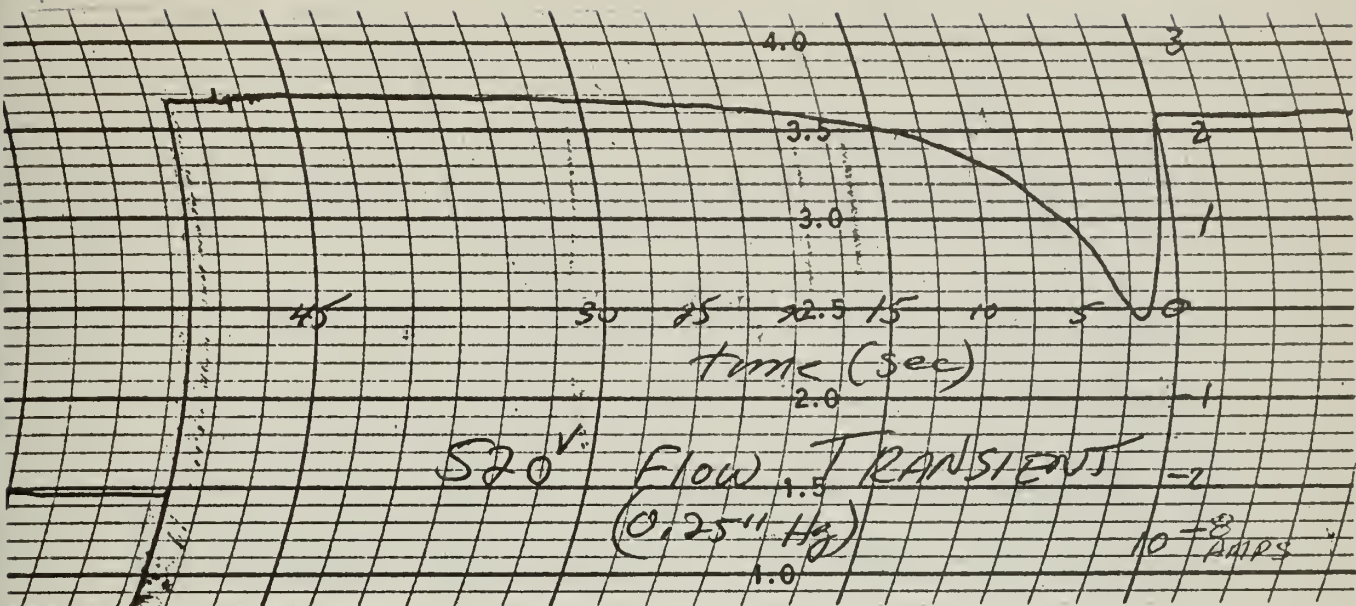


Fig. 20. current vs. Time recorder tape for 520 and 1000 volt Start flow transients.

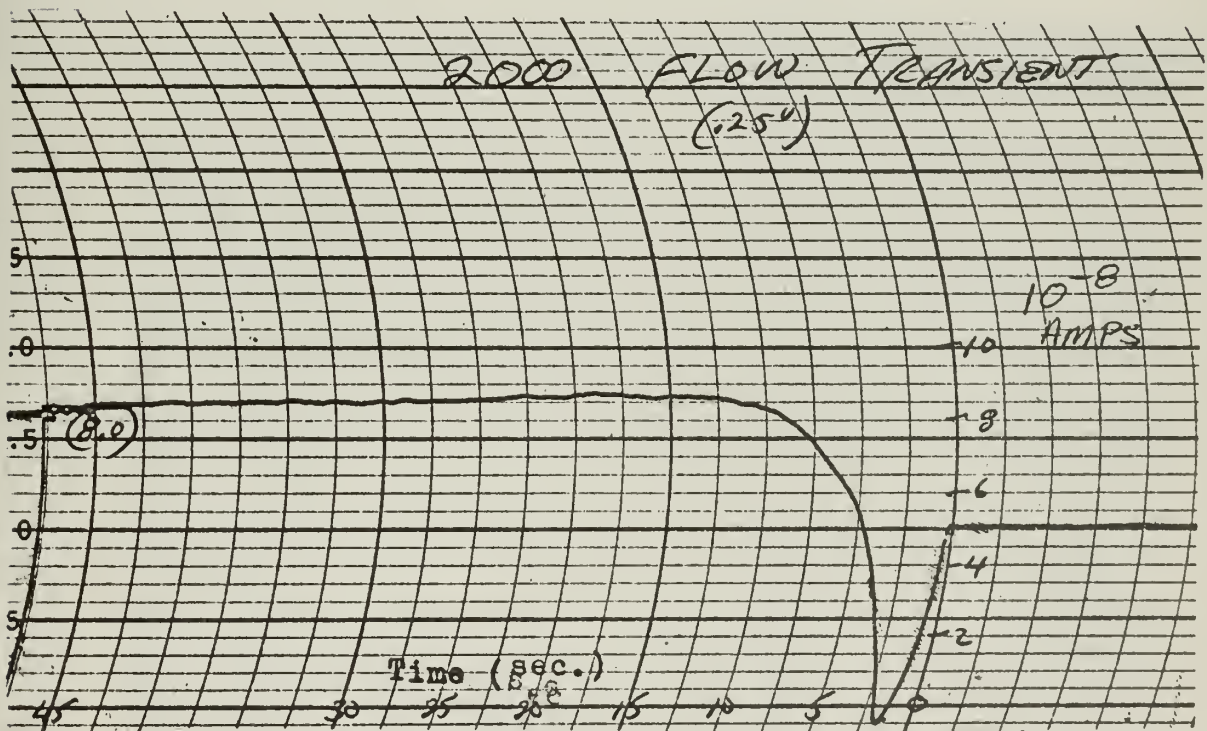
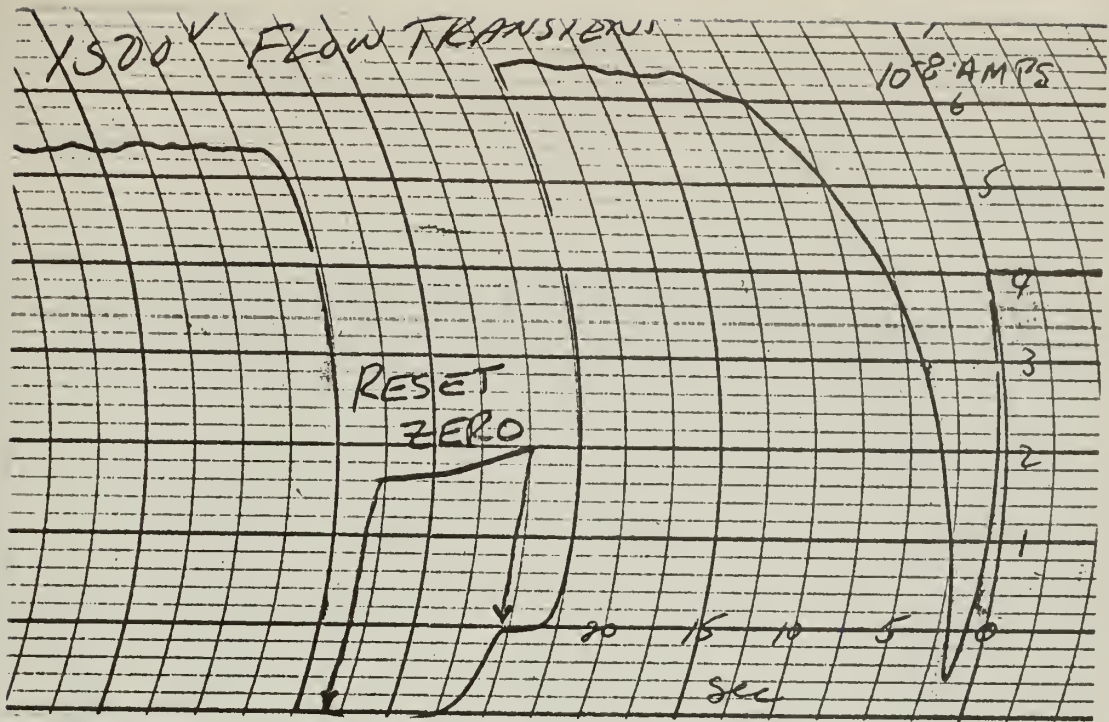
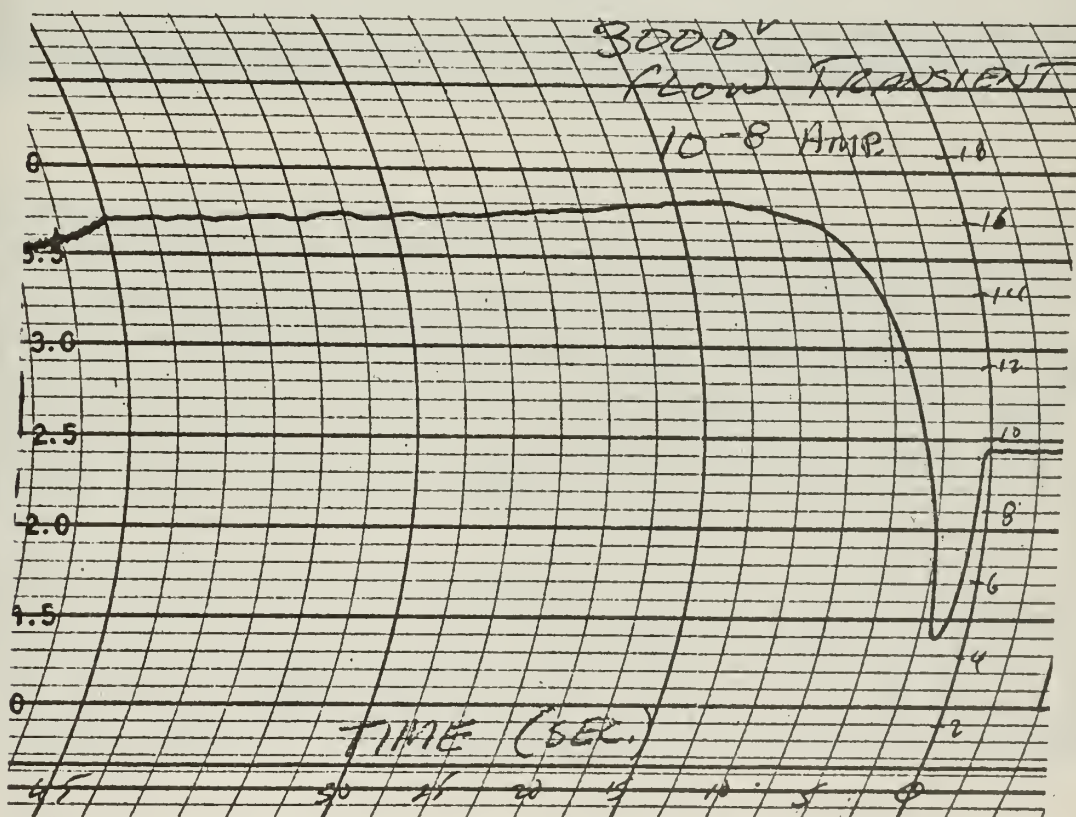
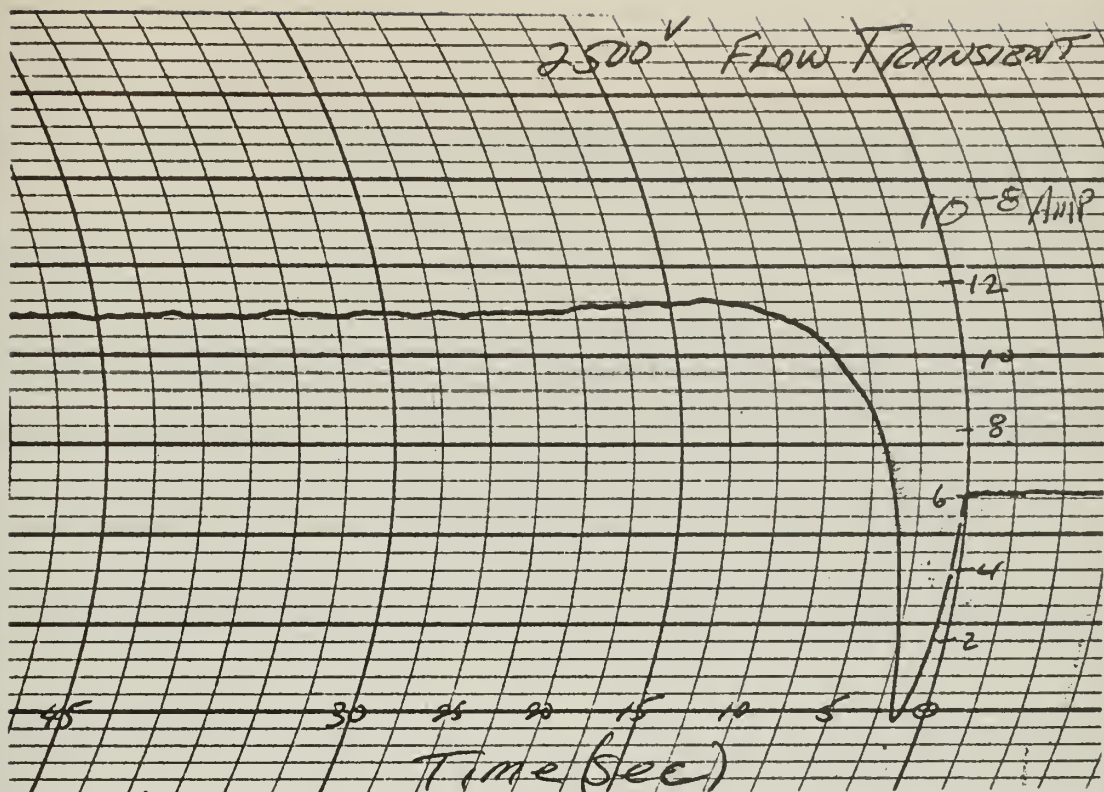


Fig. 211. Current vs. Time recorder tapes for start flow transient for 1500 and 2000 volts.



— Fig. 22. Current vs. Time recorder tapes for start flow transient for 2500 and 3000 volts.

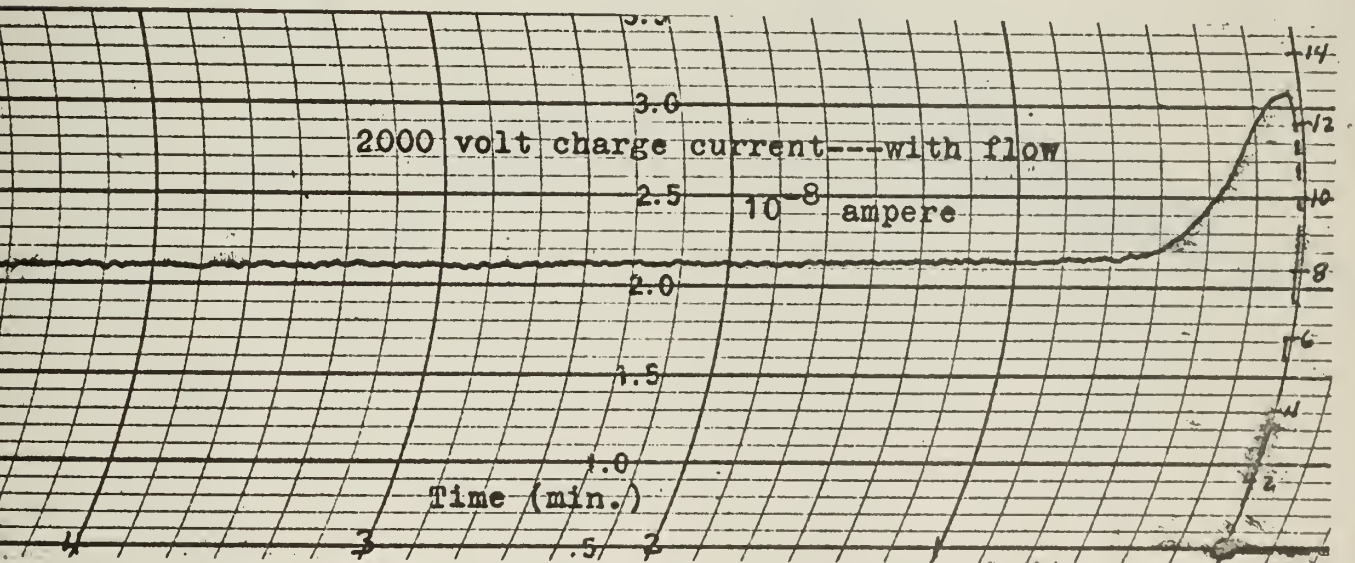
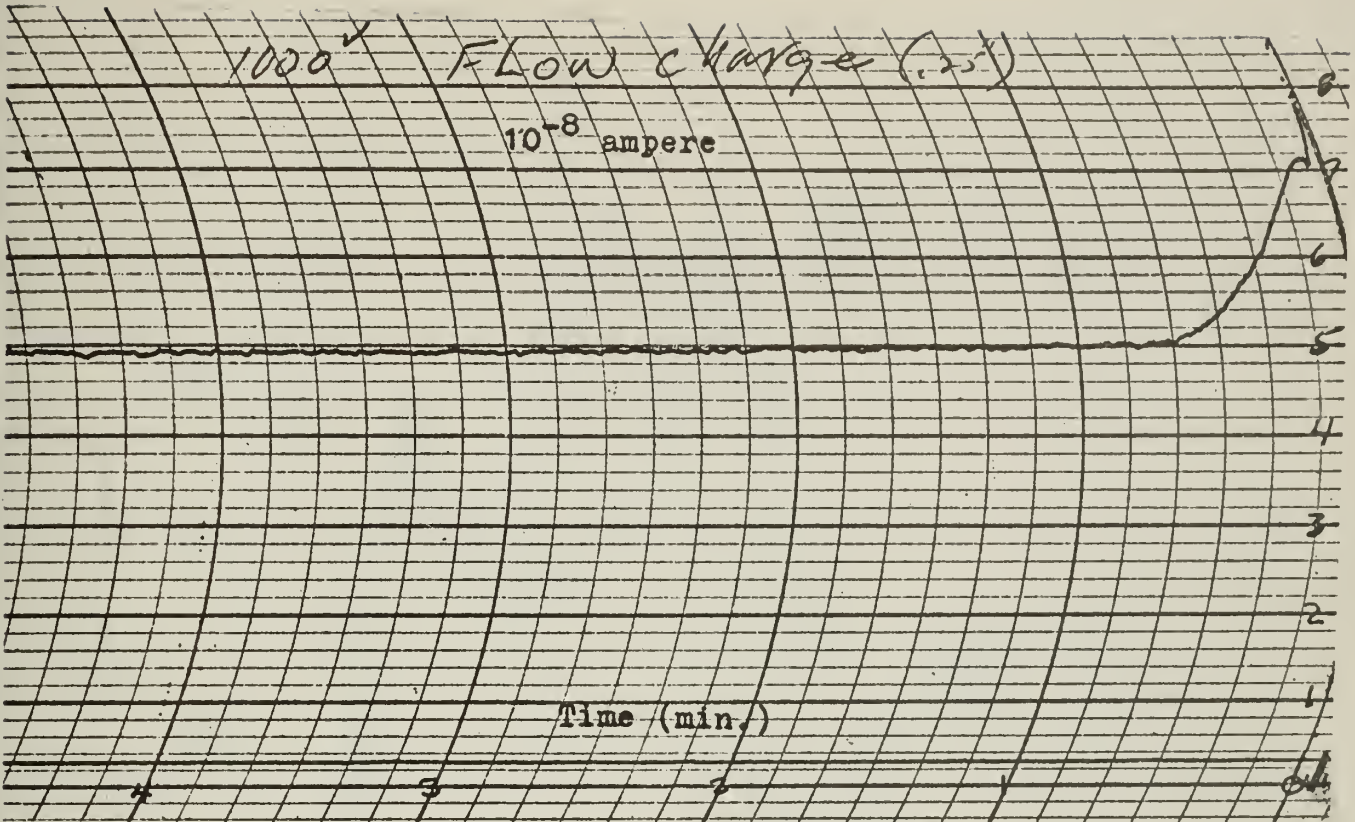


Fig. 23. Current vs. Time recorder tapes for flow charge at 1000 and 2000 volts.

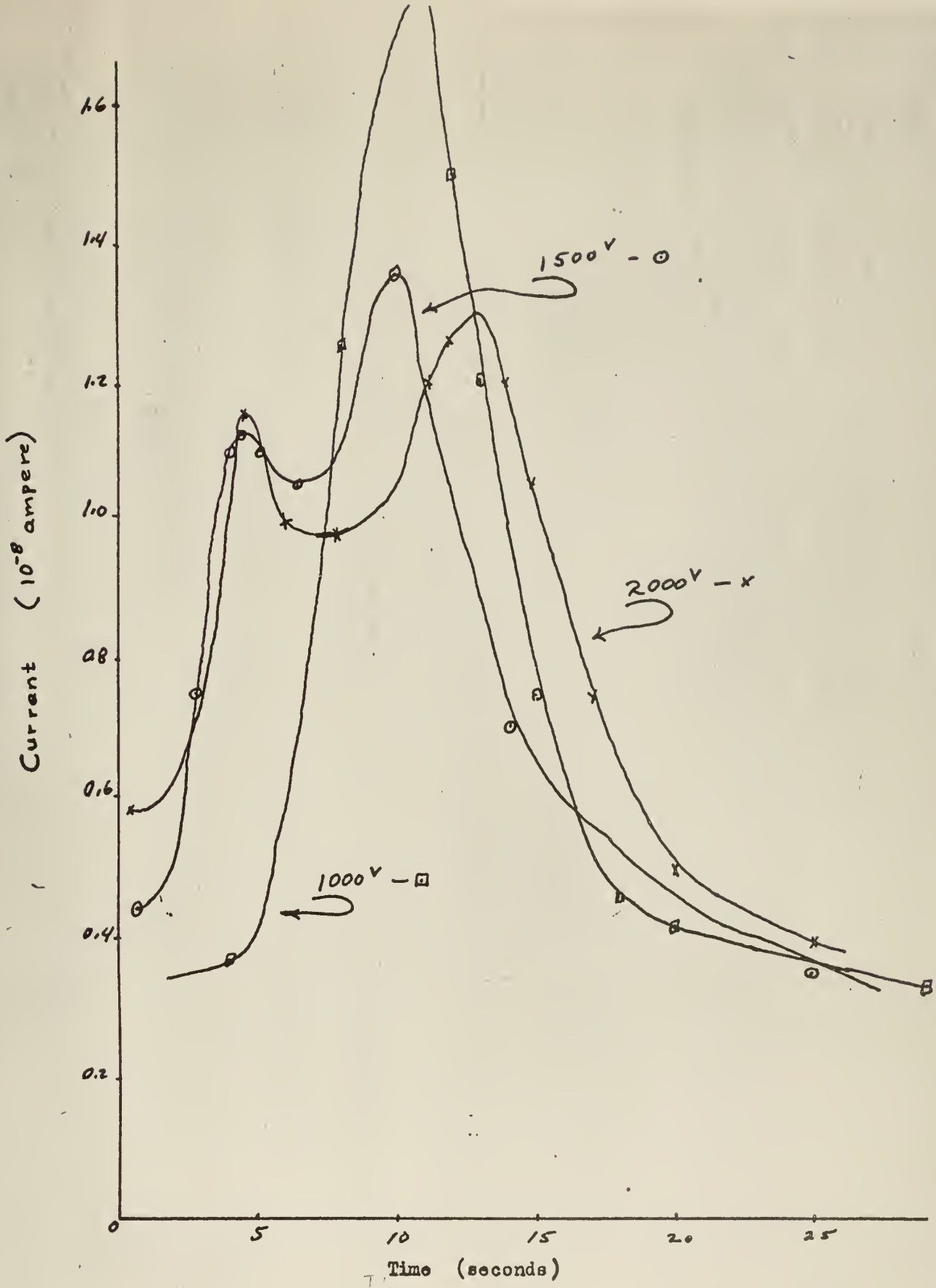
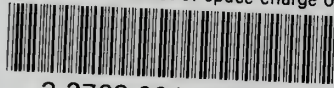


Fig. 24. Current vs. Time curve for potential reversal in static fluid for 1000, 1500, and 2000 volts.

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