The Measurement of the Transient Power and Energy Dissipated in Closing Switch Contacts

By W. B. ELLWOOD

(Manuscript received July 29, 1955)

A new technique is described for the measurement of the power and energy dissipated in the contact gap of a glass-sealed reed relay (switch) on the closure of a special coaxial circuit of which the switch is a part. The method uses two cathode ray oscilloscopes with provisions made to study time intervals of from one microsecond to less than a millimicrosecond. Also, a brief resume is given of some experimental results on a few switches.*

INTRODUCTION

The loss or transfer of metal due to the electrical erosion of contacts used in the telephone system results in reduced life, increased maintenance, or the use of more costly contact metals. All this presents an important economic problem to the Bell System, promoting extensive study of contact phenomena.

In the ordinary uses of electrical contacts, the making and breaking of electrical circuits lead to discharges across the contacts, which may last up to the order of 500 microseconds. The behavior of some of these forms of discharge is fairly well understood† because their long duration and approximately constant voltage permit ready measurement of the effects and an analysis of causes and remedies for the behavior. As a result, these gross effects are under the broad control of the designer, who can allow them when the circuit application permits, but who can reduce them by "protection circuits" at increased cost. The use of sealed

* Recent Developments in Relays — Glass-Enclosed Reed Relay, W. B. Ellwood, Elect. Eng., **66**, pp. 1104–1106, Nov., 1947. Development of Reed Switches and Relays —O. M. Hovgaard and G. E. Perreault, B.S.T.J., **34**, pp. 309–333, March, 1955.

† Numerous papers by L. H. Germer, M. M. Atalla, and associates in Bell Telephone Laboratories.

reed switches is an alternative potential means of erosion control with other attractive features such as speed and reliability. As the use of these switches is extended to ever greater numbers of operations, the need increases for greater understanding and control of the various forms of discharge taking place therein.

The sealed reed switch has various aspects with more ramifications than switches operating in air. Once the contacts are enclosed in their own private atmosphere, the precious metals may be of less importance and the determination of the best combination of contact metals and gas atmosphere inside the tube becomes of considerable practical and economic interest. There is thus a need to understand the fundamentals of the process taking place in the switch both during the discharge and as a result of it. Since discharges with good switches involve times of a few microseconds only, significant measurements become more and more difficult as interest is extended into the transition and formative regions of the discharge.

Much of the experimental difficulty is due to the inseparability of switch and circuit. The life and behavior of the switch are dependent on the circuit which may have properties which are not well understood. Because of the short time intervals involved it is necessary to use circuits with known properties at high frequencies. In order to test the switch a standard circuit is needed. To study the phenomena in the switch the rest of the circuit should be a pure resistance, uncomplicated by energy storage elements. This requirement has not been fulfilled in previous contact studies but is solved by the coaxial cable circuit described here. This new circuit not only provides a practically pure resistance for the reed switch but also provides means of calibration, compensation, and cross-checking features, and can detect differences in time between events to ½ millimicrosecond. The uncompensated energy storage amounts to less than one per cent of the energy dissipated in a switch. Other circuits may give different effects with the contact but this circuit is a reference standard.

I. STATEMENT OF PROBLEM

A. The Circuit Aspects of the Switch Problem

A switch is always used as a part of a circuit, and the behavior of the switch is affected by this circuit as well as the current and voltages which it controls. The interchange of stored energy associated with the other circuit elements is modulated by the switch during the transition period in an at present unknown manner. Thus, the dissipation of energy in the switch itself is determined by (1) the rate at which energy can be supplied to the switch from these storage elements and (2) the reaction of the various processes going on in the switch to the instantaneous current through it. The power dissipated in the contact region should provide important clues to the nature of the reactions taking place during the transition. The wear of the switch contacts depends on the electrical energy dissipated in the contact region and is known to be much greater than the wear of mechanical origin.

In order to obtain a true picture of the switch phenomena with minimum modification by circuit phenomena, it is necessary to study the switch in a circuit free from frequency sensitive and also other non-linear elements. This means the switch itself must be specially made to match the test circuit. The circuit used here influences the behavior of the contact in a simple manner instead of the usual complicated one. All data on switches included here is under one circuit condition, 150 ohms series resistance, which roughly approximates practical operating conditions.

B. The Switching Aspects of the Circuit Problem

In the usual texts discussing linear circuits including switches, the switching transition interval state is ignored. That is, the usual assumptions made in the boundary conditions eliminate the switch as a variable element. However, a certain amount of total circuit energy is always dissipated in the switch which becomes of great importance when the switch itself is under study. Furthermore, different mechanisms postulated to explain contact behavior lead to different circuit boundary conditions and it is impossible to choose between them without experimental knowledge of the current through the contact and the voltage drop across it as functions of time during the transition period.

C. The Measurement Problem

The experimental problem is to operate a test switch in a pure resistance circuit with a known battery voltage and to observe with a cathode ray oscilloscope (CRO) the instantaneous values of current and the corresponding voltage drops across the switch during the transition interval. From these observations, the instantaneous values of power and the total energy expended between the switch terminals can be calculated. This measurement must take account of the following:

(1) The non-linear nature of the contact (during transition) as a circuit element makes practical circuit analysis extremely difficult,

since the usual impedance concepts do not apply and the voltage drop and current must be determined by *separate but simultaneous* measurements. By non-linear is meant a condition where the voltage drop is not simply proportional to the current, its integral or its derivatives. In theory, the current and voltage can be calculated for any specific circuit by means of non-linear differential equations expressing the instantaneous reactions of the different circuit elements as functions of the current and the time. The resulting equations are often impossible of solution in a practically useful form and each one is a special case. In the case of the contact it is necessary to find an empirical expression for the voltage reaction as a function of both current and time before an analytical solution of the transition circuit can be attempted.

In the case of the coaxial cable, a measurement of voltage alone suffices to determine both voltage and current in the cable as the surge impedance of the cable is known and substantially independent of frequency. In the circuit described here the cable, the contact, the CRO and the battery constitute a form of ohmmeter in which the instantaneous voltage drop across the contact is compared with the corresponding drop across the cable with the same instantaneous value of current. The circuit aspects of the combination thus yield a number which is a ratio of resistances whatever the physical processes taking place in the contact.

(2) The shortness of the transition time (of the order of 10^{-7} to 10^{-10} seconds or possibly less) corresponds to extremely high frequencies so that the reactance of even one cm of wire is not negligible, neither are the admittances to ground.

(3) The non-repetitive behavior of practical contacts makes it necessary to observe single transients.

(4) Transmission phenomena ordinarily complicate both the phenomena to be observed and the interpretation of the observations. Some sort of parallel connections have to be made between the test circuit of which the switch under study is a part and the CRO which is used to measure the voltage and currents. The attached wiring constitutes a transmission line or lines, which provide delay times comparable to the time intervals under study and reflections and attenuation of the wave forms with possible mutual couplings.

These fundamental difficulties have long prevented an easy access to the basic information on the physical behavior of the contact under non-reactive circuit conditions. The circuitry of the deflection plate system, the transit times of the electron beam, and the photography of the screen are incidental minor problems.

D. *Advantages of Present Scheme*

The contribution of the technique of the present article is that advantage is taken of well known transmission phenomena in a coaxial line subjected to a voltage step to:

(1) provide an essentially resistive circuit* in which the contact can perform;

(2) reduce the number of possible interactions between the CRO and the contact including complications from parasitic circuits and mutual couplings between such circuits (done by shunting the reactive CRO circuit with the low resistance cable);

(3) take advantage of transmission phenomena to get electrically closer to the contact† than ever before; and to divide the pattern on the CRO screen into two areas: (a) the part relating to the contact behavior with negligible modification by the reflection, attenuation, and frequency dispersion effects taking place in the circuit; and (b) the other, showing same information *significantly* modified by the attenuation, reflection, and frequency dispersion effects of the circuit; and

(4) use of two CRO tubes at different points along the length of the coaxial line provides cross-checking features and a means of separation of contact phenomena from other phenomena in the circuit.

II. THE BASIC MEASUREMENT SCHEME

There are four basic elements involved in such measurements: (1) The development of a precision CRO beyond the capabilities of those

* The ratio of reactance to resistance of this circuit is calculated to have maximum values in the neighborhood of 200 and 600 megacycles and is less than 0.15. The reactive term is due to the reactance of the CRO in parallel with the coaxial line.

† The term "closer to the contact" needs interpretation. Any contact is usually connected to the circuit by leads which have some inductance, resistance, mutual capacitance, and capacitance to ground. All these provide local parasitic energy storage reservoirs which complicate the circuit analysis. In the case of the coaxial transmission line every unit length of center conductor has an inductance which is associated with an equivalent capacitance to the sheath so that an infinitely long line acts as a resistance, independent of frequency, and is dependent only on the geometry of the conductors and the specific capacitance of the dielectric between the sheath and center wire. In the coaxial switch structure used in this work the switch and its leads are surrounded with a conducting sheath constructed to have the same value of capacitance and inductance per unit length as the coaxial line into which it is incorporated. Thus the switch acts as it would if in a pure resistance circuit (equal to the surge impedance of the line) without effects due to lead inductance or capacity. The voltages observed on the line, a short distance from the contact are the same as those which would be observed at the contact with infinitely short leads (without inductance or capacity) but appear at the point of observation after a delay time of d/V_T seconds where V_T is the propagation velocity of the line and d is the distance.

available, with associated controls whereby the operation of the CRO is sufficiently synchronized with the contact under study, or vice versa, so that the phenomena in question appear on the CRO face at the proper instant and are photographically recorded; (2) The experimental development of the fundamental measurement circuit in which the contact operates and which has the properties outlined above; (3) The simple analysis (illustrated in Fig. 5) whereby the CRO record can be interpreted in terms of the basic parameters, voltage, current, power, and time without the need for complicated calculation; and (4) The experimental calibration of the CRO and proof of the record.

A. *The Oscilloscope and Control Circuitry*

Measurement of single transients involving time intervals of the order of nanoseconds* places special requirements on the CRO itself and the technique of operating it. The use of amplifiers at these frequencies introduces many circuit problems which are best avoided by using the CRO plates directly. The voltage sensitivity of the CRO tubes used permitted this study to be made in a useful range of voltage without need for amplification.

There are two CRO tubes used in these measurements — one (CRO-1) to record voltage† as a function of time, the other (CRO-2) to record voltage as a function of charge from which the energy dissipated can be calculated directly. There are also incidentally two cameras and counters associated with them so that corresponding photographs will be identified by the same number. The action of the oscilloscope control circuits will be described in Appendix A. A block diagram of both the oscilloscope control circuit and the coaxial line contact test circuit is given in Fig. 1. A schematic diagram of the arrangement of camera, counter and CRO tube face is shown in Fig. 2.

B. *The Coaxial Cable Switch Test Circuits (Figs. 1, 3 and 4)*

(1) *The Test Switch*

The glass sealed reed switch comprises a pair of contact reed springs of magnetic material sealed in opposite ends of a glass tube filled with an appropriate atmosphere. The normal gap between the contact ends of

---

* Unit of time equal to a millimicrosecond (American Standard Definition of Electrical Terms, Revised 1955). The abbreviation *ns* will be used hereafter for millimicroseconds. Also, from the same reference the term picofarad (*pf*) will be used as equal to micromicrofarad.

† The CRO tube is a voltage operated device. In the coaxial line both voltage and current waves coexist and are related to the characteristic impedance. One CRO reading defines both.

the springs inside the glass may be closed to make contact by application of a magnetic field along their axes. The distance between the contact spring end and where it is available for connection outside the glass is about three centimeters. This has an appreciable inductance at the frequencies which are involved in the closure of the contact. It was desired to test switches as manufactured without modifications such as auxiliary electrical connections through the glass. To do this the switch

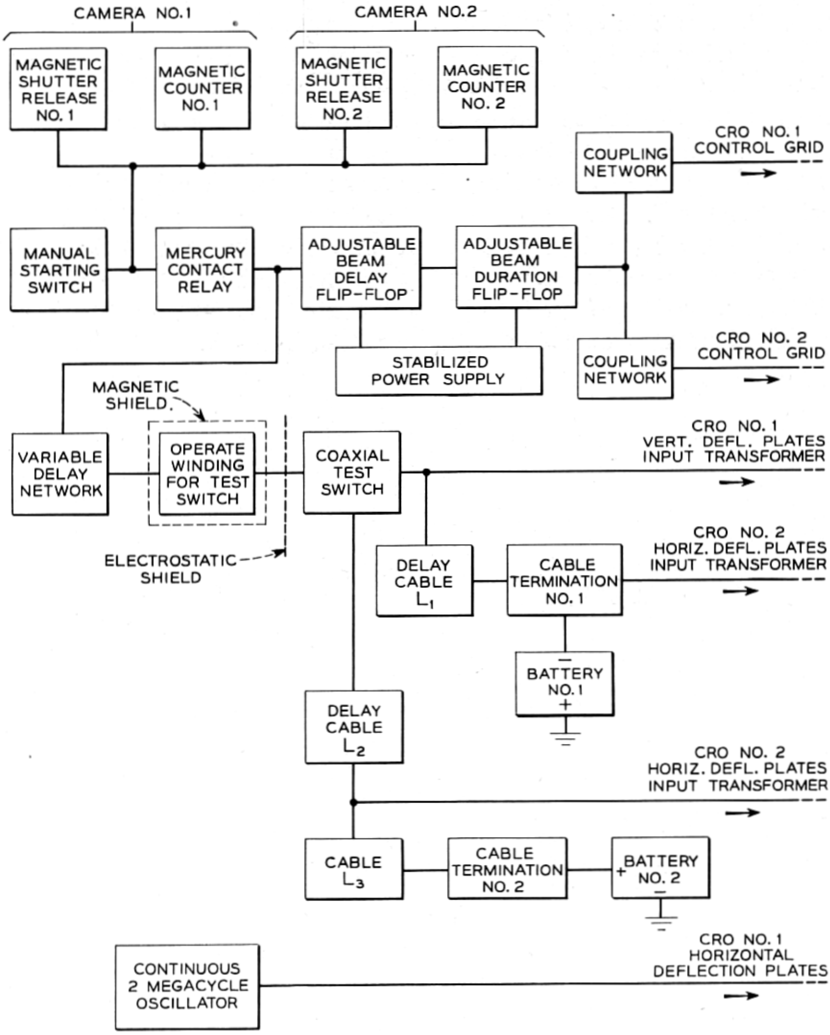


Fig. 1 — Block diagram of control and test circuits.

(Fig. 3) is supported inside a metal tube with an internal diameter so chosen that the switch elements and the tube combined form a length of coaxial conductor indistinguishable in surge impedance from the rest of the coaxial cable which is attached at each end. The operating winding of the switch is wound on the outside of the tube and outside the winding is a shell of permalloy to shield the nearby oscilloscope tube from the stray magnetic field of the switch and winding. This structure will be referred to as a COLS (coaxial line switch) for convenience.

(2) *The Contact Test Circuit* (*Fig. 4*)

The COLS is incorporated into a coaxial line* which is divided into three sections of length L_1, L_2, and L_3 feet. (Figs. 1 and 4). The COLS is connected between L_1 and L_2. The inner conductor of L_1 is connected to a battery (− pole) through a high resistance R_1 while the inner conductor of the $L_2 + L_3$ sections is connected in similar way to an *equal* battery (+ pole). The other end of each battery is connected to the sheath of the cable. The contacts of the COLS thus have twice each battery voltage across them when open. The vertical plates of CRO-1 (in series with R_3) are bridged with as short leads as possible between the inner and outer conductors of L_1 at one end of the COLS. The horizontal

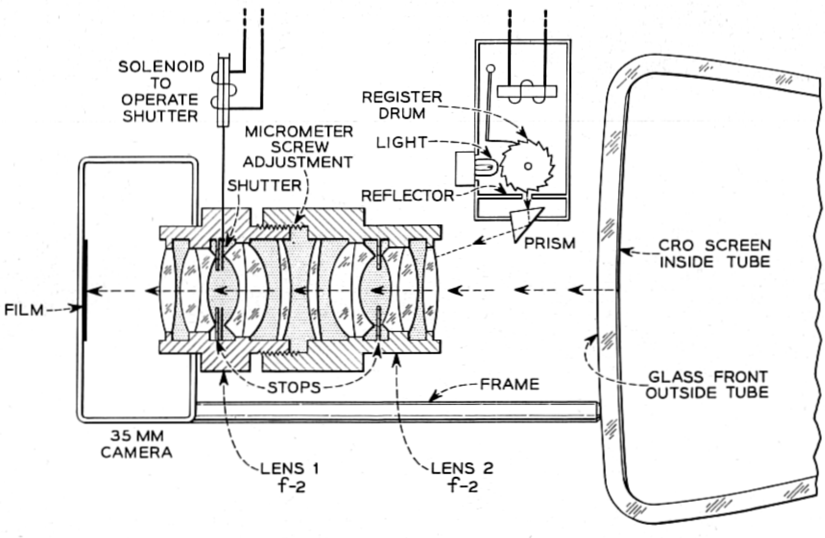


Fig. 2 — Schematic of camera lens system, operating solenoid, counter and CRO.

* Western Electric No. 724, which is a copper cored, polyethylene insulated, coaxial cable with a double sheath of copper braid and a surge impedance of 75 ohms. The double sheath is important as single braid sheaths leak appreciable energy to adjacent circuits.

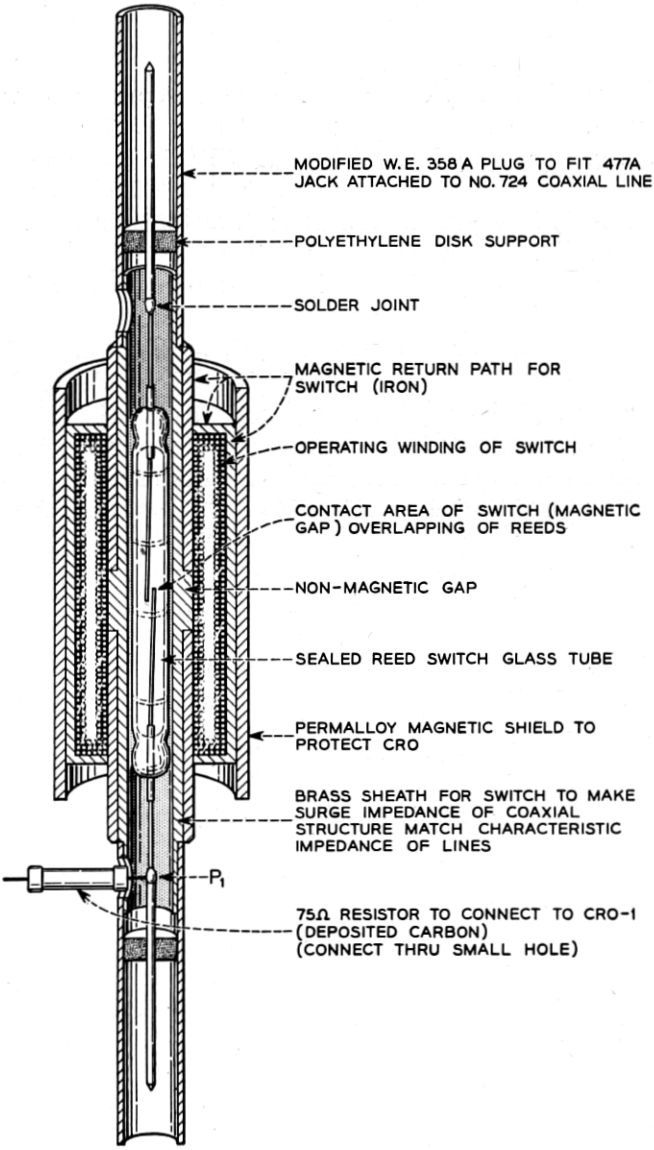


Fig. 3 — Schematic diagram of coaxial line switch.

plates $S - S'$ of CRO-1 are connected to a two megacycle oscillator which serves as a sinusoidal sweep. Thus CRO-1 simply plots the voltage between the center wire and sheath of L_1 near the COLS as a function of time on a sinusoidal scale. This is ½ the voltage drop (e) across the COLS as it closes. When the contact is open the CRO traverses a straight line at the voltage of battery No. 1. When the CRO indicates a steady zero voltage it is usually assumed the contact is closed. The latter is subject to further study if reflections take place prior to closing.

The plates of the second oscilloscope CRO-2 are bridged between the center conductor and sheath at point P_2, the junction of L_2 and L_3. The vertical plates of CRO-2 (capacitance C_0) see the same voltage as CRO-1 except that the voltage arrives nearly L_2/V_T seconds later and is slightly modified by the cable attenuation. The quantity V_T is the velocity of transmission of a pulse impressed on the cable.

Section L_1 is terminated with a resistance R_2 and a capacitance C_1 and is bent around so that the horizontal plates of CRO-2 connect directly to the terminals ($A - A'$) of C_1. The total capacitance $C = C_1 + C_0$.

If the transmission times corresponding to L_1 and L_2 are made *equal* then for every voltage drop, e, occurring in the COLS as it closes (and appearing as $e/2$ on the vertical plates of CRO-2) there will be a corresponding voltage change dv on the horizontal plates. Thus CRO-2 plots $e/2$ as a function of

$$v = v_0 - \int_0^t dv \quad \text{(Fig. 6)}$$

with $dq = idt = C\,dv$ where i is the current through the COLS and q

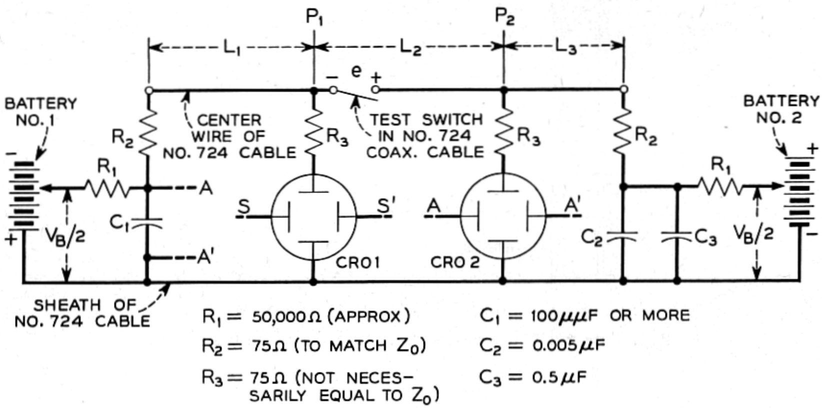


Fig. 4 — Coaxial line switch test circuit diagram.

the charge. Thus a typical vertical element of area dv wide and $e/2$ high is

$$\frac{e\,dv}{2} = \frac{e}{2}\frac{dq}{C} = \frac{ei\,dt}{2C} = \frac{P\,dt}{2C} = \frac{dw}{2C}$$

where P is the instantaneous power corresponding to the voltage e and w is the energy dissipated or stored. If the power is integrated* over the time from 0 to τ, (the time the switch requires to close) the total energy w dissipated on closing is obtained from CRO-2. Practically the upper limit of time is set up by the arrival of the reflected wave from the far end of L_1 which sets a limit on the time during which the coaxial cable may be regarded as a pure resistance. The COLS should then be closed ($e = 0$). However, in the case of some persistent discharges, this may not be true and the integration only applies to that portion of the closure process which occurs prior to the arrival of the reflected wave.

Section L_3 is long enough that reflections from that end do not return in time to interfere with observations on either scope. Nevertheless, such reflections should not be allowed to reverberate between the ends of the line. The far end of L_3 is therefore terminated in a dissipative network R_2 $(C_2 + C_3)$.

(3) *The Oscilloscope Deflection Plate Circuits*

The resistance R_3 in series with the plates of the oscilloscopes plus the inductance of the lead wires both inside and outside the glass walls of the CRO tube and the capacitance of the scope plates constitute an r.f. coupling transformer,† (or impedance matching network) Fig. 7(a),

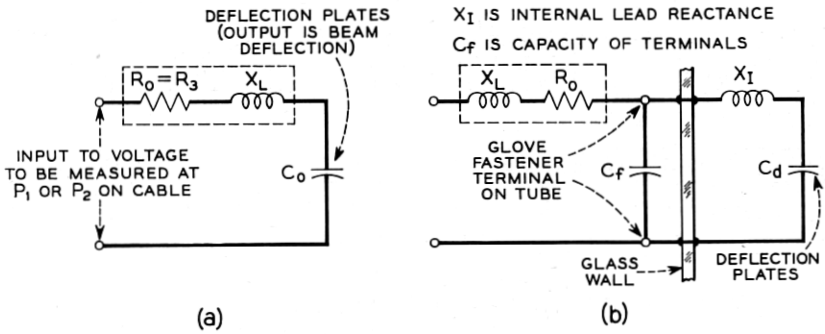
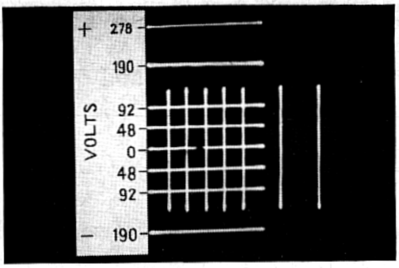


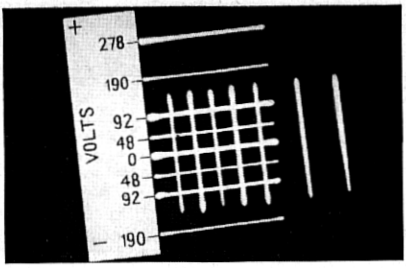
Fig. 7 — Vertical deflection plate circuits of CRO-1 and CRO-2. "Input transformer" or impedance matching network.

* A discussion of the errors of integration will be given later.

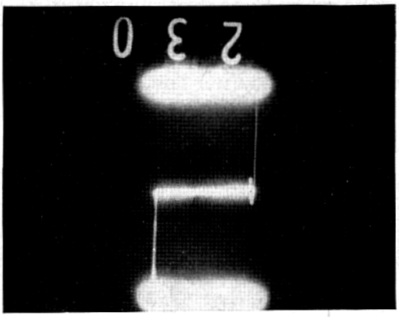
† Lee, R., Electronic Transformers and Circuits, 1st Ed. p. 123, 1947. Lewis, I. A. D., and Wells, F. H., Millimicrosecond Pulse Techniques, pp. 174–177, 1954.



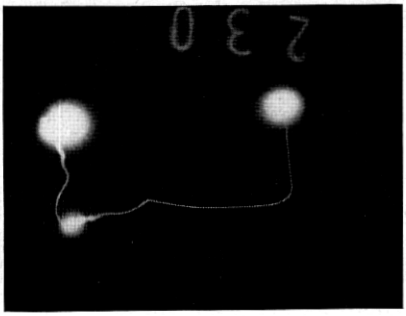
CRO-1



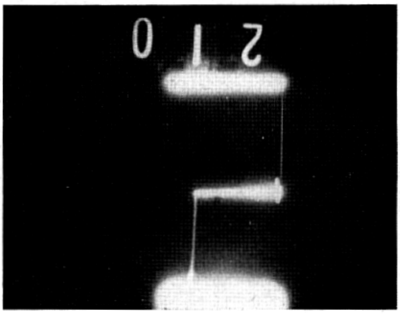
CRO-2



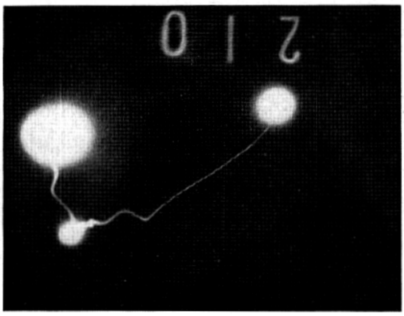
$L_1 - L_2 = 1$ ns



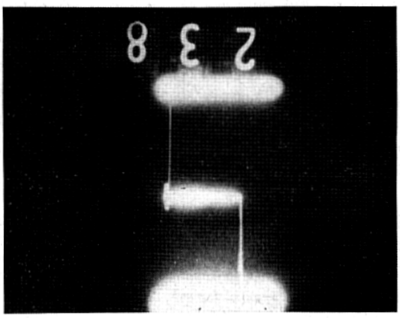
$C_0 = 4$ pf



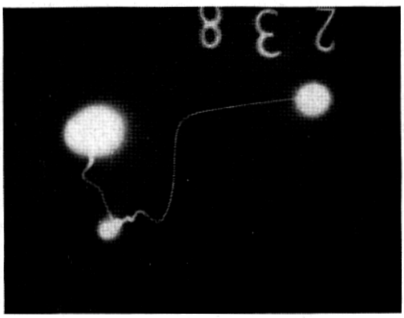
$L_1 = L_2$ ns



$C_0 = 4$ pf



$L_2 - L_1 = 1$ ns



$C_0 = 4$ pf

Plate A — Calibration and check data for CRO-1 and CRO-2.

which will be discussed (Appendix C) later. It is not to be confused with a simple RC circuit.

The CRO plates respond equally to all frequencies up to about 400 megacycles after which the response falls off rapidly. This means that an event taking place in a time of ¼ period or longer (0.6 ns) may be resolved on the screen and that time longer than this may be regarded as significant. Data presented in Plate A, Nos. 210, 230 and 238 (discussed later) may be taken as experimental confirmation of this time resolution.

III. THE INFORMATION DERIVABLE FROM THE OSCILLOSCOPE PATTERNS

A. Oscilloscope No. 1 (CRO-1) Voltage — Time Diagram, Fig. 5

This plots the cable voltage at point P_1 as a function of time on a sinusoidal scale. Point P_1 is as close to the contact as practical (within two inches of cable). A typical record is shown schematically in Fig. 5. The diagram has two important areas with special features.

(1) In between the O line (contact open) and the C line (contact closed) is a connecting line (OVD) with varying degrees of intensity depending on the velocity of the beam at the moment of recording. This line is the record of the voltage changes taking place both in the cable and in the contact as the current increases during the transition interval from open to closed. This is the *original* voltage change vs time data (OVD) — modified only by the attenuation of the two inches of coaxial line, the limitations of the coupling transformer and any electron transit time effects taking place between the oscilloscope plates.

(2) At the bottom of the CRO plate is a third horizontal line, the R line, caused by the reflection of the wave corresponding to the closed contact. In between the C line and the R line is a connecting line (RVD) which is the same data as above but modified by the effects of the cable attenuation and the energy absorption during reflection from the network at the end of L_1. This RVD line is considerably heavier than its OVD counterpart due to the slower CRO beam velocity resulting from the selective elimination of the higher frequency components in the cable attenuation and reflection processes. This RVD line provides additional useful data because (1) the effects of attenuation and reflection by various lengths of coaxial cable can be studied by variation of L_1 and L_2 and C_1 while observing the corresponding changes in the RVD line; (2) the behavior of the RVD line is often modified by reopening or reclosing of the contact (chatter) and can be used as an indicator thereof; and (3) with prolonged discharges the interaction of the reflected wave can be studied.

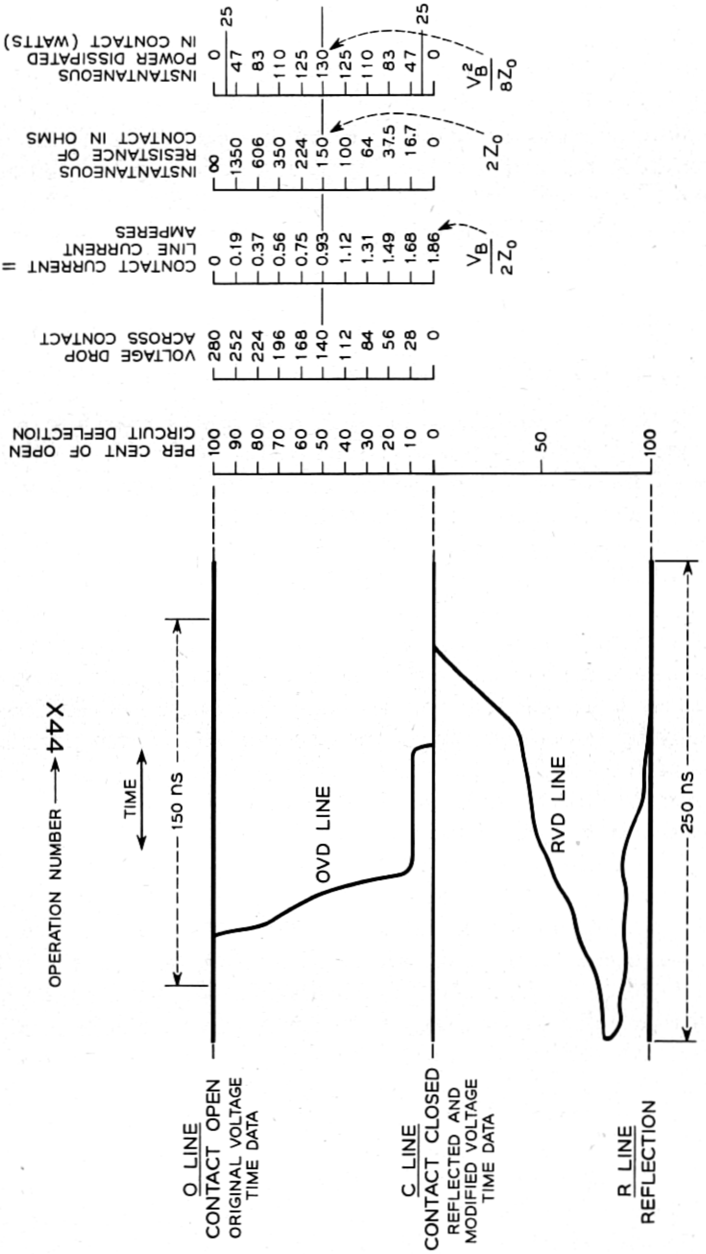


Fig. 5 — Data analysis of typical voltage time diagram for CRO-1 (voltage 280 R_0 = 150 ohms).

(3) Properties of the *OVD* line (Fig. 5*). The *OVD* line is terminated at the top by the *O* line and at the bottom by the *C* line. A scale of *voltage* reading from zero to the total battery voltage may be erected normal to the *C* line. A corresponding time scale may be provided along the *C* line. From these scales the voltage drop in the COLS at any time during the transition interval may be read directly. The voltage drop vs time is, however, not the only information obtainable from this *OVD* line. Since the cable is a pure resistance the corresponding concurrent values of current, power dissipated, and instantaneous resistance of the switch, as functions of time are all simply related to this voltage drop as shown in Fig. 5. The power scale is double valued with its maximum in the middle.

B. Oscilloscope No. 2 (CRO-2) Voltage Charge Diagram, Fig. 6

This provides additional and important information some of which is not available from the record of the first oscilloscope.

(1) It provides a greatly expanded non-linear time scale (about 15×) (Fig. 6) for the initial portion of the voltage drop record. This expanded scale is provided by the discharge of the condenser C_1 when the fall in voltage taking place in the contact reaches the far end of L_1. Means for (a) calibrating the non-linear time scale, and (b) checking the over-all transmission or recording characteristics of the oscilloscope and its coupling transformer, are provided by adjustment of the differential line lengths $(L_2 - L_1)$ in discrete steps corresponding to known time intervals.

(2) The pattern on CRO-2 (Fig. 6) is also divided into two areas corresponding to the *OVD* and the *RVD* lines of CRO-1 (Fig. 5). The demarkation is indicated by a sharp increase in voltage from the zero voltage base line and occurring at a time nearly $3T$ ns after the initiation of the voltage fall in the COLS contact: (T is the one-way transmission time of a coaxial segment $L_1 = L_2$) or $2T$ ns after the voltage starts to fall on CRO-2.

(3) The voltage corresponding to the voltage changes taking place in the COLS contact closure interval (vertical deflection) and recorded by CRO-2 may all be interpreted similarly to CRO-1 in terms of power, resistance and current. They are slightly modified by the attenuation of the line L_2 but this error can be determined by comparison of long and

* Fig. 5 shows a numerical example worked out for the highest voltage used, taken in round numbers as 280 volts. Values are worked out for voltage steps of 10 per cent. These quantities are all related through the surge impedance of the cable otherwise separate determinations of voltage and current as functions of time would be required.

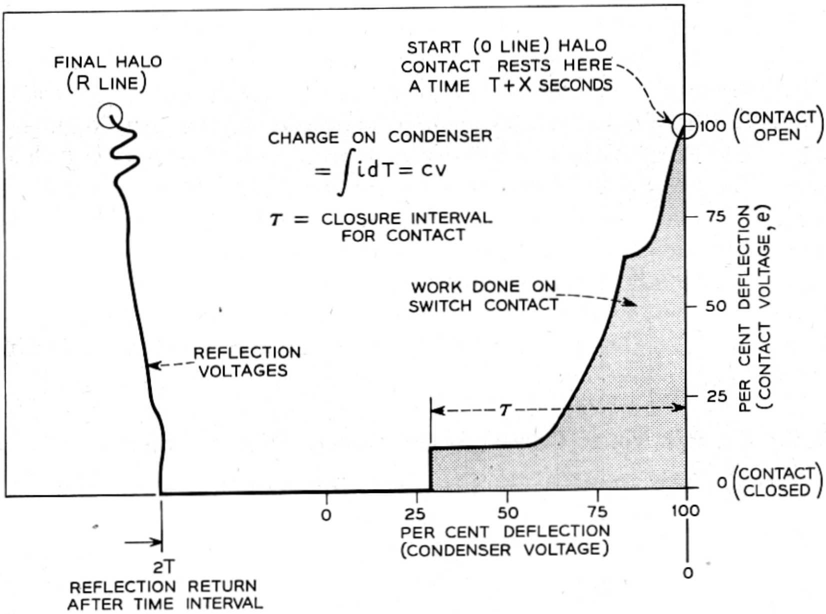


Fig. 6 — Data analysis of typical voltage charge diagram for CRO-2 (work diagram).

short lines. The steepness of the wave fronts shown in Plate A, Nos. 210, 230 and 238, show the error to be less than 10 per cent for the 100 ns coaxial lines and one ns time interval.

(4) The total area under the curve from zero to $2T$ represents the total energy dissipated from the beginning of the closure process up to $2T$ microseconds. For times greater than $2T$ the record has only qualitative significance but provides important clues as to the behavior of the contact at later times. The record may be complex because of the effect of reflections and thus require rather detailed study before conclusions can be drawn from it.

(5) A feature of CRO-2 is the ability to detect the flow of small currents at substantially constant voltage by using very small values of C_1. These currents may not be observable on CRO-1 as the voltage drop (iZo) across the cable may be too small. In the CRO-2 circuit the small currents produce a definite horizontal change $\Delta v = i\Delta t/C$.

C. Procedure for Equating Transmission Delay Times of L_1 and L_2

To do this one must consider the circuit with C_1 equal to the capacity (C_0) of the horizontal plates of CRO-2 alone (total $C = C_1 + C_0$).

Referring to Figs. 4, 6 and 8, the beam of CRO-2 remains at its initial position, corresponding to the voltage $V_B/2$ on the cable section L_2, until the COLS closes. This starting position is represented by the spot or halo at $-V_B/2$, $+V_B/2$ (shown reversed (as $+V_B/2$) in diagram to coincide with photograph). As soon as the COLS begins to close the voltage changes and a voltage wave propagates from the COLS in each direction. No voltage change with time takes place (that is the beam stands still producing the halo at the right) for either the horizontal or vertical plates of CRO-2 until this wave reaches them.

If L_2 is longer than L_1, Fig. 8(a), then the beam of CRO-2 remains at the battery voltage $V_B/2$ while it moves horizontally as the horizontal plates are discharged by the voltage pulse arriving at the end of L_1. If the difference between L_2 and L_1 is small, then the horizontal line will be terminated by a sharp drop in voltage corresponding to the arrival of the voltage wave at the end of L_2. Thereafter, the voltage on both the horizontal and vertical plates of CRO-2 will fall at a rate determined by their discharge time constants while the corresponding line drawn on the screen will start off at a steep angle toward the origin.

On the other hand, if L_1 is greater than L_2 then the vertical voltage

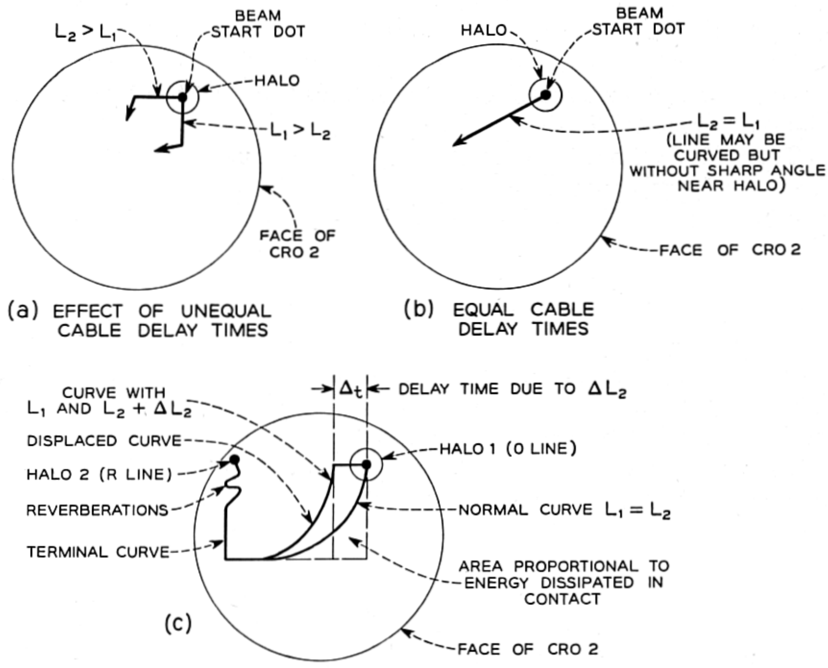


Fig. 8 — CRO patterns for equalizing cables and time calibration.

will fall before the horizontal voltage changes. Then the beam will move vertically down from its initial position until the L_1 wave has arrived at the end of L_1 when the combined effect is to move the beam at a roughly 45° angle.

If, however, L_1 and L_2 (Fig. 8(b)) are *exactly* equal the two waves arrive at the horizontal and vertical plates at the same time and the beam moves directly from the initial position toward the origin Plate A, No. 210. This condition will be referred to as the balanced condition. If the contact were linear or closed instantaneously and there were no parasitic oscillating circuits, the line traversed by the beam would be a straight line directed from the initial (open) position toward the origin. The end of this process may be indicated by a small spot corresponding to zero contact voltage from which there is a sudden rise in voltage corresponding to the arrival of the reflection of the closing contact condition from the end of L_1 ultimately ending in a second halo (at the left) corresponding to the R line of CRO-1.

Plate A, Nos. 230, 210 and 238, show the effects obtained for a one ns difference between L_1 and L_2 with $C_0 = 4$ *pf* only. It will be noted that for the balanced condition ($L_1 = L_2$), the theoretical straight line is departed from in a number of ways. One, initially the line is very slightly curved concave upward; two, the latter part of the line is terminated in certain wiggles showing the existence of a parasitic circuit which is excited by the impinging voltage waves. This time scale is roughly 400 times faster than CRO-1.

The cable lengths L_1 and L_2 are always made equal or balanced in this manner with C_1 equal to the scope plate capacity C_0 only. Now we will consider the behavior of the circuit with moderately large values of C_1.

D. *Analysis of The Work Diagram*

Assume the above balanced condition is provided initially and then C_1, Fig. 4 is set to a known capacity of 100 *pf* or more. A typical result is shown schematically in the diagrams of Figs. 6 and 8(c). It will be seen (Fig. 6) that the voltage fall recorded by the vertical plates changes initially much more rapidly than the corresponding change on the horizontal plates as the charge of the condenser changes relatively slowly since the current through the contact is very small. In the later stages of the discharge through the COLS contact, the current is much larger and the change in charge of C_1 causes a much larger horizontal deflection than the corresponding change in vertical deflection. If the COLS contact closes to zero resistance in a time less than $2T$ the vertical deflection may drop to zero while the horizontal deflection of CRO-2 may still continue to increase. After a time interval $3T$ from the start of the discharge the reflected wave from the distant end of L_1 arrives at CRO-2. The sign of this wave is opposite to the sign of the wave causing the initial vertical deflection of CRO-2, causing the second vertical deflection of CRO-2 to increase from zero sharply and eventually to return to the initial voltage. This may be denoted by a second halo spot. The time difference between the starting dot on the CRO-2 and the upward break in voltage is thus $2T$ (in this case 200 ns) — the beam remaining at the starting point for a time T plus whatever time interval X occurred between the initiation of the beam and the start of the fall in contact voltage. During this time interval $2T$, the vertical deflection is proportional to the voltage drop across the COLS, and the horizontal deflection is proportional to $\int_0^t \frac{idt}{C}$.* The events taking place after the time $2T$ are not subject to this analysis for the cable L_1 can no longer be considered purely resistive for times greater than $2T$. However, contact events such as sudden arc extinctions or contact opens, taking place after this time interval may cause variations in the charge reaching C_1 and hence produce horizontal deviations in the slope of the line starting at $2T$. A horizontal change toward the starting dot indicates an opening of the contact, a change away from it, the termination of an arc or glow.

The *time intervals* corresponding to the horizontal deflections of the work diagram may be estimated by deliberate introduction into L_2 of additional lengths of line ΔL_2 with known times of traverse. This causes the beam to move horizontally a distance corresponding to the time of traverse of ΔL_2 before the vertical motion starts (Fig. 8(c)). In this manner a calibration of the horizontal charge scale as a function of time can be determined. A typical pattern with $\Delta L_2 = 10$ ns is shown in Plate B, No. 132. In Plate B, No. 594, $\Delta L_2 = 5$ ns.

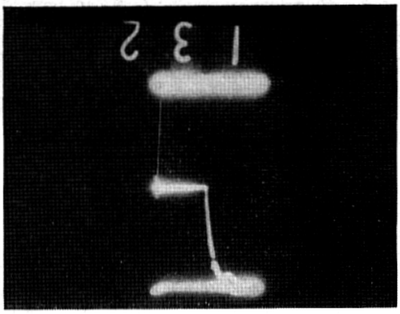
In the examples shown here all tests are made with the nominal length of L_1 or L_2 equal to a travel time of 100 ns and a ΔL_2 of 5 ns.† C_1 is 100 *pf* and $R_2 = Z_0 = 75$ ohms.

E. The Voltage Calibration Scales

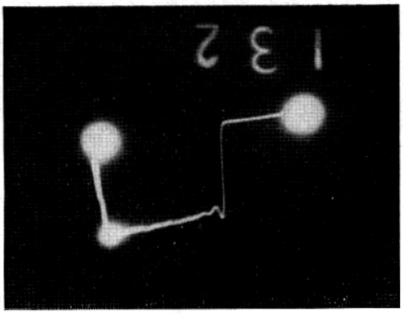
The conversion of CRO deflection to numerical values is an important part of the measurement process. For calibration purposes a voltage grid of the two CRO tubes was made and it is shown at the top

* The errors of integration will be discussed in Appendix C.

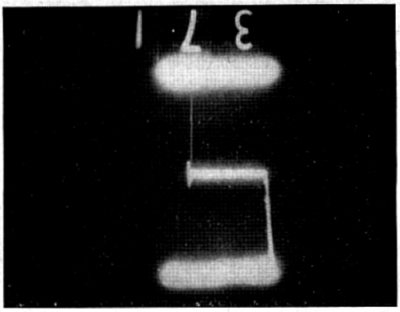
† For side-stepping the starting spot halo (Appendix C). This time interval may be insufficient to side step the halo for slow forming discharges like glows.



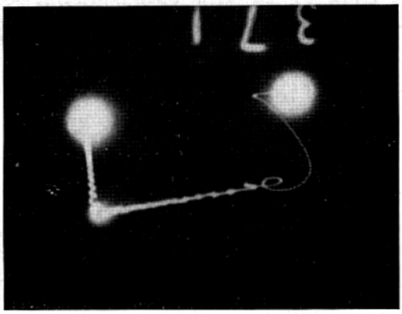
$L_2 - L_1 = 10$ ns



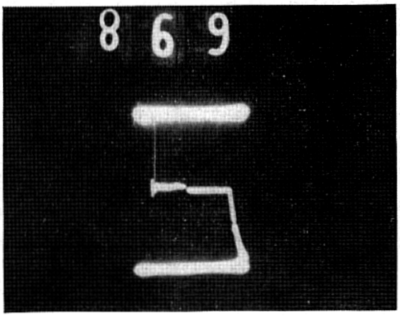
$C_0 + C_1 = 104$ pf

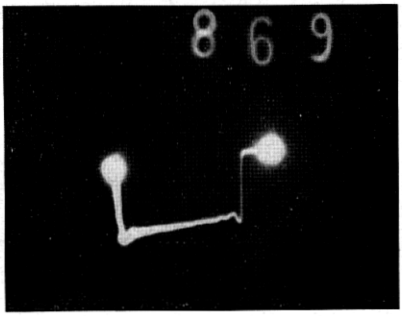


$L_2 - L_1 = 1$ ns

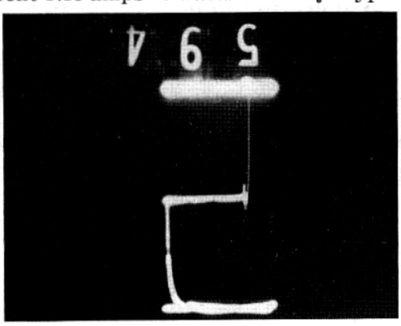


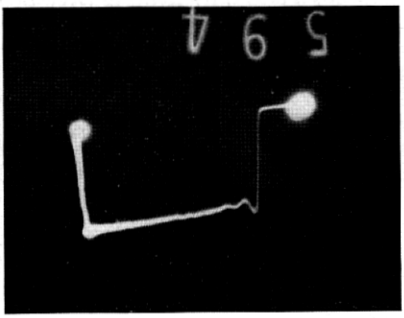
$C_0 + C_1 = 104$ pf





$V_B = 190$ volts — short arc 14 volts duration about 85 ns to metallic closure current 1.15 amps 16 watts 137 mmj. Typical initial arc voltage about 35 volts.





$V_B = 278$ volts. Drop to 14 volt arc. Initial arc voltage 63 volts. Drop in 2.5 ns at 200 ns arc voltage is still 24 volts, at 15 ns voltage is 32 volts. Very typical behavior every time. Switch A.

Plate B — Upper half, continuation of Plate A. Lower half, data on Switch A.

of Plate A. All voltages were measured by superimposing a transparent copy of this grid on the CRO pattern. The distances were measured to ±0.01 inch on a three time enlargement which corresponds to ±3 volts or 1 per cent of full scale. Since there is an error of positioning of about the same amount the combined error is about ±5 volts. Variations less than this are of no significance. The six degree rotation of CRO-2 grid is a mechanical condition. For both CRO's the coordinate axes are perpendicular within experimental error. Also, the zero voltage line (horiz.) has a burned spot on the phosphor providing a fiducial point for zero contact voltage.

F. Effects After 2T Time

The two oscilloscopes at first see the *same* events displaced in time by the delay interval T. For times greater than $2T$, this simple condition is no longer true and CRO-1 and CRO-2 may give results that are seemingly quite contradictory. The behavior of the two scopes may be reconciled and understood, however, in terms of the reflections which take place both at the end of the line and at the contact gap. The CRO-2 originates no large reflections and gives a fairly true picture of the behavior of the switch from 0 to $2T$. The CRO-1 is located next to the contact but the voltage it measures after $2T$ ns depends on the state of the contact gap at the moment the reflected wave returns. If the gap is closed to zero resistance, the reflected wave is merely recorded and goes on past both CRO-1 and CRO-2 to be absorbed in the termination at the end of L_3. If the gap is open, or has a discharge (arc or glow) of some kind, the instantaneous resistance of the gap or discharge is added into the circuit and the contact gap becomes a discontinuity in the line causing the first reflected voltage to be partially transmitted through the switch and partially reflected. The amount and sign of the new voltages are determined by the ratio of gap resistance to the cable impedance. Thus from a detailed comparison of the reflected and transmitted voltage waves as measured by the two CRO tubes one can study the impedance of the arc and glow discharges still present at $2T$ time. This is a major contribution of this dual CRO and coaxial cable technique; however, application of it to specific cases is very complicated and is not discussed further.

IV. EXPERIMENTAL RESULTS ON SWITCHES

With the CRO circuit designs as shown in Figs. 7(b) and 9(b) (see Appendix C for discussion), the study of various switches was under-

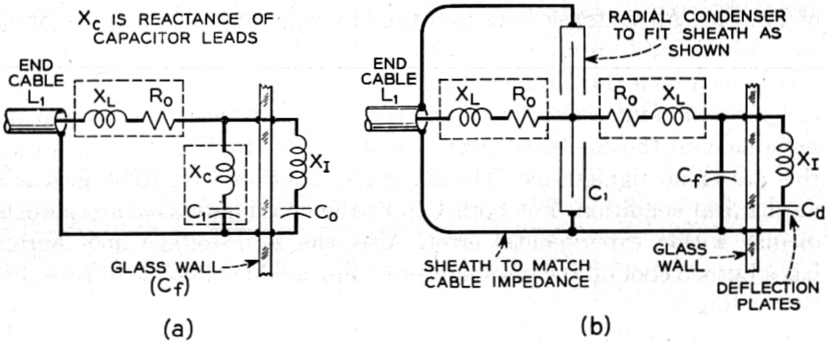


Fig. 9 — Horizontal deflection plate circuits for CRO-2.

taken. Some typical data on a few switches (listed in Table I) are presented to indicate the power of the measuring system to reveal the fine structure in typical discharges; and to illustrate a few typical phenomena associated with the closure transition. All the switches are of the glass enclosed reed type — differences being ascribed primarily to filling the tube with different gases. The surface of the contact area of the reeds is plated with 0.0001″ of gold which is diffused into the base metal (either No. 52 alloy* or 45 perminvar†) by heat treating in hydrogen for a con-

Table I

Switch	*A*	*C*	*K*	*E*
Metal	Perminvar	52 Alloy	Perminvar	Perminvar
Gas	97% N_2–3% H_2	Air	Helium	Hydrogen
MBV* Volts	240	327	210	292
Pressure ATM	1.7	1	1	1
Comment on behavior character of switch	Very fast, uniform	Slow, irregular	High voltage glows† frequent	High voltage glows, metallic closure at low voltage

* The minimum breakdown voltage (MBV). All values of MBV are from Meek and Crags Electrical Breakdown of Gases.
† The terms arc and glow are used to refer to discharges with voltage characteristics in the range usually encountered with discharges with similar names but taking place between fixed electrodes. The end of the arc can be identified by a distinct step in voltage.

* Driver Harris alloy of 50 to 51 per cent Ni balance Fe used to seal to Corning 0120 glass. Resistivity 43.2 microhm cm M.P. 1425°C. Thermal conductivity −183 watts/cm/°C; TS 70,000 to 15,000 p.s.i. sp.g. 8.247; coefficient of expansion at 20° to 100°C, 9.3×10^{-6}.

† Elmen, G. W., Perminvar — Alloy of 45% Nickel 25% Cobalt 30% Iron, Elec. Eng., **54,** pp. 1292–9, 1935.

trolled time and temperature. The reed assemblies are sealed in glass and the switches filled after only a short exposure to air.

The switches were tested under the fcur battery voltage conditions given in Table II with the corresponding values of current and peak power which are dissipated in the contact when it matches the combined cable impedances = 150 ohms.

Discussion of the Data

Table III shows some typical data obtained for the *four different switches* with a battery voltage of 278 volts, which condition brings out the greatest contrast in behavior. Table IV shows the behavior of *one switch at four different battery voltages.* In addition to the Tables, the following discussion is a brief resume of the effects observed for closing contacts.

(1) At low voltages (48 volts) the data shows extremes of behavior ranging from closure (to metallic contact) in one ns or less with no trace of an arc for the hydrogen switch, to the rather long drawn-out changes in voltage drop of the air filled switch taking almost ½ microsecond to go from 48 volts to zero.

TABLE II

Battery E.M.F., volts	Max. contact current, amperes	Max. power (P), dissipated watts
48	0.32	3.84
92	0.615	14.0
190	1.26	60.0
278	1.86	129.0

(2) Other phenomena encountered were: (a) metallic closures with no arcing (Plate C, No. 851), (b) closures to the 14 volts "short arc" followed by metallic closure (Plate B, No. 698), and (c) metallic closure first (Plate C, No. 857), followed by arcing at 14 volts.

(3) In general as the battery voltage is increased the frequency of closures without arcing decreases and the number of arcs and their duration time increases. There are many rapid closures to the 13- to 14-volt arc condition which is substantially constant for its duration which may range from about 10 ns to over several hundred. It should be pointed out that the voltage across the contact is ultimately removed by the reflected wave. The initial drop to the 14 volts arc (Plate B, No. 698) may take place in a time less than the resolution of the scope which is about ½ ns.

(4) The initial rapid drop in voltage may not proceed directly to the 14-volt level at the higher battery voltages. The end of the rapid drop which takes from 1.5 to 2.5 ns may be in the neighborhood of 40 to 60 volts depending on the switch. After this, the voltage tapers off at a rate

TABLE III — COMPARISON OF SWITCHES AT 278 VOLTS, MAX. CURRENT 1.86 AMPS. EFFECT OF DIFFERENT GASES WITH ONE CONTACT METAL AT ONE VOLTAGE

	Switch A	Switch C	Switch K	Switch E
Gas	97% N_2 + 3% H_2	Air	Helium	Hydrogen
Voltage of first glow (volts)	—	—	220*	242
Current in glow at end (amps)	—	—	0.39	0.24
Power in glow at end (watts)	—	—	85	58
Approx. duration of first glow (ns)	—	—	250	200
Voltage at end of second glow (volts)	—	—	206	—
Current at end of second glow (amps)	—	—	0.48	—
Power at end of second glow (watts)	—	—	99	—
Recovery of voltage to (volts)	—	—	262	278
Current at recovery (amps)	—	—	0.100	0
Power at end of recovery (watts)	—	—	26	0
Voltage at beginning of arc (volts)†	63‡	150§	137‖	102¶
Current in arc at start (amps)	1.43	0.85	0.94	1.17
Power in arc at beginning (watts)	90.5	128	129	120
Voltage at arc at 200 ns (volts)	24	20	120	56
Current in arc at 200 ns (amps)	1.70	1.72	1.05	1.47
Power in arc at end of 200 ns (watts)	41	34.5	126	82
Energy expended in 200 ns in nj	13,000	16,200	15,500	20,200
Voltage at beginning of alternate arc (volts) (B7 BL17)	—	62§	60‡	53‖
Current at beginning of alternate arc (amps)	—	1.44	1.45	1.50
Power at beginning of alternate arc (watts)	—	89	87	80
Voltage after 200 ns (volts)	—	10	20	15
Current after 200 ns (amps)	—	1.72	1.72	1.75
Power after 200 ns (watts)	—	34.5	34.5	26
Energy expended in 200 ns in nj	—	12,000	12,000	10,600

* Plate D, Nos. 129 and 432 — also compare with the MBV values of Table I.
† These are new results — compare with the usually accepted values of the order of 14 volts and 0.5 ampere for the short arc.
‡ Plate B, No. 594.
§ Plate C, No. 945.
‖ Plate D, No. 129.
¶ Plate D, No. 432.

which is approximately a straight line on the work diagram (CRO-2) ultimately ending in the 14-volt region before extinction, either by metallic closure, or by the arrival of the reflection from the end of L_1.

(5) The discharge may often persist for a time interval greater than $2T$. In this case the energy represented by the above straight sloping line in

this time interval may be calculated easily without integration. The height of the line represents the instantaneous power at this point so the average power is estimated by calculating the power in watts at the beginning of the straight line and again at the end of the 200 ns interval and multiplying the sum by 100. The result is the energy in nanojoules for the 200 ns time interval. These are the values given in Tables III and IV.

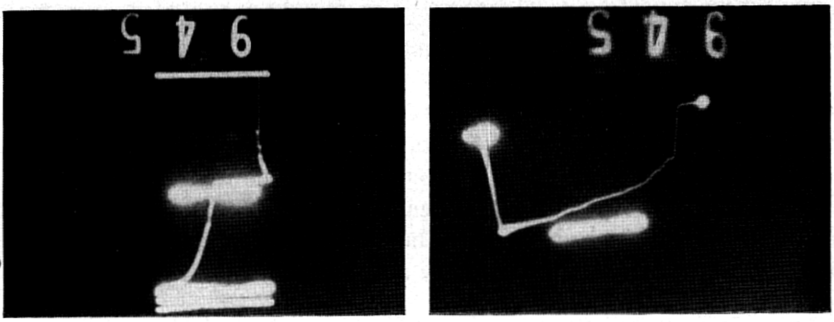
(6) Comparison of the photograph (Plate B, No. 594 is typical) shows the high initial voltage drop to take a time of about 2.5 ns which is a significant time interval and within the resolution of the scope. The energy associated with this process is about 270 nj. This represents the energy requires to initiate the arc process assuming the line gradually sloping from 60 to 14 volts represents an arc.

(7) At the highest voltage used (278) the greatest difference between the switches is revealed. The switch filled with hydrogen (Plate D, No. 432), reveals a pre-arc discharge at 242 volts which may be presumed an "abnormal glow". The transition to this voltage takes place at a much slower rate than the transition to an arc. Once formed it may persist or dwell for a considerable interval of time; often sufficient that interaction occurs between the glow and the voltages reflected from the end of the line. This may produce apparent inconsistencies between the patterns displayed by CRO-1 and CRO-2 as shown in Plate D, No. 432, and render interpretation of the patterns complicated.

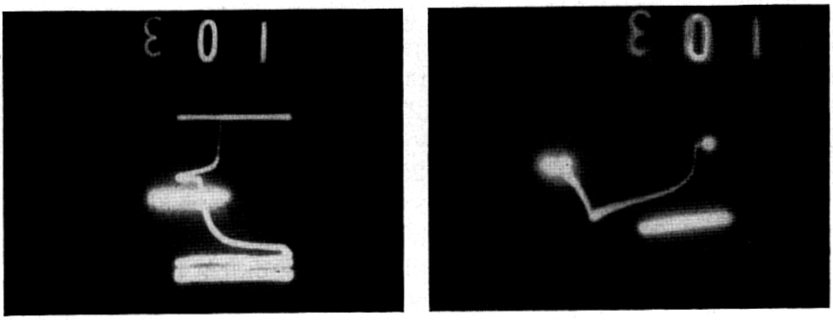
The helium switch yielded a two stage glow ending at 206 volts Plate D, No. 129, while the forming gas and air switches proceeded directly to the "arc" without a glow condition. The glow condition did not take place every operation but was present for about ½ the number of opera-

Table IV — Behavior of One Gas (Forming Gas) and One Metal at Various Voltages

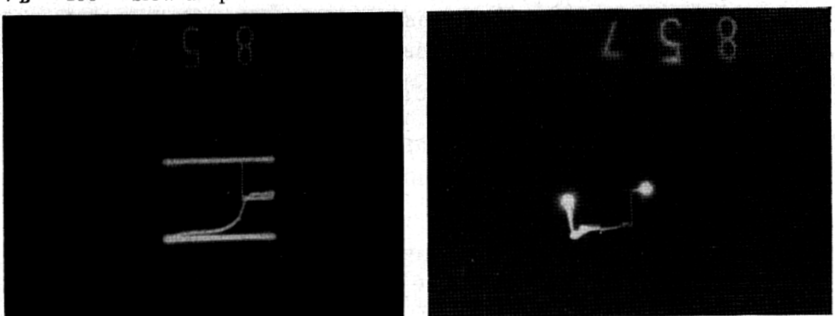
Behavior of One Switch (A)	Voltages			
	48	92	(190V)	(278V)
Max. closed cir. current (amps)	0.32	0.61	1.26	1.86
Voltage at end of sudden drop (volts)	14	14	35	63
Current in arc at same point (amps)	0.22	0.52	1.03	1.43
Power in arc at same point (watts)	3.2	7.3	36	90.5
Voltage at last stage of arc (volts)	14	14	14	14
Current at last stage of arc (amps)	0.22	0.52	1.17	1.76
Arc voltage at 200 ns (volts)	—	14	14	24
Arc current at 200 ns (amps)	—	0.52	1.18	1.70
Power in arc at 200 ns (watts)	—	7.3	16.5	40.5
Time required for sudden drop (ns)	—	1	1.5	2.5



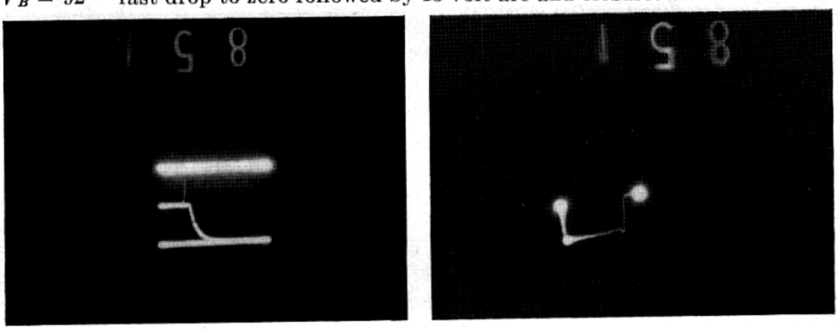
V_B = 278 volts — long arc — 20 volts 1.72 amps at 200 ns. Initial voltage 150 current initial .86 amperes. Note voltage plateaus at approximately 150, 104, 80 and 70 volts shown on both CRO-1 and CRO-2.
ΔL_2 = 5 ns — zero voltage base line superimposed for checking.



V_B = 190 — slow drop to 40V arc 0 — calibration line

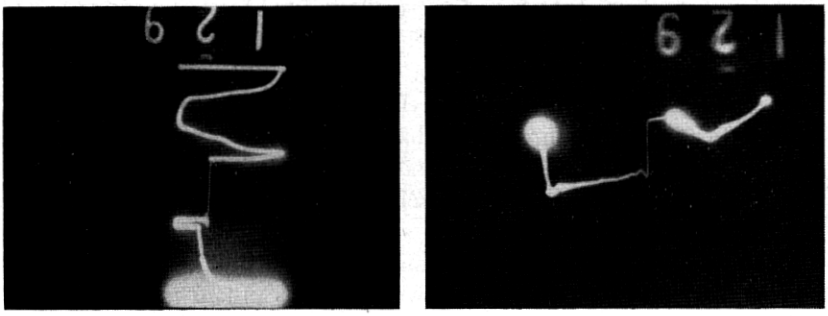


V_B = 92 — fast drop to zero followed by 13 volt arc and closure. Switch E.

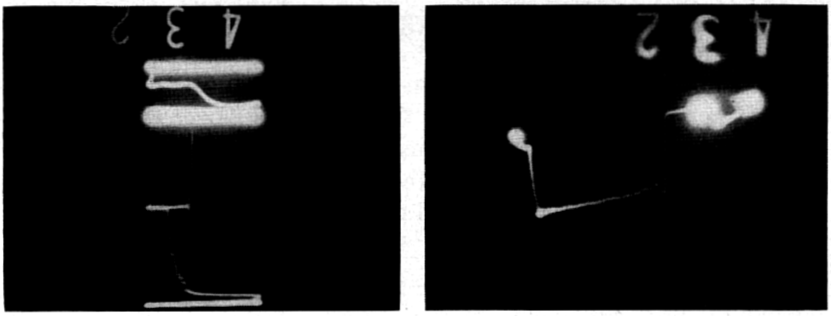


V_B = 92 — straight closure without arcing in 10^{-9} sec.

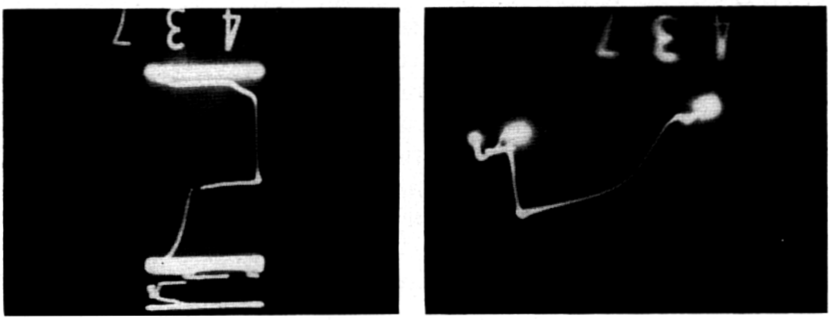
Plate C — Upper half, data on switch C (Air). Lower half, data on switch E (H_2).



V_B = 278. Slow glow type drop of 58 volts, dwell, further slow fall of 14 volts, dwell, slow recovery of 56 volts, dwell, rapid fall of 125 volts slow arc fall of 17 volts, eventual arc extinction at about 1000 ns. Typical pattern of this switch. Switch K.



V_B = 278 — Slow drop to glow at 242 volts — reflection of glow mixed with glow-dwell — fast drop of 176 volts to long arc final extinction. Switch E.



V_B = 278 — Two stage glow 255 and 248 volts — reflection coincident with second stage glow and reflection and ultra long arc with reflections. Switch E.

Plate D — Glow and arc discharges with reflection interference.

tions for the helium switch and most of the time for the hydrogen. The remainder of the operations resembled the discharge with forming gas.

(8) The air filled switch gave a fairly smooth and slow transition Plate C, Nos. 945 and 103, from the open condition to the usual arc voltages. Often the nature of the discharge changes from the slow type illustrated in Plate C, Nos. 945 and 103, to the fast type of Plate B, Nos. 594 and 698. Whether the switch is "activated" or not there is more than one discharge process.

(9) Another phenomenon of significance revealed by CRO-2 is the variable flow of charge in the glow discharge, and in the glow to arc transition. Sometimes the current is interrupted (no horizontal motion of CRO-2) followed by prebreakdown currents at roughly constant voltage (horizontal motion only) terminated by an arc. Examples are shown in Plate D, Nos. 129, 432, and 437. A possible explanation is that the discharge shifts from one surface irregularity to another but must start the breakdown process afresh.

These examples also illustrate the complication in the CRO patterns due to the discharges enduring for time intervals longer than $2T$ ns as described previously. It must be remembered CRO-1 has only two fixed references lines — the O line and the R line. The intermediate points are the resultant of the original and the reflected waves.

CONCLUSION

This circuit, and its oscilloscopic accessories, is shown to be a powerful tool for exploring contact phenomena both (1) under the ideal condition of an essentially resistive circuit where the interest is in study of the contact unmodified by frequency selective circuit elements and (2) under circuit conditions with frequency selective elements with reflections and other transmission phenomena. In the first condition, it is easy to relate the oscilloscope patterns to fundamental quantities. With the second condition interpretation of the patterns requires considerable detailed study. If the contact is not closed at the time the reflected wave arrives, the contact becomes the source for a new reflection and also may permit transmission in the forward direction. The study of such data should yield useful information as to the nature of the discharge process as well as information of a circuit engineering character.

The minimum of data presented here for illustration of the technique is the beginning of a collection which must be taken into account in any theories of contact behavior.

The author acknowledges his indebtedness to many individuals for help in the course of this development and in particular to S. O. Rice and associates for assistance with the mathematical and transmission aspects of the problem. E. F. Thunder also gave valuable assistance in operation of the oscilloscope and made numerous improvements in its design.

APPENDIX A — DESCRIPTION OF OSCILLOSCOPE

Two Dumont K1068 oscilloscope tubes with metallized P11 screens were used in this work. The tubes are the post deflection acceleration type, with 4,000 volts (electron gun negative) used for the normal acceleration of the electron beam before entering the (ground Potential) deflection plate region plus 25,000 volts after leaving it. The deflection plates of these tubes give about equal beam deflections (Plate A) in either horizontal or vertical planes and the horizontal and vertical plates are shielded from each other. The connection to the deflection plates and shield are brought out directly through short leads to glove fastener terminals fused into the glass walls of the narrow neck of the tube.

The two tubes are mounted side by side about 6 inches between centers. Fig. 2 shows a schematic diagram of the relation between the tube face, the camera, and the counter.

The high voltages required by the post accelerator rings are supplied from a shielded potential divider with short connections to the terminals of the post deflection accelerator rings on the tube. Corona was suppressed by waxing over the connections from wires to tubes.

A separate shielded insulated grid to cathode battery for each CRO tube which could be varied in 1½-volt steps was found essential for stability.

The over-all design of the system enabled the two scopes to operate with satisfactory stability at the maximum beam intensity or whatever value was found desirable for the conditions at hand.

Sequence of Events in Oscilloscope and Relay Control Circuits (*Fig. 1*)

The closure of the hand operated control switch (or manual start switch) opens the camera shutters which remain open for a time interval (2–5 milliseconds) and then automatically close, after which time the counters step on to the next number. The same manual control contact operates a truly chatterless contact on a mercury contact relay* which in turn connects the operating winding of the relay under test to a local battery. The closure of the mercury contact also causes a flip-flop circuit

* Brown, J. T. L., and Pollard, C. E., Recent Developments in Relays — Mercury Contact Relays, Elec. Eng., pp. 1106–1109, Nov. 17, 1947.

to start measuring off an appropriate delay interval, (operate delay time of the test switch is about 1 millisecond) after which a second flip-flop circuit turns on the beam current of the oscilloscope, then turns it off a few microseconds later to prevent screen damage. The delay of the delay flip-flop* is adjustable only in steps so that a continuously variable delay network is also necessary so that the contact of the test relay may be adjusted to close during the time interval the oscilloscope beam is on. This arrangement is used so that no load is placed on the contact other than the test circuit in which it operates. The CRO beam on period and the test contact transition interval are thus independent but arranged to coincide. If the test contact exhibits multiple closures (chatter) the delay networks can be adjusted so that any one of them can be observed if desired. In this case the first closure only is considered.

APPENDIX B — THE PHOTOGRAPHIC RECORD

The arrangement of tubes and camera and counters is shown schematically in Fig. 2. The cameras are Kodak 35 bodies fitted with special lenses and operated by magnetic solenoids. The counters are provided with a viewing prism and their own illuminating lamps. In photographing the flying spot on the P-11 screen a 1/1 image/object ratio was used, in order to obtain a large photographic record. Also, it was found necessary that the image of the flying spot be in very sharp focus on the film to avoid gaps in the record of high velocity beams due to the lack of contrast between the illuminated region and the adjacent regions.

Two 50-mm $f/2$ Raptar lenses were mounted front-to-front as shown in Fig. 2, giving a lens corrected for focusing divergent light (from the beam spot) instead of *parallel* light as is usual with camera lenses. The arrangement also gives an increased ratio of diameter to focal length as well as sharper focus.

The film was Eastman Kodak Linograph Pan film LP-135, developed with a special developer D19A† which increases the effective speed of the film in the fast or faint parts of the trace.

The numbers on the film are upside down for mechanical reasons.

APPENDIX C — CIRCUITRY AND SOURCES OF ERROR

Circuit Restrictions and Modifications

For the short time intervals studied here the inductance and capacitances of very short lengths of wire (even one cm) are important. Most of the inductive reaction of resistances and lead wires can be compensated

* Term used here refers to a one shot multivibrator circuit which is arranged to turn a current on and then turn it off after a preset time interval.

† Methods of Increasing Film Speed, J. Photographic Soc. Am., **12**, pp. 586–610.

for by making them the central conductor of a coaxial line structure by providing a coaxial sheath with the proper diameter.

In the oscilloscope itself, however, one has a parasitic circuit comprising the capacitance of the glove fastener connections passing through the wall of the glass — the inductance of the lead wires inside the glass to the deflection plates, and the capacitance of the plates themselves. This circuit is shown in Figure 7(b) and is mechanically and electrically unchangeable with available CRO tubes. This circuit has very little damping, thus if a very sharp pulse is applied to the scope plates this circuit tends to ring and superimpose its own oscillations which interfere with the interpretation of the record. At best they can be used as a reference time scale once their frequency has been determined. Connecting too high a resistance R_0 outside this circuit only slows down the rate of discharge of the total capacity of the combination and damages the high frequency response of the over-all system.

Capacitances also have residual inductance due to the length of lead wires ordinarily required to connect them in the circuit. There are, however, "feed-through" coaxial type condensers which practically eliminate the effects of lead inductance.

With these facts in mind the oscilloscope plate input transformer circuit details must be considered. The usual simple diagram, shown in Fig. 7(a), must be replaced by the circuit shown in Fig. 7(b) for the vertical plates of either CRO-1 or CRO-2. The initial corresponding horizontal deflection plate circuit of CRO-2 is shown in Fig. 9(a). Because of the above considerations, it was modified along the lines indicated in Fig. 9(b), providing the necessary cavity to terminate the line L_1 in a resistance and capacity only. This reconstruction is not deemed necessary for the vertical plates as the reactance of $(R_0 + X_L)$ could be matched to $C_0 = C_f + C_d$ and the over-all Q of this circuit made nearly equal to unity so oscillations are not excessive. On the other hand, the parasitic reactances of Fig. 9(a) produce definitely reproducible effects like those shown in Plate B, No. 371, rendering the work diagram uninterpretable. A typical effect obtained with the reconstructed circuit, Fig. 9(b), are shown in Plate B, No. 594. It will be seen that the circuit simplification and compensation has eliminated all the difficulties from parasitics except those due to the internal structure of the vertical plates of the oscilloscope. The resonant frequency (about 400 megacycles) of this parasitic circuit is determined in terms of ΔL_2.

Sidestepping the Starting Spot Halo

In the balanced condition ($L_1 = L_2$) a portion of the initial record of the motion of the CRO-2 beam spot is rendered unobservable by the large halo caused by the beam resting at the starting position for a relatively long time. This undesirable effect may be sidestepped by experimentally choosing an appropriate and small value of ΔL_2 say corresponding to 5 ns (Plate D, No. 594) and leaving it in the circuit. In this case the initial motion of the beam starts horizontally from the starting dot and comes out of the halo for a short distance ΔL_2 when it proceeds to fall as before. The corresponding times are measured from this instant up to the time $2T$.

Comment on the CRO deflection Plate System — Error from Finite Beam Velocity

With the 4,000-volt first acceleration voltage, the velocity of the beam electrons through the deflection plate region is 3.78×10^9 cm/sec giving a transit time of the electrons between the plates of about 0.4 ns which is the minimum rise time which can be observed with these tubes.

Errors in Energy Measurement By CRO-2

(1) In the work diagram, it has been assumed that the voltage drop in the COLS contact traces out an area corresponding to a significant amount of energy. In the case of an ideal or instantaneous closing contact, there would still be some small area traversed even if there were no energy loss in the COLS. This area is the area under the exponential decay line drawn through the starting dot and corresponding to the discharge of the vertical plates of CRO-2 alone from the battery voltage $V_B/2$. The area under this line corresponds to 4 nanojoules (nj)* for a 45 volt V_B and about 160 nj for the 280-volt battery. Energies in excess of these values measured with this system may be ascribed to the dissipation of the contact.

(2) For sufficiently large values of R_2C_1 (Fig. 4) with $R_2 = Z_0$ the *charge* is accurately measured by the change in voltage of C_1 (neglecting C_0). However, for small values of R_2C_1 the change in voltage of C_1 becomes an appreciable fraction of and opposing the voltage producing i.

TABLE C-I

n	Q_{C1}/Q_∞	n	Q_{C1}/Q_∞
1/10	0.976	2	0.633
1/2	0.885	3	0.518
1	0.786	4	0.382

* 100 *nj* equal 1 erg.

Hence i is decreased and the change in voltage is a measure of the reduced i. Thus with small capacities the area traced by CRO-2 is always less than the true area were a large enough capacitor used. In general the correction factor cannot be calculated. However, for a *constant unit* contact voltage step the charge Q_{C1} is

$$2i_0R_2C_1(1 - e^{-(t-T)/2R_2C_1})$$

(which is restricted to values of time between $t = T$ and $t = 3T$, and i_0 is the initial current). With an infinite capacity the charge is

$$Q(C = \infty) = i_0(t - T)$$

The ratio of

$$(Q_{C1}/QC = \infty) = \left(\frac{2R_2C_1}{(t - T)}\right)(1 - e^{-(t-T)/2R_2C_1})$$

If

$$\frac{t - T}{R_2C_1} = n$$

then

$$(Q_{C1}/Q\infty) = \frac{2}{n}(1 - e^{-(n/2)})$$

Values of the ratio as a function of n are given in Table C-I. The error is $1 - Q_{C1}/Q^\infty$ and is always in the direction of measuring less charge than actually passed through the contact.

To obtain high time resolution in the early parts of the discharge a small value of R_2C_1 should be used. In this data R_2C_1 is 7.8 ns. The energy dissipated is always at least as great $(Q_{C1})/(Q^\infty)$ as that indicated by the area. For the later and slower parts of the discharge appropriately large values of R_2C_1 are used.

(3) Within the time limits from zero to $2T$, where $T = 100$ ns the resolution is excellent. However, one cannot stretch T out to long time intervals (of the order of several microseconds) without attenuation in the cable rounding off of the corners of the voltage step functions.