Contact Phenomena in Telephone Switching Circuits*

By A. M. CURTIS

The phenomena occurring at the closing and opening of contacts carrying weak currents have been investigated by means which include a study of the high-frequency transient voltages and currents. These influence the erosion in a complex manner which varies with contact materials, surface conditions and surrounding atmosphere. Three principal classes of effect have been distinguished. These are: (1) Disruptive sparkovers initiating a series of metallic arcs lasting less than a microsecond each; (2) A nitrogen gas glow discharge at about 300 volts, preceded by a brief group of disruptive sparkovers; (3) High field breakdowns due to cold point discharges which cause transient metallic closures of approaching contacts and similar transient reclosures of separating contacts.

THE operation of a telephone system depends on the proper performance of many millions of electrical contacts, a large proportion of which are in relays. The relays must be designed for a life during which they operate from as few as five thousand to as many as four hundred million times. Although the nominal currents and voltages carried by the contacts are rather low, the large number of operations may cause erosion which in a very small percentage of cases leads to failures to close or open the circuit. The difficulties caused by even very rare failures make the control of contact erosion a problem of major importance for the telephone companies.

Research and development work on contacts has of course been carried on continuously since very early in the development of the telephone system. The aim is to design contacts to have a life at least equal to that of the apparatus of which they form a part and to require a minimum of maintenance. Although this aim has in general been successfully met there have been some cases in which the contacts have worn out too rapidly.

Although it had long been realized that contact operation necessarily involved the generation of high-frequency transients, there was at first no apparatus available which would permit these transients to be studied. The Dufour oscillograph was for a long time the only instrument which covered the range of frequencies involved. It was em-

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ployed as early as 1926 in studies of contact sparking but it was very cumbersome in use, often introduced artificial conditions into the circuit of the contacts, and progress with its use was necessarily very slow. During the past few years rapid advances have been made in the development of glass envelope cathode ray oscillograph tubes. By employing the latest types of tubes, and combining them when necessary with wide band high-frequency amplifiers and with circuits which permit synchronization of the tube sweep circuit with the contact operation, it has been possible to make thousands of observations in the time originally taken by a single oscillogram, and to cover the entire range of currents, voltages, and frequencies involved. We now have available means which will permit the visual observation of transient voltages at frequencies as high as 400 megacycles per second, and transient currents with components reaching 20 megacycles per second. Single pulses lasting a small fraction of a microsecond, and complex transients containing components as high as 5 megacycles, can be clearly resolved and photographed while the envelopes of still higher frequencies can be recorded.

In order to study the transients at contacts operating at 50 volts and steady currents under one ampere, in common types of telephone circuits, voltages as high as 2000 and currents reaching 20 amperes must be within the range of the apparatus. A detailed description of the apparatus will not be attempted in this article, but the results of observations made with it and photographs of the more significant transient components will be presented.

Study of the currents requires an amplifier as an impedance matching device and some circuit conditions make a shielded input transformer necessary. An input impedance of from 0.4 to 2 ohms, a voltage gain of about seventy-five times, and a substantially flat characteristic of output versus input from 20 kilocycles to 20 megacycles are usually employed. Lower frequencies may be observed with other amplifiers and the range from zero to 10,000 c.p.s. is studied by means of the "Rapid Record" oscillograph.

With earlier cathode ray tubes, beam currents of 40 microamperes at 5000 volts were employed. The latest tubes give a beam current of about one milliampere at this voltage. A Leica camera with an F1.5 Xenon lens and ultra speed panchromatic film has been used in most of the photographic work. The photography is complicated by the presence in a single transient photograph of some components in which the beam speed may be a thousand times as fast as it is in others. However, beam speeds in excess of 200 kilometers a second are photographed, and a continuous sine wave of 5 megacycles frequency may be clearly resolved on a single transit. Sweep speeds which permit resolution of much higher frequencies are employed for visual observation, where the transient component being studied can be found by frequent repetition of the contact operation. As the occurrence of a particular component varies in time of its position in the entire transient, very high sweep speeds are impractical for photography as a prohibitively large proportion of exposures would be blanks. A sweep speed of about 15 kilometers per second is about as high as is useful except in some special cases.

We may commence the discussion by setting up what appears to be a very simple circuit (Fig. 1), a pair of contacts, one of which is con-

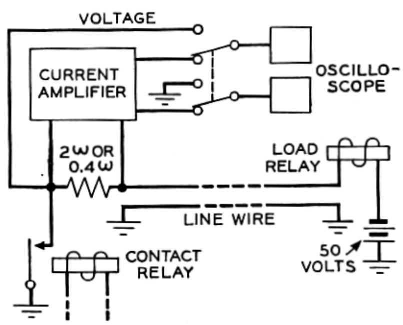

Fig. 1—Typical relay and contact circuit.

nected by a length of wire to a relay winding, which is in turn connected to one pole of a 50-volt battery. The mate contact and the other pole of the battery are grounded by very short wires. The oscillograph is arranged so that the voltage between the contacts and the current through them can be observed, great care being taken to insure that the added apparatus does not appreciably change the circuit characteristics even at very high frequencies. A low power microscope may be set up to observe the operating area of the contacts.

When the contacts close, the first thing that happens is the discharge of the relay structure (a capacity) and of the wire through the contacts. The wire may be thought of as a radio antenna, more or less open-circuited at the load relay winding terminal, and either grounded or opened at the contacts. The wire forms an oscillatory circuit of moderately heavy damping with a surge impedance of about 100 ohms. As it is charged to 50 volts, when the contacts come together an oscillation having a peak current of 0.5 ampere occurs and is over before the steady current through the relay winding has more than started to build up. The frequency of the line oscillation depends on the length and other characteristics of the wire, but it is (in the telephone plant) rarely lower than 500,000 cycles, and on short leads it may be many megacycles. Fortunately most contacts are not much affected by closing a half ampere. Erosion and build-up will occur, but at rather slow rates, and they are usually completely obscured by effects due to the contact opening. Of course, if the contacts bounce,[1] the effect will be more complex, but we are assuming for the moment that they do not bounce. The structure of the relay itself, including the pair of springs separated at its base by an insulating sheet, is also an oscillating circuit. We have not been able to get inside of this circuit and measure the current surge but its oscillation frequency seems to be about 250 megacycles for certain telephone relays.

Now suppose that the simple circuit of our closing contacts is complicated by an additional wire connected to the contact spring terminal. This is also charged to 50 volts before the contacts close, and being a second circuit of a hundred ohms surge impedance in parallel with the original wire, the current peak discharged through the contacts will now be about one ampere. But now the contacts are likely to act differently. About a microsecond after the current reaches its peak, but before the charge in the wires has been completely dissipated, the circuit is interrupted and the discharge stops. A spark, which is visible in the microscope, suggests that the current carrying areas have been exploded and blown apart. A few microseconds later they again close and the rest of the energy is discharged, but some of the contact metal must have been destroyed.

If several "idle" wires are attached to the contact, the current surge, and the number and duration of the contact reopenings, increase, but not usually in direct proportion to the number of wires. If the idle wires are attached to the load relay winding terminal instead of to the contact, the current is smaller, as the length of single wire from relay winding to contact is effectively in series with them.

In the telephone relay circuits which we are considering, the steady state current plays little part during contact closing if the contact carrying relay is properly adjusted, as the contacts come to rest while the current is still held at a small fraction of its final value by the inductance of the load relay winding.

Under some conditions which are more likely to occur in telegraph than in telephone circuits the contact closure phenomena are somewhat different from those described above. Assume, for example, that the potential between the open contacts may be adjusted in a range be-

[1] Bounce, as distinguished from chatter, reopens the contacts after several thousandths of a second.

tween 30 and 250 volts while the final direct current is limited by circuit resistance to less than 0.5 ampere. At the low voltage, observations of the current and voltage transients indicate that the closing contacts merely discharge the line. As the voltage is raised so that the current surge peak is in the range between 0.5 ampere and 1 ampere the reopenings, due presumably to overheating of the contacting areas by the discharge, are observed. These become more frequent as the voltage and current increase, and a new type of current surge begins to appear. This is placed on the time axis ahead of the point at which the initial closures have been occurring (usually 5 to 10 microseconds earlier) and consists of one or more irregularly spaced heavily damped pulses of current lasting only a small fraction of a microsecond and evidently discharging only a minute amount of the energy stored in the system. They occur perhaps once in a hundred closures at 30 volts, nearly every closure at 100 volts, and several for every closure at 250 volts. It is believed that the transients observed indicate the formation of minute metallic bridges [2] between the approaching contacts due to a softening of the metal by a cold point discharge and its deformation by the static field, and that once formed they are exploded by the discharge of current from the relay structure and adjacent wiring. The high fields necessary for phenomena of this type are of course due to the minute distances as the contacts approach final closure. A good deal of the erosion on telegraph relay contacts operating on capacitative loads or shunted by resistance-capacity "spark-killer" circuits is probably due to these "preclosures," but they are not thought to be of much importance at the lower battery voltages of the telephone plant.

Having now described the phenomena as contacts close in a doubtless over-simplified manner, we may consider that they have been closed for a long time, the direct current and the magnetic field of the load relay are established and the contacts are to be separated. The action now becomes really complicated and much of it is as yet only surmised. Several different things may happen, and these are influenced by humidity, dirt, surface films, absorbed gases and many other factors, including the speed of contact separation, the roughness of the surfaces, and the presence or absence of a wiping motion as well as the physical properties of the contact materials.

If the steady current exceeds certain well-known values ranging between 0.4 ampere and 1 ampere, characteristic of the contact materials,

[2] "The Formation of Metallic Bridges between Separated Contacts," G. L. Pearson, *Phys. Rev.*, Sept. 1, 1939, Vol. 56, pp. 471–474.

a metallic arc is formed as the contacts separate.[3] This is maintained at an initial potential of about 15 volts, and increases to a final value usually below 30 volts. The arc may last several milliseconds, but when it breaks it is followed by a complex transient lasting possibly another millisecond. These transients may be of two general types to be described later. This case is not of much importance in the telephone plant as the steady current is ordinarily kept below the value at which prolonged arcing occurs.

Metallic arcs lasting several ten thousandths of a second, and also followed by complex transients, may occur in breaking steady currents considerably less than those ordinarily believed to cause arcing. The effect of these transient arcs on contact life has not been studied separately, but they can hardly fail to increase the erosion. Their effect is unavoidably included in the studies of contact life in the higher range of direct current values. Figure 2 shows the voltage between a pair of opening silver contacts in which the steady current (0.25 ampere) is strong enough so that a brief metallic arc (indicated by the upward deflection of the trace to a new horizontal position) precedes the final transient.

If the steady state current is low enough so that neither prolonged nor brief metallic arcs are formed at the initial contact separation, one of two general types of complex transients occurs, or both types may be mixed. These have been designated the "A" and "B" types. The "B" type transient seems to be the more normal and it is difficult, probably impossible, to set circuit and contact conditions which will never give a "B" transient. It is identified by a bright spark between the contacts, showing in a spectroscope bright lines of the vaporized metal, and consists of a series of disruptive sparkovers at gradually increasing voltages. Each sparkover is individually very complicated. The appearance of the contacts during the "A" type transient is radically different from that during the "B" transient. There will be a minute bright spark, surrounded by a violet cloud which spreads out from the immediate contact area over the negative contact and sometimes travels as far as a sixteenth of an inch from the working area.

As a result of thousands of observations of the transient currents and voltages, and many experiments, and discussions with several physicists and engineers with whom the writer is associated, a plausible explanation of the phenomena has been arrived at and will be given as at least a working hypothesis.

[3] "Minimal Arcing Current of Contacts," H. E. Ives, *Jour. Franklin Institute*, October, 1924.

The voltage wave form of an entire "B" transient, covering the time from the initial separation of the contacts to the final subsidence of the voltage charging the line wire, is shown in Fig. 3, and the a-c. components of the current in the range from 20 kilocycles to 20 megacycles are shown in Fig. 4. The low-frequency components of the current are comparatively weak. A line and load relay were chosen to give a relatively simple transient with the important components at frequencies which could be photographed. A 500-ohm Western Electric U-type relay and a line of 300 ft. of No. 22 switchboard pair were used. The mate wire of the pair was grounded at both ends. The currents and voltages were not photographed simultaneously but the types of the transients were correlated by repeated observations. A current picture will not exactly correspond to a voltage picture, as the transients produced by successive operations of a contact are never identical.

The "B" transient may be explained as follows, using as a basis the simple circuit of Fig. 1. The steady current is established and the contacts start to separate, moving apart at a speed, which is at first surprisingly slow (about an inch a second). The contacts have been deformed by the pressure between them, and as this is relaxed the current density and the temperature at the contacting areas rapidly increase until at some light pressure the area becomes so small that the current explodes it. There may be some necking out of the softened contacts before this and under some conditions there are indications of a metallic arc lasting a fraction of a microsecond, but at any rate an initial rupture occurs between hot and soft metal areas.

The wire has been at ground potential, but the battery plus the collapsing magnetic field of the load relay commence to charge it at a rate depending on the line and relay winding capacity and the relay inductance and losses. In ten or twenty microseconds, it has reached at the contacts a potential of from 50 to 200 volts. This is below the voltage at which sparkover due to ionization of the air can occur, but something usually happens which recloses the circuit. This is believed to be caused in somewhat the same manner as the "preclosures" mentioned earlier. It is probable that a cold point discharge reheats the contacts. This is followed by a collapse of the voltage to about 15 volts above zero in the direction of the previous voltage, indicating the formation of a metallic arc. This lasts a fraction of a microsecond and the voltage then drops to nearly zero, suggesting that the contact areas heated by the field current and the arc have been drawn together in solid metallic contact. The line is discharged with an oscillation of comparatively low damping (which is characteristic of the line wire) reaching a current peak usually ranging from 0.5 to 2 amperes. The first cycle of the oscillation is distorted by the higher resistance of the path to ground caused by the arcing stage in the reclosure. After a few microseconds the contacts are opened a second time by the continued motion. Occasionally they reclose a second time but they usually stay open until the voltage has built up by the continued discharge of the load relay inductance to a value between 300 and 350 volts. Then a spark occurs at what is usually considered the minimum sparking potential between contacts in air.

Figures 5 and 6 show the voltage and current of the initial opening and reclosure of the contacts at the start of a "B" transient. The brief arc at initial opening is barely detectable in Fig. 5. Figures 7 and 8 show similar voltages and currents at an increased sweep speed. In Fig. 7 the metallic arc established during the reclosure is plainly evidenced by the collapse of the voltage to about 15 volts and its maintenance at this value for about a microsecond before it drops to zero. The effect of the arc in distorting the oscillating discharge of the current from the line wire is evident in Fig. 8. The current oscillation of Fig. 8 may be duplicated merely by charging the line wire to a suitable voltage through a high resistance and closing the contacts, the far end of the line being grounded through the load relay and a large condenser which replaces the usual battery.

It is likely that the point discharge precedes the arc on reclosure by such a short time that it cannot ordinarily be resolved. Nevertheless disturbances of the voltage and current are occasionally found which seem to indicate that a discharge path formed and was checked (possibly by melting off the point) without establishing an arc or metallic bridge. Such a disturbance of the rising voltage is indicated in Fig. 9 by a high-frequency oscillation about 5 microseconds after the first rise of the voltage trace. Figure 10, which shows the current of the second of two initial reclosures, indicates a similar phenomenon. Five microseconds after the rupture of the circuit, shown by the downward deflection of the zero line, a dim line upward records a current surge lasting a fraction of a microsecond and reaching about 3/4 ampere. This surge, however, did not result in the immediate formation of an arc which was established about 5 microseconds later.

The initial separation of the contacts does not always result in a metallic reclosure. Figure 11 shows the voltage of the early part of the "B" transient. Here the first collapse of the voltage is a sparkover from about − 300 volts which establishes an arc at about − 15 volts. This arc is broken and, as the line is not completely discharged, the voltage between the contacts rises to about + 140 volts; a second arc is established at + 15 volts and broken in its turn. Possibly because of the continually increasing distance, the arc is not reestablished, and the voltage builds up with oscillations of a frequency characteristic of the line wire insulated at both ends until it reaches − 300 volts a second time and another spark passes. This time only one arc is formed, and the recovery of the voltage starts from the positive side of the zero axis. The current surges corresponding to the voltage collapses of Fig. 11 are shown in Fig. 12. Here the first pulse represents a sparkover which formed only one arc. As the current from the line reached about 4 amperes it was checked and the conducting arc was broken (possibly by being extended laterally into the region of cooler metal). The second pulse shows the current of a sparkover which formed two arcing periods.

These phenomena are shown in more detail in Figs. 13 and 14 which show the voltage and current of a sparkover forming only one arc, and 15 and 16 which show the wave forms when two arcs are formed. Note that the frequency of the current oscillation is that of the line grounded at one end only (the impedance of the load relay being high at this frequency) and is about half that of the voltage oscillation which is that of the line open at both ends. Oscillations of both frequencies may be found in the line at a distance from either end.

Corresponding observations may be made of the occurrence of 3, 4 and 5 arcing periods, the pattern followed being about the same. The higher the voltage at sparkover the more arcing periods; an odd number of arcing periods is followed by a recovery of the voltage from the opposite side of the zero axis from that of the voltage before sparkover, an even number by recovery from the same side of the zero axis. The arcing periods are individually complex, having superposed on them oscillations believed to be due to the relay structure and the leads to the oscillograph which are too fast to be resolved photographically by the means available. These oscillations may be observed visually by using higher sweep speeds and reach frequencies of 250 megacycles.

While the arcs ordinarily do not exceed a microsecond in duration, they are probably an important factor in determining contact erosion, as several hundred may occur at each contact opening.

As may be seen from Fig. 3 the sparkovers continue to occur, the successive voltage breakdowns corresponding to the normal sparking potential as the contact separation increases with time (with some irregularities due to residual ionization in the gap) until the separation is finally so large that the energy remaining in the load relay cannot charge the line to the breakdown voltage. At this stage the line dis-

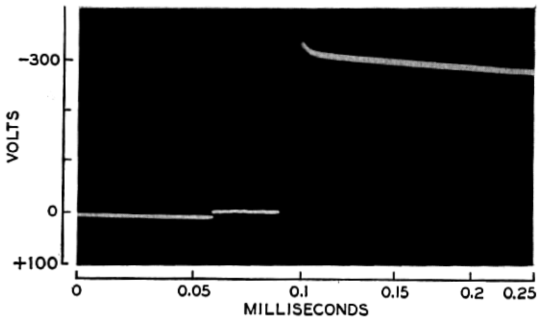

Fig. 2—"A" transient starting with metallic arc (voltage).

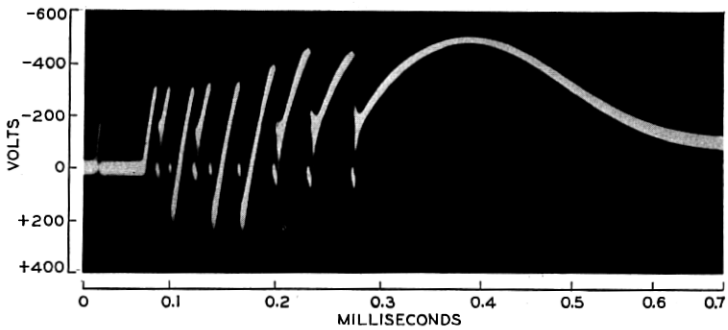

Fig. 3—Entire "B" transient (voltage).

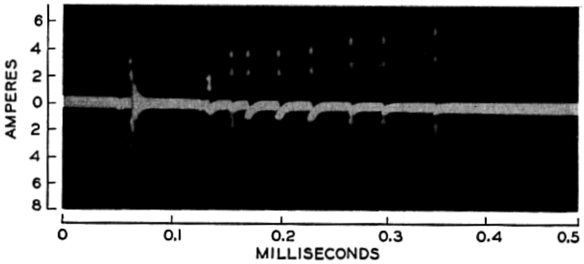

Fig. 4—Entire "B" transient (current).

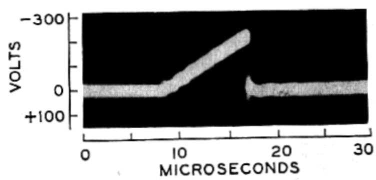

Fig. 5—Initial opening and reclosure—"B" transient (voltage).

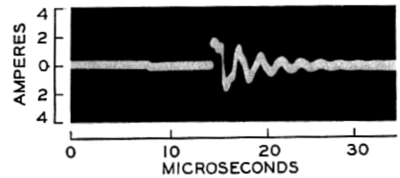

Fig. 6—Initial opening and reclosure—"B" transient (current).

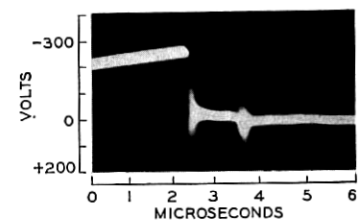

Fig. 7—Initial opening and reclosure—"B" transient (voltage) rapid sweep.

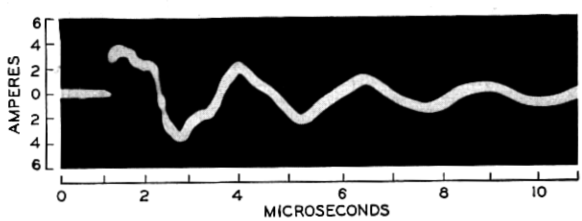

Fig. 8—Initial opening and reclosure—"B" transient (current) rapid sweep.

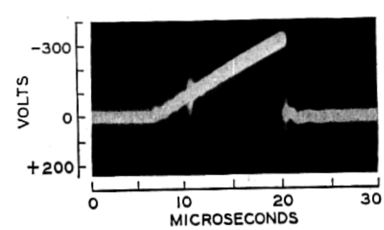

Fig. 9—Evidence of point discharge, voltage.

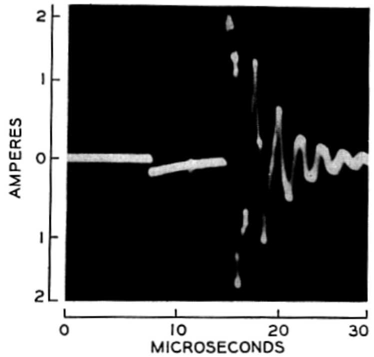

Fig. 10—Evidence of point discharge, current.

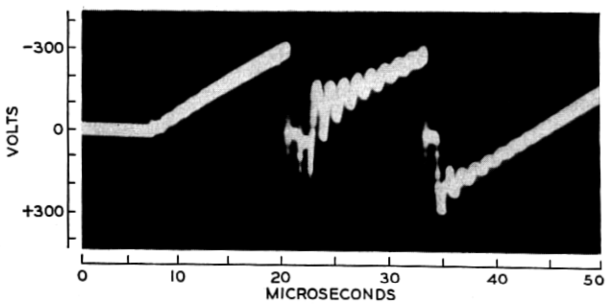

Fig. 11—Early part of "B" transient, voltage.

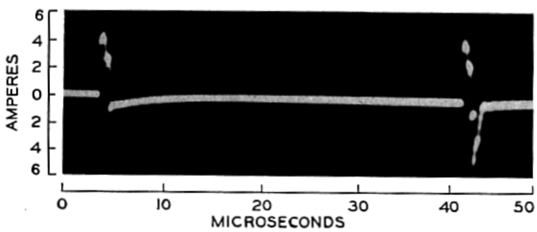

Fig. 12—Early part of "B" transient, current.

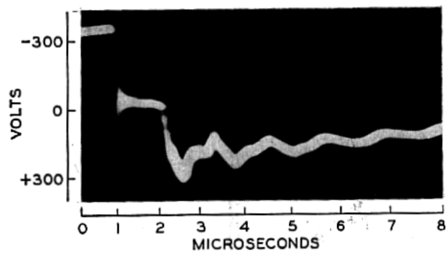

Fig. 13—Single sparkover of "B" transient, with single arc (voltage).

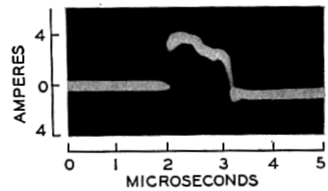

Fig. 14—Single sparkover of "B" transient, with single arc (current).

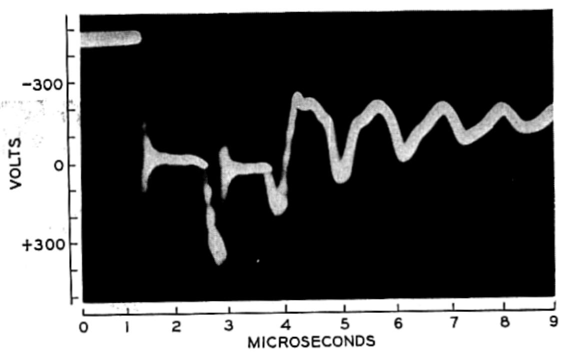

Fig. 15—Single sparkover of "B" transient, with double arc (voltage).

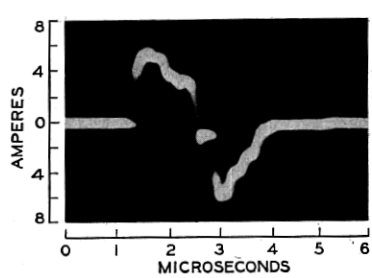

Fig. 16—Single sparkover of "B" transient, with double arc (current).

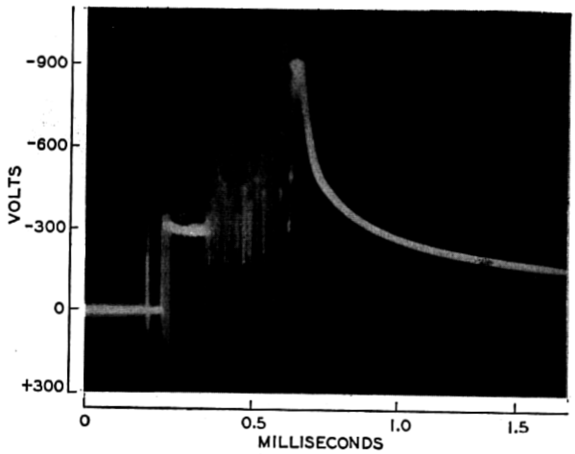

Fig. 17—Typical "mixed A and B" transient (voltage).

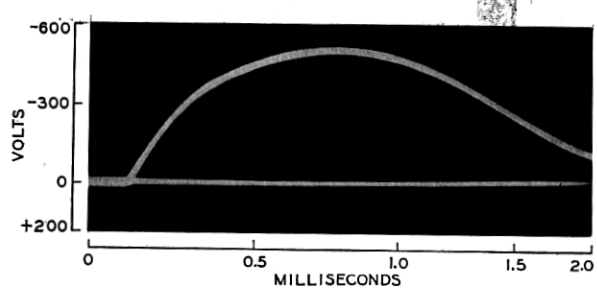

Fig. 18—Effect on voltage transient of changing wire line length—1100 ft.

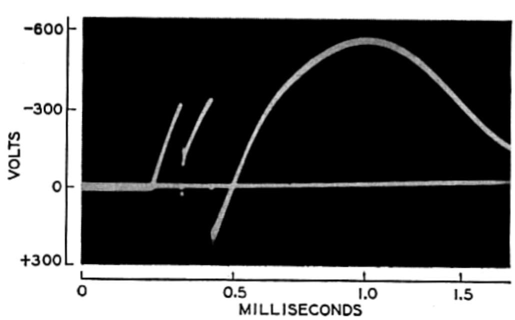

Fig. 19—Effect on voltage transient of changing wire line length—600 ft.

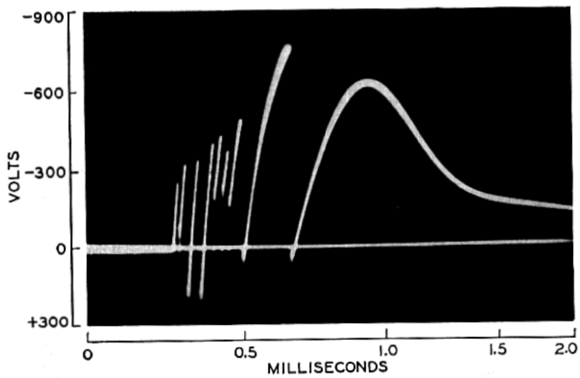

Fig. 20—Effect on voltage transient of changing wire line length—150 ft.

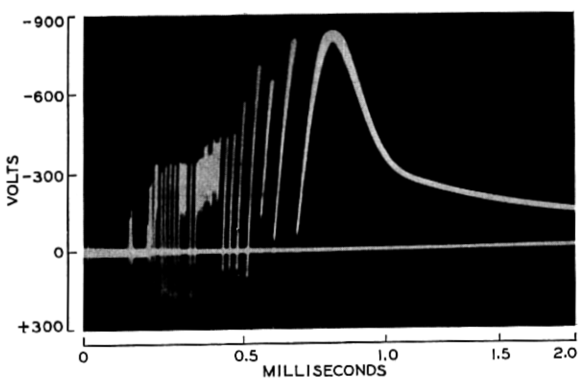

Fig. 21—Effect on voltage transient of changing wire line length—50 ft.

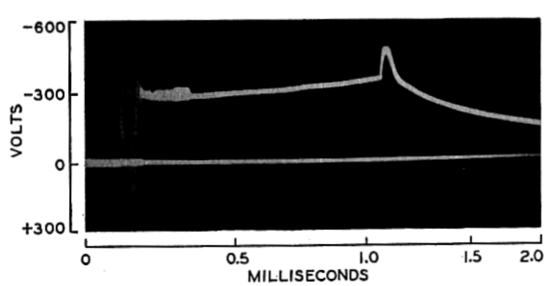

Fig. 22—Effect on voltage transient of changing wire line length—10 ft.

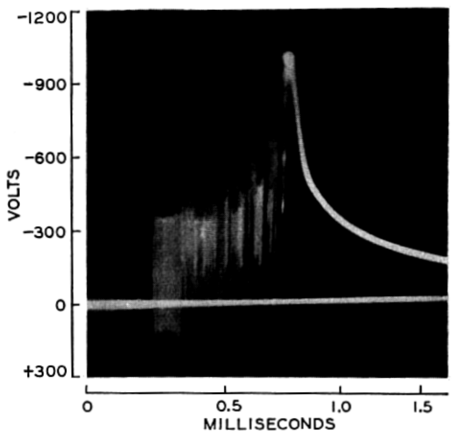

Fig. 23—Effect on voltage transient of changing wire line length—10 ft.

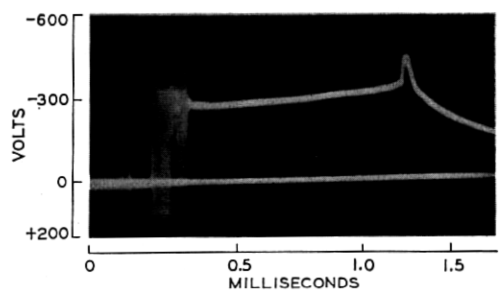

Fig. 24—Effect on voltage transient of changing wire line length—10 ft.

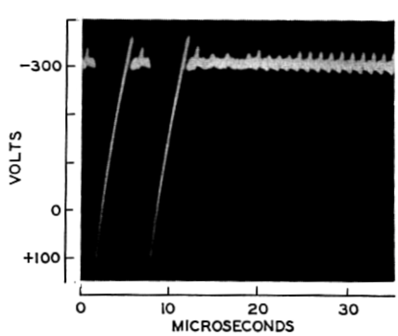

Fig. 25—Oscillation on glow discharge of "A" transient (voltage).

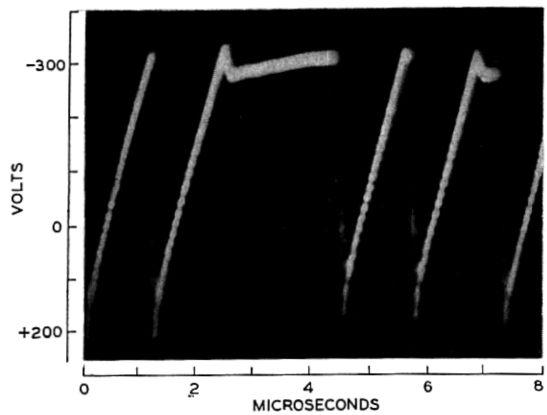

Fig. 26—Start of "A" transient (voltage).

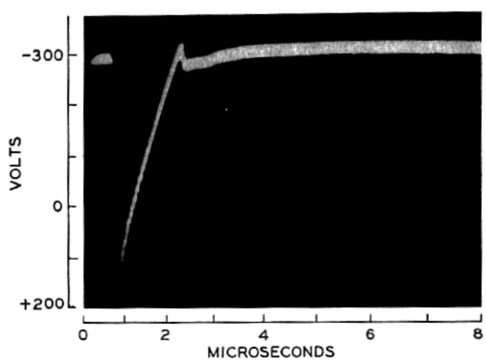

Fig. 27—Start of stable glow discharge of "A" transient (voltage).

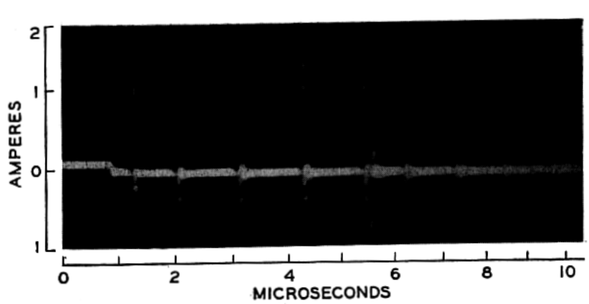

Fig. 28—Start of "A" transient (current).

charges slowly back through the load relay to the battery voltage. The peak voltage reached may be as high as 2000 volts.

The principal characteristics of the "B" discharge can be produced by a simple experiment which does not use a load relay, The transient is not dependent on a load inductance, but only on a source of voltage which will charge a wire at a sufficiently rapid (but not too rapid) rate while a pair of contacts, which initially ground the wire, are separating. If a wire about 100 ft. long is connected to a source of somewhat more than 350 volts through a resistance of from 5000 to 20,000 ohms, and is also grounded by a contact at one end, a transient is produced when the contacts open which shows the characteristics of a "B" type transient except the final dying away of the voltage to 50 volts.

It must not be understood that every spark transient is purely of either the "A" or the "B" type. It is very common for the "A" type transient to break down into the "B" type and less often the "B" transient establishes the gas glow discharge for a brief period in the middle of the sparkovers.

A "mixed" transient is shown in its entire duration in Fig. 17. Here, after a group of sparkovers, a period in which the voltage is maintained steadily at about 300 volts for about 0.0002 second intervenes, and is followed by more sparkovers from considerably higher voltages. In order to produce this transient the length of the line wire was reduced to 10 ft., at which length and with a 1000-ohm load relay the tendency is to produce intermittent groups of "A" or "B" transients, interspersed with the mixed type shown, when the relay is operated frequently.

The number of sparkovers in each "B" transient varies with the circuit conditions. As many as a thousand may be found with a load consisting of a number of relays in parallel on a wire of moderate length and as few as one in the limiting case.

While the occurrence of the "B" transient is favored by long line wires and high impedance relay loads, beyond a certain length which with telephone relays and wiring is from 300 to 2000 ft. (the longer lengths being associated with the lower impedance relays) no sparkovers at all occur. The voltage build-up is so slow that the sparkover potential is not reached at any time during contact opening and the contacts may be said to be protected by the line wire. The series of voltage oscillograms, Figs. 18 to 24 inclusive, shows the change from a smooth transient with no sparkovers through the "B" type with an increasing number of sparkovers to the final "A" type. The "A" type transient of Fig. 22, which has superposed on the 300-volt gas glow discharge stage a relaxation type of oscillation, the "B" transient of Fig. 23 and the simple "A" transient of Fig. 24, were all produced under identical conditions in quick succession. The change in characteristics from Fig. 18 to Fig. 24 was produced merely by a reduction in the length of the connecting wire from 1100 ft. through three intermediate stages to 10 ft., a 1000-ohm load relay being used. This explains a puzzling effect noted with many contact materials. With a supposedly identical circuit, the erosion will be small with very short wires, increase rapidly as the wiring length increases, and then decrease again becoming very small with very long wires.

The "B" transient is more frequently observed with freshly filed contacts, at high humidities, and with a rolling or wiping motion of the contacts in opening. It is always found if the contacts are of oxidized metal or operate in an oxygen atmosphere. In fact, there seem to be good reasons for believing that its production is bound up with the presence of oxygen on or in the surface of the active contact metal.

It may be seen from the last series of oscillograms that if the circuit and the conditions of the contact surfaces are just right, the "B" transient is replaced by a much simpler and less stable type, the "A" transient. It will occur usually when the wiring is short or the load relay is of low impedance, with contacts which have been operated until the original surface has been burned off and have not stood idle more than a few minutes. It starts much as does the "B" type, but after a dozen or a hundred sparkovers from about 350 volts, which come much closer together in time than those of the "B" transient, the voltage becomes steady at about 300 volts. This condition lasts for perhaps 0.6 millisecond, then the voltage rises to about 400 or 450 volts and gradually reduces, reaching the battery voltage after several milliseconds. A typical "A" type transient is shown in Fig. 24. It is suggested as a hypothesis that, during the sparkover stage, the oxygen is being exhausted from the surfaces of the current carrying areas of the contacts by burning the metal and that when this has been completed, a nitrogen gas glow discharge is formed and maintained during the rest of the contact opening, if the supply of energy from the load inductance through the line is rapid enough to prevent the voltage from dropping below about 280 volts.

The glow discharge phase of the "A" transient is unstable. If transient voltages induced by the operation of relays in other circuits reach the contact gap during the time that a sustained glow discharge is attempting to form, its formation is interfered with and a mixed or "B" type transient results. Occasionally, as illustrated in Fig. 22, the glow discharge of the "A" transient has superposed on it a sawtoothed oscillation of from 10 to 50 volts peak-to-peak. Part of an "A" type transient showing this peculiarity is illustrated by the oscillogram of Fig. 25. This appears to be a relaxation oscillation such as is commonly produced in ionized gas tubes, riding on the normal 300-volt axis of the gas glow discharge. The conditions which lead to the occurrence of this oscillation at atmospheric pressure have not been identified, but it is found to be quite stable in some cases where contacts have been sealed in a mixture of air and gases at about half atmospheric pressure.

A typical "A" transient is shown in detail in Figs. 26, 27, and 28. The circuit consisted of a 250-ohm relay connected to the contacts by 10 ft. of wire, the battery being 50 volts as usual. Figure 26 shows the voltage of the early part of the transient during which rapid sparkovers are interspersed with two brief periods during which a gas glow discharge was established but not maintained. Figure 27 shows the final sparkover before the establishment of the glow discharge at about 300 volts. A group of the current pulses corresponding to the initial part of the sparkover stage is shown in Fig. 28. These are complicated by the line oscillations (which should be of about 30 megacycles frequency) and appear to last less than 0.1 microsecond.

It may be seen that the individual sparkovers at the start of the "A" transient are somewhat different in form from those of the "B" transient. The voltage reaches 320 volts in a microsecond or so, and in some cases collapses to zero or beyond immediately. There are sometimes indications of arcing periods lasting much less than 0.1 microsecond and the voltage recovers with oscillations of the line wire but the duration of the phenomenon is too brief for very accurate analysis. But in many cases, the voltage, having reached its peak, drops to an intermediate value of 280 volts and recovers to 320 volts before it collapses. This is probably due to the temporary formation of the nitrogen glow discharge, which is finally established and maintained during the remainder of the contact opening when for some reason the sparkover does not occur. In cases where the contacts are on the verge of producing a "B" transient the voltage may rise to 500 volts and then collapse to the 300 volts of the gas glow discharge.

It is very interesting to set up a circuit which will cause the "A" transient to predominate, and start operating freshly filed contacts several times a second observing the transient voltage at contact opening on the oscilloscope. The first transient will always be of the "B" type. Usually the first few dozen will also. However, after a while one of the transients will show a flat top at about 300 volts for a very brief period and this tendency increases until finally a complete

"A" transient occurs. After this, the "A" transients become more and more common until finally the "B" transients occur perhaps once in a hundred openings. If, then, a gentle stream of oxygen is blown on the contacts, only "B" transients will occur until a few seconds after it has been turned off. Blowing the breath on the contacts has a similar but less definite effect, while a stream of dry compressed air has no effect.

If, on the contrary, the circuit conditions are selected so that "B" transients predominate, a stream of nitrogen will induce "A" transients. That is, "A" transients are not found in oxygen and "B" transients are rare in nitrogen.

If, instead of operating the contacts several times a second, they are operated at longer intervals, the tendency to produce the "A" transient is reduced. When contacts are operated in air a certain interval between operations can be found which causes all transients to be of the "B" type. This probably depends on humidity and also on circuit conditions and contact material. In one experiment, a wait of 45 seconds between operations gave all "B" transients with silver contacts, while a wait of five minutes was required with palladium contacts. This is possibly due to a different rate of film formation.

Life tests on palladium contacts show much lower erosion with "A" transients than with "B" transients. The effect of the two types of transient in terminating the life of silver contacts is not markedly different. The contours of the eroded surfaces exhibit a wide variety, and it is not easy to correlate the transient type with its effect. It is evident, however, that areas of the contacts which have never been in the direct current path may be severely eroded.

When we consider that the "B" transients produce oscillations in the line wires reaching several hundred volts and often fifteen amperes, it is not to be wondered at that clicks will be produced in circuits in the immediate neighborhood of unprotected relay contacts. The "A" transients produce much weaker currents than the "B" transients and many contacts on successive operations will produce "A", "B", or mixed types. This explains the common observation that relay clicks vary over a wide range of amplitudes. The arrangement of telephone circuits in which the cabled wiring always contains a large number of grounded conductors, and is often enclosed in a lead shield, prevents any appreciable free radiation of the spark transient oscillations.

With the foregoing information available the contact erosion process at opening contacts appears briefly to be as follows. At very minute separations high field strengths exist even for moderate voltages. The resulting cold point discharge is often followed by a metallic arc which softens a tiny point on the contact which is pulled out and fused into metallic contact under the action of the high fields. After rupture by increasing separation or increasing current density, the process may repeat or, as is more likely, the separation is too great for another metallic bridge to form. The high field discharge then sets the stage for the next type of conduction or breakdown. This may be either a series of sparkovers interspersed with metallic arcs of extremely short duration or a gas glow discharge, initially intermittent and then more or less stable. Factors predisposing toward one or the other type of discharge are known thus far only in a most general fashion and much remains to be done before the relation between contact erosion and the transient currents and voltages can be predicted accurately. There is ample evidence that molten metal may be expelled from the immediate contact area at high velocity and may be deposited at distances of at least 0.1 inch. It also appears that both the ionized nitrogen cloud of the "A" transient and the disruptive sparks of the "B" transient may corrode the contacts and their supports at locations and distances which never enter directly into the rupture of the current path.

We have seen that the line wire contributes to the current surges through contacts due to its properties as an oscillatory circuit, charged repeatedly by the energy stored in the magnetic field of the relay. The surges and the resultant erosion may be reduced in several ways. If a radio frequency choke coil is connected between the contact and the line wire, the discharges of the latter are much reduced, and the "A" type gas glow transient favored. A group of many current surges of 15 amperes peak may in most cases be reduced to one or two of 0.15 ampere or less, and a radical reduction in erosion secured. Unfortunately choke coils are expensive and inconvenient. The usual line wire may be terminated in approximately its surge impedance by shunting both ends to ground with a resistance of about 100 ohms in series with a condenser of the order of 0.01 mf. This heavily damps the line oscillations and greatly reduces the number and severity of the current surges. It is also expensive. Instead of the copper line wire, a material such as iron or permalloy plated copper having a high surge impedance and large high frequency a-c. losses may be used. This seems more practical, but brings up new problems in design, handling, and soldering.

The most effective means of reducing erosion is of course the well known "spark-killer" (consisting of a condenser and resistance in series, shunted across the contact or load), which can be designed to hold the voltage below the sparkover point at least until the contacts have separated a safe distance.

When the conventional spark-killer is used it is generally assumed that what sparking then occurs is due to the discharge of the condenser when the contacts close, provided that the "spark-killer" prevents the voltage at contact opening from reaching 350 volts. Unfortunately the "reclosure" effect described earlier appears unless the initial rise of voltage as the contacts separate is held down to a value considerably below the sparking potential by a suitable choice of the resistance in series with the "spark-killer" condenser. If the rate of increase of the initial voltage in relation to the speed of separation of the contacts exceeds a figure which seems to depend on the contact material and the condition of its surfaces, the high field point discharge comes into play and causes the separating contacts to reclose metallically while they are still at a minute separation and moving apart very slowly. In "reclosing" the line wire and condenser are discharged, the current explodes the minute metallic bridge, producing a visible spark, and the circuit is thus reopened. This may occur a dozen times in some cases before the contacts finally stay separated. The higher the voltage which the spark-killer permits the more likely are the reclosures to take place, and the larger the number of reclosures at each contact opening. However, reclosures are usually not very common in cases where the voltage of the wave front is held below 50 volts. In the majority of cases in the telephone plant it is possible to do this without incurring much of a penalty due to erosion of the contacts on closing by the discharge of the spark-killer condenser.

This discussion is not more than sufficient to serve as an introduction to the problems of contact sparking as revealed by the improved observing technique used in this study. Only the simplest cases have been considered, and the telephone plant is far from being simple. Many relays have multiple windings or metal sleeves, and multiple connections to the contacts are very common. As these complications considerably modify the contact spark wave form and erosion, each contact with associated circuits presents its own problem. The solution of these problems involves the careful study of circuit characteristics of a type which are ordinarily left to the radio engineer, as well as of the mechanical, chemical, and metallurgical properties of the contact materials.

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