63. *The Coil Ignition of Some Explosive Gaseous Mixtures.*

By B. W. BRADFORD, G. I. FINCH, and (MISS) A. M. PRIOR.

MORGAN ("Electric Spark Ignition," Crosby Lockwood, 1922, pp. 19, 28, 70, and 73), Taylor-Jones ("Induction Coil Theory and Applications," Pitman, 1932, p. 196 *et seq.*), Morgan and Wheeler (J., 1921, **119**, 245), Wheeler (J., 1920, **117**, 905), and Morgan (*Phil. Mag.*, 1931, **11**, 160) have stated that coil ignition is effected by the capacity and not by the inductance component of the discharge. On the other hand, Wheeler (J., 1924, **125**, 1859) and Maxwell and Wheeler (J., 1927, 2078) found it necessary for the purposes of a comparative study of the coil ignition of paraffin–air mixtures to maintain constancy in conditions such as the rate of opening of the break and the primary current on interruption. This fact appears to conflict with the foregoing statement, because the characteristics of the capacity component furnished by a secondary circuit of given properties should be independent of the primary circuit and the conditions pertaining thereto before, at, or after break; and that this is indeed the case has recently been confirmed by cathode-ray oscillographic observations (Finch and Sutton, *Proc. Physical Soc.*, 1933, **45**, 288). In order to reconcile statement with fact it will be necessary, therefore, to suppose that the effective dielectric strength of the gap must be determined in some manner by the properties of the primary circuit. Failing direct evidence to the contrary, such change in breakdown potential cannot be reasonably ascribed to a failure of Paschen's law under what approach only mild surge conditions. A more likely supposition, however, is that electron ejection from the electrode acting as cathode at the moment of breakdown is subject to lag such that the breakdown voltage increases with the steepness of the applied potential wave-front. It is by no means easy to see, however, how the probable magnitude (according to Peek, "Dielectric Phenomena," McGraw Hill, 2nd edtn.) of such a lag phenomenon could suffice to account for the profound effect which variation in the primary break current has been found by Wheeler (*loc. cit.*) and also by Morgan to have upon the igniting power of the discharge; because the build-up time of secondary gap potential in the case of a representative commercial ignition coil assembly, with a primary inductance and capacity of, for example, 3 mH and 0·3 μF respectively, cannot exceed 0·1 m.sec., even under minimum spark energy conditions. The following experiments were therefore carried out with the object, *inter alia*, of determining if lag, or impulse ratio, as it is sometimes termed, could be held to account for the known dependence of the igniting power of ignition-coil sparks upon the primary break current; or whether ignition be due to some part of the discharge, other than the capacity component, which depends upon the primary circuit constants.

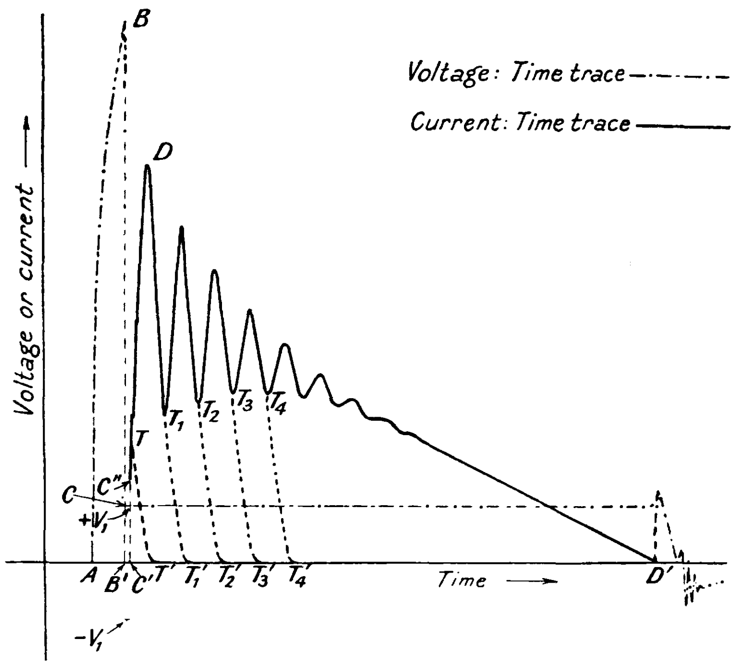
EXPERIMENTAL.

The apparatus employed was as follows: (i) a "Lucas" ignition coil, Model P4—O, Type BN7—O, as ordinarily fitted to the Austin 4-cyl., 7 h.p. engine; the self-capacity of the secondary circuit including the gap was about 80 cm.; (ii) an interrupter of special design (B.P. 1932, 381,917), by means of which the duration of open circuit in the primary could be varied continuously and with a high order of accuracy over the range between 0 and 4 m.sec., and which also served as a frequency meter; (iii) a glass explosion vessel of approx. 250 c.c., fitted with a wide-bore mercurial closed-limb manometer and with pointed 18 S.W.G. W wire electrodes; (iv) an Ardenne cathode-ray oscillograph and tripping linear time base (Finch, Sutton, and Tooke, *Proc. Physical Soc.*, 1931, **43**, 502; 1932, **44**, 190); a 1274 Ω non-inductive single-layer wound nichrome-wire resistance in series with the gap enabled suitable potentials to be applied to the oscillograph deflecting plates for the purpose of recording the discharge current; (v) a 5-l. supply of a $2CO + O_2$ mixture, sensitised by the addition of 5% H_2 and stored in a glass gas-holder over aq. glycerol, and a similar store of $CH_4 + 2O_2$. The constancy of the comp. of these mixtures could be relied upon because the expts. carried out with each mixture were completed in one day. Finally, (vi) electrolytic gas, prepared as and when required by electrolysis of recryst. $Ba(OH)_2$. Drying was effected by passage through a train of two spiral washers containing conc. H_2SO_4. Spark-igniting power was measured in terms of the least igniting press. of the explosive mixture.

With a view to maintaining constancy in any possible breakdown lag effects, each series of expts. was carried out with a primary break current of const. value, the energy associated with the inductance component being varied independently of the capacity component by means of the special interrupter, the theory and practice of which have been discussed fully elsewhere (Finch and Sutton, *loc. cit.*). It may, however, be mentioned that the interrupter enabled the primary circuit to be re-made at any desired time during the life of the inductance component, which could thus be terminated with great rapidity, because the inductance of the primary circuit of a closely coupled oscillation transformer approximates to zero as long as the secondary is short-circuited by the discharge (cf. Figs. 4, 5, 6, 7).

The frequency of the main oscillatory component of the inductance component was varied by means of a suitable mica dielectric plug-in primary condenser. Except where otherwise stated, no alterations whatever were made in the secondary circuit, the most prominent natural frequency of which in regard to the capacity component was of the order of $1{\cdot}2 \times 10^7$ c./sec. (Finch and Sutton, *loc. cit.*).

FIG. 1.



The Coil Discharge Characteristics.—The theory and characteristics of ignition-coil sparks have been discussed in detail elsewhere (Finch and Sutton, *loc. cit.*); it will suffice, therefore, to point out the outstanding features of the coil discharge as shown in Fig. 1, which has been constructed from actual oscillograms (Finch and Sutton, *loc. cit.*). The voltage–time trace begins at A, the moment of break of the primary circuit, and, provided the breakdown potential of the gap be sufficiently far within the max. potential which the coil is capable of furnishing, rises rapidly in the manner shown to B, at which point the gap breaks down. B' is the projection of B on the time axis. Between B and C the voltage trace is described by the electron beam with such velocity as to leave no visible signs on the photographic plate other than the two extremely faint unresolved spots at $+V_1$, and $-V_1$, the amplitudes of which are approximately 300V. The time interval between B' and C' is of the order of 10^{-6} sec. For the sake of clarity in Fig. 1 the units of the time scales between A–B' and B'–C' are drawn in such a manner that they are each much smaller than in the case of C'–D' and are themselves unequal, the scale of B'–C' being much more extended than that of A–B'. From C' onwards, at which time the visible trace of the inductance component current begins, the voltage remains constant, *i.e.*, the voltage trace is horizontal, until D', *i.e.*, throughout the remaining life of the discharge; whereupon oscillations as shown are forced in the secondary on remake of the primary circuit. Whereas the breakdown potential of the gap increased with increase in gas

FIG 2.

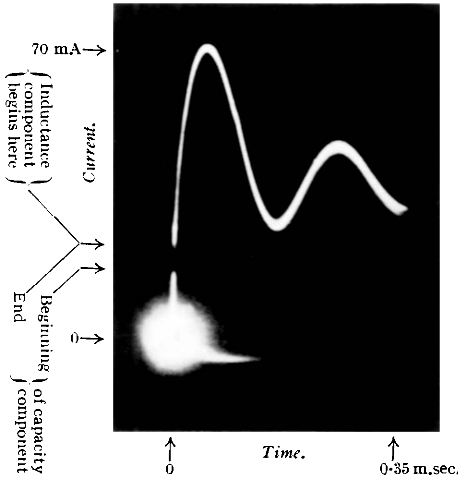


FIG. 3.—*Complete Discharge.*

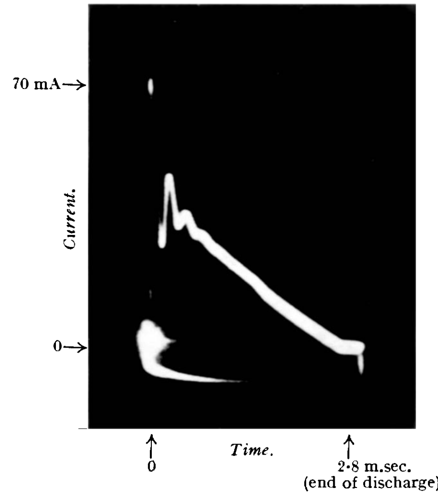


FIG. 4.—*Late Cut-off of Discharge.*

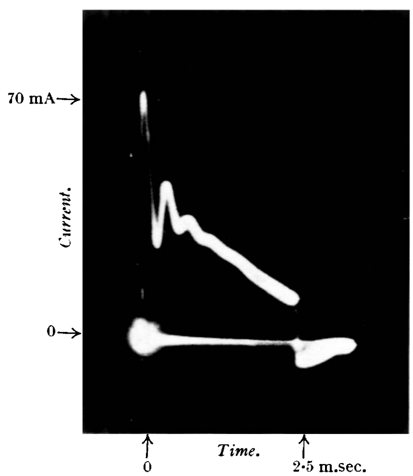


FIG. 5.—*Cut-off at* T_3.

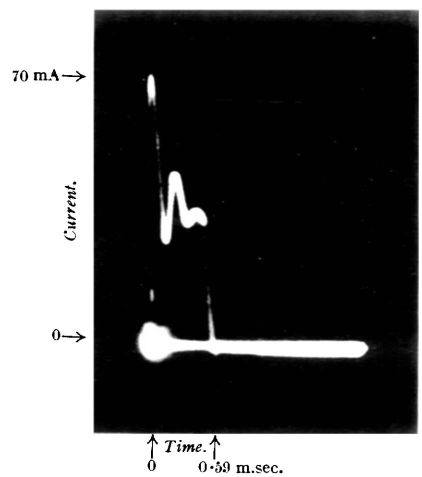


FIG. 6.—*Cut-off at* T_2.

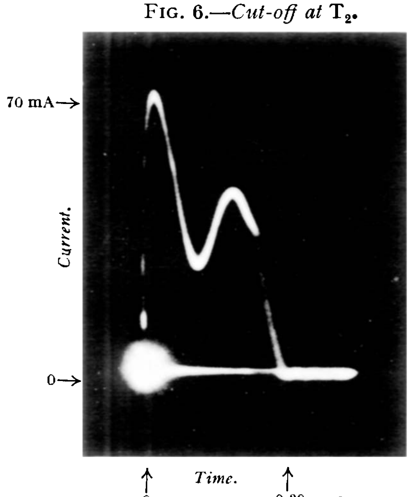
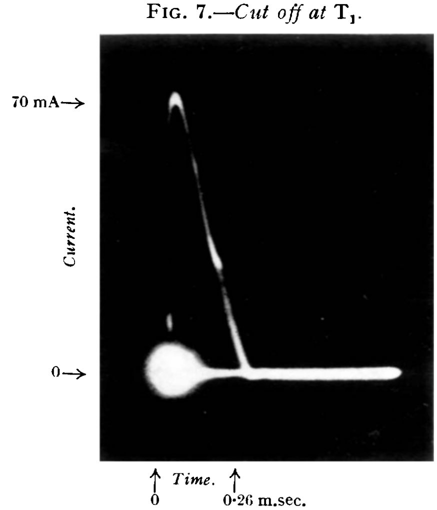


FIG. 7.—*Cut off at* T_1.



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press., the steady potential drop between the electrodes during the discharge of the inductance component was found to be practically independent of the pressure under the conditions of the experiments described below.

The corresponding current–time trace, shown as an unbroken line in Fig. 1, is not visible until C''. Current must, however, begin to flow at A, thereby charging up the secondary self-capacity to the breakdown potential of the gap. But the 1274 Ω resistance lies for the most part outside this distributed capacity shunting the secondary in which the current distribution is not uniform, and what little trace might have been described by the electron beam is obscured by the fog of the beam at rest in the zero position at A (Figs. 3—7). This normally obscured beginning of the current–time trace may, however, be made plainly visible, as is shown in Fig. 2, by the simple expedient of shunting the spark gap with a suitable air-dielectric capacity. In the time interval between B' and C' the current–time trace is invisible (see Fig. 2) because during the life of the capacity component, which begins at B and ends at C'', both the frequency and the amplitude of the current oscillations are exceedingly high. Thus the main oscillation frequency is of the order of $1{\cdot}2 \times 10^7$ c./sec., and, since the self-capacity of the secondary circuit is about 80 cm., the capacity component current must approach a peak value of 30 amp. The beam sensitivity employed was such that $\pm$ 150 mA sufficed to throw the spot off the screen; therefore, during by far the greater part of the life of the capacity component, in addition to being deflected at an extremely high rate, the beam was striking outside the screen. The capacity component oscillations occur about, and are superimposed upon, that current which flows during the interval $B'C'$, the invisible time trace of which, after intersecting the ordinate BB', ends at C''. Even the amplitude of C'' is, however, so small compared with that of the capacity component current that the oscillations may be deemed to occur about zero. The inductance component proper begins at C'' and consists of a train of rapidly decaying saw-toothed oscillations superimposed upon a main train of damped sinusoidal oscillations (Fig. 3) which are themselves superimposed upon a linearly decaying component. The flow of the inductance component current is throughout unidirectional. The saw-toothed oscillations are generally damped out before the end of the first sinusoidal oscillation. The discharge ends at D'. The total duration of the discharge is of the order of up to 4 m.sec., depending chiefly upon the value of the primary break current and the effective gap width. Under certain conditions, extinction of the discharge may occur in the troughs T_1, T_2, etc., of the inductance component, in which case each subsequent resumption of the discharge is preceded by a capacity component and a renewal of the saw-toothed oscillations. In the expts. to be described below, however, each discharge was continuous in the sense that only one capacity component occurred, and the inductance component current never fell to zero until the complete and final extinction of the discharge.

By means of the special interrupter, the energy associated with the inductance component could be varied as desired and independently of the primary current and thus without in any way affecting the breakdown potential of the gap and hence the capacity component. The heavily dotted traces TT' and $T_1 T_1'$, $T_2 T_2'$, etc. (cf. with Figs. 7, 6, 5, and 4), show the manner in which the inductance component current–time trace falls to zero when the primary circuit is remade shortly after discharge of the capacity component or at the times when the inductance component current is approaching the troughs T_1, T_2, etc., respectively. The energy associated with the whole or any part of the inductance component was determined by evaluating the effective area enclosed by the inductance component current–time trace and the horizontal time axis (Fig. 3, Finch, Sutton, and Tooke, *loc. cit.*, is self-explanatory of the method employed).

Results.—Series I. The primary current at break was 3·00 amp. The break was shunted by a primary capacity of 0·90 μF. The frequency of the main oscillatory component of the inductance component was 5,800 c./sec. The spark-gap was set to an approx. breakdown potential of 4,000 volts steadily applied pressure in the CO–O_2–H_2 mixture at 100 mm. Hg. The 1274 Ω resistance was included in the secondary circuit.

Under these conditions the complete discharge, including the whole of the inductance component, ignited the mixture without fail at 106 mm. The energy associated with the inductance component was 20·5 mJ and was dissipated in 2·81 m.sec. Cut-off of the inductance component energy to 20·2 mJ, *i.e.*, to a much lesser degree than that shown in Fig. 4, dissipated in 2·6 m.sec., reduced the igniting power of the discharge to such an extent that ignition no longer occurred until the pressure was raised to 109 mm.

Series II. The effect of a wider range of reduction in the inductance component energy upon the spark incendivity was now examined. Apart from the times of cut-off, the conditions were as in Series I. The results are incorporated in Table I.

TABLE I.

Cut-off (see Fig. 1).	Inductance component energy, mJ.	Duration of inductance component, m.sec.	Igniting power = 1000/(least igniting press. in mm.).	Least igniting pressure, mm.
D'	20·5	2·81	9·43	106
T_4	9·2	0·79	7·70	130
T_3	7·4	0·59	7·41	149
T_2	5·2	0·39	6·50	154
T_1	2·4	0·20	5·13	195
T	*ca.* 0·15	0·02	<4·26	>235

Series III. In these expts., in addition to the energy associated with the inductance component, the frequency of the sinusoidal oscillations was also varied. It should be noted that a change in the value of the primary capacity affects not only the sinusoidal oscillatory component frequency, but also the rate of build-up of the gap break-down potential in such a manner that the impulse ratio, if greater than unity, and hence also the energy associated with the capacity component, must increase with decrease in primary capacity. The results are given in Table II, the units being as in Table I. The primary break current was 3 amp.

TABLE II.

Cut-off.	4000 c./sec.			5800 c./sec.			8300 c./sec.		
	Inductance component.			Inductance component.			Inductance component.		
	Energy.	Duration.	Igniting power.	Energy.	Duration.	Igniting power.	Energy.	Duration.	Igniting power.
D'	19·5	2·78	9·71	20·5	2·81	9·43	20·2	2·81	9·17
T_4	11·9	1·1	8·26	9·2	0·79	7·70	6·7	0·54	7·25
T_3	9·6	0·81	7·81	7·4	0·59	7·41	5·4	0·39	6·54
T_2	7·1	0·53	7·10	5·2	0·39	6·50	3·3	0·25	5·52
T_1	3·5	0·24	5·59	2·4	0·20	5·13	1·6	0·12	4·45
T	*ca.* 0·15	<0·02	<4·45	*ca.* 0·15	<0·02	<4·26	*ca.* 0·15	<0·02	<4·00

Series IV. A primary current of 4 amp. at break was now employed; otherwise the conditions were as in Series I. The results are in Table III:

TABLE III.

Cut-off.	Inductance component energy.	Duration of inductance component.	Igniting power.
D'	33·6	3·64	12·8
T_4	12·5	0·79	10·3
T_3	10·3	0·61	9·40
T_2	6·5	0·40	8·20
T_1	2·8	0·19	7·00
T	*ca.* 0·3	0·02	<5·00

Series V. In this series, expts. were carried out under conditions similar to those in Series IV, with the exception that electrolytic gas was used instead of the $2CO + O_2 + 5\%\ H_2$ mixture.

TABLE IV.

Cut-off.	Primary current = 3 amp.			Primary current = 4 amp.		
	Inductance component.			Inductance component.		
	Energy.	Duration.	Igniting power.	Energy.	Duration.	Igniting power.
D'	20·5	2·81	8·77	33·6	3·64	11·5
T_4	9·2	0·79	8·27	12·5	0·79	10·9
T_3	7·4	0·59	8·14	10·3	0·61	10·4
T_2	5·2	0·39	7·85	6·5	0·40	9·61
T_1	2·4	0·20	7·46	2·8	0·19	8·55
T	*ca.* 0·15	0·02	<6·25	*ca.* 0·3	0·02	6·37

Series VI. Finally, $CH_4 + 2O_2$ mixtures were ignited, the exptl. conditions being otherwise as in Series V (see Table V).

TABLE V.

Cut-off.	Inductance component. Energy.	Inductance component. Duration.	Igniting power.
D'	20·5	2·81	6·67
T_4	9·2	0·79	5·50
T_3	7·4	0·59	5·40
T_2	5·2	0·39	5·30
T_1	2·4	0·20	5·28
T	*ca.* 0·15	0·02	5·20

DISCUSSION.

The experimental results of Series I show that, in the case of a sufficiently insensitive mixture, the igniting power of the spark is associated with the whole discharge, even to the extreme final section of the inductance component. The results of Series II onwards confirm this observation and establish further the fact that the igniting power of the spark decreases with progressive suppression of the inductance component. It is clear, therefore, that a wide range of conditions can be, and in our experiments has been, realised under which ignition is not due solely to the capacity component. In connexion with these results, it is important to note that in all experiments where the primary current at break and the primary capacity were constant, the breakdown potential of the gap and hence also the energy of the capacity component, far from decreasing with increasing least igniting pressure, must have increased; because it is well known that Paschen's law holds with considerable accuracy within the range of pressures employed. Moreover, the results of Series III show that, for a constant primary current, variations in the value of the primary capacity have no effect on the igniting power of the capacity component combined with a given amount of inductance component energy, except for an inconsiderable variation which does not appear with cut-off at, or earlier than, T_4 (see Fig. 1). Hence, the rate of build-up of the secondary voltage, and therefore variations of the impulse ratio, which undoubtedly do occur, either have no effect whatever on the igniting power of the capacity component, or have such a small effect as to escape detection under the conditions of our experiments—a result which certainly throws a new light on the supposed importance hitherto attributed to the capacity component in ignition. It is pertinent to point out that 80 cm. (the secondary self-capacity) is, if anything, a value which is higher than that ordinarily met with in practice.

A criticism (Bradford and Finch, J., 1930, 1540) of certain conclusions drawn by Smithells, Whitaker, and Holmes (*ibid.*, p. 185) from their experimental results was based on the view put forward by Morgan, Taylor-Jones, Wheeler, and others (*locc. cit.*) that ignition by an induction-coil discharge was effected solely by the capacity component. It has now been shown, however, that such is not necessarily the case. Furthermore, the experimental results of Series II, III, IV, and V enable the conclusion to be drawn that under the conditions of our experiments the igniting power of the capacity component in relation to $2H_2 + O_2$ and $CO + O_2 + 5\%\ H_2$ mixtures is feeble as compared with that of the whole, or even of the first oscillation, of the inductance component. It follows that the experimental results set forth above invalidate the aforesaid criticism, and Smithells and his co-workers were, therefore, justified in concluding from the results of their experiments that hydrogen was more effective than water in increasing the sensitivity towards ignition of a $2CO + O_2$ mixture.

It should not be inferred, from the fact that the capacity component is not necessarily always responsible for bringing about ignition, that this component plays no rôle whatever in the ignition of mixtures which are too insensitive to be ignited by its agency alone but respond when the capacity component is followed by a greater or lesser part of the inductance component. On the contrary, our results suggest that in such cases the capacity component and, indeed, all that part of the discharge which passes up to the moment of ignition, is employed in the preparatory work of setting up a sufficient concentration of suitably excited molecules from which flame propagation starts. Thus, the relationships between total spark energy dissipated and igniting power of the discharge towards the $2H_2 + O_2$ and $2CO + O_2 + 5\%\ H_2$ mixtures respectively, are similar in character, but are quite different from that obtained with the $CH_4 + 2O_2$ mixture. In the former cases, the first part of the inductance component has a profound and far greater effect upon the igniting power of the spark than has the addition of the remainder of the inductance component. On the other hand, with a $CH_4 + 2O_2$ mixture, the igniting power of the spark increases roughly linearly with the increasing spark energy. Thus, whilst a $2CO + O_2 + 5\%\ H_2$ mixture is relatively insensitive to ignition by the capacity component as compared with a $CH_4 + 2O_2$ mixture, the position is completely reversed when the energy associated with the inductance component is increased to more than about 10% of its maximum possible value.

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