CCCCXXV.—*Explosions in Closed Cylinders. Part I. Methane–Air Explosions in a Long Cylinder. Part II. The Effect of the Length of the Cylinder.*

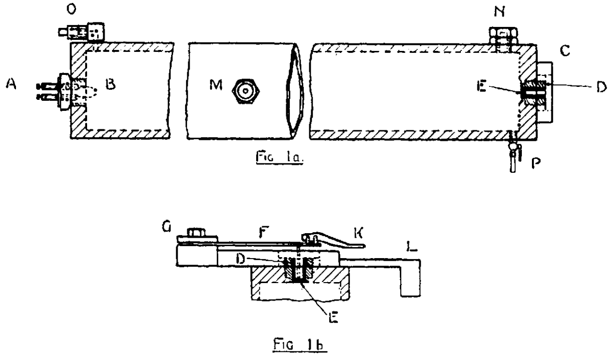
By William Anthony Kirkby and Richard Vernon Wheeler.

The object of this research is the correlation of the movement of flame with the development of pressure during explosions in a closed cylinder the length of which is much greater than its diameter, conditions which may be presumed to cause the movement of flame to differ considerably from that in a cylinder, the length and diameter of which are nearly equal, or in a sphere or cube, as in the experiments of Ellis and Wheeler (J., 1925, **127**, 764; 1927, 153).

Similar work has been carried out by Woodbury, Lewis, and Canby (*J. Soc. Automotive Eng.*, 1921, **8**, 209) with acetylene–air mixtures in a vertical cylinder 30·5 cm. long and 10·15 cm. in diameter. The mixtures were ignited at the base of the cylinder and simultaneous records were taken of the development of pressure and the movement of the flame as photographed through a window formed by a glass rod extending throughout the length of the cylinder. From the records it would appear that in each explosion the time of attainment of maximum pressure coincided with that of the passage of flame through the mixture, whilst the time–pressure curves indicated arrests in the development of pressure simultaneous with arrests in the movement of the flame.

FIG. 1.

Explosion-cylinder and pressure gauge.



Morgan (*Proc. Inst. Auto. Eng.*, 1925, **15**, 27; *Phil. Mag.*, 1927, **3**, 1161) studied the development of pressure during explosions of coal-gas–air and methane–air mixtures in horizontal cylinders 4·45 cm. in diameter and either 30·5 or 61 cm. long, ignition being at one end. This work will be discussed more particularly in Part II, but the important point noted was the occurrence, under certain conditions, of strong and rapid vibrations at the crests of the time–pressure curves.

Method of Experiment.—The gun-metal cylinder (supported horizontally) is 200 cm. long and of 10 cm. internal diameter, its capacity being about 16 litres. Fig. 1*a* shows its two ends in cross-section and a side view of a portion of its length. At one end is an ignition plug, A, carrying platinum electrodes, B, projecting 1 cm.

into the cylinder and forming a spark-gap of 4 mm. The other end carries on a boss, C, a pressure recorder, shown in detail at Fig. 1*b*. The sleeve, D, of hardened steel, is screwed into the end of the cylinder, and the hollow piston, E, also of hardened steel, moves freely in it, being prevented from entering the cylinder by a thin collar. The movements of the piston under pressure developed by an explosion within the cylinder are transmitted to the apex of a strong triangular spring of tempered steel, F, by a loose steel link. The spring is clamped at its base, G, and its apex carries a thin strip of steel, K, with a scribing style, the movement of which is traced on a smoked-paper chart on a revolving drum mounted at L. At intervals of 20 cm. along the cylinder are plug fittings, one of which is shown at M (Fig. 1*a*), and another in cross-section at N, which are normally used for the insertion of circular windows of quartz, 6·3 mm. in diameter, through which the flame of an explosion as it passes can be photographed. For such photographs a camera with a quartz lens is used, with a revolving drum on which "Lumière" sensitised paper is wrapped. The plug fittings also serve on occasion for the introduction of screen-wires, whereby the passage of flame can be recorded electrically, or for firing-plugs, when it is desired to ignite the mixture otherwise than at the end of the cylinder. Valves at O and P allow of the evacuation of the cylinder and the admission of the explosive mixture.

In carrying out an experiment, the cylinder was filled with the required mixture, prepared beforehand in a gas-holder over glycerol and water. Ignition was effected by a single secondary discharge from an 8-inch induction coil, produced by breaking a current of 5 amps. in the primary circuit. The moment of ignition was recorded on both the pressure chart and the photographic paper, the speeds of revolution of both drums being obtained by means of a tuning fork of 50 frequency.

Results of Experiments.

A. Ignition at One End of the Cylinder.—When ignition was at one end of the cylinder, the time taken for the flame to travel throughout its length, in all the mixtures of methane and air studied, corresponded with the time of attainment of maximum pressure recorded by a manometer at the far end. The time at which the flame reached the far end of the cylinder was recorded either (*a*) by the fusion of a fine screen-wire of copper or (*b*) photographically (at a window 1·0 cm. from the end). The results are given in Table I.

The speed of flame. The mean speed of propagation of flame over the 200-cm. length of the cylinder was for all mixtures considerably faster than the mean speed from the centre to the wall of

TABLE I.

Explosions of Methane–Air Mixtures in a Cylinder.

(Ignition at one end.)

Methane, %.	Time of maximum pressure (sec.).	Time of travel of flame (sec.). By method (*a*).	By method (*b*).
7·15	1·57	—	1·58
8·30	0·76	—	0·76
8·40	0·67	0·67	—
8·75	0·66	0·66	—
9·30	—	0·58	0·55
9·50	0·55	0·55	—
9·75	0·55	0·55	—
9·80	0·56	—	0·56
9·90	0·57	0·57	—
9·95	0·49	—	0·49
10·00	0·52	0·53	—
10·25	0·60	0·60	0·60
10·90	0·63	0·62	—
11·30	0·89	—	0·89
13·45	2·50	2·53	—

a sphere of 15·6 cm. radius (Wheeler, J., 1918, **113**, 840); thus, for a 9·8% mixture the mean speed was 410 cm. per sec. as compared with 144 cm. per sec. for the sphere. In a sphere, with central ignition, the flame moves at a nearly uniform speed until it approaches the walls. In a long cylinder, on the other hand, the progress of the flame is by no means uniform, and measurements of the mean speed over the whole distance have little significance. This is illustrated by the photographic analysis of the movement of flame in a 9·7% methane–air mixture reproduced at (1) on Plate I (much reduced in size).

From the times at which the flame first appeared at each window, the mean speed over each successive length of 20 cm. can be calculated. Calculations for mixtures containing 9·6 and 10% of methane are recorded in Table II.

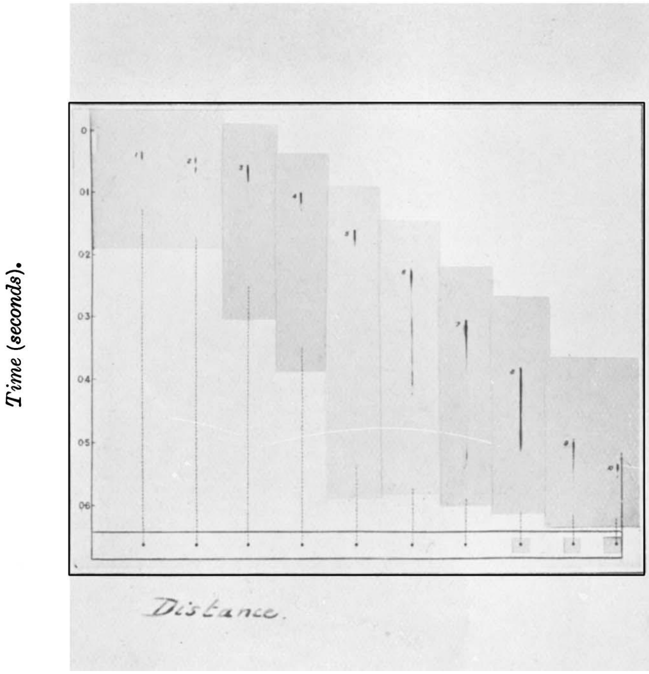
TABLE II.

Speed of Flame in a Long Cylinder.

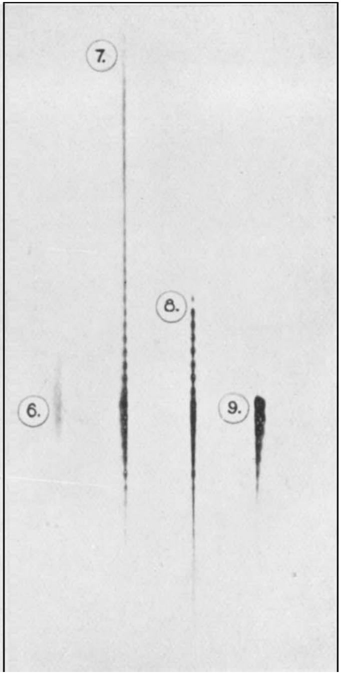
Distance (cm.).	Speed (cm. per sec.). $9{\cdot}6\%\ CH_4$.	$10{\cdot}0\%\ CH_4$.	Distance (cm.).	Speed (cm. per sec.). $9{\cdot}6\%\ CH_4$.	$10{\cdot}0\%\ CH_4$.
0— 20	800	1000	100—120	300	333
20— 40	2000	2000	120—140	210	281
40— 60	1165	1000	140—160	196	181
60— 80	715	500	160—180	181	162
80—100	345	317	180—200	500	385

These results, which are typical of the most explosive mixtures of methane and air, show that at the outset the flame darts forward at a rapidly increasing speed. A retardation then occurs, and becomes

PLATE I.



(1)
Explosion of a 9·7% methane–air mixture.
Flame at windows along 200-cm. cylinder.



(2)
Similar explosion to (1), showing details
of flame at windows 6 to 9.

most marked by the time the flame has travelled about one-third of the length of the cylinder. A comparatively slow speed is then maintained until within 20 cm. of the end of the cylinder, whereupon the flame moves forward more rapidly. The majority of the photographs show that the flame assumes a vibratory character at the end of its travel. In some photographs, vibrations also appear after the flame has travelled half-way along the cylinder. For mixtures containing from 9·5—10·0% of methane, the frequency of the later vibrations, which are always strongly marked (see 2, Plate I), is about 200. When vibrations occur midway along the cylinder, their frequency is about 115.

The development of pressure. In a spherical vessel with central ignition, the flame in mixtures of methane and air containing between 7 and 11% of methane reaches the wall simultaneously at all points, so that the whole of the mixture is inflamed before any appreciable cooling can take place. In a long cylinder, on the other hand, with ignition at one end, part of the flame touches the walls long before propagation is complete, and cooling of products of combustion begins at an early stage. The rate of development of pressure can therefore be expected to be slower than in a sphere, and the maximum pressure to be lower. In Table III the maximum pressures (above atmospheric) recorded for a number of mixtures of methane and air (*a*) in a 16-litre sphere (with central ignition) and (*b*) in the cylinder (capacity about 16 litres) are compared.

TABLE III.

Maximum Pressure on Explosion of Mixtures of Methane and Air in (a) *a Sphere and* (b) *a Cylinder.*

	Maximum pressure, atms.			Maximum pressure, atms.	
CH_4, %.	(*a*).	(*b*).	CH_4, %.	(*a*).	(*b*).
6·05	2·86	1·70	10·30	—	3·87
6·85	4·35	2·04	10·80	6·80	3·54
7·80	5·85	2·72	11·90	6·40	2·72
8·80	6·66	3·74	12·80	5·78	2·24
9·80	6·94	4·00			

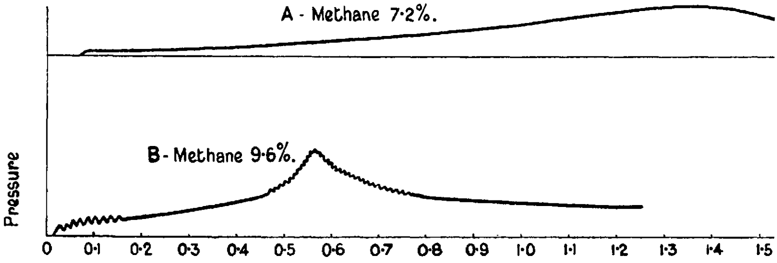
The time–pressure records were of two types, dependent on the composition of the mixture. If the mixture contained less than 8 or more than 11% of methane, smooth curves of the type reproduced at A, Fig. 2 were obtained. With 8—11% of methane, the curves showed marked vibrations at their crests (see B, Fig. 2). These vibrations had the same frequency, about 200, as those of the flame as it reached the end of the cylinder. Indeed, the development of pressure throughout corresponded closely with the movement of the flame, as the time–pressure and time–distance curves reproduced in Fig. 3 illustrate. Both curves relate to a 10% methane–air mixture, the former showing the development of pressure up to the time of its maximum, and the latter the time of passage of the flame from end to end of the cylinder.

Correlation of Flame-movement with Pressure-development.

When comparing the time–pressure and the time–distance curve in Fig. 3, it must be remembered that the latter was obtained from records of the passage of flame at small windows 20 cm. apart. Between any two windows, fluctuations in the movement of the flame may have occurred of which no record was obtained. Nevertheless, the two curves correspond closely in character and exhibit the following features.

FIG. 2.

Typical time–pressure curves.



Time, seconds.

(*a*) A rapid rise in pressure, shortly after ignition, corresponding with a rapid movement of flame over the first 20 or 30 cm. During this stage, there is but little cooling of the products of combustion, since the flame moves rapidly along the axis of the cylinder and but a small part of its surface comes in contact with the walls (see Part III, following paper).

(*b*) An arrest in pressure-development, corresponding with an arrest in flame-movement. At this point the " skirt " of the flame (see Part III) comes in contact with the walls of the cylinder. Following this arrest, both the movement of the flame and the development of pressure are comparatively slow over a distance of about 150 cm.

(*c*) A rapid rise in pressure to a maximum as the flame moves rapidly towards the end of the cylinder. Rapid vibrations (omitted from Fig. 3) are shown by both the pressure curves and the flame photographs.

(*d*) At any moment before the flame has travelled throughout the mixture, the fraction of the total distance travelled is greater than the fraction of the total pressure development. Hence the flame surface, so long as it is not vibratory, must be advanced along the axis of the cylinder, tailing off towards the walls.

B. Position of Point of Ignition varied.—A series of experiments was made, with mixtures containing between 9·5 and 9·8% of methane, in which the position of the point of ignition was varied. To effect this, the ignition plug was removed from the end of the cylinder and screwed into one or other of the window holes disposed along its length, the electrode points, 4 mm. apart, being carried to the horizontal axis of the cylinder.

Measurements were made of the times taken for the flames to reach each end of the cylinder, of the maximum pressure recorded by a gauge fixed at the end nearer the point of ignition, and of the time of attainment of this maximum pressure (" time of explosion "). The results are summarised in Table IV, in which the end of the cylinder to which the pressure gauge was attached is termed A, and the other end B.

FIG. 3.

Comparison of time-pressure and time-distance curves.

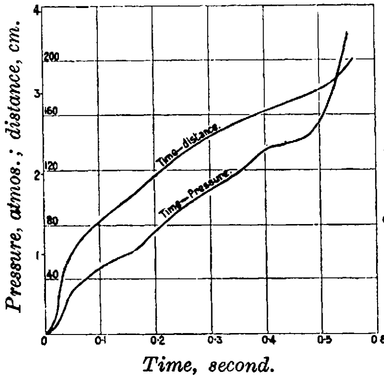
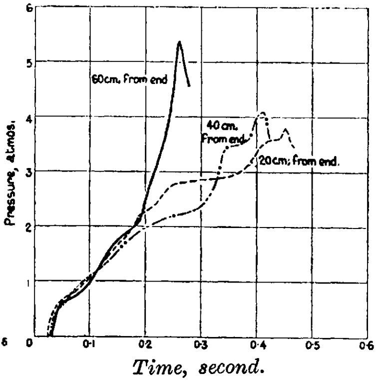


FIG. 4.

Point of ignition varied.



In each experiment the maximum pressure was recorded at the moment when flame had reached the end of the longer limb of the cylinder. Unless there was considerable disparity in length between the two limbs, there was a marked tendency for the flames travelling to right and left from the point of ignition to reach the ends of the cylinder simultaneously, and the attainment of maximum pressure could then be said, in general, to synchronise with the complete inflammation of the mixture.

When ignition was effected at a distance of about 40 cm. or less from one end of the cylinder, the flame reached the near end, and was extinguished with consequent rapid cooling of the products of com-

TABLE IV.

Explosions of Methane–Air Mixtures in a Cylinder.

(Position of point of ignition varied.)

Point of ignition.	CH_4, %.	Time (sec.) for flame to travel from point of ignition to		Max. press. (atm.; above atmospheric).	" Time of explosion " (sec.).
		End A.	End B.		
At end A.	9·50	—	—	4·07	0·52
	9·75	—	—	4·35	0·48
	9·90	—	—	4·28	0·50
20 Cm. from A.	9·55	—	0·41	4·07	0·41
	9·40	0·18	0·41	—	—
40 Cm. from A.	9·40	0·25	0·38	—	—
	9·60	—	0·44	3·81	0·44
60 Cm. from A.	9·30	0·27	0·34	—	—
	9·40	0·30	0·35	—	—
	9·60	—	0·27	5·44	0·26
80 Cm. from A.	9·50	0·21	0·21	—	—
	9·85	—	—	5·88	0·19
100 Cm. from A (*i.e.*, midway).	9·50	—	—	5·85—6·12*	0·18
	9·50	0·18	0·19	—	—
	9·55	—	0·24	5·72—5·98*	0·24

* Measurements uncertain owing to vibrations.

bustion, some time before it reached the far end. For this reason the maximum pressure attained was less than when ignition was at the middle. For the same reason, the maximum pressure increased in magnitude as the point of ignition was moved towards the middle of the cylinder, whilst the interval between ignition and the attainment of maximum pressure decreased. The maximum pressure recorded when ignition was at the middle of the cylinder was higher than when ignition was at one end. The three curves reproduced in Fig. 4 represent the rate of rise of pressure when ignition was at a point 20, 40, or 60 cm. from one end of the cylinder.

C. Simultaneous Ignition at Two Points.—A series of experiments was made in which methane–air mixtures containing between 9 and 10% of methane were ignited at some point along the cylinder and at one end simultaneously, a pressure gauge being fixed at the opposite end. The object was to determine whether a higher pressure would be attained than that recorded when ignition was solely at the middle of the cylinder. The results are summarised in Table V.

Typical time–pressure curves are reproduced in Fig. 5, and from curves A, B, and C it will be seen that the rate of rise of pressure to the maximum became more rapid as the second ignition point was moved nearer to the middle of the cylinder (100 cm. from end A). The initial rate of development was then more rapid than with single ignition in any position. When the second ignition point

TABLE V.

Explosions of Methane–Air Mixtures in a Cylinder.

(Simultaneous ignition at one end and at some point along the cylinder.

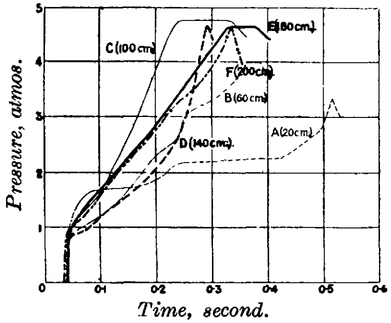
CH_4, %.	Position of second ignition plug (cm. from end plug).	Max. pressure (atms.; above atmospheric).	" Time of explosion " (sec.).
9·75	(Ignition at one end only)	4·35	0·48
9·80	20	3·33	0·52
9·80	60	3·98	0·37—0·39*
9·80	100	4·80	0·24—0·33*
9·80	140	4·70	0·29
9·45	180	4·66	0·33—0·38*
9·75	200	4·66	0·34

* Period of sustained pressure.

was 20 cm. from end A (curve A), there was a long period during which the rate of development of pressure was very slow, and the pressure ultimately attained was considerably lower than when ignition was solely at one end of the cylinder. The maximum pressure with double ignition was obtained when ignition was at one end and at the middle of the cylinder, but this pressure was lower than when ignition was at the middle of the cylinder only.

FIG. 5.

Dual ignition (distances are those of second ignition plug from end plug).



The important factor with respect to the production of pressure on explosion of a given mixture in a long cylinder is the time taken for the flame to travel throughout the mixture. When the mixture is ignited simultaneously at two points, the movement of one flame affects the movement of the other, hindering its development (see Part III). It thus results that the inflammation takes longer to complete when two flames are started simultaneously within the cylinder than when flame spreads from one point along the cylinder only. The three time–pressure curves (B, C, and E in Fig. 5) for explosions started simultaneously at one end of the cylinder and at 60, 100, or 180 cm. from that end, illustrate the retardation of the flames moving towards each other, for the period of maximum pressure is prolonged to a remarkable extent (0·02 to 0·09 sec.) corresponding with the slow approach of the flames.

Part II. The Effect of the Length of the Cylinder.

With a 200-cm. cylinder (10 cm. in diameter), it has been shown that in all explosions of methane–air mixtures containing 8—11% of methane, ignition being at one end of the cylinder, the flames became strongly vibratory towards the end of their travel. In earlier experiments with a cylinder of the same diameter but only 50 cm. long, no such vibrations were observed during the explosion of any mixture of methane and air. This accords with observations by Morgan to which reference was made in Part I. An explosion of coal-gas and air in a steel tube 4·45 cm. in diameter and 61 cm. long (ignition being at one end) was strongly vibratory, whereas an explosion of the same mixture in a similar tube of half the length showed no vibrations. Morgan considered the vibrations to be due to two interdependent factors—the rate of heat generation at the flame front and the vibration frequency of the gas space in the explosion vessel.

In order to study this matter more closely, by determining the limit at which an explosion becomes vibratory, arrangements were made for altering the length of our cylinder at will, by means of a piston that could slide within the cylinder and be locked in any position, the piston-head forming a pressure-tight end-plate. The ignition plug was at the centre of the piston-head, and the pressure gauge at the other end of the cylinder. On exploding mixtures of methane and air containing about 9·5% of methane, records were obtained of the maximum pressure developed (P, in atms.), the time of attainment of maximum pressure (T_m), and the time (T_f) taken for the flame to travel throughout the cylinder, the length (l) of which was varied between 2·5 and 200 cm. Some of the results are recorded in Table VI.

TABLE VI.

Explosions of a 9·5% Methane–Air Mixture in Cylinders of Different Lengths (10 cm. diam.).

l, cm.	P.	T_m, sec.	T_f, sec.	l, cm.	P.	T_m, sec.	T_f, sec.
2·5	5·8	0·035	0·009	70	4·9	0·27	0·22
3·5	6·1	0·037	0·015	80	4·7	0·31	0·26
5	5·9	0·047	—	100	4·6	0·34	0·30
6	6·3	0·043	0·024	120	4·3	0·38	—
10	6·3	0·07	0·04	140	4·1	0·45	0·44
20	5·9	0·11	0·08	160	3·8	0·48	0·47
30	5·8	0·15	—	165	3·7	0·50	0·49
40	5·5	0·18	—	170	3·7	0·48	0·48
50	5·5	0·20	—	180	4·0	0·49	—
60	5·3	0·24	0·20	200	4·0	0·55	0·55

The critical length of cylinder for the production of a vibratory explosion with a 9·5% methane–air mixture was 140 cm. With shorter lengths, the movement of flame and the rate of production of pressure were regular, the time–pressure records being characterised by a steady period of maximum pressure lasting from 0·005 sec. for a cylinder 3·5 cm. long to 0·03 sec. when the length was 120 cm. All such explosions were quite silent. When the cylinder was 140 cm. long, or longer, rapid vibrations were usually developed by the flames towards the end of their travel, and, synchronising with these vibrations, the time–pressure records (*e.g.*, B, Fig. 2) showed fluctuations at their crests. All such explosions were accompanied by a shrill screech.

When the explosion was vibratory, the time of attainment of maximum pressure (" time of explosion "), which always corresponded closely with the time taken for the flame front to travel throughout the cylinder, varied as between one experiment and another, performed under what were intended to be identical conditions, within fairly wide limits. For example, when the cylinder was 160 cm. long, the time of explosion was 0·466, 0·596, 0·565, and 0·483 sec. in successive experiments. It would seem that the moment at which vibrations were induced (and the subsequent course of the explosion thereby determined) was affected by slight inadvertent changes in the experimental conditions such, *e.g.*, as the condition of the inner walls of the explosion vessel. Similarly, a slight intentional change in the experimental conditions would transform a silent explosion into a noisy and vibratory one. A 6·85% methane–air mixture, initially at atmospheric pressure, exploded in the 200-cm. cylinder (ignition being at one end), was always silent and non-vibratory (time of explosion, 1·56 sec.), but when the initial pressure was increased to 3·6 atm. (absolute) the explosion was vibratory (time of explosion, 1·95 sec.). Similar results for pentane–air mixtures have been recorded by Maxwell and Wheeler (*J. Inst. Pet. Tech.*, 1928, **14**, 175).

The vibrations that occur, following the " uniform movement," when an explosive mixture is ignited at the open end of a long tube closed at the other end, have been shown by Mason and Wheeler (J., 1920, **117**, 36) to be due to resonance in the column of gases ahead of the flame, their frequency corresponding with that of the fundamental tone of the tube. The same explanation can apply to these closed-tube vibratory explosions, although on what the establishment of resonance depends is not clear. Morgan's (*loc. cit.*) suggestion, which appears to be accepted by Egerton and Gates (*Proc. Roy. Soc.*, 1927, *A*, **116**, 524), that the rate of heat generation at the flame front is the main factor involved, receives support from the fact that in a cylinder 120 cm. long the explosion of a 6·75% ethane–air mixture (time of explosion, 0·215 sec.) is vibratory, whereas that of a 9·5% methane–air mixture (time of explosion, 0·386 sec.) is not. On the other hand, some of Maxwell and Wheeler's (*loc. cit.*) results are at variance with this suggestion, for they found that, under the same conditions of experiment, the explosion of a 3·5% pentane–air mixture (time of explosion, 0·19 sec.) was vibratory, whereas that of a 2·95% benzene–air mixture (time of explosion, 0·17 sec.) was not. It would seem reasonable to believe that with a given explosive mixture, say a 9·5% methane–air mixture, the establishment of resonance in the column of gases ahead of the flame would depend, *ceteris paribus*, upon the rapidity with which the column was compressed. Thus it would depend upon the speed acquired by the flame front, which in turn would depend on the length of the cylinder. When explosions of different gases under the same conditions are compared, however, this explanation is insufficient. We believe the character of the reactions taking place behind the flame front to have an important bearing on the matter; we are now investigating this subject.

The relationship between the time of explosion and the length of the cylinder (for 9·5% methane–air mixtures) is shown in Table VI. There was close correspondence between the time of explosion and the time of passage of flame when the explosions were vibratory, *i.e.*, when the cylinder was 140 cm. long or longer. In the shorter cylinders, the flame front, travelling without vibrations, apparently reached the end before the attainment of maximum pressure. This is explicable by reason of the shape of the flame front which, when travelling in a horizontal tube, is inclined, the upper portion being in advance. After the flame has appeared at a window at the end of the horizontal axis, it still has to travel into the lower portion of the tube.

The time of explosion does not increase proportionally with the length of the cylinder, as it would if the mean speed of the flame were constant, but is less by so much as the mean speed of the flame is greater in the longer cylinders. This greater speed is due to the greater freedom of movement, at the outset of the explosion, of the unburnt gas ahead of the flame in the longer cylinders (see Part III), the conditions during the early stages of the spread of flame approximating more and more to those of constant pressure as the length of the cylinder is increased.

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SHEFFIELD.

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