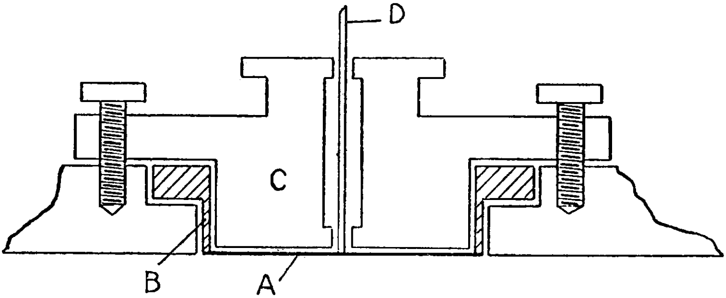
XXVI.—*The Movement of Flame in Closed Vessels: Correlation with Development of Pressure.*

By Oliver Coligny de Champfleur Ellis and Richard Vernon Wheeler.

It has been generally assumed in the past that, when a highly explosive mixture is ignited at the centre of a sphere, the moment of attainment of maximum pressure must synchronise with the moment of complete inflammation of the mixture, *i.e.*, with the moment at which the flame, the propagation of which follows regular concentric spherical surfaces, reaches the boundary of the vessel, which it does simultaneously at all points (see J., 1925, **127**, 764).

Langen (" Mitteilungen u. Forschungsarbeiten aus dem Gebeite des Ingenieurwesens," 1903, 8) seems to have been the first to realise that, if this assumption be correct, the interpretation of time–pressure diagrams, and particularly of cooling-curves, obtained by means of a continuously recording pressure-gauge attached to the wall of the explosion-vessel, can best be made when the vessel is spherical and ignition central. His experiments, made mainly for the purpose of determining the specific heats of gases at high temperatures, were therefore carried out under such conditions, his explosion-vessel having a spherical cavity of 33·5 litres capacity. Regarding such work, Dugald Clerk ("The Gas, Petrol, and Oil Engine," Vol. 1, p. 136, London, 1910) stated that "all physicists who have experimented on the subject agree in considering that inflammation is complete * when the highest pressure is attained."

FIG. 1.

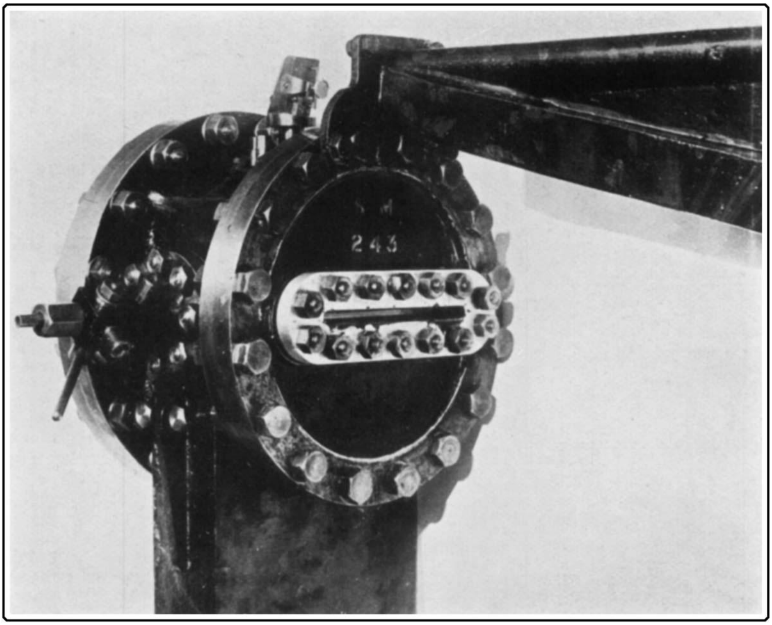


This assumption has recently been challenged. Wheeler (J., 1918, **113**, 840) obtained experimental proof of the fact that in mixtures of methane and air containing between 7·5 and 12·5% of methane, ignited at the centre of a spherical bomb of 4 litres capacity, the times taken for the attainment of maximum pressure (measured from the moment of ignition) synchronised with the times taken for the flame to reach the walls; but the measurements of the last-named time-intervals were made by means of a "screen-wire" method which might have involved an indeterminate experimental error. It seemed desirable, therefore, to attempt direct synchronisation of the rate of development of pressure and the rate of spread of flame in an explosive mixture by simultaneous photographic registration on a rapidly revolving drum.

The apparatus devised for our purpose consists of an explosion-vessel (Plate I) of phosphor-bronze, the interior of which can be rendered spherical or cubical at will, fitted with windows through which the flame can be photographed and with a pressure-gauge of the diaphragm type.

* Meaning, thereby, the complete spread of flame throughout the vessel, but not necessarily complete combustion.

PLATE I.



[*To face p.* 154.]

PLATE II.

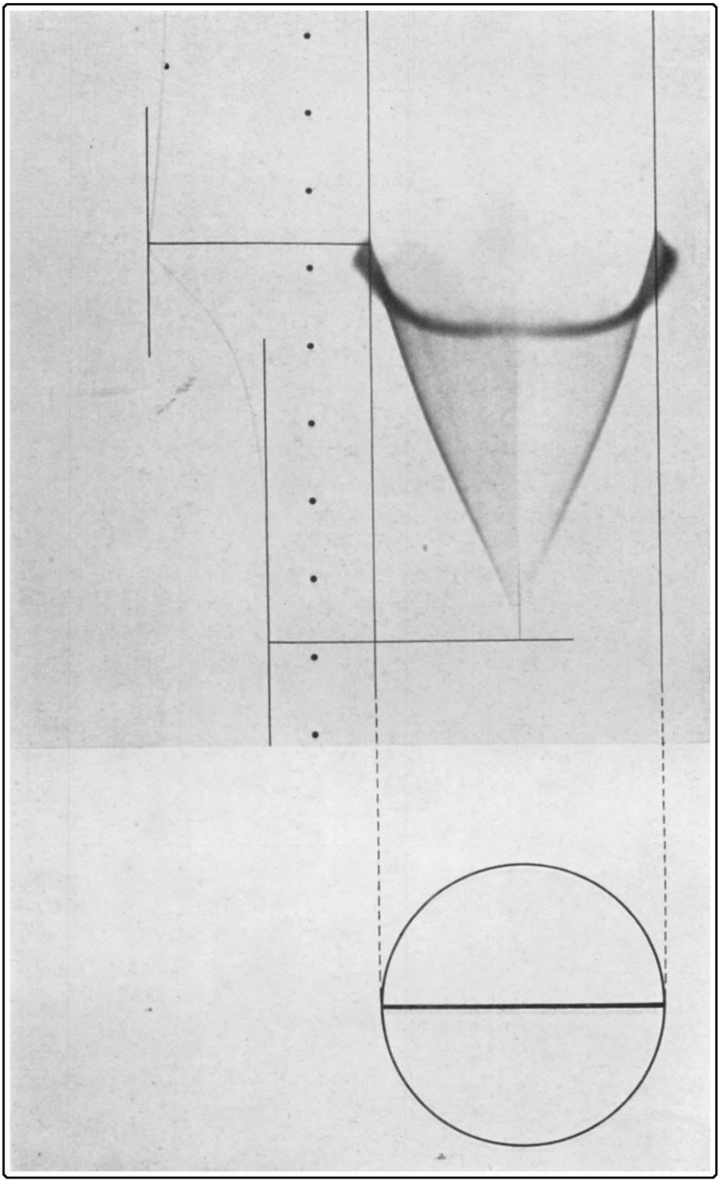
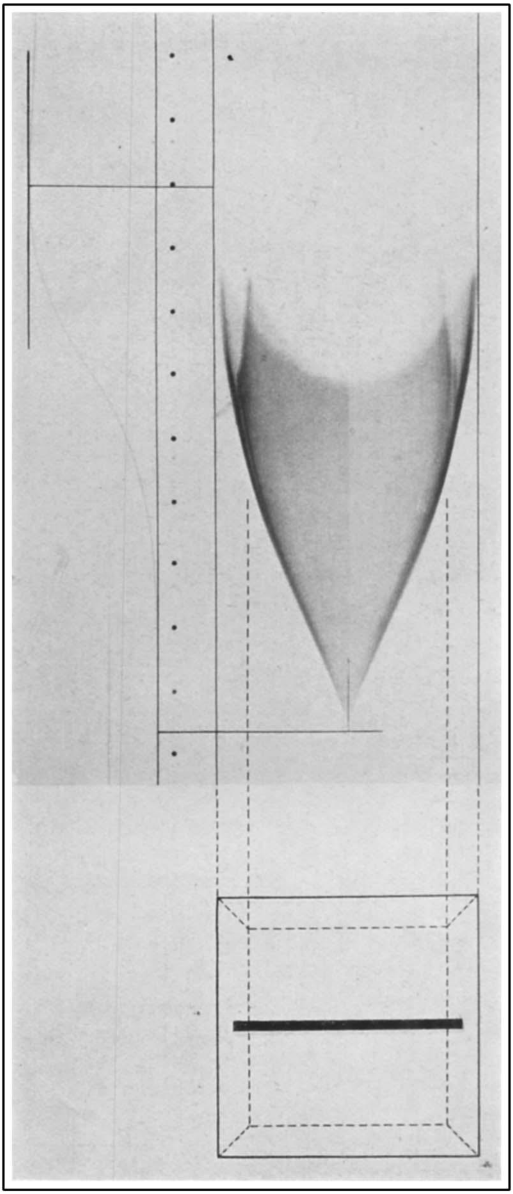
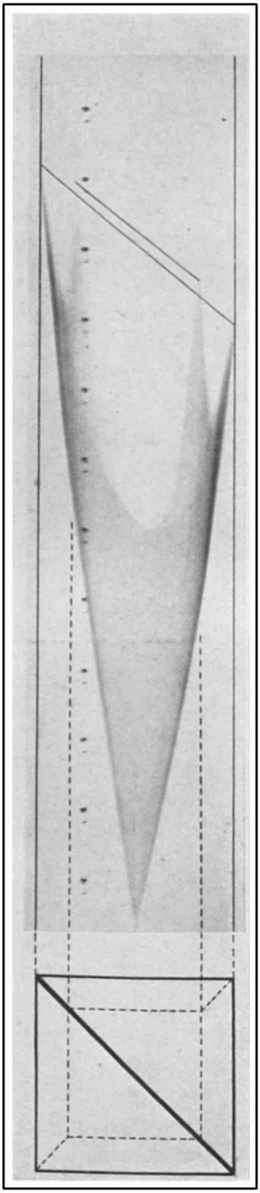


PLATE III.

(*a*)



(*b*)



(*a*) Window horizontal. (*b*) Window diagonal.

The pressure-gauge (Fig. 1), which is a modification of that designed by Rice (*U. S. Bureau of Mines, Bull. No.* 167, p. 51, 1922), has an optical indicator which is so arranged as to throw a spot of light on the same revolving drum as is used for obtaining a photographic record of the movement of the flame. The diaphragm, A, is of steel, 0·051 mm. thick, gold-plated to resist corrosion, and fitted flush with the inner surface of the explosion-vessel. It forms the base of a cylinder, B, of 34·92 mm. diameter, machined from tool-steel and having a thick collar to avoid distortion when clamped firmly in position by the flanged plug, C. Through a hole in this plug passes a rod D, 1·59 mm. in diameter, one end of which is in contact with the diaphragm, the other being attached to a bell-and-crank lever which bears against a lever carrying a small mirror.

For the experiments described in this paper, the explosive mixtures were of carbon monoxide and air, saturated with water vapour at 19°. Ignition was effected exactly at the centre of the vessel by means of a secondary discharge at a 1·5 mm. spark-gap between platinum electrodes sheathed side by side within a glass rod of 3 mm. diameter. This rod fitted into a recess in an insulating plug of bakelite in the wall of the vessel, suitable electrical connexions to the electrodes being made through it to terminals outside.

Explosions within a Sphere.—The spherical cavity of the explosion-vessel was 14·8 cm. in diameter. In order to obtain a photograph of the flame within it, a slit, 2 mm. wide, was cut half-way through the walls horizontally from the window. There were thus left two thin, fin-shaped slots in the sides of the casting abutting on the window, in which, as appears in the photographs, flame was forced during the explosions. When the camera lens was focussed on the spark-gap, there was obtained during an explosion a record on the revolving drum of the movement of the flame in a horizontal plane in both directions from the spark. Such a photograph of the flame in a 60% carbon monoxide–air mixture is reproduced (reduced in size) on Plate II. The boundary of the spherical cavity is indicated on this photograph by the parallel lines drawn thereon as projections from the slit shown diagrammatically at the bottom. The flame forced (towards the camera and therefore out of focus) into the fin-shaped slots previously mentioned, appears as a collar around the upper part of the record. It will be noticed, also, that the image of the flame is divided equally into portions of different densities. This is due to the flame being partly obscured by the glass rod covering the electrodes.

The record also bears the time–pressure chart. It will be seen that the moment of attainment of maximum pressure corresponds almost exactly with the moment at which the flame reached the sides of the vessel.

Measurements made from this and similar records obtained with other mixtures of carbon monoxide and air are summarised in Table I.

TABLE I.

Explosions of Carbon Monoxide and Air within a Sphere. (*Mixtures Saturated with Water-vapour at* 19°.)

CO (%).	Time-intervals (in 1/100ths of a second). (1) Between ignition and attainment of maximum pressure.	(2) Between ignition and flame reaching boundary of sphere on horizontal axis.	Difference between (1) and (2).
20·25	17·17	16·02	+1·15
25·05	9·10	9·08	+0·02
29·40	6·40	6·38	+0·02
39·90	4·56	4·56	±0·00
45·25	4·24	4·28	−0·04
50·10	4·51	4·50	+0·01
58·70	5·18	5·20	−0·02
69·30	11·61	11·16	+0·45
74·00	24·44	20·28	+4·16

It is clear from these results that with all mixtures save those in which the flame-front travelled very slowly (mixtures containing less than about 25% or more than about 65% of carbon monoxide) the moment of maximum pressure coincides, within less than half a millisecond, with the arrival of the flame-front at the boundary of the vessel. When the flame-front travels so slowly that its movement is affected by convection, it reaches the top of the vessel, and can be seen at the ends of the window along the horizontal diameter, whilst there is still a considerable volume of mixture in the lower part of the vessel through which it has not travelled. The pressure therefore continues to rise after the flame has reached the boundary of the sphere on its horizontal axis.

Explosions within a Cube.—By removing two shaped castings of phosphor-bronze from within the casing of the explosion-vessel, a cubical cavity of 15 cm. edge was produced, the arrangement of manometer diaphragm, firing electrodes, and horizontal window remaining the same as when the cavity was spherical, except that the window now had an effective width of 4 mm. In addition, the removal of the castings that had formed the spherical cavity uncovered a window 4 mm. wide, which passed diagonally from corner to corner across the face of the cube opposite to that in which the horizontal window was fitted. By an arrangement of inter-connected chain-gearing, simultaneous photographs, on two revolving drums, could be taken of the flame-front as it moved from the centre of the cube (*a*) towards the walls and (*b*) towards the corners. The time–pressure chart was recorded only on the drum used for photographing the horizontal window.

Mixtures of carbon monoxide and air were used similar to those when the cavity was spherical. Typical records, obtained with a mixture containing 60% of carbon monoxide, are reproduced on Plate III (these are reduced in size, but not in the same proportion as for Plate II). When interpreting these records, the lenses of both cameras, which were focussed on the igniting spark, may be regarded as looking into the interior of the bomb from either side, the one through a horizontal and the other through a diagonal window.

Considering first the record obtained through the horizontal window (*a*, Plate III): The lens will "see" best of all the flame as it travels across a vertical plane through the spark-gap, on which the lens has been focussed. Nearer, and in less accurate focus, it will see the front edges of the two sides of the cavity. Farther away, and in better but not perfect focus, it will see the two-sided corners formed by the sides and back of the cavity. The two pairs of curved V-shapes on the record show the progress of the flame after it has reached the sides of the cavity and is travelling (the outer pair) towards the front corners and (the inner pair) towards the back corners.

In the photograph obtained through the diagonal window, the lens "sees" four three-sided corners and the record shows the times at which the flame reaches, (i) and (ii), the upper and lower near corners of the cube (the outer "horns" in the photograph), and (iii) and (iv), the upper and lower far corners (the inner horns).

Measurements obtained from series of photographs similar to those reproduced on Plate III are recorded in Table II. From these measurements it is apparent that pressure continues to be developed slowly after the flame-front has touched the walls of the cube and whilst it is squeezing itself into the corners.* Thus the moment of attainment of maximum pressure when the explosion-vessel is cubical does not synchronise exactly, even when ignition is central, with the moment of "complete inflammation" of the mixture, but is antecedent to it, no doubt because, whilst the flame-front at each of the eight corners is nearing the end of its journey, there is considerable cooling of the gases, burnt earlier during the explosion, at the faces of the cube.

A comparison of the time–pressure charts obtained with the same mixture (60% carbon monoxide in air) exploded in the two

* The photographs reproduced on Plate II of our paper (J., 1925, **127**. 764) help to explain why this should be so.

TABLE II.

Explosions of Carbon Monoxide and Air within a Cube.
(Mixtures Saturated with Water-vapour at 19°.)

CO (%).	Time-intervals, measured from time of ignition (in 1/100ths of a second). Attainment of maximum pressure.	Flame at sides (see *a*, Plate III).	Flame at two-sided corners (see *a*, Plate III).	Flame at top corners (see *b*, Plate III).	Flame at bottom corners (see *b*, Plate III).
20·30	22·86	6·7	19·75	21·36	25·25
30·20	7·78	4·9	6·84	8·28	8·58
40·20	6·04	4·0	5·32	6·49	6·56
45·20	5·70	3·9	4·98	6·13	6·13
50·00	6·09	4·2	5·40	6·46	6·69
60·40	8·64	5·7	7·65	9·39	9·78
69·55	25·02	10·2	20·64	22·44	27·50

shapes of vessel (see Plates II and III) brings out clearly the extent to which cooling occurs during the development of pressure when part of the flame-front can touch a cold metal surface whilst the remainder is still travelling through part of the mixture. It will be seen also that the character of the " cooling-curve " is affected by the shape of the explosion-vessel. In this connexion, we would emphasise our previous observation (*loc. cit.*, p. 767) that, when attempting to interpret the character of time–pressure curves obtained from gaseous explosions in closed vessels, due consideration must be paid to the shape of the vessels and to the position of the point of ignition.

This work forms part of a research that we are carrying out for the Safety in Mines Research Board, to whom our thanks are due for permission to publish this paper.

SAFETY IN MINES RESEARCH LABORATORIES,
SHEFFIELD. [*Received, October* 15*th*, 1926.]