CCVII.—*Striated Photographic Records of Explosion-Waves.*

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IN a previous paper (J., 1926, 3010) attention was directed to the notable appearance of a moving-film record of the explosion-wave passing through the mixture $2CO + O_2$. Fig. 11 in that paper is remarkable in that closely striated illumination is recorded behind the trace of the wave-front, and not the uniform illumination which occurs in the great majority of previously published photographic records of explosion-waves. Close examination of some of Dixon's records (*Phil. Trans.*, 1903, *A*, **200**, 315; notably Fig. 11, $2CO + O_2$, and Fig. 21, $CS_2 + 2O_2$) discloses striations similar to those now described, but they are ill-defined and do not appear to have been noticed hitherto. The present paper deals with experiments made with a view to define some of the conditions required for the production of such striated records.

The explosive mixture under observation (moist $2CO + O_2$, unless otherwise stated) was contained in a horizontal glass tube 2—3 m. long, usually 15 mm. in internal diameter and 2·5—3·0 mm. in thickness of wall, open at the far end. The flame in this mixture was initiated by the explosion of a hydrogen–oxygen mixture contained in a similar tube in a co-axial position, complete separation of the two mixtures until a very short time before firing being

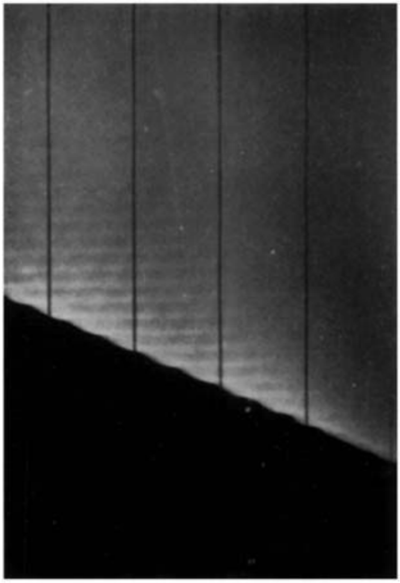
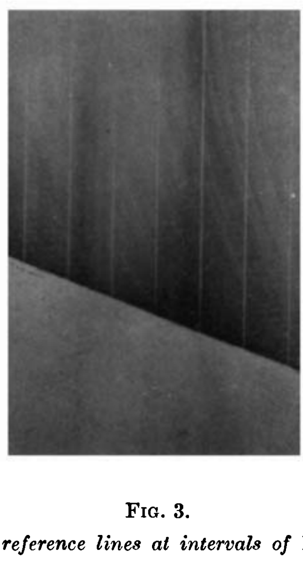


FIG. 1.



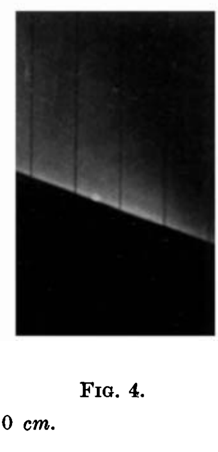


FIG. 2. FIG. 3. FIG. 4.

Vertical reference lines at intervals of 10 *cm.*

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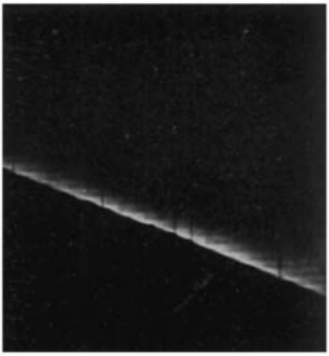

Fig. 5.

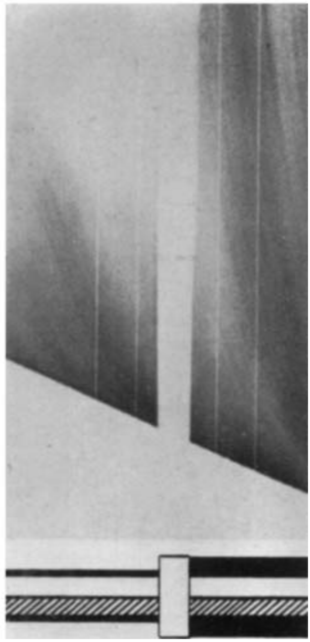

Fig. 6.

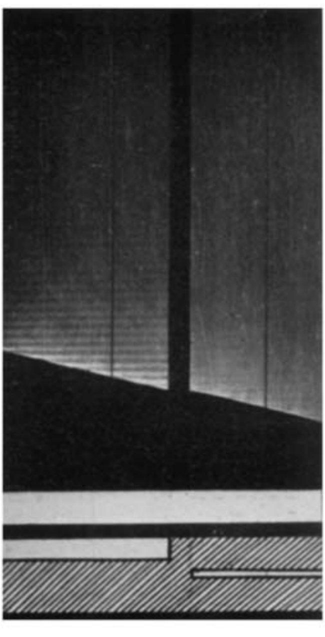

Fig. 9.

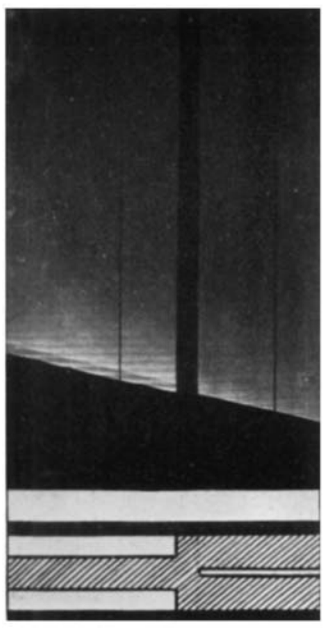

Fig. 10.

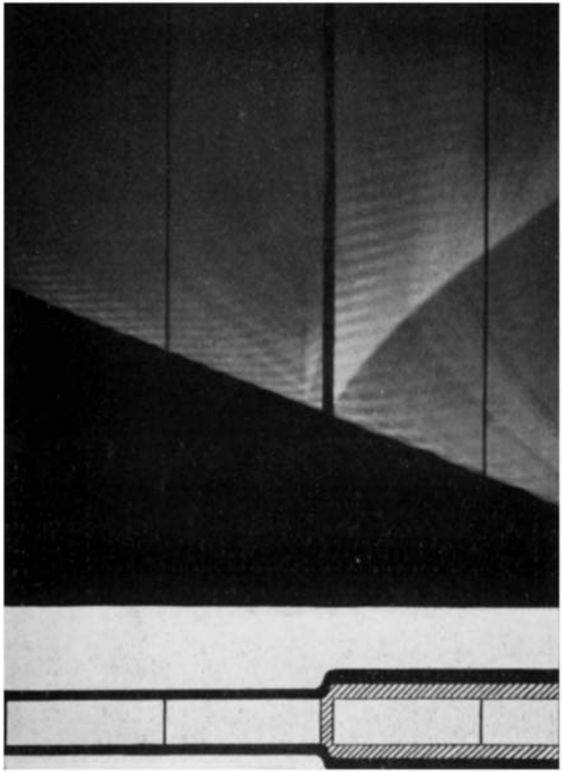

FIG. 7.

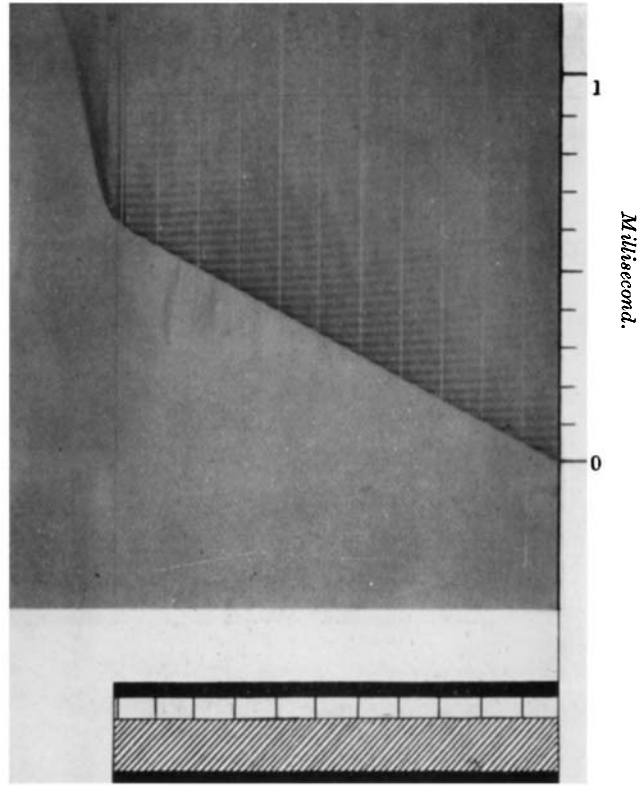

FIG. 8.

Vertical reference lines at intervals of 10 cm.

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effected by a metal shutter. The flame was photographed by means of a drum-camera having a peripheral speed of about 45 m./sec. Details of the experimental arrangements are given in our former paper (*loc. cit.*).

The first striated record we obtained was given by the flame in the mixture $2CO + O_2$ to which about 2% of hydrogen had been added (Fig. 1). The mixture was fired by the flame produced by detonating the mixture $2H_2 + O_2$. The flame edge in this record presents a regular undulatory appearance, but the mean rate of progress of the wave is uniform and characteristic of the explosion-wave in this mixture (about 1770 m./sec.). The *apparent* propagation is *per saltum*, each spurt taking place at approximately equal intervals of 45 mm. in the tube, the frequency of the undulations in this record being thus of the order of 39,000 per second. The major portion of the luminosity behind the wave-front is segregated into bands, each of which appears to have its origin in one of the undulations of the wave-front. The bands appear to be equally spaced; they are straight in this record, but definitely curved in others. They are inclined at a small angle to the horizontal in a direction opposite to that of the movement of the explosion-wave, suggesting a reverse motion at some tens of thousands of metres per second. The very high value of this rate is not favourable to the simple interpretation of the bands as a series of waves sent back from the front of the explosion-wave through the burning gases. Moreover, in some records the bands are horizontal, and in two they actually slope forward.

Mode of Ignition.—The production of striated records from $2CO + O_2$ was independent of the means taken to establish the explosion-wave, for they were obtained in equal intensity and with a similar period when the method of ignition was by the explosion-waves from (i) mixtures of hydrogen and oxygen other than $2H_2 + O_2$; (ii) from $C_2N_2 + O_2$; (iii) from $2H_2 + O_2$, which had itself been ignited by a uni-directional spark; or by (iv) direct sparking of $2CO + O_2$ containing about 2% of hydrogen. (Without the presence of a little hydrogen, we failed to obtain the explosion-wave in moist $2CO + O_2$ by direct sparking in a tube 12·5 mm. in diameter and 8 m. long.) In each of these experiments, the photographic record was taken after the explosion-wave had been established. We were unable to detect any differences in records made in similar experiments on Kodak orthochromatic film and on Lumière paper. Figs. 2, 3, 6, and 8 are copies of the negatives obtained with Lumière paper; the remainder are prints made from Kodak films.

Composition of Gases.—When increasing quantities of carbon monoxide in the mixture $2CO + O_2$ were replaced by hydrogen, the striations remained distinct until the mixture contained about 3% of hydrogen; as the hydrogen content was increased up to about 6%, they became rapidly less distinct; and they were no longer visible when between 6 and 20% was present. Figs. 2, 3, and 4 show this gradation of appearance with 2·2, 3·6, and 10%, respectively, of hydrogen. The compositions of the mixtures are recorded in Table I.

TABLE I.

Mixtures saturated with water vapour at 15°.

Fig.	CO.	O_2.	H_2.	Appearance of record.
	100	50	0	Striated.
1	98	50	2	,,
2	96·7	50	3·3	Faintly striated.
3	94·6	50	5·4	,, ,,
	91	50	9	Not striated.
4	85	50	15	,, ,,

The distance between successive undulations in the wave-front may be dependent to some extent on the amount of added hydrogen, but this cannot yet be stated with certainty since, as will be shown later, the distance is dependent on the internal diameter of the experimental tube, and differences in the measured distances may be due to slight indeterminate variations in the bores of the glass tubes used.

The presence of hydrogen in a carbon monoxide–oxygen mixture is not essential for the production of a striated record, for such records were obtained of the wave in the mixture $2CO + O_2$, not only when it was saturated with water vapour at room temperature, but also when fairly well dried with sulphuric acid.

The addition of diluent gases (carbon monoxide, nitrogen, and oxygen) to $2CO + O_2$ did not produce any change in the appearance of the records, striations being obtained in each experiment with the mixtures $3CO + O_2$, $4CO + O_2$, $CO + O_2$, and $2CO + O_2 + N_2$. The distance between successive undulations in the wave-fronts did not vary substantially from 45 mm. when the tube was of 15 mm. internal diameter.

Some experiments were made with $2H_2 + O_2$ in which small amounts of the hydrogen had been replaced by carbon monoxide, but no striated records were obtained. Mixtures of hydrogen and oxygen varying in composition from $6H_2 + O_2$ to $2H_2 + 3O_2$ also failed to give striated records. In order to increase the actinic value of the flame in the more dilute mixtures of these gases, the experimental tube was dusted with thorium oxide, and under these conditions very faint striations were obtained only with mixtures containing a large excess of oxygen.

The explosion-wave in certain mixtures of oxygen with methane, ethane, ethylene, carbon disulphide, and cyanogen also gave striated records similar to that reproduced in Fig. 1.

Initial Pressure.—A number of experiments were made with $2CO + O_2$ at initial pressures greater than atmospheric, the experimental conditions being the same as before, save that the far end of the tube was closed. The compression apparatus described by Ellis (J., 1923, **123**, 1435) was used. Striated records were given in all experiments, and the distances between successive undulations were not materially different from those obtained at atmospheric pressure, being 46 and 45 mm. when the initial pressures were 2 and 3 atm., respectively. Fig. 5 is the record obtained at 2 atm. The narrowness of the exposed strip of film is due to the very rapid shattering of the explosion tube after the passage of the wave.

Diameter of Tube.—When explosion tubes of internal diameters less than 15 mm. were used, the records bore striations similar to those obtained with the 15 mm. tubes, but the undulations in the traces of the wave-fronts were nearer together. The striations were thus more closely packed and less easily resolvable. Tubes having internal diameters of 12·5 and 10 mm. were used. The lengths of the undulations, constant in each record, are given in Table II.

TABLE II.

$2CO + O_2$ *saturated with water vapour at* 15°.

Bore of tube, D (mm.).	Distance between undulations, L (mm.).	Ratio L/D.
15	45	3·0
12·5	36	2·9
10	29	2·9

It appears that, within the limits examined, the distance between the undulations is closely related to the bore of the experimental tube. Since the velocity of an explosion-wave is normally unaffected by the diameter of the tube through which it passes, the frequency of the undulations is also related to the bore.

Fig. 6 is a record of the explosion-wave in $2CO + O_2$ contained in an 8 mm. tube; it shows undulations in the wave-front 25 mm. apart ($L/D = 3·0$), with striations lying closely together in the burning gases behind. An additional variant made in this experiment was in the thickness of the walls of the tube. The tube was composite, consisting of two portions cemented together in a metal sleeve (represented on the record by the broad vertical band). The internal diameter was constant throughout, but the thickness of wall changed at the junction from 4 mm. to 1·5 mm. No difference in the characteristic undulations of the trace of the wave-front in the two portions can be detected. In the diagrammatic representation of the tube given in Fig. 6 (and in succeeding figures) the unshaded area indicates the position of the window in the paper covering of the tube, the solid areas representing the thickness of the tube wall; the diameters are not to scale.

Fig. 7 shows the explosion-wave passing from a 15 mm. into a 9 mm. tube. The two portions of this experimental tube were fused together, and the change in diameter at the junction was made as abrupt as possible. The velocity of the explosion-wave is unaltered by the change in diameter of the tube (see Campbell, J., 1922, **121**, 2483), but the spacing of the undulations is decreased immediately on the entry of the wave into the narrower tube. In the latter, $L = 28$ mm., whence $L/D = 3{\cdot}1$. The tube was intact after the experiment. The striations in the narrow portion of the tube do not appear to exist entirely independently of those in the wider portion, for near the junction the former are apparently retarded, and more markedly so in the gas some distance behind the wave-front. We have here an explosion-wave displaying undulations of two distinct frequencies simultaneously in different portions of the same tube.

A further interesting observation has been made in records showing both detonation-waves and slow flames accelerating rapidly towards detonation. Whereas the explosion-wave is striated, the earlier flame is comparatively uniform, and the striations are usually sharply confined to that portion of the gas which has detonated. In other words, the burning gases in one portion of a tube may show striations, whilst in another portion of the same tube the illumination is normal.

A few of the slow pre-detonation flames which we have photographed show traces of striations of a period similar to those in the later explosion-wave. Because of their narrow and regular spacing these undulations must be regarded as distinct from those of the "vibratory movement" or of the "uniform movement" that precedes it. The undulations of the latter are well-known features of slow flames and result from the establishment of resonance, the flame-front acquiring an undulatory motion leading to vibrations which vary in amplitude according to the extent of the resonance, and in period according to the length of the tube (Mason and Wheeler, J., 1920, **117**, 36).

Photographic Definition.—In order to avoid fogging of the photographic film by extraneous reflexions, the experimental tube was usually enclosed in a sheath of light-proof paper, the light from the explosion reaching the camera through a horizontal slit cut in this covering. Usually the width of this window was equal to the internal diameter of the tube. The records already described (with the exception of Fig. 6) were obtained through such a window. Although reduction in the width of the window decreased the intensity of the exposure, the striations did not become more clearly defined. However, enhanced photographic definition was secured when a 4 mm. window was cut near the upper (instead of at the middle) portion of the tube. Fig. 8 was obtained with such an arrangement, the position of the window (viewed horizontally from the camera) being shown diagrammatically in the figure. This record is of further interest in showing how the striations persist in the burning gases for some time after the wave-front has reached the open end of the explosion-tube.

An experiment was arranged in which a central window 2 mm. and an upper window 4 mm. wide were cut in the paper sheath over different lengths of the same tube. The record (Fig. 9) shows the clearly defined striations from the upper window, whilst the exposure from the central window produced a greater number of less well-defined striations. In a further experiment, a lower window 4 mm. wide was made in the second portion of the same tube. The record (Fig. 10) shows that there was in the illumination from each of these windows an independent series of undulations out of phase with one another, their alternate appearances occurring at approximately equal time intervals (about 1/80,000 sec.). Undulations visible through narrow central windows have periods considerably shorter than those recorded when the window is of the same width as the diameter of the tube. A similar, but temporary, effect has been observed through wide windows during the first 20 cm. of travel of the flame in $2CO + O_2$ after its ignition by the flame of $2H_2 + O_2$ (*e.g.*, in Fig. 1), before the flame-speed had completed its fall to that normal for the detonation-wave in $2CO + O_2$.

Summary.

Some of the conditions required for the production of an apparently undulatory form of the explosion-wave have been examined. This form appears to be characteristic of the wave in the mixture $2CO + O_2$ and in some of the more dilute mixtures of carbon monoxide and certain other gases with oxygen or oxygen and nitrogen. The presence of about 6% of hydrogen in $2CO + O_2$, saturated with water vapour at the ordinary temperature, eliminated visible undulations.

Increase in the initial pressure of the gaseous mixtures to 3 atm. did not effect any definite change in the distance between the undulations, but this was found to depend directly on the internal diameter of the explosion-tube. The most sharply defined records

were obtained when only the layers of gas near the walls of the tube were visible to the camera. The undulations visible through a window in the extreme upper portion of a tube occurred alternately with those visible through the extreme lower portion.

The experimental evidence is not yet sufficient to afford a complete interpretation of the striated records. It does not indicate whether they are due to induced vibrations of the apparatus or to a periodic propagation of the explosion-wave. It can be said, however, that the striations are not due to mechanical chattering of the heavier parts of the camera, since undulations of two different periods can be obtained on one and the same record.

An interpretation based on the assumption that the records disclose what is actually occurring in the flames has been communicated to us by Mr. E. F. Greig, who suggests that the part of the wave-front, the light of which affects the photographic film, traverses a helical path on the walls of the tube. The extension of this interpretation to the illumination from the outer layers of the burning gases *behind* the wave-front would also imply a rotation of the source of light affecting the photographic film. It is clear that a wave being propagated along a helical path could account for the dependence of the length of the undulations on the bore of the tube and for the alternate production of undulations in the records from the upper and lower windows. Further experiments are in progress to test the validity of this and the other possible interpretations mentioned above.

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