CCXCV.—*The Propagation of Explosion Waves in Gases Contained in Tubes of Varying Cross-section.*

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THE movements of the flames produced during the explosion of gaseous mixtures have been studied photographically by von Oettingen, Le Chatelier, Dixon, and others. Most of the experiments described by these investigators were conducted in tubes of uniform diameter; in other experiments, where the diameter altered, it did so gradually and only to a small extent.

The present investigation is an attempt to photograph explosion flames in different gaseous mixtures as these flames pass along tubes which are abruptly constricted or enlarged. Before describing the experiments, it is necessary, however, to refer briefly to some previously discovered characteristics of explosion waves in uniform tubes.

1. The velocity of the detonation wave in any given gaseous mixture is independent of the material composing the tube (Berthelot—see Dixon, *Phil. Trans.*, 1893, [A], **184**, 99). Thus tubes of glass, metal, or rubber give approximately equal rates.

2. When a detonation wave meets the further, closed, end of the containing tube a wave of compression is sent back through the burning gases (Dixon, *ibid.*, 1903, [A], **200**, 326). The velocity of this compression wave is approximately equal to that of a sound wave in the hot gases under the same conditions.

3. The velocity of the detonation wave is affected by the presence of a flexible junction (say of rubber) between two parts of the tube. At such a junction, the flame is damped down and takes some time to recover its original speed (Dixon, *ibid.*, p. 335).

4. It has also been found (author's unpublished results) that the diameter of the containing tube has some influence on the velocity of the detonation wave. With rapid mixtures, for example, $C_2N_2 + O_2$, the difference in the rates observed in tubes of 6 mm. and 19 mm., respectively, is small. If, however, a diluent gas is added and the rate consequently lowered, the difference in the rates observed in the two tubes becomes very considerable, for example, in the mixture $C_2N_2 + O_2 + 2N_2$ the rates for the 6.5 mm. and 19 mm. tubes are, respectively, 2161 and 2238 metres per sec.

The present research may be conveniently divided into four sections, according as an explosion wave passes from one tube into (1) another tube of smaller diameter—"normal-narrow"; (2) a narrower tube and thence to a third of diameter equal to the first—"normal-narrow-normal"; (3) a wider tube—"normal-wide"; (4) a wider tube and then to one of original diameter—"normal-wide-normal."

By a "normal" tube must be understood one in which the diameter is sufficient, but not greatly in excess of that required, to allow the detonation wave, travelling in any particular mixture, to assume its maximum velocity. On comparing the rates of several mixtures in tubes of different diameters, it was seen that a tube of about 10 mm. diameter would satisfy the conditions for a normal tube (Table I). Accordingly, tubes of diameter 10 mm. to 16 mm. were chosen as normal tubes.

TABLE I.

Velocities of explosion waves in tubes of different diameters.

Mixture.	6 mm.	9 mm.	12.7 mm.	15 mm.
$2H_2 + O_2$	—	2821	—	2828
$2H_2 + 4O_2$	—	1927	1921	—
$2H_2 + O_2 + 3N_2$	—	2055	—	2089
$C_2N_2 + O_2 + 2N_2$..	2161	2230	2230	—

As far as possible the tubes were constructed entirely of glass and the different portions of the tube were fused together at the common junction. In all cases this junction was so constructed that the change in diameter was very abrupt and not a gradual widening or narrowing. In the case of very wide tubes, it was not possible to construct them all in one piece and a special device (described later) had to be adopted in order to overcome this difficulty without introducing any flexible joint. In some experiments,

A 3.—Detonation wave passing into a narrower tube.

B 4.—Flame velocity increased at junction with narrower tube.

D 3.—Tube shattered. Apparent decrease in flame velocity.

E 1.—Flames in normal-narrow-normal tube.

E 2.—Same tube as E 1. Stopper kept in position.

L 1.—Detonation wave retarded at junction with wider tube.

L 6.—Retarded flame checked by pressure-wave.

S 4.—Wide cavity between two narrower tubes.

the very wide tube was made of stout glass tubing, whilst in others metal tubes were used; the results did not indicate any difference in the behaviour of the flames due to these differences in material. In each series of experiments the normal tube was joined to a length (several metres) of lead pipe of the same diameter; this lead pipe carried a sparking-piece and brass tap at its further end. The initial movements of the flame preceding the formation of the detonation wave took place in the lead pipe, and the flame which entered the glass tube was quite steady—in fact the detonation wave itself.

The movements of the flames were analysed on a rapidly moving wheel carrying a photographic film—like the apparatus described in a previous research (*Proc. Roy. Soc.*, 1914, [A], 90, 506). Slight alterations were made in the method of driving the wheel and in the addition of a device for timing its speed. The explosion tubes were placed horizontally and the flames traversed them from left to right. The film was moving vertically downwards at the point where it received the image of the flame; the photographs, therefore, show lines which are compounded of two velocities at right angles and in every case the print of the film indicates a line starting from the right-hand bottom corner and inclined at an angle to the horizontal. In most of the experiments the flame in the normal tube is visible and its velocity known; the speed of the wheel can therefore be calculated. In all the photographs thin, dark, vertical lines appear; these are caused by strips of black paper fastened across the front of the tubes at distances of 10 cm., measured from the junction of the two tubes. These lines serve as reference marks and are useful in measuring the photographs. In order to obtain the same width of flame in two tubes of different diameters, black paper was fastened round both tubes, leaving at the front only a horizontal opening of equal width along the whole length of tube photographed.

I. "Normal-narrow."

Since the detonation wave is the wave of maximum velocity which can traverse a particular gaseous mixture at a definite temperature and pressure, a sudden diminution in the diameter of the containing tube cannot cause any *increase* in velocity unless one or both of these factors are altered. It is possible that the increased lateral pressure exerted by the walls of the tube might cause an increase in rate. This effect is likely to be very small, however, for Dixon (*Phil. Trans.*, 1893, [A], 184, 179) has shown that the rate of the detonation wave in one particular gaseous mixture was only increased from 2775 metres per sec. to 2872 metres per sec. when the initial pressure was raised from 500 mm. to 1500 mm.

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It is more probable that a *decrease* in velocity should occur owing to the great cooling effect of the walls of the tube—especially in those cases where the diameter is very small. It is conceivable that the two effects—one of increase of velocity and one of decrease—might compensate one another in the case of one particular mixture, but it is unlikely that it would happen in a number of different mixtures.

Accordingly, five different gaseous mixtures were used in four different tubes (named series A, B, C, D respectively). In Table II the dimensions of the tubes used in these experiments are given and in Table III the results of the various experiments.

TABLE II.

Series.	Dimensions of tubes.		
	Normal tube. Diam. in mm.	Narrow tube. Diam. in mm.	Length in cm.
A	16	9	33
B	15	7	33
C	16	5	33
D	9.5	6	33

TABLE III.

Series.	No.	Mixture.	Change in rate at junction.	Remarks.
A	1	$2\text{H}_2 + 3\text{O}_2$	None	
	2	$\text{C}_2\text{N}_2 + \text{O}_2 + 2\text{N}_2$	"	Tube shattered.
	3	$2\text{H}_2 + 3\text{O}_2$	"	
	4	$2\text{H}_2 + 3\text{O}_2$	"	Cork maintained in position.
B	1	$\text{H}_2 + \text{O}_2$	None	
	2	$\text{H}_2 + \text{O}_2$	"	
	3	$2\text{H}_2 + 3\text{O}_2$	Slight increase	} Probable obstruction in the lead pipe.
	4	$2\text{H}_2 + 3\text{O}_2$	" "	
	5	$2\text{H}_2 + 3\text{O}_2$	" "	
	6	$3\text{CS}_2 + 5\text{O}_2$	None	
	7	$3\text{CS}_2 + 5\text{O}_2$	"	
C	1	$2\text{H}_2 + 3\text{O}_2$	None	
	2	$3\text{CS}_2 + 5\text{O}_2$	"	
	3	$\text{C}_2\text{N}_2 + \text{O}_2 + \text{N}_2$	"	
	4	$\text{C}_2\text{N}_2 + \text{O}_2 + \text{N}_2$	"	
	5	$\text{C}_2\text{N}_2 + \text{O}_2 + 2\text{N}_2$	Slight increase	Tube shattered.
	6	$2\text{H}_2 + 3\text{O}_2$	None	
	7	$\text{C}_2\text{N}_2 + \text{O}_2 + 2\text{N}_2$	Slight increase	Tube shattered.
	8	$2\text{H}_2 + 3\text{O}_2$	None	
D	1	$2\text{H}_2 + 3\text{O}_2$	None	
	2	$2\text{H}_2 + 3\text{O}_2$	"	
	3	$\text{C}_2\text{N}_2 + \text{O}_2 + 2\text{N}_2$	Slight decrease	Tube shattered.

In most of the experiments, the explosion wave had the same velocity in the normal and the narrow tubes. In experiment D 3 the tube was shattered; this may account for the apparent decrease in velocity of the flame when it had traversed about 10 cm. of the

narrow tube. In those few experiments where there was an increase in velocity at the junction (see Table III), the *initial* flame was not constant, but was increasing in speed as it approached the junction. It is probable that the detonation wave had been damped down by some slight obstruction in the lead tube and had not again reached its maximum velocity when it was photographed. At the junction the high pressure produced initiated a wave—probably the detonation wave—in the narrow tube, and also gave an intense return wave in the partly burnt and still burning gases in the normal tube (B 4).

It is established, therefore, that when a detonation wave, travelling in a tube of uniform diameter, suddenly enters a much narrower tube, there is no appreciable change in velocity at the junction. In the mixtures used, the detonation wave can traverse at least 30 cm. of glass tubing 5 mm. or more in diameter.

Attention must also be directed to a slower secondary wave which follows the detonation wave starting from the junction and moving towards the end of the narrow tube (see photograph A 3). It is probably a wave of compression and is caused by forward moving gas in the wake of the detonation wave increasing the pressure at the junction. This pressure tends to release itself—forward in the narrow tube and backwards in the wider tube. Since the gas is already moving forward in the narrow tube, but is almost stationary in the wide tube, the forward wave moves faster than the backward wave.

The return wave of compression produced when the initial detonation wave collides with the cork, is clearly seen in all the photographs. In some cases, it is slightly curved, owing to the movements of the gas *en masse*, but in most cases is quite straight—indicating a constant velocity. In Table IV, the measurements of the tangents of the angles which the reflected waves in the normal and narrow tubes make with the horizontal are compared.

TABLE IV.

Mixture.	Photo.	Tangents of angles of return wave in	
		Normal tube.	Narrow tube.
$2\text{H}_2 + 3\text{O}_2$	A 1	0.33	0.36
"	A 3	0.33	0.34
"	A 4	—	0.34
"	C 6	0.32	0.36
"	C 8	0.35	0.37
$3\text{CS}_2 + 5\text{O}_2$	B 6	0.44	0.45
"	B 7	0.41	0.46
"	C 2	0.37	0.40
$\text{C}_2\text{N}_2 + \text{O}_2 + \text{N}_2$	C 3	0.26	0.27
"	C 4	0.28	0.30

The individual values depend on the velocity of the photographic wheel as well as on the velocities of the flames, but the table brings out the fact that the return wave in the normal tube is more rapid than that in the narrow tube—the velocities of these waves being inversely proportional to the tangents of the angles. This difference in velocity may be due to the fact that in the normal tube the gas is almost stationary, whereas in the narrow tube it is still moving forward towards the closed end. Also, the narrow tube may cool the gas more rapidly than the normal tube.

II. "Normal-narrow-normal."

It has been shown by Le Chatelier (*Ann. Mines*, 1883, 4, 319) that a mixture of methane and air (containing 10.4 per cent. of the former) will not propagate a flame in glass tubes of 3.2 mm. diameter, and that metal tubes prevent the propagation more effectively than glass tubes of the same diameter. Payman and Wheeler (T., 1918, 113, 656) have shown that 2 cm. of brass tubing (of diameter up to 8 mm.) will prevent a slow flame in a mixture of methane and air from spreading into a second wide vessel. If the flame was allowed to attain a somewhat higher velocity (that is, by permitting it to travel a greater length in the wider vessel before it met the narrow tube), a greater length of brass tubing was required to prevent it spreading into the second vessel. The flames used in these experiments were moving with a velocity less than 100 cm. per second and therefore the cooling effect of the walls of the vessel was considerable.

In the experiments described in this paper, the flames were travelling with a velocity of more than 2000 metres per second; the temperature of the gases was raised more suddenly than in Payman and Wheeler's experiments, and the time of passage of the flame much shorter. It is not surprising, therefore, to find that the detonation waves in various mixtures of gases can traverse quite considerable distances along a very narrow tube and spread into a second wide vessel. The tubes used were constructed entirely of glass, the two end ("normal") tubes being fused to the central ("narrow") tube. The normal tubes were of equal diameter, approximately 16 mm., in all the experiments. One of them was joined to a lead coil (of equal bore), at the far end of which the gases were fired; the other normal tube was varied in length between 19 cm. and 31 cm. The central (narrow) tube was varied in both length and diameter, as the following table shows.

In all these experiments the mixture $2\text{H}_2 + 3\text{O}_2$ was employed. This particular one was chosen because, whilst it gave a fairly good light, the pressures produced did not shatter the apparatus

TABLE V.

Dimensions of tubes used in "normal-narrow-normal."

Series.	Narrow tube.		2nd normal tube. Length (cm.).
	Diam. (mm.).	Length (cm.).	
E	5.5	4.5	24
F	5.5	9.0	27.5—31
G	5.5	19.0	31
H	2.0	21.0	19
J	2.0	32.5	23.5
K	1.5	40.5	23.7

as often as the less diluted but more actinic mixtures would have done. The end of the tubes was closed by a tightly fitting cork, which was usually allowed to blow out; a few experiments were performed with the cork held firmly in position; this made little difference, if any, to the general phenomena observed.

In experiment E 1 (photograph reproduced), the detonation wave, travelling at uniform speed, collided with the junction wall (at $\uparrow_1$) through which the narrow tube continued. Here an intense wave of reflection was sent back, but the original wave passed through the narrow tube with unchanged velocity. At the second junction, the wave became much less luminous and travelled forward at a velocity which appeared almost constant, but was much less than the velocity of the original wave. At a point about 21.5 cm. from $\uparrow_2$, the flame was checked and an intense wave—possibly of reflexion—passed back through the burning gases. This return wave appears to have been caused by a wave of compression which had preceded the flame and had suffered reflexion from the cork—situated 24 cm. from $\uparrow_2$. At the point of collision between the pressure-wave and flame, the latter continued to advance towards the cork, which was finally forced out.

The return wave in the burning gases was nearly constant in velocity and where it collided with the junction wall at $\uparrow_2$ the luminosity was very great—suggestive of a very high pressure. At $\uparrow_2$, part of the wave continued its journey into and through the narrow tube and part was again reflected.

This photograph (E 1) is similar to many others taken in tubes of similar shape but of different dimensions. Photograph E 2 shows the effect of keeping the cork firmly fixed in position. The confined gas continued to burn for some time and was crossed and recrossed by waves of pressure—reflected in turn from the cork and from the junction-wall $\uparrow_2$. An increase in length of the middle narrow tube to 9 cm. and then to 19 cm. did not appreciably affect the velocity of the flame in this narrow tube (F and G experiments).

When the diameter of the narrow tube was reduced to 2 mm.,

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the amount of light given out was very small and few good photographs were obtained. The wave in this narrow tube still appeared constant in velocity even when it traversed a length of 32 cm. With further increase in length (to 40.5 cm.) and further diminution in diameter (to 1.5 mm.), no good photograph was obtained, but the flame passed through the narrow portion and ignited the gas in the further tube.

The velocities of the retarded flames in the end tube can be calculated from the velocity in the centre tube and from the measurements of the angles formed by these flames in the photograph. The velocity of the flame in the centre tube is assumed to be that of the detonation wave in the mixture used ($2\text{H}_2 + 3\text{O}_2$) and is probably about 2120 m. per sec.

The values of $\tan \alpha$ and $\tan \beta$ (in Table VI) are calculated from the measurements of the angles (in the photographs) formed by the flame in the narrow and normal (end) tubes respectively.

TABLE VI.

Measurement of angles made by flame edges.

Experiment.	$\tan \alpha$.	$\tan \beta$.	$\frac{\tan \alpha}{\tan \beta}$.	Velocity of retarded flame in m. per sec.
E 1	0.13	0.53	0.25	530
E 2	"	0.52	0.25	530
F 1	"	0.44	0.29	610
F 3	"	0.54	0.24	510
F 6	"	0.51	0.25	530
F 7	"	0.50	0.26	560
F 8	"	0.49	0.27	580
F 9	"	0.50	0.26	560
G 1	"	0.44	0.29	610
G 2	0.14	0.48	0.29	610
			Mean	560
H 1	0.13	0.70	0.19	410
J 2	0.15	0.74	0.20	430
J 3	0.14	0.72	0.20	430
			Mean	420

These results appear to indicate that where the expansion at $\uparrow_2$ is from a 5 mm. tube to a 10 mm. tube the velocity of the retarded flame is about 560 m. per second, but where the expansion is greater (that is, from 2 mm. to 10 mm.) the retarded flame is slower, namely, 420 m. per second.

We may summarise the results of experiments in normal-narrow-normal tubes as follows :

1. An explosion wave in the mixture $2\text{H}_2 + 3\text{O}_2$ can pass from a normal through a narrow and into a second normal tube. In glass tubes, the middle section may be as narrow as 1.5 mm. and flames will pass through a length of *at least* 40 cm. of this narrow

TABLE VII.

Measurements of flame angles:

Mixture $2\text{H}_2 + 3\text{O}_2$.

Expt.	Diam. of wide tube in mm.	Initial wave. Tan α .	Retarded flame in		
			1st 10 cm. Tan β_1 .	2nd 10 cm. Tan β_2 .	3rd 10 cm. Tan β_3 .
L 1	22	0.15	0.37	0.37	
L 2	22	"	0.36	"	
L' 3*	22	0.16	0.37	"	0.37
M 1	35	0.16	0.56	0.57	0.57
M 2	35	0.17	0.52	0.52	0.52
O 1	62	0.15	0.68	0.85	
O 2	62	0.13	0.66	0.67	0.67
O 3	62	"	0.68	0.69	
Q 1	85	0.13	0.55		
Q 2	85	0.12	0.60		
Q 3	85	0.14	—		
Q 4	85	0.15	—		
Q 5	85	0.12	0.61		
R 3	91	0.16	0.78 †	0.78 †	
R 5	91	"	0.75 †	0.75 †	

* L' 3. Length of wide tube = 70 cm.

† Mean values of 20 cm.

Mixture $\text{C}_2\text{N}_2 + \text{O}_2 + 2\text{N}_2$.

Expt.	Diam. of wide tube in mm.	Initial wave. Tan α .	Retarded flame in		
			1st 10 cm. Tan β_1 .	2nd 10 cm. Tan β_2 .	3rd 10 cm. Tan β_3 .
L 3	22	0.15	0.45	0.60	—
L 4	22	0.16	0.47	0.59	0.61
L 5	22	0.15	0.43	"	0.67
L 6	22	0.16	0.45	0.64	0.70
L' 1*	22	"	0.46	0.58	0.69
M 3	35	0.16	0.55	0.78	0.85
N 1	45	0.16	0.65	0.79	0.81
N 2	45	—	0.62	1.1	
P 2	65	0.12	0.65	0.94	
R 1	91	0.16	0.86	0.97	
R 2	91	0.14	0.84	1.14	
R' 1*	91	—	0.89	0.91	1.10

* Length of wide tube in L' 1 and R' 1 = 70 cm.

tube. The luminosity of the flames is small in these very narrow tubes.

2. The explosion wave in a tube of diameter not less than 2.0 mm. suffers no appreciable change in velocity over a length of at least 30 cm.

3. The explosion wave suffers a diminution in velocity when it enters the end tube, and this retarded flame is preceded by a wave of compression.

III. "Normal-wide."

The experiments in II have shown that a considerable retardation of the flame occurs at the point where the flame, having travelled through a very narrow tube, suddenly debouches into a wider tube. The experiments to be described here, show that the detonation wave itself, travelling in a tube 10 mm. in diameter, is similarly retarded at the junction ($\uparrow$) with a much wider tube (photograph L 1). Photographs have been obtained of this retarded flame in tubes, the narrow part of which was always 10 mm. wide, whereas the wide part differed in diameter. Since some of the flames after retardation were not constant in velocity, the angles made by these flames in each 10 cm. section of the wide tube (counting from the junction) have been measured separately and are called β_1 , β_2 , β_3 , respectively (Table VII). Except where indicated, the wide tube was approximately 30 cm. long.

From the mean values of $\tan \alpha$ and $\tan \beta$, and from the known values of the initial explosion waves in the two mixtures, the velocities of the retarded flames have been calculated (Table VIII).

TABLE VIII.
Velocity of Retarded Flame.

Mixture.	Diam. of wide tube in mm.	Mean $\tan \alpha$.	Mean $\tan \beta_1$.	Velocity of flame in m. per sec.
$2\text{H}_2 + 3\text{O}_2$	22	0.15	0.37	890
"	35	0.165	0.54	640
"	62	0.135	0.67	430
"	85	0.125	0.60	450
"	91	0.16	0.78	440
			Mean $\tan \beta_2$.	
$\text{C}_2\text{N}_2 + \text{O}_2 + 2\text{N}_2$	22	0.16	0.60	590
"	35	0.16	0.78	455
"	65	0.12	0.80 *	640
"	91	0.15	1.06	310

* This figure is mean $(\tan \beta_1 + \tan \beta_2)/2$ because the flame edge is curved.

The results show the very great retardation produced at the junction. The velocity of the retarded wave is apparently dependent on the particular explosive mixture used and on the relative diameters of the wide and the narrow tube. Under the conditions of these experiments, the 91 mm. tube appears to cause very little more retardation than a 65 mm. tube, and a limit has probably been reached.

It may be assumed that the gases in the wave-front (continuously fired by adiabatic compression) are at a very high temperature and pressure. At the junction, the great lateral pressure exerted by the sides of the tube is suddenly removed, the hot gases are

free to expand in every direction and are consequently cooled. The phenomenon may be compared with the expansion through a nozzle of a gas under pressure. The greater the difference in the diameters of the normal and narrow tubes, the greater will be the expansion and consequent retardation of the flame. Experiments performed in wide tubes of greater length than 30 cm. show that the retardation of the flame at the junction is the same as for a shorter tube of the same diameter; a few photographs, taken further along a tube 70 cm. in length, show that the flame is again gathering speed and is probably on the way to set up the explosion wave once more.

The means adopted to close the end of the tube did not affect the amount of retardation of the flame. This was shown by experiments where the end was closed by a cork or rubber stopper loosely inserted or firmly inserted, by a metal disk lightly cemented over the end, or even by a piece of paper gummed over the end. In those experiments where a rubber stopper was tightly inserted and consequently less air was drawn into the tube, the mixture remained luminous for a longer time.

A few experiments were performed at pressures less than atmospheric. In two experiments at 370 mm. pressure, the flame in the mixture $2\text{H}_2 + 3\text{O}_2$ did not travel very far in the 10 mm. tube, whereas at 500 mm. the flame was visible and the stopper violently ejected, but no photograph was obtained. With the mixture $2\text{H}_2 + \text{O}_2$, the flame died out in the 10 mm. tube when the pressure was 270 mm., but at 400 mm. pressure the explosion wave—probable velocity 2800 metres per second—was retarded at the junction as in the experiments at atmospheric pressure. The retarded flame had a velocity in the 91 mm. tube of about 560 metres per second.

In photograph L 6, the retarded flame is seen to have been checked at a point 26 cm. from the junction ($\uparrow$), the stopper of the tube being 3.5 cm. further on. In another experiment where the advancing flame was still slower, it was stopped at a point 22 cm. from the junction, the stopper being 9 cm. further on. It is believed that this checking of the flame is caused by a wave of pressure which has *preceded* the retarded flame, has been reflected from the closed end of the tube, and on its return journey has checked the flame and become visible in the hot gases behind the wave-front. An attempt has been made to calculate the velocity of this pressure-wave in different experiments, assuming (1) that the pressure-wave starts its independent existence at the junction, and (2) that it is reflected from the stopper without loss of velocity—a condition which may only obtain with waves of small amplitude.

The velocity of sound in the mixture $2\text{H}_2 + 3\text{O}_2$ at 16° is about 410 m. per second calculated by the Laplace formula, the value of γ being assumed to be 1.40. The value of γ for cyanogen probably lies between the limits 1.25 and 1.30, giving values of γ for the

mixture $C_2N_2 + O_2 + 2N_2$ of 1.36 or 1.37. Calculated on the latter value, the velocity of sound in this mixture is about 306 m. per second. The velocities of the pressure-waves in the preceding tables are seen to be much faster than the velocity of sound in the same mixture. Where the diameters of the wide and the narrow tubes are very different, the pressure-wave appears to move about 50 per cent. faster than the sound wave; where the diameters are more nearly alike, the pressure-wave is a concussion wave of which the velocity is more than double that of sound. If these pressure-waves lose velocity on reflexion, as stated by Crussard (*L'Onde de Choc*, p. 34), their velocities will be higher than the values given in Table IX.

When a quite narrow tube—5 mm. in diameter—debouches into a wider tube of 16 mm. diameter, the pressure-wave produced in the latter travels at about 640 m. per second (mixture $2H_2 + 3O_2$)—a value which is near the rate found in experiments O 1, O 2, O 3 (Table IX).

The course followed by the wave of pressure after its collision with the flame is seen to advantage in photograph L 6 (Fig. L 6A). The wave proceeded from left to right through the burning gases at nearly constant velocity until it reached the junction, where it was almost completely reflected; in its return journey towards the end of the tube, it overtook the flame front, helped it along, and was again reflected from the stopper. Similar phenomena were observed in experiments with different mixtures and under different conditions. Measurements of the velocities of these waves of pressure were made in nineteen different experiments, and a number of deductions of a general character are possible. It was found, of course, that the velocity of the wave moving in the burning gases (for example, GH in Fig. L 6A) was very much greater than the calculated velocity of the pressure-wave (in the cold gases) which produced it (CX or XG). Higher values of CX gave higher values for GH , but this relationship only held for each single mixture. At H , part of the pressure-wave was reflected, but in almost every case there was a considerable loss of velocity at this point. This loss was most noticeable where the difference in the diameters of the wide and the normal tube was small; where the junction approximated to an unpierced disk, the reflexion of the pressure-wave was almost complete. The gas itself was, almost certainly, in violent motion and the velocity of the pressure-wave moving in this gas would be increased or diminished by the direction and amount of the movement of the medium. The velocity of the pressure-wave would also be dependent on the temperature of the flame through which it was passing and this temperature would

vary, not only with the mixture, but also with the cooling (by expansion) at the junction.

IV. "Normal-wide-normal."

A number of experiments were performed in tubes containing a central ("wide") portion between two narrower ("normal") portions. The central portion was about 12 cm. long and 47 mm. in internal diameter. The end portions were 10 mm. in diameter, one end being fitted to the lead tube and firing-piece and the other being closed in the usual way. Three different mixtures were used, namely, $3\text{CS}_2 + 5\text{O}_2$, $2\text{H}_2 + 3\text{O}_2$, and $2\text{H}_2 + \text{O}_2$. In each case, the initial explosion wave was retarded at the first junction ($\uparrow_1$) (see photograph S 4—mixture $2\text{H}_2 + \text{O}_2$) and moved with almost constant velocity through the central wide tube. In the $3\text{CS}_2 + 5\text{O}_2$ mixture, the retarded flame soon gathered speed again. At the second junction ($\uparrow_2$) there was a great increase in the intensity of the light. The wide portion of the tube was so short that the retarded flame and the pressure-wave which preceded it were reflected from ($\uparrow_2$) at almost the same instant, and it was impossible to distinguish their separate effects. A very rapid flame goes forward from ($\uparrow_2$) in the end tube. This appears to be the detonation wave, which has been re-started at the junction ($\uparrow_2$).

Summary.

The following general conclusions can be drawn from all the experiments with the different tubes:

(a) An explosion wave does not change its velocity appreciably when it passes into a narrow tube, whether this narrow tube is closed at the further end or whether it opens again into a wider tube. The distance over which this flame can travel will probably depend on the material of the tube, but very narrow glass tubes (about 2 mm. in diameter) will allow the flame in the mixture $2\text{H}_2 + 3\text{O}_2$ to travel at least 40 cm. without appreciable retardation.

(b) An explosion flame is suddenly retarded at any point where a sudden expansion of hot gases may occur. In some gaseous mixtures, this flame then moves at a fairly constant velocity for some distance; in others, it continues to be retarded. Probably it finally gains speed and reproduces the detonation wave. The retardation of a detonation wave as it passes through a flexible joint between two rigid tubes (as recorded by Dixon, *Phil. Trans.*, 1903, [A], 200, 334) is probably due to a sudden expansion at the junction. Where the joint is smooth and rigid and the tubes of equal diameter, no expansion occurs, and therefore no retardation takes place.

(c) The retarded flame is preceded by a compression wave, more or less rapid according as the expansion has been small or great, and this, after collision with the closed end of the tube, is reflected and checks the advancing flame.

(d) The rates of the retarded flame and of the preceding pressure-wave are dependent on the gaseous mixture, the relative sizes of the different portions of the tube, and possibly the initial pressure. The greater the difference between the diameters of the two portions of the containing tube, the less the velocities of the retarded flame and of the preceding pressure-wave in any one mixture. These velocities reach a lower limit in a very wide tube.

EXPERIMENTAL.

The Tubes.—In experiments with tubes of diameter less than 65 mm., these tubes were made entirely of glass, the different sections being fused together. When the diameter exceeded 65 mm., several kinds of tubes were employed. In the earlier experiments, a tube of mild steel was used; it was open at one end and closed at the other except for a central hole of 10 mm. diameter. A steel ferrule projected outwards from this end-plate, and the narrow tube was cemented into this ferrule. A window of plate-glass covered a horizontal slot (10 mm. wide), cut out of the steel tube, and the window was fixed in position by cement. Since the window was displaced by each explosion, this steel tube was replaced, in later experiments, by a very thick-walled glass tube. One end was fitted with a steel end-plate and ferrule as described above; this end-plate was clamped to a steel annulus (which fitted over the far end of the tube) by strong bolts and nuts and the whole apparatus was supported in a wooden frame. A thin layer of cement between the metal end-plates and the glass tube rendered the apparatus air-tight.

The tubes were filled with the explosive mixture in different ways, according to their shape and construction. Where they were of small diameter, the air was displaced by a rapid stream of the explosive mixture, the cork being inserted while the gas was still passing. With wider tubes, these were tightly stoppered, rapidly evacuated to 15 mm. pressure with a Fleuss pump, and filled with gas, this operation being repeated three times in rapid succession.

The Gases.—The cyanogen was prepared from dried mercuric cyanide. It was mixed with dry nitrogen and oxygen obtained from cylinders of the compressed gases, and the mixture was stored in a gas holder over mercury. The hydrogen-oxygen mixtures were stored over water and passed directly into the explosion tube. The moisture present lowered the detonation rate by about 0.5 per cent., an amount well inside the experimental error. The carbon

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disulphide mixtures were prepared by drawing dry oxygen through two wash-bottles containing the liquid at 18°.

The mixtures were fired by a break-spark from the secondary circuit of a Ruhmkorff coil.

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