CCLXXXIII.—*The Propagation of Flame in Mixtures of Methane and Air. Part IV. The Effect of Restrictions in the Path of the Flame.*

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IN earlier parts of this research (J., 1920, **117**, 36, 1227) preliminary references were made to the high speeds attained by the flame during explosions of methane and air in a tube the diameter of which was restricted at several points. For example, it was recorded (*loc. cit.*, p. 47) that in a steel tube 30·5 cm. in diameter and 90 m. long, open at both ends, in which restrictions (consisting of thin steel rings which reduced the diameter of the tube to 28·6 cm.) were introduced at two points, the development of the detonation-wave, or some mode of combustion of similar intensity, seemed imminent. This effect of the restrictions was tentatively assumed to be one of turbulence, caused by currents induced locally as the flame passed through the restrictions. A similar explanation, an effect of turbulence, was held to account for the much greater speed at which flame travels in a given mixture of methane and air, when that mixture is passed through a tube as a current, than it does when the mixture is initially at rest within the tube.

The research has developed along two lines: (1) A study of the effect on flame speed of an artificial movement given to the inflammable mixture; and (2) a study of the propagation of flame, in an initially quiescent mixture, along a tube containing restrictions. The former is still in progress and will be described at a later date. The present paper deals with the effect of restrictions as studied mainly by experiments on a small scale in the laboratory, supplemented by tests on a larger scale. The main object of the work has been to determine the maximum speed at which flame can travel in mixtures of methane and air, initially at rest and at atmospheric temperature and pressure.

The laboratory experiments were carried out in a brass tube 5 cm. in diameter and 240 cm. long, built up of short sections bolted together. The restrictions used were brass annuli, usually 1 mm. in thickness, which could be introduced at given points along the tube between the sections. Certain sections of the tube were provided with a longitudinal window of quartz, 4 mm. wide, through which the movements of the flame could be photographed, through a quartz lens, on a rapidly revolving film. The tube was mounted horizontally and was fully open at both ends when the explosions were produced, the mixture being ignited at one end. In all the series of experiments described in this paper, mixtures of methane and air containing between 9·5 and 10·0% of methane, in which the speed of flame normally is fastest, were used.

The Propagation of Flame in an Unrestricted Tube.

In order that the effects of restrictions could be appreciated it was necessary to repeat the experiments on the propagation of flame in an unrestricted tube open at both ends made by Mason and Wheeler (J., 1920, **117**, 36). The results differed slightly * from those obtained by Mason and Wheeler and a description of them is necessary. The flame accelerated gradually over the first 80 cm. and then was slightly retarded, faint undulations of the flame front making their appearance. These undulations became more marked and eventually the flame assumed a definitely vibratory character over a distance of about 15 cm., during which its mean forward speed increased. The speed of the flame continued to increase after the vibrations had died away until the end of the tube was reached. The periodicity of the vibrations was that of the fundamental tone of the tube, namely 98. A photograph of the flame throughout its passage along the tube, is reproduced in Fig. 1, Plate I. The full length of the tube is shown in the photograph which is composite, being obtained by joining together photographs of successive sections taken in separate experiments. The flame travelled from left to right and the photographic film can be regarded as moving vertically upwards. Its speed of travel was 73 cm. per sec. Since the photograph has been reduced in size to about one-fifth, the speed of travel of the film in the reproduction can be regarded as about 14 cm. per sec. This applies also to the other photographs on Plate I. The chief difference between this photograph and that obtained by Mason and Wheeler (an important one from the point of view of the present research) lies in the absence of intense vibrations.

The Effect of One Restriction.

A number of trials were made to determine with what reduction in diameter of the tube, and at what position along it, the maximum effect would be obtained.

The Amount of Restriction.—A ring of brass, 1 mm. in thickness,

* The differences were due to the fact that a flame held at the mouth of the tube, instead of an electric spark a few cm. within the tube, as in Mason and Wheeler's experiments, was used to ignite the mixtures. As explained in a previous paper (J., 1919, **115**, 578), the mechanical disturbance caused by the electric spark induces marked vibrations of the flame. In the present experiments, it was necessary to prevent the occurrence of such vibrations as far as possible.

PLATE I.

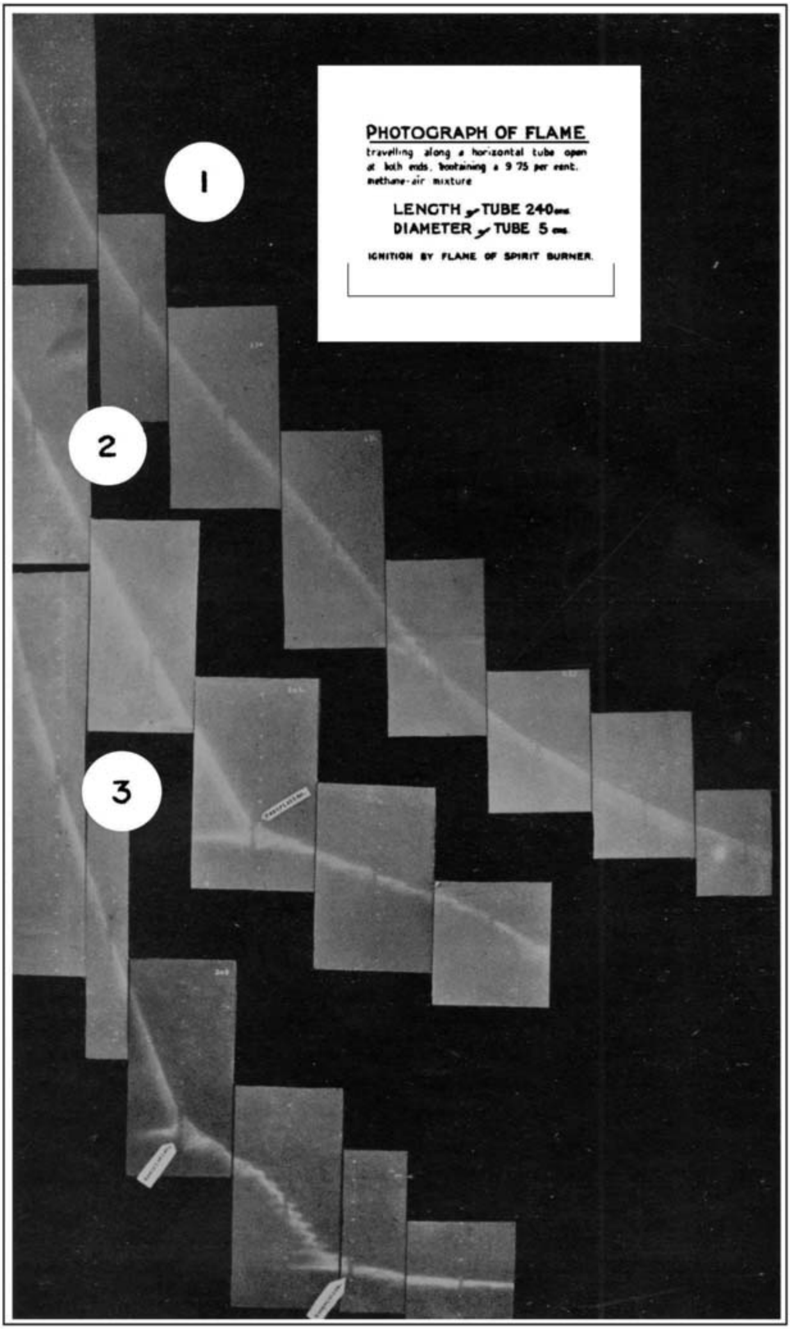

FIG. 1.—*Unrestricted tube.* FIG. 2.—*One restriction, reducing the diameter of the tube to* 2·5 *cm., at a point* 80 *cm. from point of ignition.* FIG. 3.—*Two restrictions,* 60 *and* 110 *cm. from point of ignition.*

[*To face p.* 2140.]

PLATE II.

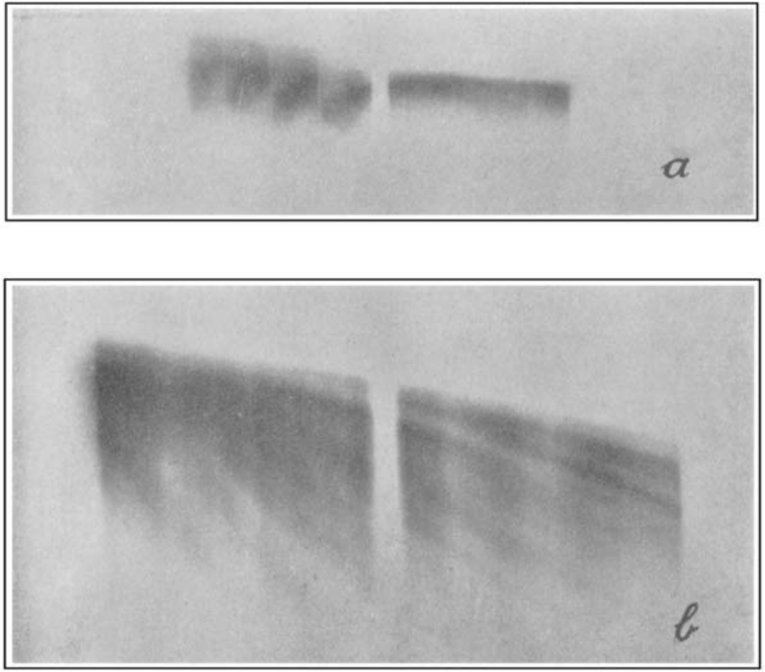

Fig. 1.

(a) *Flame passing through the last six of a series of twelve restrictions, 5 cm. apart (left half of photograph).*

(b) *Flame travelling at uniform high speed (420 m. per sec.) after passing through twelve restrictions, 5 cm. apart.*

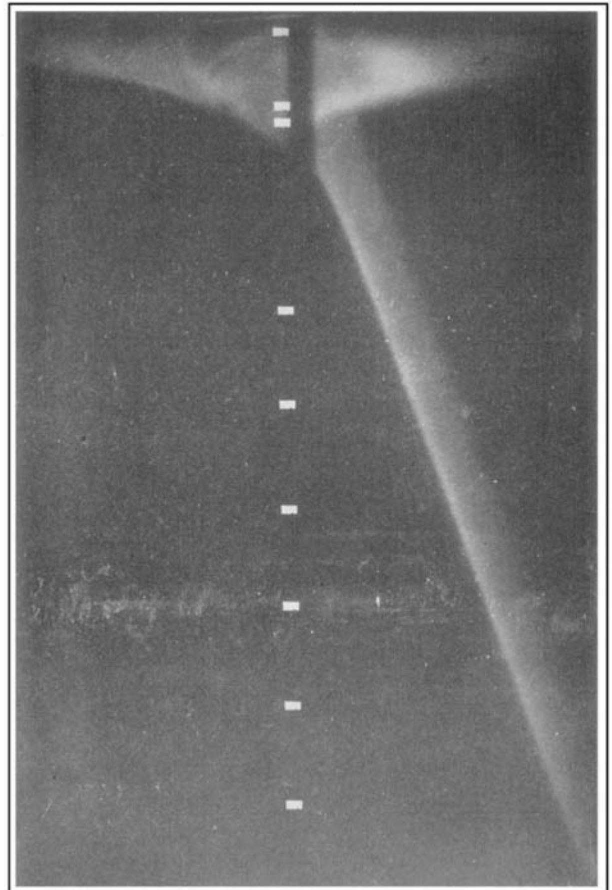

Fig. 2.—*The movements of flame at a restriction.*

was inserted at a point, somewhat arbitrarily chosen, 40 cm. from the end of the tube at which ignition of the mixture was to be effected. In successive experiments, rings with holes 3·6, 2·5, and 1·5 cm., respectively, in diameter were used, so that the effect of an increasing amount of restriction to the passage of the flame along the tube could be determined.

The mean speeds of the flames over successive intervals of 5 or 10 cm., up to and for a short distance beyond the restriction, are recorded in Table I. For comparison, the speeds obtained when an unrestricted tube was used are also recorded.

TABLE I.

The Effect of the Amount of Restriction.

Mean Speed of Flame (cm. per sec.).

Distance from point of ignition (at one end of the tube).	Unrestricted tube.	Restrictions 40 cm. from point of ignition.		
		3·6 cm. diam. hole.	2·5 cm. diam. hole.	1·5 cm. diam. hole.
5—15	106	98	98	93
15—25	134	122	118	94
25—30	146	138	121	95
30—35	158	147	124	95
35—40	170	147	124	95
		(Restriction inserted here)		
40—45	182	256	341	249
45—55	194	156	475	
55—65	206	230	600	

It will be seen that in each instance the speed of the flame was retarded before the restriction was reached, and was enhanced after the restriction had been passed, the greatest increase being produced when the restricting ring reduced the diameter of the tube by one-half. It will be noticed, also, that the speed of the flame as it travelled between the point of ignition and the restriction tended to become uniform, the tendency being more marked the greater the amount of restriction.

The Position of the Restriction.—Using the restricting ring that had been found to produce the optimum effect, *viz.*, that with a hole 2·5 cm. in diameter, a series of experiments was made in which the position of this ring along the tube was varied. The results are recorded in Table II.

The general effects of the restriction on the speed of the flame, a retardation as the ring was approached and an acceleration after it had been passed, were the same whatever its position along the tube, but the intensity of the effects increased the further the restriction was removed from the point of ignition.

TABLE II.

The Effect of the Position of the Restriction.

Mean Speed of Flame (cm. per sec.).

Distance from point of ignition (at one end of tube).	Unrestricted tube.	Restricted tube, aperture 2·5 cm. Distance from point of ignition. 40 cm.	80 cm.	105 cm.
5—15	106	98	96	103
15—25	134	118	129	135
25—35	152	123	142	143
35—40	170	124	151	147
		(Restriction)		
40—45	182	341	157	150
45—55	194	475	164	152
55—65	206	600	165	155
65—75	240	640	164	158
75—80	254	936	164	158
			(Restriction)	
80— 85	254	936	424	158
85— 95	249	779	1050	93
95—105	231	647	895	70
				(Restriction)
105—110	220	650	880	2780
110—115	220	650	880	7500
115—125	237	650	705	7500
125—135	285	725	628	2430
135—145	350	420	803	3150

The Thickness of the Restriction.—Experiments were made in which the thickness of a restricting ring, having a hole 2·5 cm. in diameter and placed 80 cm. from the point of ignition, was varied between 1 and 20 mm. The effect of this variation was slight : the thinnest ring caused the greatest increase in speed of the flame, as the results recorded in Table III show.

TABLE III.

The Effect of the Thickness of the Restriction.

Mean Speed of Flame (cm. per sec.).

Mean speed of flame.	Thickness of restriction. 1 mm.	10 mm.	20 mm.
Over 20 cm. before restriction	164	160	157
Over 5 cm. beyond restriction	424	395	380

From these results it was considered that the most marked effect on the speed of the flame would be produced, under the conditions of the experiments, if the restricting rings were 1 mm. in thickness with a hole 2·5 cm. in diameter. Such rings were used throughout the remainder of the experiments described in this paper. Fig. 2, Plate I, illustrates a typical experiment with one such restricting ring 80 cm. from the point of ignition. The speed of travel of the photographic film in this experiment was 70 cm. per sec. The movement of the flame over the first 155 cm. only is shown in this photograph.

The Effect of Two Restrictions.

The effect of placing two restricting rings in the path of the flame is illustrated by the results recorded in Table IV.

TABLE IV.

The Effect of Two Restrictions.

Mean Speed of Flame (cm. per sec.).

	Distance from point of ignition (at one end of tube).		
Mean speed of flame. {First restriction / Second ,,	40 cm. / 110 cm.	60 cm. / 110 cm.	80 cm. / 110 cm.
Over 10 cm. before first restriction	142	120	115
Over 10 cm. beyond first restriction	282	315	480
Between the two restrictions	240	255	360
Over 10 cm. before second restriction	229	240	265
Over 10 cm. beyond second restriction	3070	3680	3875

The manner of movement of the flame in the vicinity of each restriction was similar and comparable with that obtaining when only one was present. Thus, the speed of the flame, which had increased after passing through the first restriction, decreased as it approached the second, to increase again after passing through it. A typical photograph of the flame as it travelled through the first 155 cm. of the tube is illustrated in Fig. 3, Plate I. The speed of travel of the film in this experiment was 68 cm. per sec. Since for each of the photographs reproduced on Plate I the speed of travel of the film was nearly the same, direct comparison of the speeds of the flames is possible.

The Effect of Three or More Restrictions.

The sequence of events was the same at each restriction as their number was increased, provided that they were sufficiently far apart. Thus, when there were three, placed 40, 70, and 110 cm., respectively, from the point of ignition, the mean speeds of the flame over measured lengths of the tube were as follows :

Distance from point of ignition (cm.).	Mean speed of flame (cm. per sec.).	Distance from point of ignition (cm.).	Mean speed of flame (cm. per sec.).
5—15	100	(Restriction)	
15—25	114	75— 85	3,351
25—35	123	85—105	2,310
(Restriction)		(Restriction)	
45—55	491	115—135	22,500
55—65	468		

If the restrictions were placed closer together, *viz.*, 5 cm. apart, as was done in several series of experiments, there was no appreciable retardation of the speed of the flame travelling between any two of them, but a greatly enhanced speed was attained after passing each. It seemed possible, therefore, that, by introducing a sufficient number of restrictions, speeds comparable with that of the detonation-wave might be attained. Their number was accordingly increased by stages up to 20, with a distance of 5 cm. between each.

The highest speed of flame, 420 m. per sec., was obtained when 12 restrictions were present, an increase in the number effecting no change. This speed, once acquired, was maintained constant throughout the remainder of the tube. The length of the tube was varied between 2 and 3 m., and the position of the first of the set of restrictions relative to the point of ignition was varied between 1/5 and 2/5 of the length of the tube. Under all conditions, the same speed of flame, 420 m. per sec., was obtained. The quartz windows, and windows of thick plate glass used subsequently, were shattered to powder in each experiment. The flame had a much higher actinic value than that of the normal flame in methane–air mixtures, yielding a dense black image when photographed through plate glass on a film moving at a speed of 9 m. per sec. (time of exposure, 1/2000 sec.). The normal flame in methane–air mixtures produces no image when photographed under such conditions. Fig. 1, Plate II, illustrates (*a*) the appearance of the flame as it passed through some of the restricting rings, and (*b*) its uniform high speed subsequently.

Speeds of flame of the same magnitude were measured during experiments in an iron tube 30·5 cm. in diameter and 100 m. long, open at both ends, with restricting rings reducing the diameter to 10 cm. at two points 11·4 m. apart, the first being 22 m. from the end of the tube at which ignition was effected. The maximum speed of flame in the same tube without restrictions was 10 m. per sec. In these large scale experiments continuous records of pressure were obtained at several points close to the restrictions. The maximum pressure recorded, which was always obtained just beyond the last restriction, was 3·9 atm., whilst no appreciable pressure could be measured before the flame reached the first restriction.

The detonation-wave cannot be set up in methane–air mixtures initially at atmospheric pressure, and the speed attained by the flame in the present experiments with 12 restrictions in a 2·5 cm. diameter tube falls far short of the lowest at which a true detonation-wave has been measured in mixtures of methane, oxygen, and nitrogen, *viz.*, 1,150 m. per sec.* The marked actinic power of the flame, however, together with the fact that a high pressure must have been developed to shatter the plate-glass windows so completely, suggests that a mode of translation of the flame in a methane–air mixture approximating to that existing during the detonation-wave was established, temporarily, in and beyond the restricted portion of the tube.

An Explanation of the Effects Produced by Restrictions.

In every photograph of the flame as it passes through a restriction, it has been observed (1) that there is a slight acceleration of speed over a distance of 2 or 3 cm. before the restriction is reached, and (2) that, just as the flame-front has passed through the restricting ring, a secondary flame moves back rapidly, over a distance of 5 to 30 cm., towards the point of ignition. These effects are illustrated in Fig. 2 on Plate II. This is a reproduction (actual size) of a photograph of the flame as it travels over a distance of 15 cm. on either side of a restriction. The speed of travel of the film in this experiment was 66 cm. per sec.

Apart from these two local effects, the general effects of a restriction on the propagation of flame along a tube are, as already noted, to decrease the mean speed before and to increase the mean speed beyond the restriction.

The explanation originally advanced (*loc. cit.*), that the enhanced speed acquired by the flame after it has passed a restriction is due to the creation of turbulence at the restriction, is incomplete. It does not account directly for the maintenance of a high speed of flame over a considerable distance beyond the restriction. An explanation is also required for the fact that the speed of the flame is lower than normal throughout the tube before the restriction is reached, and is slightly accelerated just as it is approached. Consideration of the behaviour of the unburnt gas mixture in the tube ahead of the flame provides an explanation.

A sensitive jet of flame was caused to burn vertically in line with the explosion tube a short distance from the end to which the explosion would travel, and the movements of this flame while the explosion was being propagated were photographed by means of a high-speed cinematograph camera. The photographs showed that, throughout the propagation of the explosion, the flame-jet

* Berthelot (*Compt. rend.*, 1882, **95**, 151) records this speed for the detonation-wave in the mixture $CH_4+4O+8N$. Dixon (*Phil. Trans.*, 1893, *A*, **184**, 97) found that in the mixture $CH_4+3O+5N$ the speed of the detonation-wave was 1,880 m. per sec., and he records that in this mixture the wave was not always established.

outside the tube was deflected in the same direction as that of the flame moving within the tube, the amount of deflection being greater the greater the speed of the explosion. The incidence of a vibratory stage of the explosion was also indicated by the movements of this flame-jet, as were the changes in speed that occurred when restrictions were inserted in the explosion tube.

It can be concluded that, during the propagation of flame in a tube open at both ends, the unburnt mixture in advance of the flame-front is travelling as a current in the same direction as that of the flame, which is therefore travelling in a medium that is itself in motion. The general effects of a restriction in the tube on the speed with which flame travels from point to point along it can be explained as being effects on the speed of the medium in which the flame is moving.

The sequence of events is as follows. When a restriction such as those used in these experiments is ahead of the flame, the resistance offered by it to the movement of the unburnt mixture causes the current, and therefore also the flame, to move more slowly. Just as the restricting ring is approached, the convergence of lines of flow of the mixture causes a slight acceleration of the current, and thus of the flame (Fig. 2, Plate II). The flame passes through the restricting ring as a thin tongue and spreads laterally, so that just beyond the restriction the burning " layer " of mixture suddenly becomes considerably thicker than the normal and there is an abnormal amount of the mixture burnt locally. There is, in consequence, an enhanced speed now given to the current of unburnt mixture ahead of the flame, whilst part of the burning gas is forced back through the restriction (Fig. 2, Plate II). Thereafter, the flame moves, relatively to the walls of the tube, more rapidly because the current of mixture in which it propagates is moving more rapidly.

The effects on the behaviour of the flame, previously described, of successive restrictions spaced widely apart in its path, can be explained in a similar manner as being due to the motion of the medium in which the flame is travelling. When the restricting rings are close enough together, however, the tongue of flame that darts forward at the first restricting ring shoots right through the second and enflames the mixture beyond it whilst the portion between the two is still burning. Combustion thus spreads rapidly throughout a comparatively large volume of mixture, with the result that there is a proportionately rapid movement of the unburnt mixture ahead. By providing a sufficiently large number of restricting rings, spaced not too far apart, the volume of mixture through which this almost simultaneous combustion is induced can be augmented considerably. With the particular diameter of tube and of restricting ring employed in these experiments, a limit to the volume of mixture that can be suddenly inflamed in this manner appears to have been reached with twelve restricting rings.

EXPERIMENTAL.

The apparatus used in our experiments for obtaining photographic records of the movements of the flames did not differ materially from that described by Mason (J., 1923, **123**, 210). For the insertion of the restricting rings in the brass tube, a groove 0·5 mm. in depth was cut at each flange of the sections that built up the full length of the tube. A restricting ring fitted closely into the recess thus formed at any junction of two sections, whilst the recesses at junctions where a restriction was not desired were filled by brass rings 1 mm. in thickness of the same bore as that of the tube.

The majority of the photographs were taken on Eastman Kodak films, but for some (*e.g.*, those reproduced in Fig. 1, Plate II) Lumière paper was employed. Each photograph of a section of the tube was mounted on a black background in its correct position relative to the remainder. The composite photograph thus obtained measured about 2 feet square. For the experiments made to study the movements of the currents of mixture ahead of the flames, wherein a sensitive jet of flame was photographed, a Debrie cinematograph camera, capable of recording 250 images per second, was employed. The jet of flame was rendered highly actinic by coloration with copper salts.

The mixtures of methane and air were prepared in gas-holders over glycerol and water and were analysed before use. The tube was filled by displacing the air with 6 to 8 times its volume of the mixture, the ends being temporarily closed by brass discs having central tubulures. These discs could be slid away from the ends without causing disturbance of the mixture within the tube. Ignition of the mixture was effected in each instance by the flame of a spirit burner passed slowly across the mouth of the tube.

These experiments form 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.

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