XLVI.—*The Ignition of Gases. Part VI. Ignition by Flames. Mixtures of the Paraffins with Air.*

By NOEL STANLEY WALLS and RICHARD VERNON WHEELER.

ONE of the objects of the research of which the present paper forms a part has been to determine, more particularly in relation to problems of safety in coal mines, which mixtures of methane (firedamp) and air can be most readily ignited. It has been shown that this question can only be answered fully when the means of ignition are specified, for the answer depends primarily on the nature of the source of ignition.

For example, mixtures containing 5—6% of methane have been found to be the most readily ignited by the walls of a heated chamber into which they are admitted, the temperature required being lowest for these mixtures (J., 1922, **121**, 2079); but when the source of ignition is an electric spark, whether capacity or inductance, mixtures containing 8·25—8·5% are the most readily ignited, the sparks just capable of igniting them having the least energy (J., 1920, **117**, 903; 1925, **127**, 14).

The essential difference between these two sources of ignition lies in their time of contact with the mixture to be ignited, with respect to which they represent extremes, the heated surface being a maintained, and the electric spark a momentary, source of heat. It has been shown that ignition by a heated surface is not instantaneous; at the "ignition-temperature," * the time of contact between the heated surface and the mixture required before inflammation can occur may be many seconds, whilst even at temperatures several hundred degrees higher than the ignition temperature there is a measurable lag on ignition. On the other hand, we have given reasons for believing that the study of the ignition of gases by a momentary source of heat of high temperature should be regarded more as a study of the propagation of flame than of its initiation (J., 1924, **125**, 1858), flame spreading away from the path of an electric discharge most readily in those mixtures in which the speed of propagation normally is fastest.

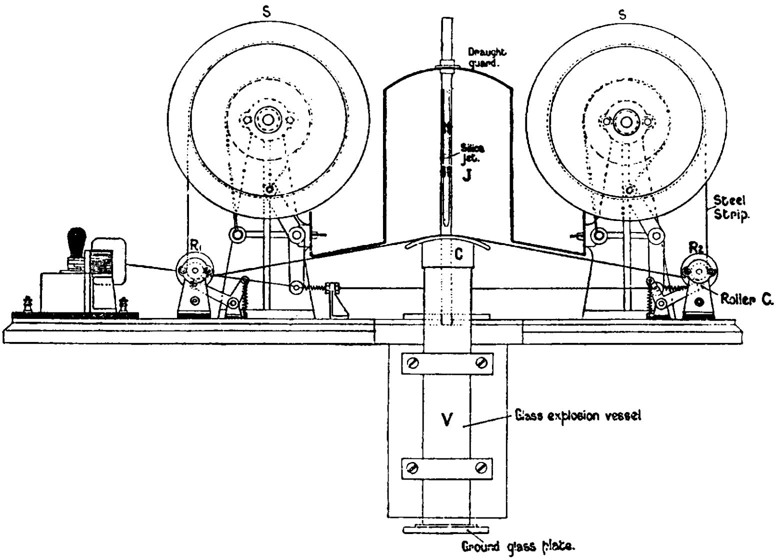
It will be realised that a heated surface, even at a very high temperature, would fail to ignite a gaseous mixture if it did not remain in contact with it beyond the duration of the period of "lag," and it can be understood that any source of ignition of high intensity, *e.g.*, a flame, might fail for the same reason. Flames

* *I.e.*, the lowest temperature, under the conditions of experiment, at which inflammation takes place, no matter how long the surface remains in contact with the mixture.

can, indeed, be projected into explosive mixtures of methane and air without igniting them, a fact which suggested means of determining the relative ignitability of different mixtures of methane and air, for, although any sustained flame is at a temperature sufficiently high to ignite any mixture of methane and air,* it should be possible, by limiting the time of exposure of a flame of given character to different mixtures, to discriminate between them.

Preliminary experiments (Safety in Mines Research Board, Paper No. 24, 1926) showed that the lag on ignition of mixtures

FIG. 1.



of methane and air by flames was sufficiently long to permit of accurate measurement, and that the duration of the lag varied with the composition of the mixture. An apparatus was therefore devised to measure the minimum time of exposure necessary for a flame of standard character to ignite mixtures of known composition. In this way, the relative ignitabilities of different mixtures could be expressed in terms of the duration of the lag on ignition under the conditions of experiment. The apparatus (for details, see "Experimental") consisted of a glass explosion vessel, V (Fig. 1), with a cap of brass, C, over which a thin steel strip could

* A possible exception is the "cool flame" observed in special circumstances, as in a gently-warmed mixture of ether vapour and air.

be rapidly moved. The exposure of the inflammable mixture to a flame playing vertically downwards from a silica jet, J, was effected when a hole, 1 cm. in diameter, in the steel strip coincided with a hole of the same diameter in the brass cap. The duration of exposure was varied by varying the speed of movement of the steel strip.

It was early found that the flame to be used as the source of ignition of a mixture of given composition must be fully aërated, otherwise it would abstract oxygen from the mixture and alter its composition before igniting it. In a series of experiments, *e.g.*, with methane and air, a false idea would thus be given regarding the composition of the most readily ignitable mixture. The flame used for the experiments described in this paper was a fully aërated coal-gas flame.

A close study of the manner in which the flame was exposed to the mixture during these experiments showed that, although its length when burning in still air was sufficient, its tip did not enter the explosion vessel when the hole in the cap was uncovered by the hole in the steel strip. The disturbance of the air caused by the rapidly moving strip caused the tip of the gas-jet to flatten in such a manner that a disc of flame was presented to the mixture. By adjusting the length of the flame when burning in still air, the diameter of the disc of flame exposed to the mixture during an experiment could be varied. With a flame adjusted to be 1 cm. in length, the disc was about half the diameter of the hole in the brass cap of the explosion-vessel; whilst when the jet was 1·5 cm. long the disc spread completely over the area of the hole. Under the latter conditions, it was not easy, with the apparatus as designed, to discriminate between the durations of exposure required to ignite mixtures of methane and air containing between 8 and 12% of methane, but with the smaller disc of flame marked differences could be measured throughout the range of inflammable mixtures.

Experiments were made with methane, ethane, propane, and pentane in admixture, severally, with air.

Mixtures of Methane and Air.—The results obtained for the lag on ignition of mixtures of methane and air, using three different sizes of disc of flame as the source of ignition, are in Table I. The recorded areas of the discs of flame are approximate. The measurements actually made to ensure that the area of flame was constant in each series of experiments were of the lengths of the jets when burning in still air.

The general conclusion to be drawn from these results is that the mixtures of methane and air most readily ignited by fully

TABLE I.

The Ignition of Methane–Air Mixtures by Flames.

Flame area : 20 sq. mm.		Flame area : 45 sq. mm.		Flame area : 75 sq. mm.	
Methane, %.	Duration of exposure required for ignition (millisecs.).	Methane, %.	Duration of exposure required for ignition (millisecs.).	Methane, %.	Duration of exposure required for ignition (millisecs.).
7·90	12·40	7·95	6·94	7·40	7·50
8·05	9·25	8·15	5·42	8·10	3·64
8·20	8·75	8·20	5·12	8·45	3·62
8·65	7·90	9·35	4·38	9·15	3·61
8·70	7·81	10·80	4·50	9·95	3·53
9·05	7·37	12·70	7·50	10·70	3·56
9·65	6·90			11·10	3·62
10·30	6·90			12·05	3·60
10·85	7·12			12·15	3·63
				12·70	6·69

aërated flames, inasmuch as the time of contact required is shortest, contain 9·5—10·0% of methane.*

The duration of exposure required for ignition to occur, as might be expected, is less the larger the area of the flame used as the source of ignition; whilst, under the conditions of these experiments, the larger the area of the igniting flame the less marked is the differentiation between one mixture and another.

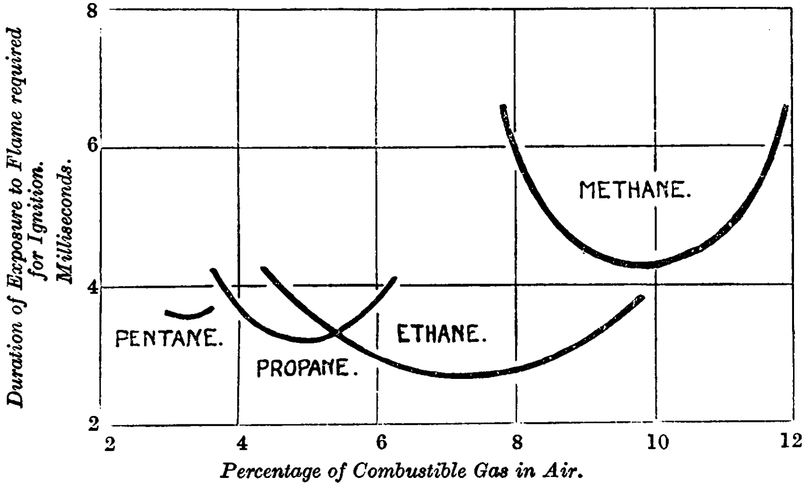
Mixtures of the Higher Paraffins and Air.—There was considerable difficulty throughout this research in maintaining such constancy of experimental conditions as would ensure that the results recorded were strictly comparable one with another, and frequent check experiments with a given mixture, adopted as standard, were necessary. In particular, great care had to be taken to avoid disturbing the position of the silica nozzle at which the igniting flame was produced, for the character of the flame as presented to the mixture to be ignited was thereby altered. If this occurred during a series of experiments, it usually saved time to start the series afresh rather than to attempt to reproduce previous conditions.

The results recorded in Table I for mixtures of methane and air were all obtained under strictly comparable conditions of experiment, but when attempting to continue the series to include the ignition of other paraffins we were not so fortunate. We have determined, however, in individual series not comparable one with another,

* In earlier experiments, when an under-aërated flame was used, the mixtures containing the lower percentages of methane appeared to be more readily ignitable, for the reason already given. A similar effect has been observed during experiments on the ignition of mixtures of methane and air by heated wires when the wire has been of a readily oxidisable metal.

the most readily ignitable mixtures of ethane, propane, and pentane, respectively, with air. We have also obtained relative values, under standard conditions, for the duration of exposure to a fully aërated flame required for the ignition of each of these most readily ignitable mixtures. From these data, curves can be constructed relating percentages of each combustible gas in air with the time of exposure to a standard flame required to ignite them, and each curve can be assigned its proper position relative to the others. Such curves are reproduced in Fig. 2.

FIG. 2.



The composition of the most readily ignitable mixture in each instance corresponds fairly closely with that of the mixture in which the initial speed of propagation of flame is most rapid. The values are recorded in Table II.

TABLE II.

Combustible gas.	Mixture in which speed of uniform movement of flame is fastest. (Combustible gas, %.)	Relative speed of flame (cm./sec.).*	Mixture most readily ignited by flame. (Combustible gas, %.)	Relative duration of exposure of flame required (millisecs.).
Methane	9·65	91	9·8—10·0	4·3
Ethane	6·05	127	6·8— 7·0	2·7
Propane	4·45	114	4·8— 5·0	3·2
n-Pentane	2·90	115	3·1— 3·3	3·5

* In a horizontal brass tube 5 cm. in diameter (Mason, J., 1923, **123**, 210).

The deduction to be drawn from these results is that the ease of ignition of an explosive mixture by a momentary source of heat is dependent essentially on the normal speed of propagation of flame in the mixture. Ease of "ignition," therefore, here corresponds with the ability of the flame to travel through the mixture after the source of ignition has been removed. This is the same deduction as was drawn with respect to ignition by the impulsive electrical discharge, and a similar explanation, *viz.*, that a certain minimum volume of an explosive mixture must be burnt in order that there shall be a spreading inflammation through it, can be advanced.

There is thus a marked resemblance between the phenomena of ignition of the paraffin hydrocarbons by means of momentary flames and by means of electric sparks. The resemblance persists when the effect of increasing the area of flame momentarily exposed to the mixtures (see Table I) is compared with the behaviour of capacity and inductance sparks, respectively. Just as increasing the area of the flame renders it more difficult to differentiate between one mixture and another with respect to its ignitability, so does the larger volume of inductance sparks, as compared with capacity sparks, have the effect of masking small differences in the ignitability of those mixtures that are most readily ignited.

EXPERIMENTAL.

Details of the apparatus used for bringing the various mixtures into contact with a flame during a measured small interval of time are as follows.

The steel strip (Fig. 1) was 0·05 mm. in thickness and 3·81 cm. broad. It was wound by means of an electric motor from one spool, S, to another under rollers, R_1 and R_2, between which the explosion vessel was mounted. Arrangements were made whereby the speed of movement of the strip could be accurately measured and, to avoid accidents due to overwinding, its movement automatically stopped a short time after the exposure of the mixture in the explosion-vessel to the jet of flame.

The explosion-vessel was 5·5 cm. in diameter and 50 cm. long. Its upper end was closed by the brass cap, C, as already explained, and the lower end could be closed by a ground-glass cover-plate whilst the mixture to be tested was being introduced. This was done by exhaustion of the air through a tap at the side and its replacement by a mixture of known composition previously prepared in a gas-holder. The hole in the brass cap, which was 1·5 mm. thick, had its lower edge brought to a thin bevel.

In carrying out an experiment, the speed of movement of the steel strip, from which the time of exposure of the flame to the mixture could be calculated, was adjusted roughly so that ignition of the mixture did not occur, and then a series of trials was made with carefully regulated speeds so as to determine accurately the duration of exposure necessary for ignition. The measurements of duration of exposure had a maximum error of 0·012 millisec.

This work has been carried out for the Safety in Mines Research Board, to whom our thanks are due for permission to publish.

THE UNIVERSITY, SHEFFIELD. [*Received, August* 31*st*, 1926.]