XLVIII.—*The Movement of Flame in Closed Vessels: After-Burning.*

By Oliver Coligny de Champfleur Ellis and Richard Vernon Wheeler.

When an explosive gaseous mixture is ignited at some point within a closed vessel, the speed at which the flame begins to spread * is compounded of the speed at which the inflammation is propagated, *i.e.*, is communicated from layer to layer of the mixture, and the speed at which the portion of the mixture about to be burnt moves

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* The effect of any initial impetus that may be given by the source of ignition employed is here ignored.

under the expansive force of the portion already burning. Unless the speed of propagation of flame is very rapid, or the vessel very small, the unburnt mixture ahead of the flame-front at first moves freely without being appreciably compressed. A time comes, however, when, owing to the nearness of the walls of the vessel, the unburnt mixture ahead of the flame-front can no longer move freely. Its movement slackens until it ceases, the whole of the mixture between the flame-front and the walls of the vessel being compressed meanwhile, and, eventually, the direction of movement tends to be reversed. The movement of the flame is affected by this slackening of movement of the unburnt mixture, an appreciable retardation of its speed occurring as the walls of the vessel are approached (see *Fuel*, 1925, 4, 356).

This behaviour of the flame is illustrated in Fig. 1, Plate I, which shows a photographic record, taken on a rapidly revolving drum, of the flame in a 58·4% mixture of carbon monoxide and air moving away from the point of ignition at the centre of a sphere of glass, 9 cm. in diameter. In taking this and similar photographs reproduced in this paper, the outside surface of the sphere was covered with a layer of dead-black paint except for a horizontal slit, 3 mm. wide, facing the camera. The lens was focussed on a vertical plane passing through the point of ignition at right angles to the axis of the lens, and the sensitised paper can be regarded as moving vertically downwards. There is thus obtained a time–distance graph of the movement of the flame-front across the slit in either direction from the centre to the sides of the sphere. The speed of travel of the paper was recorded by photographing on it the sparks produced at the mercury contacts of an electrically-maintained tuning-fork of 100 frequency. The limits of the vessel are indicated on the photograph by the vertical parallel lines drawn thereon. It will be seen that the flame travelled from the spark at a uniform speed until within 1 cm. of the walls of the vessel, when a gradual retardation began.

It will be convenient to designate these two chief phases in the propagation of flame within a closed vessel, which are exhibited whatever the shape of the vessel, as Phase I and Phase II. During Phase I, which is of far longer duration when the vessel is of large volume, the speed of the flame when ignition is at the centre of a sphere, is nearly uniform. During Phase II the speed gradually decreases.

It will be understood that during Phase I the proper motion of the flame and that of the unburnt mixture ahead of the flame-front have the same direction, the unburnt mixture being moved freely as though it were not enclosed. During Phase II, the direction of motion of the flame and of the mixture may be opposed and combustion proceeds under an enhanced, and increasing, pressure which the mixture began to experience after Phase I of the propagation of flame had come to an end. Even the most sensitive pressure-gauge, without appreciable "lag," attached to the wall of the vessel, does not begin to register pressure until Phase I of the propagation of flame has ceased. This will be demonstrated in another communication.

We are particularly concerned in the present investigation with the behaviour of the flame during Phase II, and with the condition then obtaining of the products of combustion of Phase I. In our study thereof we have employed mainly the method of "snapshot" photography previously described (J., 1925, **127**, 764), using carbon monoxide as the inflammable gas.

Explosions within a Sphere.—The series of photographs on Plate II was taken at successive stages during the explosion of a mixture of carbon monoxide and air containing 32·35% of carbon monoxide (corresponding almost to $2CO + O_2 + 3N_2$), saturated with water vapour at 15·5°, initially at atmospheric pressure. The explosion-vessel was a glass sphere, 9 cm. in diameter. Ignition was by a single secondary discharge at a 1·5 mm. spark-gap between platinum electrodes at the centre of the sphere. The photographs were taken on a vertical plane through the spark-gap. Each exposure lasted 1·67 millisecs., except that for photograph No. 12, which lasted 3·69 millisecs. For the purpose of reproduction, these photographs have been reduced to one-third of their original size. The boundary of the explosion-vessel is indicated by a white circle drawn on each photograph.

In the mixture used, flame travels at the same speed in all directions from the spark-gap. Its progress in a vertical plane can be traced in the photographs up to and including No. 6, where it can be seen touching the boundary of the vessel simultaneously at all points, the time taken for it to travel from the centre being 13·7 millisecs. It will be observed that the central portion of the vessel has become re-illuminated and remains illuminated long after the flame has touched the walls. The area illuminated gradually decreases, and the luminosity diminishes in intensity but is still appreciable 77·7 millisecs. after ignition or about 64 millisecs. after the flame has reached the boundary.

The point to which we wish to direct particular attention is that the re-illumination at the centre of the vessel began before the flame had touched the walls. It began, in fact, as soon as, or just after, what we have termed Phase II of the propagation began. At this instant, photograph No. 5 shows the presence of (i) a spherical

PLATE I.

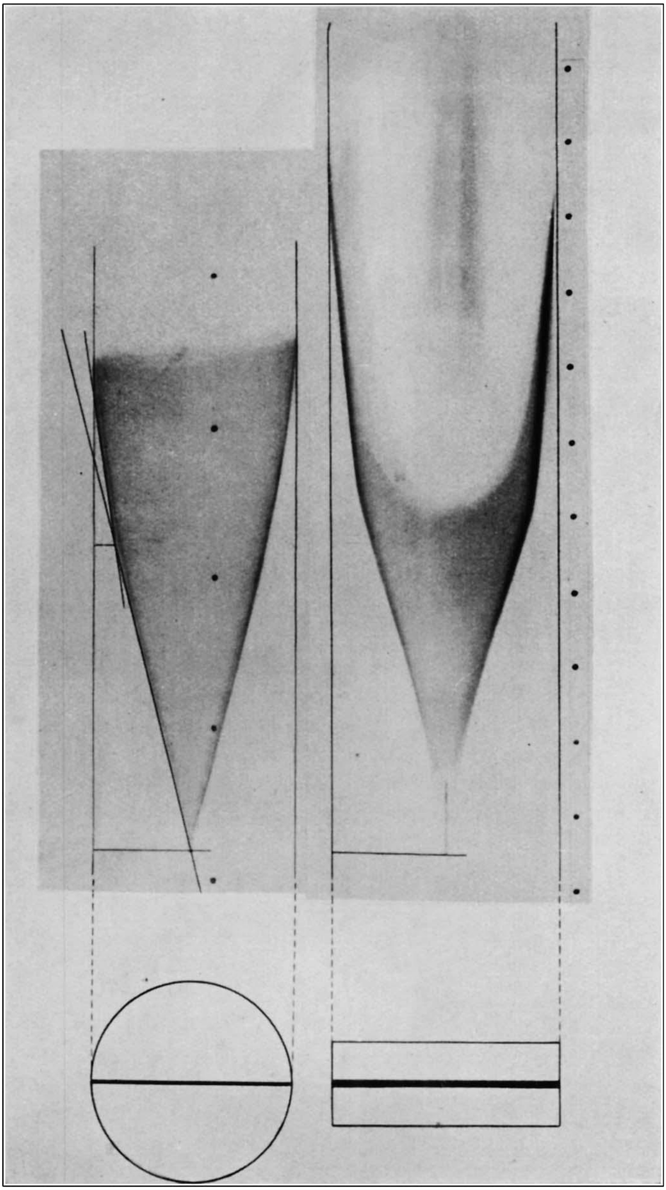

Fig. 1. **Fig. 2.**

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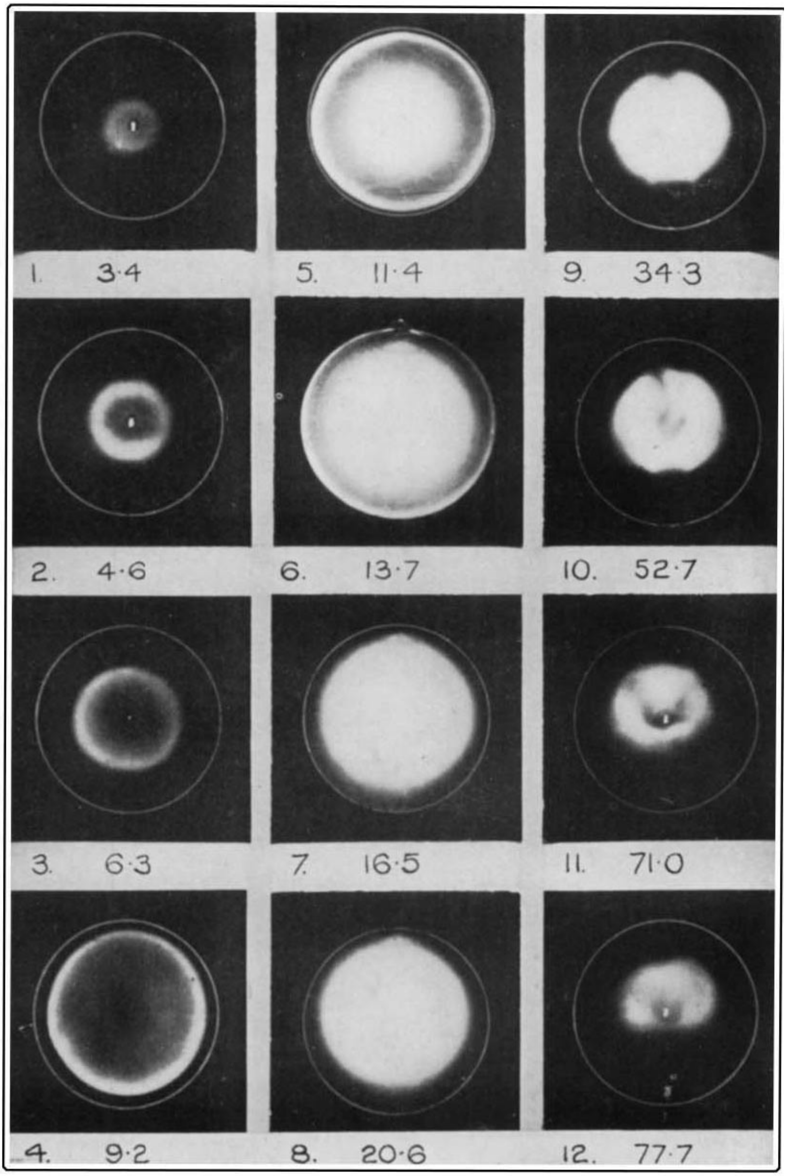
PLATE II.



1. 3·4

2. 4·6

3. 6·3

4. 9·2

5. 11·4

6. 13·7

7. 16·5

8. 20·6

9. 34·3

10. 52·7

11. 71·0

12. 77·7

The figures below each photograph record the times after ignition, in milliseconds, at which the photograph was taken.

shell of unburnt mixture between the flame-front and the walls of the explosion-vessel (non-luminous); (ii) the flame-front (luminous); (iii) the products of combustion just behind the flame-front (faintly luminous); and (iv) the residual gases from Phase I (brightly luminous).

Explosions within a Cylinder.—When the explosion occurs within a cylinder, the two chief phases in the propagation of flame have rather different characteristics from those of the corresponding phases when the explosion-vessel is spherical, but they are perhaps more clearly defined.

The photograph reproduced in Fig. 2 on Plate I was obtained in the same manner as that shown in Fig. 1 and should be compared with it. The explosion-vessel was a horizontal cylinder, 6 cm. in diameter and 16 cm. long. A 21·8% mixture of carbon monoxide and air was ignited at the centre of the vessel. The photograph is a time–distance graph of the movement of the flame-front along the axis of the cylinder in either direction from the centre to the ends. Phase I, during which the speed of the flame-front along the axis of the cylinder accelerates, ends just after the flame-front travelling transversely from the point of ignition has reached the walls of the cylinder. During Phase II the speed of the flame-front, which is now travelling in either direction horizontally only, is considerably retarded. In a cylinder of larger diameter the speed of the flame during Phase I is nearly uniform.

The series of photographs reproduced on Plate III are of stages in the explosion of a 27·7% mixture of carbon monoxide and air in the same cylinder, ignition being at the centre. The mixture was saturated with water vapour at 18° and was initially at atmospheric pressure. The intervals after ignition at which the photographs were taken are recorded below them. Each exposure lasted 2 millisecs.

As in a spherical explosion-vessel, the flame begins to travel at a uniform speed in all directions from the spark-gap, but it soon becomes egg-shaped because of its tendency to travel towards the ends of the cylinder rather than towards the sides. Phase I came to an end in photograph No. 4, 20·5 millisecs. after ignition, and signs of re-illumination at the centre of the vessel are noticeable (in the original negative) in the next photograph, taken 4·1 millisecs. later. The luminosity is well marked in photograph No. 7, just before the flame reaches the ends of the cylinder, and persists during at least 40 millisecs. after the flame has reached the ends, ultimately assuming a distinctive shape.

Similarly, numerous series of experiments, with different explosive mixtures ignited at different points within closed vessels of various shapes, have all shown that, when the luminescence we have described occurs, its inception corresponds with the beginning of Phase II. When ignition of the mixture is central with respect to the walls of the containing vessel, the luminous zone is near the centre; when ignition is asymmetric, the luminous zone occupies a position nearly central with respect to the contour of the flame-front at the end of Phase I; when there is multiple ignition, there is a luminous zone in the neighbourhood of each point of ignition. The luminescence must therefore be exhibited by the residual gases from Phase I of the propagation of flame.

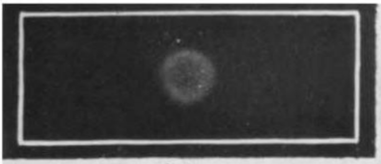
Three possible explanations of this luminescence suggest themselves. It may be due to (i) the re-association of dissociated molecules of carbon dioxide or steam; (ii) the dissociation of such molecules; or (iii) the completion of the combustion of molecules of (in the present instance) carbon monoxide that escaped being burnt whilst the flame was travelling.

Re-association. The zone of gas which exhibits the recrudescence of luminosity is that which was burnt during Phase I of the propagation of flame, *i.e.*, whilst combustion was taking place at comparatively low pressure and low initial temperature, for the unburnt mixture ahead of the flame was moving during this phase. Conversely, no luminosity (or, in some instances, which will be referred to later, but a faint luminosity) can be observed in the products of combustion formed during Phase II, which took place at comparatively high pressure and high initial temperature.

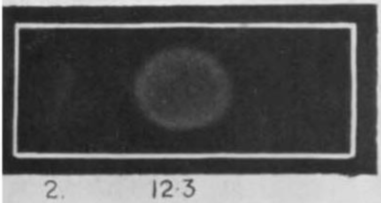
Re-association can only take place in the reactions under consideration on a falling temperature gradient, and the mass of gas in which it begins will be at a lower temperature than the remainder. But the residual gases from Phase I, at the time that they begin to show luminosity, cannot be falling in temperature, for they are being compressed owing to the combustion proceeding during Phase II. The luminescence begins long before any material cooling effect is possible. It is not normally displayed by the products of combustion of Phase II, which include those of the layer of mixture near the boundary of the vessel, when they begin to cool.

A reddish-yellow glow can often be observed after the flame in a closed vessel has completely expired. This glow can reasonably be assumed to be due to reassociation. We have not been able to photograph it, but its inception and duration could be studied by means of our apparatus, the camera being replaced by the eye, which is shielded during successively increasing intervals of time in a series of experiments with the same mixture. This dull glow is observed with mixtures which show no signs of luminescence,

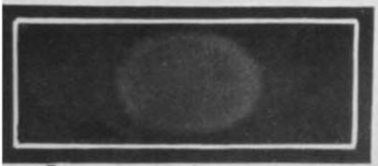
PLATE III.



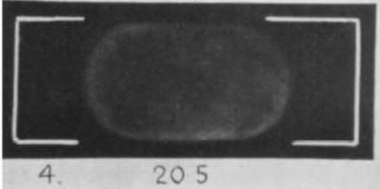
1. 8·2



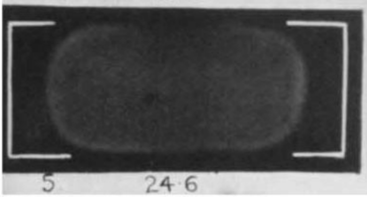
2. 12·3



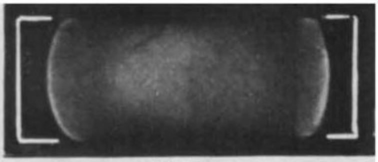
3. 16·4



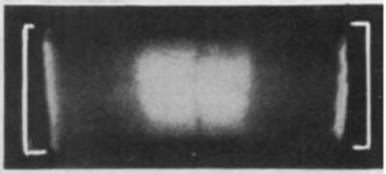
4. 20·5



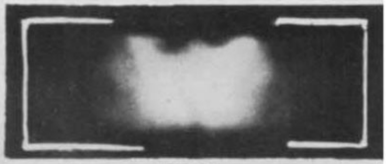
5. 24·6



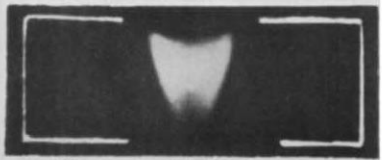
6. 28·7



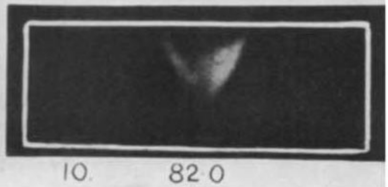
7. 38·9



8. 53·3



9. 65·6



10. 82·0

The figures below each photograph record the times after ignition, in milliseconds, at which the photograph was taken.

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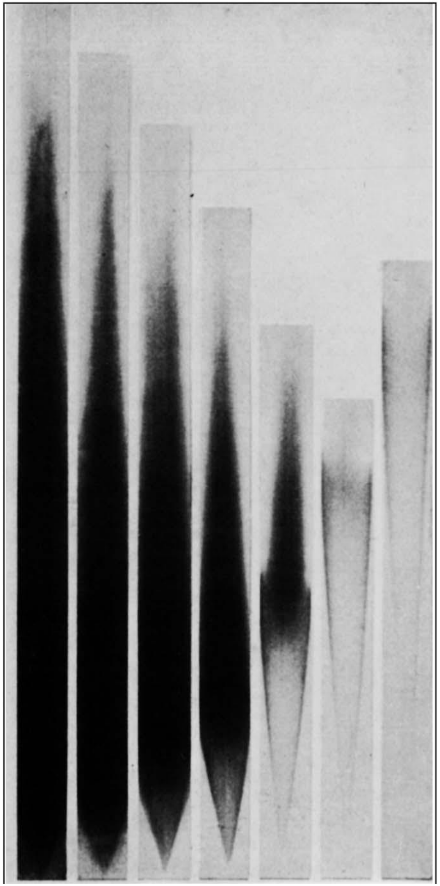
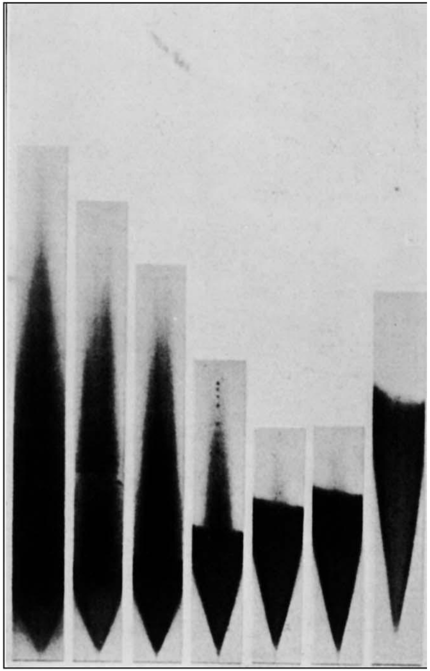
PLATE IV.





e.g., $2CO + O_2 + 4CO_2$, the calculated flame-temperature of which is about 2230° K., the amount of dissociation of carbon dioxide being about 1·5%. It is quite distinct in character from the luminescence the cause of which we are now considering. This is markedly actinic and leaves an impression on the eye of brilliant whiteness.

Dissociation. We have shown that the luminescence begins before material cooling of the gases which exhibit it can have begun. Actually, it would seem that the luminous gases, when they first make their appearance, are at a higher temperature than the products of combustion just behind the flame-front (which is then passing through Phase II) and, after the flame has reached the boundary, they represent the hottest zone within the explosion-vessel (Hopkinson, *Proc. Roy. Soc.*, 1906, *A*, **77**, 387). Confirmatory evidence of this is to be seen in the locus of the luminescence within the vessel. In a sphere, when ignition is central, its locus is above the centre of the vessel (Figs. 8—12, Plate II). In a horizontal tube, ignition being at the centre, the central zone of luminescence is banked on both sides, just as banks of warm and cold air occur in the atmosphere, the slant planes heeling over towards the denser medium. This is well illustrated in the last three photographs on Plate III.

The fact that the gases exhibiting the luminescence remain at the highest temperature removes the possibility that dissociation of carbon dioxide or steam is its cause. Such dissociation must be accompanied by the absorption of heat, not by its evolution.

We conclude, then, that the luminescence is due to the completion of the combustion, under increased pressure, of molecules of combustible gas that escaped being burnt whilst the flame was travelling. This is, we believe, the conception of the "after-burning" postulated by Sir Dugald Clerk to account for the "lost" pressure in the gas-engine cylinder when he states: "The explosion is complete when maximum pressure is attained. It does not follow from this that the combustion is complete; that is another matter. The explosion arises from the rapid spreading of the flame throughout the whole mass of the mixture, which may be called the inflammation of the mixture. More or less rapid inflammation means more or less explosive effect, but not complete combustion. The complete burning of the gases present may not occur until long after complete inflammation" (Dugald Clerk, "The Gas, Petrol and Oil Engine," Vol. I, p. 128. London, 1910). We propose to attach this meaning to the term hereafter, despite the fact that it has been used by other writers in a different sense.

After-burning.

If after-burning be the true explanation of the luminescence now described, it should be possible to decrease or augment its amount by providing more or less favourable conditions for combustion to take place whilst the flame is travelling.

The Effect of Concentration of the Reacting Gases.—A series of mixtures $2CO + O_2 + nO_2$, saturated with water vapour at 0° (*i.e.*, containing 0·63% by volume of water vapour), was fired in a sphere 9 cm. in diameter, ignition being at the centre. Photographic records of the explosions were obtained on a rapidly revolving drum in the manner already described. The secondary discharge that caused ignition was produced in an identical manner in each experiment, the current through the primary circuit of the induction-coil being adjusted to a constant value. The records show (*a*) the total time taken for the flame to travel, in a vertical plane, from the centre to the walls of the vessel, which may be termed the duration of the flame; and (*b*) the duration of the after-burning beyond that of the flame. The results are recorded in Table I.

TABLE I.

The Explosion of $2CO + O_2 + nO_2$ *in a Closed Vessel.*

(Mixtures saturated with water vapour at 0°.)

Value of *n*.	Duration of flame (centisecs.).	Duration of after-burning (centisecs.).
2	2·7	19·7
3	3·3	16·9
4	3·75	16·25
5	4·9	14·7
6	7·7	6·4
7	11·3	0·8
8	15·1	Nil.

The mixture $2CO + O_2 + 9O_2$ is near the lower limit of inflammability. It will be seen that with the mixture $2CO + O_2 + 8O_2$ the concentration of oxygen has enabled the carbon monoxide to be burnt sufficiently completely during Phase I of the propagation to prevent any after-burning outlasting the flame. In each instance the after-burning had its origin in the products of combustion during Phase I of the propagation of flame and began to be noticeable just after Phase II had begun. The products of combustion during Phase II showed no traces of after-burning.

Similarly, in the series $2CO + O_2 + nCO$, saturated with water vapour at 0°, the results recorded in Table II were obtained.

In these mixtures after-burning was evident, from the photographic records, in the products of combustion during Phase II. The photographs of series I and II, reduced in size, are reproduced

TABLE II.

The Explosion of $2CO + O_2 + nCO$ *in a Closed Vessel.*

(Mixtures saturated with water vapour at 0°.)

Value of *n*.	Duration of flame (centisecs.).	Duration of after-burning (centisecs.).
4	2·1	11·2
5	2·3	9·3
6	2·5	7·8
7	3·4	4·7
8	4·2	1·8
9	4·4	1·5
10	6·9	Nil.

on Plate IV. In each photograph, the boundaries of the vessel are at the cut sides of the strip of sensitised paper, and the point of ignition is at the centre of the bottom edge.

In each series of mixtures, the duration of the after-burning clearly corresponds with the speed of propagation of the flame, being greater the greater the speed. For a given speed of flame, the duration of after-burning is less with excess of carbon monoxide than with excess of oxygen, as would be expected from considerations of mass-action. It should be noted that the duration of the after-burning is not necessarily a measure of its amount, although duration and intensity (as judged by the density of the photographic image) appear to be correlated in such series of mixtures as those recorded in Tables I and II.

The amount of gas burnt in accordance with Phase I of the propagation of flame also depends on the speed, for Phase I extends over a greater distance within the vessel the greater the speed. It can be said, therefore, that the amount of after-burning is dependent on the extent to which the propagation of flame takes place in accordance with Phase I.

The Effect of Water Vapour.—The duration of after-burning in mixtures of carbon monoxide and air or oxygen decreases rapidly as the amount of moisture present is increased. Now in a given mixture of carbon monoxide and air the presence of water vapour increases the speed of propagation of the " uniform movement " of flame, the optimum quantity being about 6% (W. Shepherd, quoted by Payman and Wheeler, J., 1923, **123**, 1253), and therefore should, according to the experiments just described, allow of greater facility for after-burning. The results for a mixture $2CO + O_2 + 4N_2$ are recorded in Table III.

The mixtures were saturated with water vapour at different temperatures, the initial pressure in each instance being atmospheric. The total mass present grew less, therefore, as the temperature rose, and the proportion of the mixture $2CO + O_2 + 4N_2$

TABLE III.

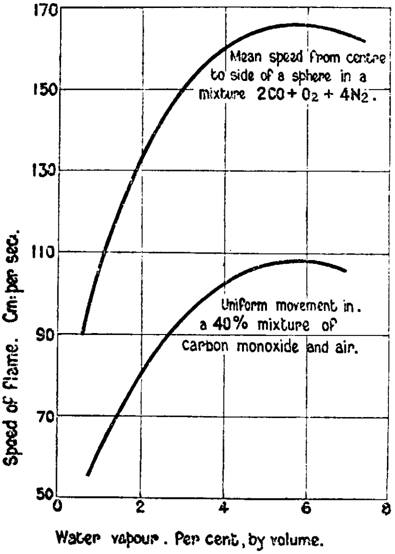
The Explosion of $2CO + O_2 + 4N_2$ *in a Closed Vessel.*

(Mixtures saturated with water vapour at different temperatures.)

Saturation temp.	Water vapour, %.	Duration of flame (centisecs.).	Duration of after-burning (centisecs.).
0°	0·63	5·1	15·8
5	0·85	4·7	15·1
10	1·21	4·0	15·2
15	1·68	3·6	15·0
20	2·31	3·2	14·1
25	3·13	3·0	13·7
30	4·20	2·8	13·2
35	5·55	2·7	11·6
40	7·28	2·8	10·4
45	9·47	2·8	9·7

in the mass grew less as the moisture content increased. A graph (Fig. 3) relating percentages of water vapour in the mixture with the mean speed of the flame from the centre to the side of the explosion-vessel bears a close resemblance to that obtained for the uniform movement of flame in a 40% carbon monoxide–air mixture, as determined by Shepherd for a tube 2·5 cm. in diameter (*loc. cit.*), and, as with the uniform movement, shows that the optimum amount of water vapour to develop the full speed of the flame under the conditions of experiment was about 6%.

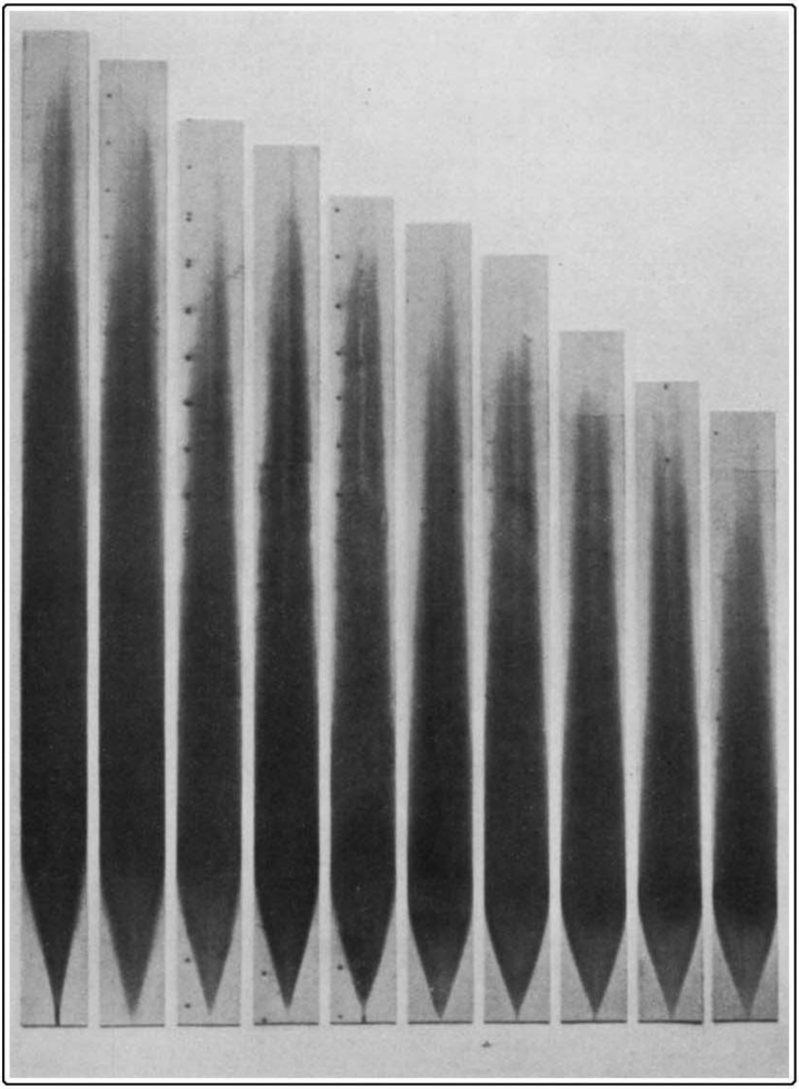
FIG. 3.



The records from which the values recorded in Table III were obtained are reproduced in Plate V. It will be seen that, despite the fact that the mean speed of the flame increased, both the duration and intensity of the luminescence decreased markedly as the moisture-contents of the mixtures increased. This effect we ascribe to the greater ease of combustion of the carbon monoxide during Phase I of the propagation of flame, due to the presence of the water vapour, there being in consequence less residual combustion or "after-burning."

The Effect of Diluent Gases.—Series of experiments were made in which different diluent gases, nitrogen, argon, and helium, were

PLATE V.



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added to the basic mixture $2CO + O_2$ in the same proportions, in order to vary the speed of flame without altering the relative concentrations of the combining gases. In each series, the proportion of water vapour was varied by saturating the mixtures at known temperatures. The results are recorded in Table IV.

TABLE IV.

The Explosion of $2CO + O_2 + 4X$ *in a Closed Vessel.*

Duration of (a) *Flame and* (b) *After-burning* (*centiseconds*).

Saturation temp.	Water vapour %.	$X = N_2$.		X = A.		X = He.	
		(a).	(b).	(a).	(b).	(a).	(b).
0°	0·63	5·1	15·8	3·4	20·3	2·1	16·6
5	0·85	4·7	15·1	3·2	19·2	2·1	16·2
10	1·21	4·0	15·2	2·9	18·4	1·8	14·9
15	1·68	3·6	15·0	2·6	17·6	1·55	14·55
20	2·31	3·2	14·1	2·4	17·2	1·5	13·6
25	3·13	3·0	13·7	2·2	16·1	1·3	13·2
30	4·20	2·8	13·2	2·1	16·0	1·15	13·2
35	5·55	2·7	11·6	2·0	15·1	1·1	12·9
40	7·28	2·8	10·4	2·0	14·1	1·2	12·3
45	9·47	2·8	9·7	2·0	11·6	1·3	10·7

Similarly, dilution of the basic mixture $2CO + O_2$ was effected by the participants in the equilibrium $2CO + O_2 \rightleftharpoons 2CO_2$, with the results shown in Table V.

TABLE V.

The Explosion of $2CO + O_2 + 4Y$ *in a Closed Vessel.*

Duration of (a) *Flame and* (b) *After-burning* (*centiseconds*).

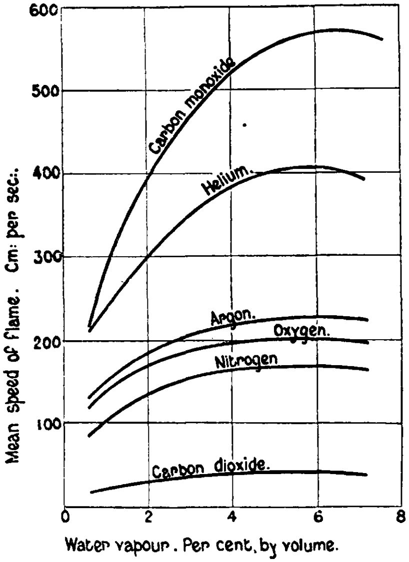
Saturation temp.	Water vapour %.	Y = CO.		$Y = O_2$.		$Y = CO_2$.	
		(a).	(b).	(a).	(b).	(a).	(b).
0°	0·63	2·1	11·2	3·75	16·25	23·3	11·5
5	0·85	1·8	11·3	3·3	16·3	20·4	11·0
10	1·21	1·45	10·35	3·0	16·0	(Not determined.)	
15	1·68	1·25	9·85	2·8	15·0	15·9	Nil.
20	2·31	1·1	9·3	2·6	14·0	13·9	,,
25	3·13	0·95	9·3	2·5	13·5	12·7	,,
30	4·20	0·85	9·15	2·4	12·8	12·5	,,
35	5·55	0·8	8·9	2·2	12·8	11·3	,,
40	7·28	0·75	7·95	2·3	11·5	11·75	,,
45	9·47	0·8	7·4	2·3	10·5	11·8	,,

From these series of experiments, we can form some judgment as to the effects of the various factors that influence the transference of heat during and after the propagation of flame, on flame-speed, and on the duration of after-burning.

The effect on flame-speeds can be studied by means of graphs

(Fig. 4) relating mean speeds of flame (measured from the centre to the side of the explosion-vessel) with percentages of water vapour in the different mixtures. As with the uniform movement of flame (Coward and Hess, quoted by Payman and Wheeler, Faraday Society Discussion, June 14th, 1926), the dependence of the flame-speed on the specific heat of the diluent gas and on its conductivity is readily apparent in the series of mixtures. The most striking comparison lies, however, in the effect of increasing the concentration of water vapour when excess of either of the two reacting gases, carbon monoxide and oxygen, is used as diluent. The effect is much more marked when carbon monoxide is in excess, although, as with all the diluents, the same optimum concentration of water vapour is indicated. The extent to which the reactivity of carbon monoxide is dependent on the presence of water vapour is thus strikingly displayed.

FIG. 4.

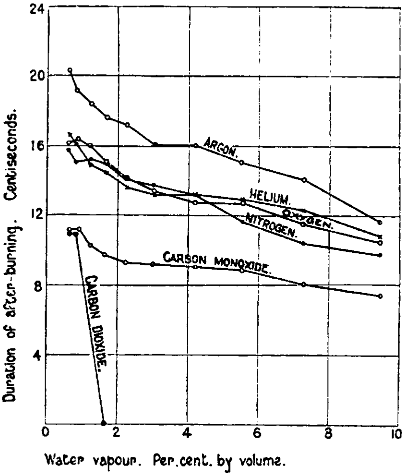


As regards the duration of after-burning, it will be understood that the records given are of the after-burning subsequent to the flame reaching the walls of the explosion-vessel, whereas we have shown that indications of after-burning begin before the flame reaches the walls. It is conceivable, in fact probable, that the inception of after-burning in the series of experiments recorded in Tables IV and V has varied with the character of the diluents X and Y. We cannot, from our present records, form an absolute estimate of the extent of variation in the time of inception of after-burning with the different mixtures (it appears to begin just after Phase II of the propagation begins); but, since by far the greater proportion of the after-burning occurs subsequent to the flame reaching the walls of the explosion-vessel, comparison of the figures recorded in Tables IV and V should serve our purpose.

It can be assumed that the amount of after-burning (residual combustion), as gauged by its duration, might be dependent upon (*a*) the degree of incompleteness of combustion during the propagation of flame, and (*b*) the facility afforded for the residual combustion to proceed. Any factor that would tend to accelerate the residual combustion would shorten its duration, and might increase its intensity.

In the several series of experiments that we have carried out, by progressively increasing the concentration of water vapour up to the optimum for the combustion of carbon monoxide, we have provided, with each diluent gas, a gradually increasing facility for completeness of combustion during the propagation of flame. By studying the general trend of variation in the duration of after-burning throughout each series, we should therefore be able to gauge the relative effect of the presence of each diluent gas in accelerating or retarding the residual combustion, as distinct from its original influence on the completeness of combustion during the propagation of flame. In Fig. 5, the duration of the after-burning, beyond that of the flame, is plotted against the proportion of water vapour in the mixtures for each of the series $2CO + O_2 + 4X$ (or 4Y).

FIG. 5.



All the photographs from which the records in Tables IV and V were obtained were taken on Lumière paper from the same source of supply. They were developed during the course of one day, each being treated during 150 secs. in a bath of standard developer at a uniform temperature of 5°. The duration of after-burning can be measured accurately within 0·1 centisec.

A fact to be noted is that no support can be obtained for the suggestion that the luminescence that we ascribe to after-burning may be due to the recombination of dissociated carbon dioxide or steam molecules. The amount of dissociation would be greatest with those mixtures having the highest "flame-temperature." The duration of after-burning is, for all concentrations of water vapour, greatest with the argon mixtures (calculated flame-temperatures, 3520° K.), and is markedly greater than with the helium mixtures, for which the calculated flame-temperatures are the same. Moreover, the duration of after-burning with the helium mixtures is nearly the same as with the nitrogen and the oxygen mixtures, although the calculated flame temperatures for these are much lower (2890° K.). With the carbon monoxide mixtures (calculated flame temperatures, 2890° K.), the duration of after-burning is throughout considerably the shortest. With the carbon dioxide mixtures, in which the speed of flame is exceptionally slow (calculated flame-temperatures, 2230° K.), there is no after-burning when the concentration of water vapour exceeds about 1·5%, but with the lowest concentration (0·63%) it is nearly as long as with carbon monoxide.

We are unable at present to offer a complete explanation of the effect of argon. We have noticed that, not only is the duration of the after-burning longest when this gas is the diluent, but its actinic effect, and that of the flame also, is greatest. In another research, in which the propagation of flame in mixtures of hydrogen and air is being studied, the substitution of argon for the nitrogen has been found greatly to affect the actinic power of the flames. It may well be that in these experiments the high actinic value of the luminescence when argon is present enables it to be registered photographically for a longer period than in the other series.

This leads us to a consideration of the relative actinic effects of the luminescence and of the flames. The photographs reproduced on Plates II and III show, what is a general observation, that the luminescence has a greater effect on a photographic plate than the flame itself. It is true that the flame is moving whilst it is being photographed, whereas the luminescence is nearly stationary, but, making allowance for this, the difference is so great as to suggest that different forms of radiation are being emitted during the two phenomena of flame propagation and after-burning. On the other hand, there is no evidence that the chemical reactions during the after-burning differ in character from those during the propagation of flame. On the contrary, it is clear (see Fig. 5) that the combustion of carbon monoxide during the after-burning is facilitated by the presence of water vapour just as it is during the propagation of flame. The actinic power of the luminescence may therefore be due solely to the fact that the combustion of the residual carbon monoxide is proceeding at a high temperature and pressure. This question can perhaps be determined by spectroscopic methods of research, which we now have in hand. The research is being continued, also, to include the combustion of gases other than carbon monoxide.

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