CCCXXXVII.—"*After-Burning*" *during Gaseous Explosions: Its Ability to cause Ignition.*

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WHEN an explosive gas-mixture is ignited at the centre of a closed sphere, at an initial pressure P_i, the burning gas cannot materially fall in temperature until, at a moment usually designated P_m or T_m (the moment of maximum pressure), the flame-surface reaches the

wall of the sphere. Then, as the gases there cool, the combustion reactions are completed on a falling temperature gradient. These supplementary chemical reactions must begin at the wall of the sphere and, as the gases there contract in volume, the adjacent layers of gases nearer and nearer to the centre of the sphere lose heat by expansion and conduction, and complete the combustion reactions.

This prolonged combustion is not the " after-burning " to which, in a previous paper (J., 1927, 30), we have drawn particular attention. Without excluding consideration of the prolonged combustion now mentioned, we were then principally concerned with a phenomenon of reluminescence during gaseous explosions which, some time before there is any possibility of cooling of the burning gases at the wall of the explosion-vessel, is first manifested near its centre (if ignition is at the centre) and spreads outwards. Combustible gas mixtures can be chosen of such a nature that this central " after-burning " is the only phenomenon of markedly actinic reluminescence that survives the period of inflammation.

We have shown that, in gaseous explosions in a closed sphere (with central ignition), as the flame-surface approaches the wall the almost motionless gases at the centre are hotter than those in a dark zone where gases are moving rapidly inward from the flame-surface. This is illustrated on Plate I, Fig. 1, which is a snapshot taken in a vertical plane 54 milliseconds after the ignition of a mixture of carbon monoxide and air (20·2% CO, saturated with moisture at 13°) at the centre of a glass sphere 9 cm. in diameter. The luminous central gases have risen within the shell of flame, which has nearly reached the wall of the sphere. With the simple combustion reactions of carbon monoxide with a mixture of oxygen and nitrogen, this delayed emission of energy under the conditions of experiment suggests that the rise in pressure exerts upon the chemical equilibrium an effect that outweighs the tendency for reversal consequent on the equivalent rise of temperature.

Under the simple conditions described, therefore, the central " after-burning " is primarily caused by the rise in pressure, whilst the " after-burning " that starts at the wall of the explosion-vessel is primarily caused by the fall in temperature.

Additional evidence that combustion is incomplete in the neighbourhood of the flame-surface has been obtained by a new optical method of studying flames, devised by Ellis and Morgan, a description of which will shortly be published. By this method it can be shown that, during an explosion in a sphere, the temperature rises to a maximum at the centre when ignition is at the centre, whereas, failing continuance of the emission of energy in the recompressed

PLATE I.

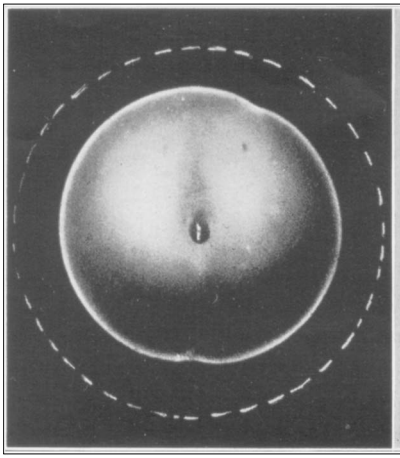


FIG. 1.

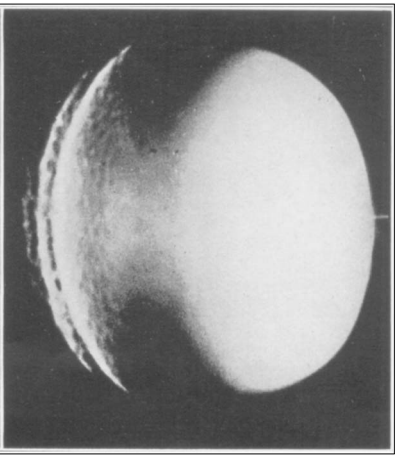
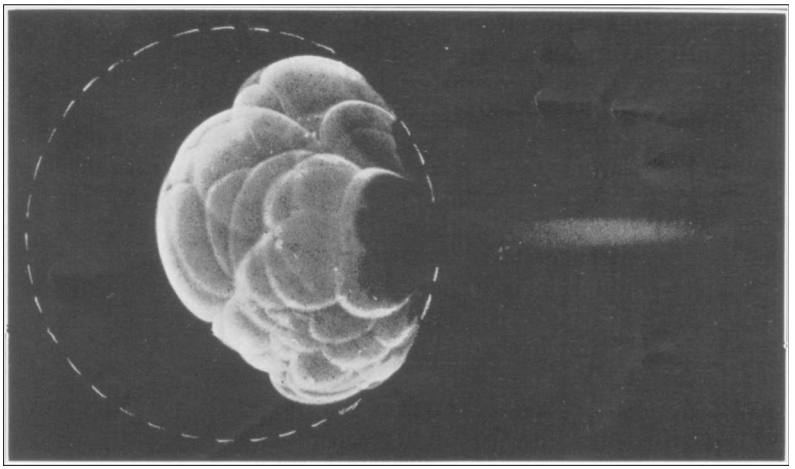
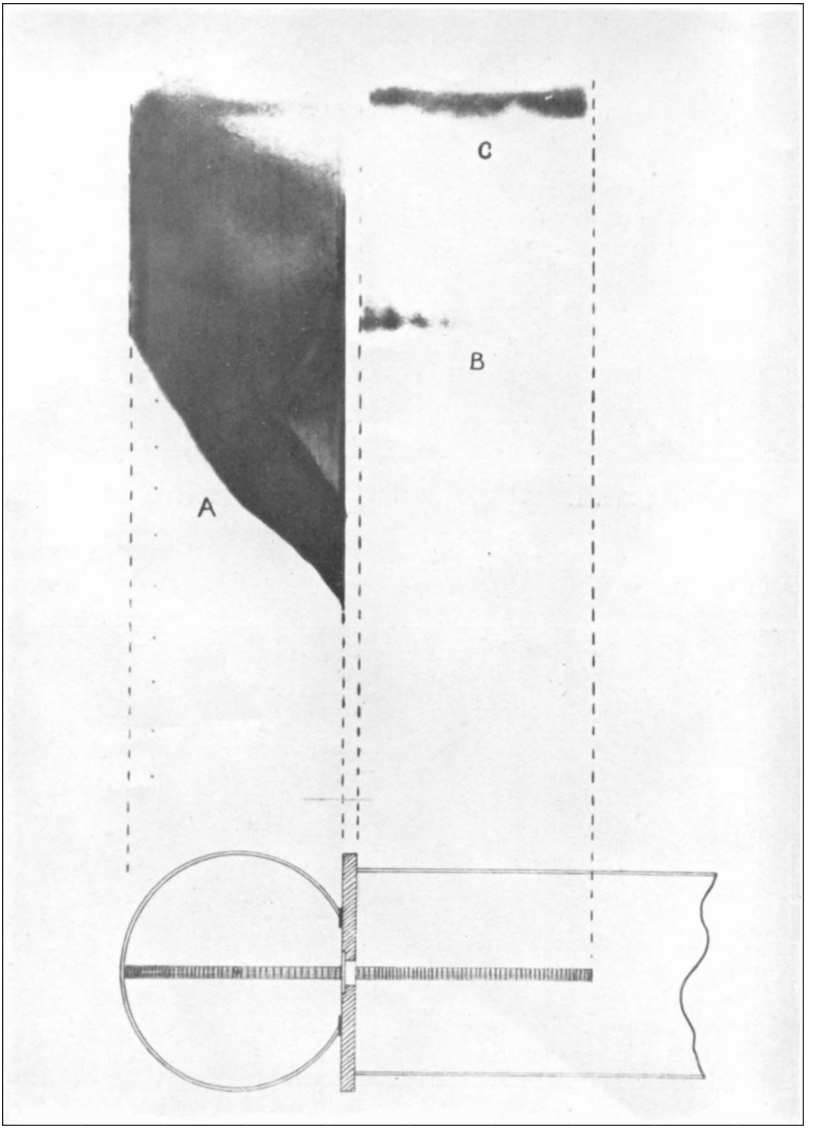


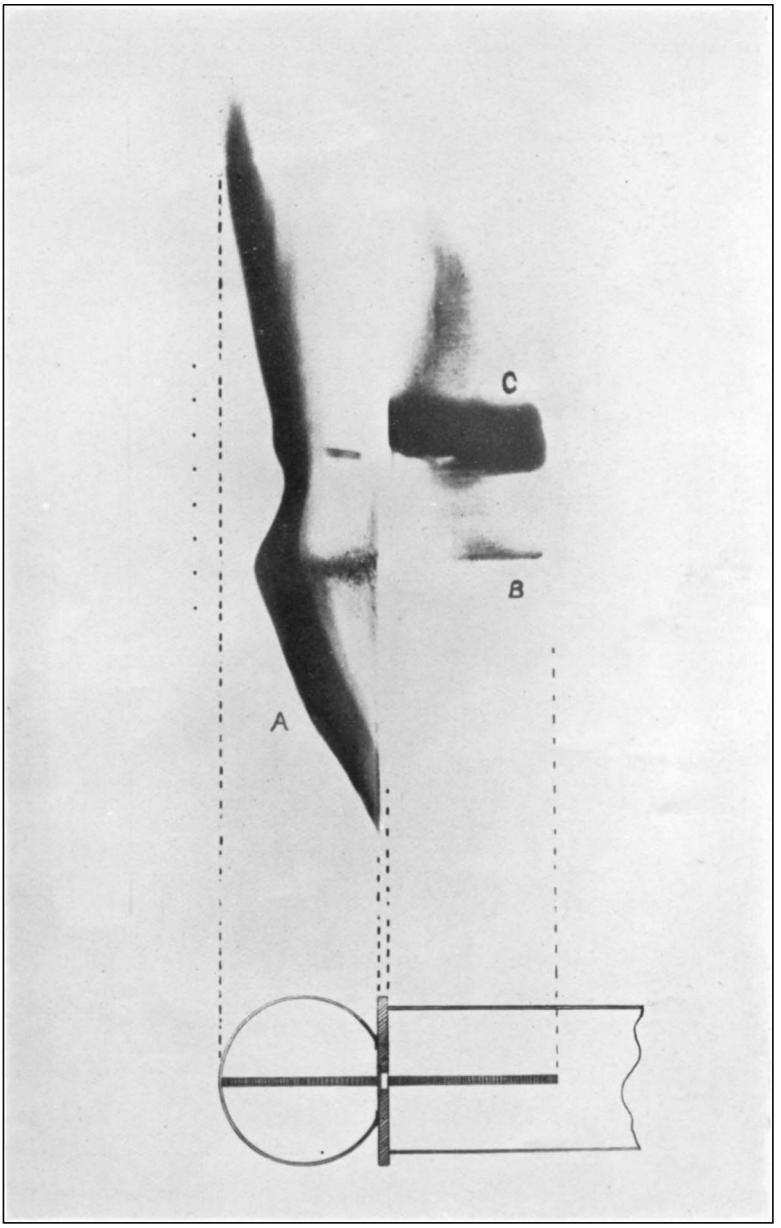
FIG. 2.



[*To face p.* 2468.]



The ignition of a methane–air mixture by the "after-burning" of a carbon monoxide–air explosion. A, flame-surface of carbon monoxide–air explosion; B, "after-burning" gases; C, flame of methane–air explosion.



The ignition of a 24% carbon monoxide–air mixture by the "after-burning" of a similar mixture. A, flame-surface; B, "after-burning" gases; C, flame of mixture ignited by the "after-burning" gases.

gases within the flame, the temperature would fall towards a minimum at the centre.

It may now be recalled (Ellis and Wheeler, *loc. cit.*, p. 314) that the region where the pre-cooling reluminescence is first manifested is near the point of ignition of the explosive mixture, wherever that may be, provided that the mixture is motionless at the moment of ignition. If ignition is at the wall of the explosion-vessel, therefore, the "central" type of reluminescence occurs in gases lying quite close to the wall. This fact enables us to demonstrate the ability of these reluminescent gases to ignite a fresh explosive mixture of either methane and air or carbon monoxide and air when suitably projected from their environment into it.

Mr. J. Harwood, M.Sc., has, at our request, carried out parallel series of experiments in which jets of argon, heated by sudden compression of the gas to 1/80th of its original volume, have been projected into different inflammable mixtures. The more readily ignitable mixtures, such as hydrogen and oxygen, could occasionally be inflamed by such jets, but mixtures of methane and air or carbon monoxide and air could not be ignited, despite the high temperature of the jets; considerably higher, according to calculation, than that of the jets of "after-burning" gases in our experiments.

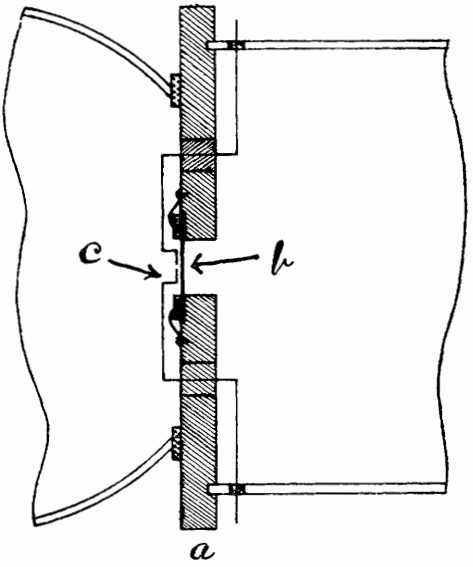
Experimental.

In carrying out the experiments, it was essential that no gases forming at the moment any part of a flame-surface should be projected with them. This consideration determined the position of the point of ignition of the primary explosive mixture. It had to be within that region of the wall of the explosion-vessel from which the "after-burning" gases were to issue. It is true that, under these conditions, the gases immediately in contact with the wall before their projection would be cooled, but the cooler sheath would rapidly be stripped off the shaft of gases as it emerged. The necessity for avoiding the projection of any of the flame-surface determined also the time at which release of the "after-burning" gases should take place. It had to be remembered that the local release of pressure that would necessarily occur at that moment would cause the flame-surface to be distorted by the general motion towards the vent (see Ellis, *Trans. Inst. Min. Eng.*, 1930, **80**, 45). Lest this distortion should be so great that part of the flame-surface would follow the "after-burning" gases through the vent, the flame was allowed to spread a considerable distance from the point of ignition before the vent was opened.

The necessity for these arrangements will be grasped from the photographs on Plate I, Figs. 2 and 3, of the ignition of explosive

mixtures at the wall of a sphere. In Fig. 2, the vent, near the point of ignition at the right-hand side, has not yet been opened, and there are three superposed snapshots of the final stages of combustion. The expiring flame-surface (three images) can be seen on the left-hand side, whilst the right half of the sphere is filled with "after-burning" gases. In Fig. 3, a single snapshot, the vent was opened far too soon for our purpose, and part of the flame-surface has been projected through the vent. In the experiments now to be described, the movements of the flame-surface were registered by a continuous photographic record on sensitised

FIG. 1.



paper wrapped on a revolving drum. No ignition of the external explosive mixture has been attributed to "after-burning" gases if such a photograph has shown that the flame-surface had approached the vent.

The wall of a spherical explosion-vessel of glass, 12·1 cm. in diameter, was ground down so as to leave a small opening with a plane rim. A three-way tap was fitted diametrically opposite this opening. The rim of the opening (see Fig. 1) bore on and protected a thin rubber washer between it and a brass plate, *a*, 7 mm. thick and 12·3 cm. in diameter, having a circular vent, 12·5 mm. in diameter, concentric with the opening in the wall of the sphere. In a shallow recess in the brass plate, concentric with the vent, lay a microscopist's "cover-glass," *b*, 0·1 mm. thick, its margin

moistened with metaphosphoric acid. This glass disc was held in position by a steel washer secured by steel clips. Electrodes passed through ebonite bushes in the brass plate near to the steel washer and terminated in sparking-points, *c*, 1·5 mm. apart, bent over so as just to clear the surface of the glass disc. On the other side of the brass plate there was a deep circular groove, concentric with the vent and 10·4 cm. in diameter, which received one end of a glass cylinder, 62 cm. in length, which could be closed at the other end. The sphere and the cylinder were clamped together in a frame, with the brass plate as a party wall. Both vessels were painted dead black except for a central window, 7 mm. wide, stretching across the sphere and 12·5 cm. along the cylinder, through which the lens of the revolving-drum camera was focused on the plane of the spark-gap.

The two vessels were evacuated simultaneously at the same rate, so as to avoid displacement or injury of the thin glass disc. They were then slowly filled, at the same rate, with the required explosive mixtures which had been prepared beforehand in glass gas-holders. The mixture in the sphere was then ignited, the outer end of the cylinder having been opened just beforehand. When a sufficient pressure had been attained within the sphere, the glass disc gave way, as though being punched out, and a jet of " after-burning " gases was projected into the cylinder.

Two records thus obtained are shown, much reduced in size, on Plates II and III. It was noticeable throughout the experiments that the luminance of the " after-burning " gases, when in rapid motion and projected as a tongue only 12·5 mm. in diameter, was considerably poorer than that of the same gases when at rest within the explosion-vessel. Often, the luminous gases yielded no photographic record. Usually, the first image on that portion of the sensitised paper that related to the end of the cylinder near the sphere was that of a flame-surface returning towards the sphere, the secondary ignition having occurred in the cylinder about 30 cm. from the vent.

Plate II records an experiment in which " after-burning " gases from a mixture of air and carbon monoxide (29% CO, saturated with moisture at 19·8°) were released into a mixture of methane and air (9·5% CH_4). These gases, which, it will be noted, emerged when the flame-surface, A, had nearly reached the far boundary of the sphere, produced a faint image, B, on the sensitised paper. Ignition of the methane–air mixture occurred within a region 30—32 cm. from the vent and the resulting flame, C, can be seen on Plate II returning towards the sphere, which it reached 5 centiseconds after the " after-burning " gases had issued from the vent,

and in part passing into the sphere. The " lag " on ignition of the methane–air mixture being rather long, it is assumed that the portion of the tongue of " after-burning " gases that ignited it was the tip, splayed out when its speed of movement had nearly ceased.

When the position of the mixtures was reversed, methane–air being in the sphere and carbon monoxide–air in the cylinder, there was hardly any " lag " on ignition of the latter, and it is supposed that the side of the jet of " after-burning " gases caused ignition, quite close to the vent, when moving at its muzzle velocity.

When methane–air mixtures were in both vessels, the lag on ignition of that in the cylinder was considerable, and ignition could be prevented altogether by a slight modification of the experimental arrangements.

With carbon monoxide–air mixtures of the same composition in both vessels, ignition by the " after-burning " gases projected from the sphere was obtained with all mixtures containing between 22 and 29·4% of carbon monoxide (saturated with moisture at room temperature). The example given on Plate III relates to 24% mixtures. Ignition was also obtained when the mixtures contained more than 29·4% of carbon monoxide, but this was not necessarily by " after-burning " gases, for, when there was excess of combustible gas in the mixture in the sphere, the expelled gases, though barely luminous as they emerged through the vent, became highly luminous on passing through air.

In carrying out these experiments, we had expected to find sufficient unintentional variation in thickness of the glass discs to cause material differences in the times at which, with the same explosive mixture, the " after-burning " gases were released. The disappointingly uniform quality of the cover-glasses, however, did not enable us to study this effect. Discs 0·127 mm. thick did not break sufficiently quickly.

For assistance in carrying out this work, we wish to thank Messrs. G. A. Russell and H. Staples. Our thanks are due also to the Safety in Mines Research Board for permission to publish the results, which form part of a research that we are carrying out for them.

SAFETY IN MINES RESEARCH LABORATORIES,
SHEFFIELD. [*Received, August 5th,* 1931.]