

PRODUCTION OF GAS LAYERS FOR LARGE-SCALE GAS EXPLOSION STUDIES
PART 1. PRELIMINARY INVESTIGATIONS

by

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PRODUCTION OF GAS LAYERS FOR LARGE-SCALE GAS EXPLOSION STUDIES PART 1. PRELIMINARY INVESTIGATIONS

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#### SUMMARY

A series of experiments on the formation of roof layers of buoyant flammable gas, using mixtures of natural gas and air and also 100 per cent natural gas, is described in which both vertical and horizontal distributions of gas concentration were determined.

Mixing of the introduced flammable gas with air in the explosion chamber was reduced by the adoption of appropriate input conditions. The distribution of gas in horizontal planes in all mixtures was found to be uniform but the vertical distribution of gas indicated the formation of diffuse layers, particularly when introducing 100 per cent natural gas. The effects of filling rate and also the change of concentration with time in a quiescent layer are described.

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#### INTRODUCTION

The explosion at Ronan Point, a high rise block of flats, which resulted in the catastrophic collapse of part of the structure, probably resulted from the ignition and explosion of a mixture of leaking town gas and air in one of the flats. Such leaking of gas from a pipe would produce a layer of gas/air mixture at ceiling level. Research is in progress at the Fire Research Station to obtain accurate information on the explosion of layers of flammable gas, which may or may not contain air, in compartments which are equipped with relieving vents, in order to obtain data for the design and construction of buildings which will remain structurally intact in the event of such explosions.

The main previous study of ceiling layer formation, produced by differences in the buoyancy of flammable gases, has related to methane in mines. The situation in mines, with large length to cross-section ratios and with controlled rates of ventilation is, however, markedly different from that in occupied rooms or compartments the dimensions of which are of the same order, and where the atmosphere is comparatively stagnant, and may not therefore be directly applicable. More appropriately, studies have been made of the effect of mechanical ventilation on the explosion hazard of gas leakages in rooms. and of diffusion on the production of separate layers of flammable gas in rooms.

The research at Fire Research Station requires the development of suitable methods for reproducibly producing, in compartments, layers of flammable gas which are of homogeneous composition and reasonably discrete. As any variation in layer thickness or of the distribution of gas within a layer could result in variations in the explosion parameters measured, it is important to establish accurately the best techniques for the consistent formation of layers. An earlier programme at Fire Research Station concerning the use of the exhaust gas from a jet engine as an inerting medium presented a useful criterion for the efficient formation of layers, which was adopted for this present work<sup>6</sup>.

This Note describes preliminary experiments on the method of formation and on determining the composition of flammable gas layers for the selection of appropriate methods for the main experimental programme on explosions in compartments fitted with pressure relieving vents.

#### **EXPERIMENTAL**

The experiments were carried out in a rectangular chamber, volume 28 m<sup>3</sup> (1000 ft<sup>3</sup>), internal dimensions 3.65 m x 3.05 m x 2.44 m high (12 ft x 10 ft x 8 ft), constructed from steel plates, and designed to withstand internal pressures of about 35 kN/m<sup>2</sup> (5 psi), Fig.1<sup>7</sup>. A vent for relieving explosions in the chamber was constructed on one of the shorter sides. Flammable gases were metered into the chamber through diffusers, described below. The composition and development of gas layers were measured with an automated high-speed gas chromatogrphic system, which could accept samples from probes at 5 sites<sup>8</sup>. Therefore, when more than 5 sites were required for sampling of the gas layers over a larger area, several replicate experiments were performed with different sitings of the probes.

Criteria for introducing a gas lighter than air into a chamber in order to minimise mixing with the existing atmosphere in the chamber and to promote distinct layering are:

- a) introduction close to the ceiling, and
- b) a value of dimensionless number  $N_1$  greater than unity, where

$$N_1 = \frac{\Delta p}{V^2} \frac{gL}{V^2} \qquad \dots (1)$$

and L = vertical dimension of entry duct

V = velocity of gas as it leaves duct

e density of injected gas

△P = difference between densities of injected gas and existing gas

g = gravitational constant

N<sub>1</sub> is related to the local Froude number at the entry point and is the ratio of the buoyancy forces which promote layering, and the gas momentum forces which might promote turbulence and stir the contents of the chamber<sup>5</sup>.

Previous investigations by the Fire Research Station have shown that reasonable layering can be obtained by the introduction of the gas through an efficient diffuser of large enough area to give a low value for the velocity of

entry<sup>8</sup>. Similar methods were therefore investigated in the experimental chamber with gas flow conditions meeting criteria (a) and (b) above. In tests of the ignition of layers in 'bunkers' where flexible porous material was used as the diffusing media, considerable care had to be exercised with the material and its packing to ensure uniform diffusion of gas. Concentric layers of wire gauze proved ineffective in this context, but flexible polyurethane foam wrapped around the gauze cylinders improved diffusion. Because the flammable foam was exposed to the explosion flame, it had a relatively short lifetime and hence was unsuitable for the present work. Ideally, the materials constituting the diffusing system should be non-flammable and withstand exposure to flames and hot gases.

In the preliminary experiments described in this Note, initially a single box-type diffuser of sheet metal packed with non-flammable mineral wool was used in one configuration with two open sides (see Fig.2b) and then in a different configuration with the upper side open (see Fig.2c) and finally a pair of diffusers each with the upper side open was used (see Fig.2d). The production and metering of the gas flow through diffusers into the chamber and the method of assessing the distribution of gas in a given layer are described elsewhere 7,8.

## EXPERIMENTS AND RESULTS

A limited number of exploratory experiments were made with a single diffuser using configurations Figs 2b and 2c ( $N_1$  between 10 and 41). Neither method gave satisfactory gas layering because of 'channelling' of the gas through the diffuser packing. The major part of this experimental programme on layering was therefore undertaken using the double diffuser system (Fig.2d).

The first series of experiments were designed to ascertain the effectiveness of the gas metering and diffusing system in establishing good horizontal and vertical distributions of gas in layers of given gas mixtures and air. A filling rate of approximately 0.9 m³/min was adopted for most experiments with natural gas/air mixtures giving a total filling time of 30 minutes. However, when natural gas alone was introduced, the filling rate was approximately 0.3 m³/min. The air displaced from the chamber by the gas/air mixtures was vented to atmosphere through ports at the bottom of the chamber sides.

## Horizontal distribution of gas

The horizontal distribution of gas was measured initially by investigating the increase of gas concentration with time using five separate probes distributed across the chamber at a common depth. The results of similar

experiments at different depths permitted the study of the gas distribution in the explosion chamber at any given time during the layering of gas/air mixtures. These experiments were carried out with a 7 per cent (lean) natural gas/air mixture ( $N_1$  = 31) as this was considered to be in a range of gas/air mixtures for which discrepancies in horizontal distribution would be most likely, because of the small differences between the properties of the gas/air mixture and those of air, and thus less likely to form stable layers. The increase of gas concentration with time for 5 probes at common depths of 0.61, 0.92, 1.22 and 1.52 m (2,3,4 and 5 ft) is shown in Figs 3 to 7 inclusive. Figures 6 and 7 are repeat tests at 1.52 m. The increase of concentration with time is sufficiently similar for each sampling point to allow a common curve to be drawn. As the above results showed that acceptably uniform horizontal distributions of gas mixtures were being obtained, no further investigations were made.

#### Vertical distribution

Because of the uniformity of horizontal distribution indicated above, only central probes were used. Profiles of concentration versus probe depth (ie vertical distribution) at fixed times, were constructed from Figs 3-7 for a nominal 7 per cent natural gas/air mixture ( $N_1 = 31$ ) and these are shown in Fig.8 for the central probe at times of 10, 20, 30 min. Because ceiling layers were being investigated, the depth of probe, or distance into the layer, is measured from the top of the chamber (zero reference) in all the experiments described in this note.

# Effect of composition

Experiments similar to those described above were carried out with gas concentrations of approximately 8 per cent, 10 per cent and 12.5 per cent natural gas in air and for 100 per cent natural gas (the latter at the lower filling rate of 0.3  $\rm m^3/min$ ). The increase of gas concentration with time at various depths in the explosion chamber, is plotted in Figs 9-12. Figure 12 for 100% natural gas shows that although the value of N<sub>1</sub> (6900) is conducive to good layering, the concentration in the chamber at 0.61 m is only half that of the introduced gas. The variation in gas composition about the interface at different times of filling, from results of the kind given in Figs 9-12, is plotted for 10 per cent and 100 per cent natural gas in Figs 13 and 14. When a more detailed study of the diffuse nature of the interface was required, the five probes were modified so that the atmosphere in the explosion chamber could be sampled at closer vertical intervals and further experiments were carried out under these conditions.

Examination of Figs 13 and 14 shows that a diffuse layer, at least 0.5 m deep, separates the introduced gas from the existing air in the chamber. Factors involved in the production of such diffuse interfaces are air entrainment and mixing caused by the introduction of the flammable gas into the chamber, convection, and molecular diffusion. The first two factors are not likely to be important in this work because the flammable gas was introduced at low velocity upwards against the ceiling of the chamber from which it spreads laterally at an even lower velocity, and the lower density of the flammable gas would reduce disturbance of the air in the chamber to a minimum. The effect of convection would also be at a minimum because the gas mixture, made warmer by pumping, was introduced near the roof of the explosion chamber, the contents of which were at a positive pressure of about 25 mm (1 in) water gauge relative to the outside atmosphere during gas layering.

The contribution of molecular diffusion to the production of the diffuse interface was examined by three groups of experiments.

Firstly, natural gas/air mixtures were introduced at approximately  $0.45 \text{ m}^3/\text{min}$ ,  $N_1 = 20$ . The lower velocity of gas entering the chamber would reduce the possibility of air entrainment. The increase of concentration of flammable gas with time at different levels in the chamber is shown in Fig.15. Comparison with Fig.10 indicates, for example, that a 9.5 per cent layer 0.92 m thick was obtained after 49 minutes at the lower rate of filling (Fig.15) whereas at the faster rate this concentration was obtained at the same level in 18 minutes. At the same time the concentrations at the 1.22 m level were 6 per cent and 3.9 per cent of natural gas. These results indicate that the faster filling rate gave a less diffuse interface, indicating that the time dependent factor of molecular diffusion was the most important factor in the production of the diffuse interface.

It was not possible to make such comparisons for layers produced from 100 per cent natural gas because the gas metering equipment did not permit a higher flow rate than 0.3 m<sup>3</sup> min to be used. However, a comparison can be made between experimental results and values calculated from the laws of molecular diffusion<sup>10</sup>. Such curves for a filling period of 30 minutes are presented in Fig. 16. The experimental data is derived from Fig. 14. The similarity in the form of the curves is apparent. Thirdly, by continuing gas analysis at different depths after cessation of filling, any disturbance of the gas mixture by

convection could be determined. Sampling was restricted after cessation of gas filling to reduce disturbance of the introduced layers by the sampling process. Data is presented in Fig. 12 for 100 per cent natural gas and in Figs 17 and 18 for 10 per cent and 12 per cent natural gas/air mixtures respectively. Figures 17 and 18 indicate little if any consistent change in gas concentration after cessation of filling. However, Fig. 12 for 100 per cent natural gas injection shows an increase in gas concentration at all sampling positions although the two uppermost curves should have been at or above the filling level. There is thus no evidence of rapid convective diffusion.

Additional experiments with 100 per cent natural gas

The distribution of gas concentration in layers formed using 100 per cent natural gas was considered unusual in that after 30 min filling time an extremely diffuse distribution was obtained with, for example, only 94 per cent gas at 0.31 m (1 ft) and 57 per cent gas at 0.62 m (2 ft) depths respectively (Fig. 14). It was necessary, therefore, to establish that anomalous results were not being obtained for such reasons as:

- a) leakage
- b) convection at lower parts of the chamber
- c) loss of gas through the ports at the base of the chamber when introducing the gas layer.

The filling rate, 0.3 m<sup>3</sup>/min, used in all previous experiments for 100 per cent natural gas input, gives approximately 0.8 m (2.6 ft) layer depth over 30 min. Five analysis probes were arranged on the central axis of the chamber to investigate, over the whole height of the chamber, the increase in gas concentration with time. Results are presented in Fig.19 for the upper four analysis probes. The lowermost probe registered air only for the whole duration of the test.

Independent experiments showed that no gas was being lost from the exhaust ports and that the chamber itself was free from leaks. A numerical integration of the content of natural gas was carried out by a method given elsewhere 11. This approximate method of calculation accounted for 94 per cent of the natural gas introduced, in reasonable agreement with the expected amount. Thus, the possibility of leaks and of unexpected distribution of gas can be rejected.

#### CONCLUSIONS

The layering of flammable gas introduced into a chamber containing air has been studied by monitoring the concentration in different positions in the chamber and the following conclusions have been drawn:

- i) The system of diffusers used for the introduction of gas produced uniform horizontal distribution.
- ii) Vertical distribution of the flammable gas in the chamber showed a marked gas concentration gradient at the interface, particularly when natural gas alone was used, but the gas distribution approximated to that which could be expected from molecular diffusion.
- iii) A limited number of experiments have shown that a filling rate of  $0.9 \text{ m}^3/\text{min}$  produces less diffusion than a slower rate of  $0.45 \text{ m}^3/\text{min}$ .
  - iv) The layers, formed by the introduction of flammable gas/air mixtures for a given period of time, have been found to be reasonably stable for times up to ten minutes after the gas flow had stopped.

The work reported here indicates that molecular diffusion is the limiting factor governing the sharpness of the separation between the injected flammable gas and the existing air in the chamber. Attention will be paid to means of improving the separation between the layers, in the main explosion programme.

#### ACKNOWLEDGEMENTS

Thanks are due to Mr M Senior and Mr C F J Berlemont who carried out much of the chromatographic analyses described in this work.

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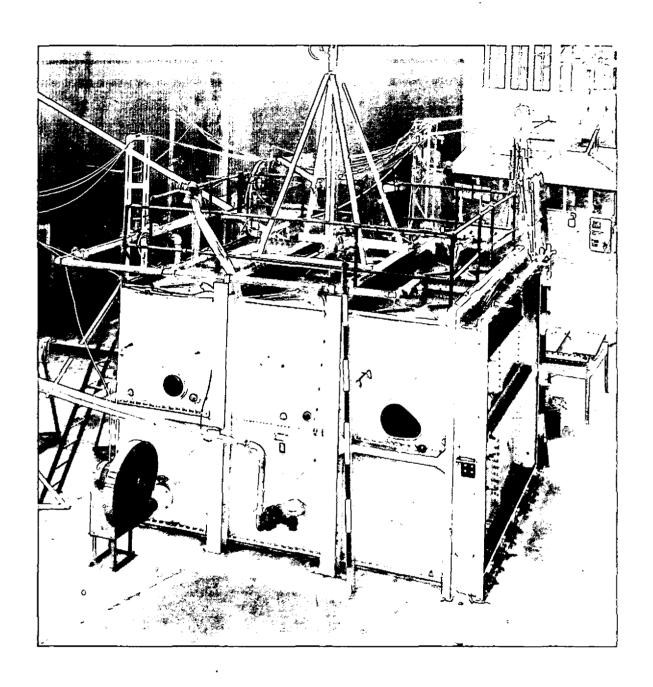
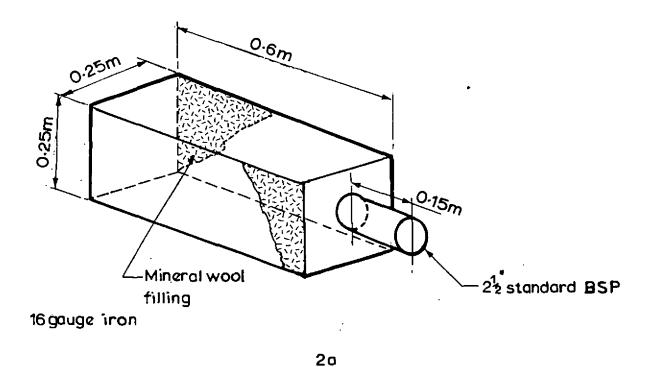


FIG.1 EXPLOSION CHAMBER





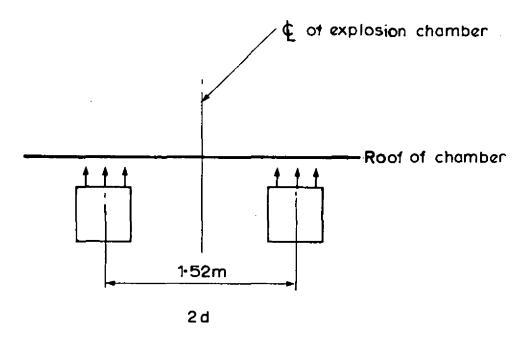


Figure 2 The gas diffuser, siting and methods of use in the explosion chamber

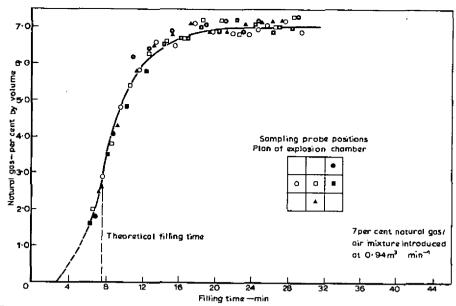


Figure 3 Increase in natural gas concentration in plane 0.61m below ceiling of explosion chamber

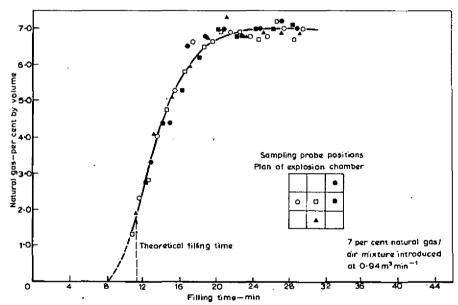


Figure 4 Increase in natural gas concentration in plane 0.92m below ceiling of explosion chamber

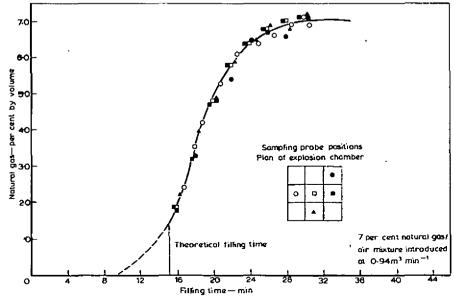


Figure 5 Increase in natural gas concentration in plane 1.22m below ceiling of explosion chamber

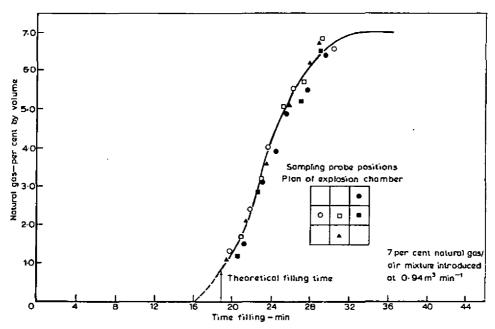


Figure 6 Increase in natural gas concentration in plane 1.52m below ceiling of explosion chamber

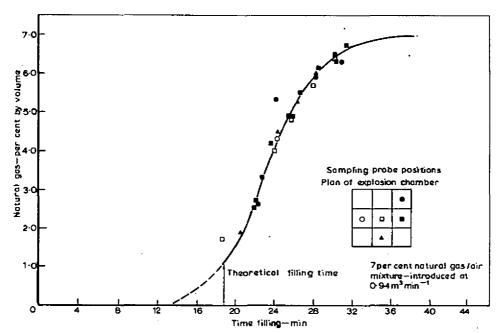


Figure 7 Increase in natural gas concentration in plane 1.52m below ceiling of explosion chamber

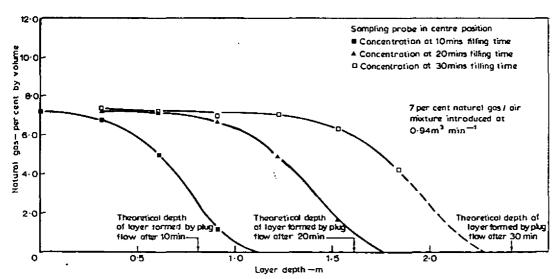


Figure 8 Gradient of natural gas concentration at 10, 20 and 30min filling time

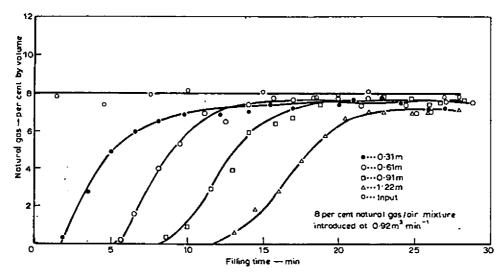


Figure 9 Increase of natural gas concentration at 0,0.61,0.91 and 1.22m below ceiling of the explosion chamber

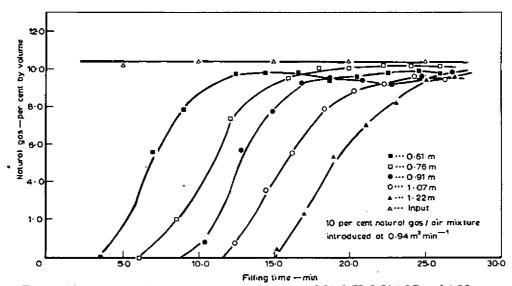


Figure 10 Increase of natural gas concentration at 0.61, 0.76.0.91,1.07 and 1.22m below the ceiling of the explosion chamber

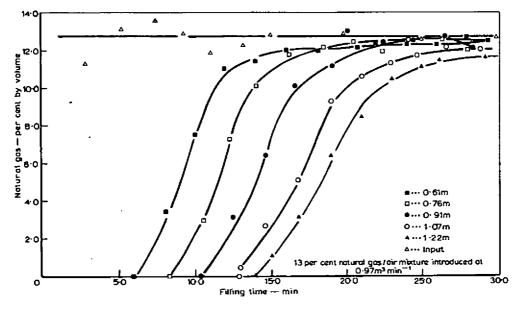


Figure 11 Increase of natural gas concentration at 0.61 0.76 0.91 1.07 and 1.22m below the ceiling of the explosion chamber

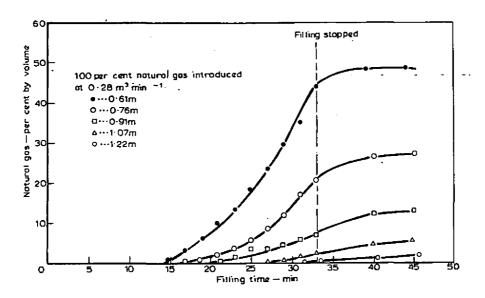


Figure 12 Increase of natural gas concentration at 0.61, 0.76, 0.91, 1.07 and 1.22m below ceiling of the explosion chamber

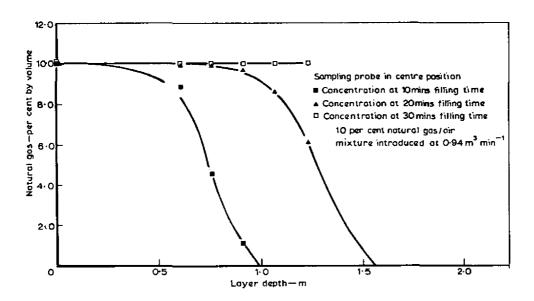


Figure 13 Gradient of natural gas concentration at 10,20 and 30 minutes filling time

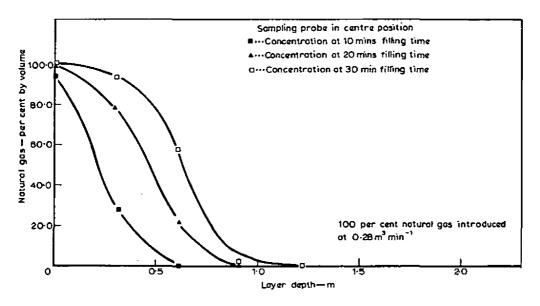


Figure 14 Gradient of natural gas concentration at 10,20 and 30 min filling time

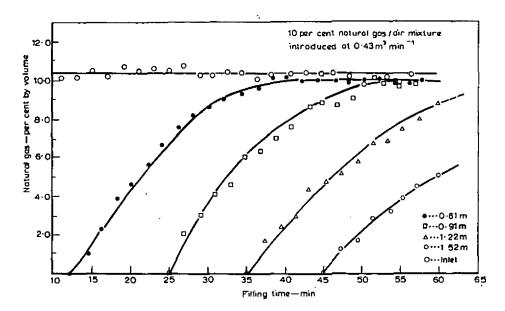


Figure 15 Increase of natural gas concentration at 0.61,0.91,1.22 and 1.52m below ceiling of the explosion chamber

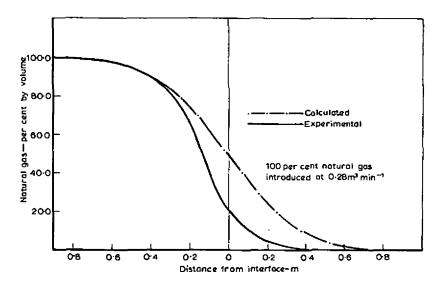


Figure 16 Comparison of theoretical and experimental gas distribution near the interface between natural gas and air in explosion chamber

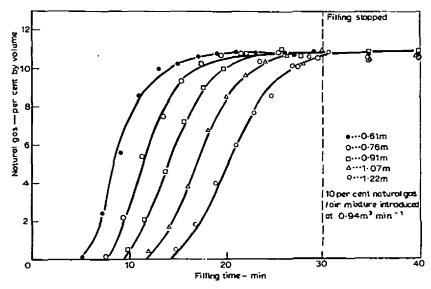


Figure 17 Increase of natural gas concentration at 0.61, 0.76, 0.91, 1.07 and 1.22m below ceiling of the explosion chamber

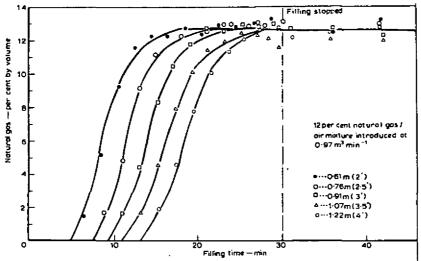


Figure 18 Increase of natural gas concentration at 0.61.0.76, 0.91, 1.07 and 1.22m below ceiting of the explosion chamber

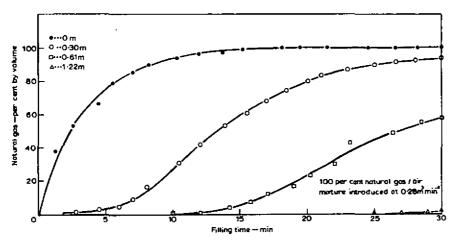


Figure 19 Increase of natural gas concentration at 0,030,061 and 1.22m below ceiling of the explosion chamber

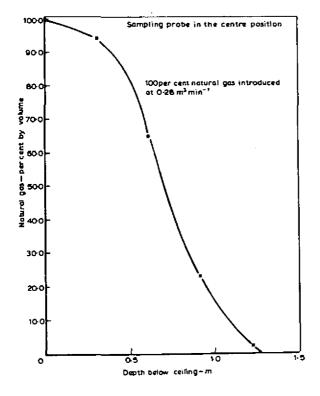


Figure 20 Final gradient of natural gas concentration in the explosion chamber after 30min filling