# RELIEF OF EXPLOSIONS IN DUCT SYSTEMS

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## SUMMARY

**The authors describe research work carried out by the Joint Fire Research Organization to determine the amount of relief required for ducts connecting plant items.**

**The influence of size and siting of relief vents on their ability to reduce maximum pressure and flame speeds of explosions in duct systems are investigated and practical recommendations are made.**

### Introduction

Ducts are frequently used in industry to convey flammable vapours and gases from one part of a plant to another. Although the main precaution taken against explosions is to ensure that flammable mixtures with air do not occur, it is still possible that by mischance an explosive atmosphere may form and become ignited. If this possibility is accepted, there are two main courses open to a design engineer. The first is that the plant should be built to withstand the maximum pressure of an explosion. For relatively short ducts and most explosive mixtures of the majority of flammable gases with air, this is of the order of 100 $lb/in^2$ if the initial pressure is atmospheric. However, most flammable gases form certain mixtures with air which can give rise to detonation in a duct system if this is sufficiently long or complicated. Under these conditions, pressures of the order of 1000 $lb/in^2$ might be reached. The second course is to design the plant in such a manner that the progress of an explosion is kept under control and the resulting pressure is limited to an acceptable maximum. The provision of relief vents is one aspect of this approach. A substantial amount of work[1] has been done to provide design data for relief vents for certain individual items of plant, particularly, for example, drying ovens.[2] There is little information available, however, on the amount of relief required for ducts that may connect items of plant or even for items of plant in the shape of ducts.

To fill this gap, a programme of research is being carried out by the Joint Fire Research Organization. The object of this work is to find the influence of the size and siting of relief vents on their ability to reduce the maximum pressure and flame speeds of gaseous explosions occurring in ducts and to develop practical methods of installing these vents. In practice, duct systems may be extremely complicated and a wide range of flammable gases and vapours may be conveyed in them. To obtain a rational picture of the problem it has been necessary in the first place to confine the experiments to very simple systems, in which the gas is initially stationary. The duct systems reported upon in this paper are thus limited to straight lengths, and to lengths containing a single obstacle in the form of a central orifice, a central strip across the duct, a T piece, or a bend. The flammable component has been limited to either propane or pentane, but these vapours may be considered as having explosive properties typical of a wide range of flammable gases and solvents of industrial importance which have fundamental burning velocities of 1–1·6 ft/s. Some of the results that have been obtained so far are presented below. In spite of the limitations of the experiments, these results allow the formulation of general principles that should guide the provision of explosion relief for duct-shaped vessels and duct systems, and also provide empirical data for the design of this relief which has not before been available.

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### Experimental

*Apparatus*

Experimental explosions were carried out in mild steel ducts of 3 in. and 6 in. in diameter and 1 ft square-section. The ducts were made in flanged sections 6 ft long which could be bolted at the flanges either directly or to include some obstruction. In addition, relief-vent assemblies could be bolted to the ends of the ducts. Some of the sections of the 1 ft square-ducts were flanged at the top also, as indicated in Fig. 1.

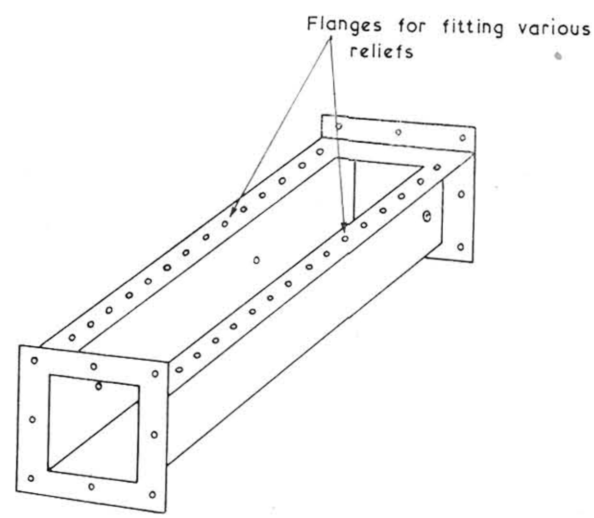



Fig. 1.—*Diagram of 1 ft square duct flanged at top*

These flanges allowed relief vents of various designs and sizes to be fitted at any position on the top of the duct. The circular ducts were Class C (B.S. 806 : 1954) and were tested

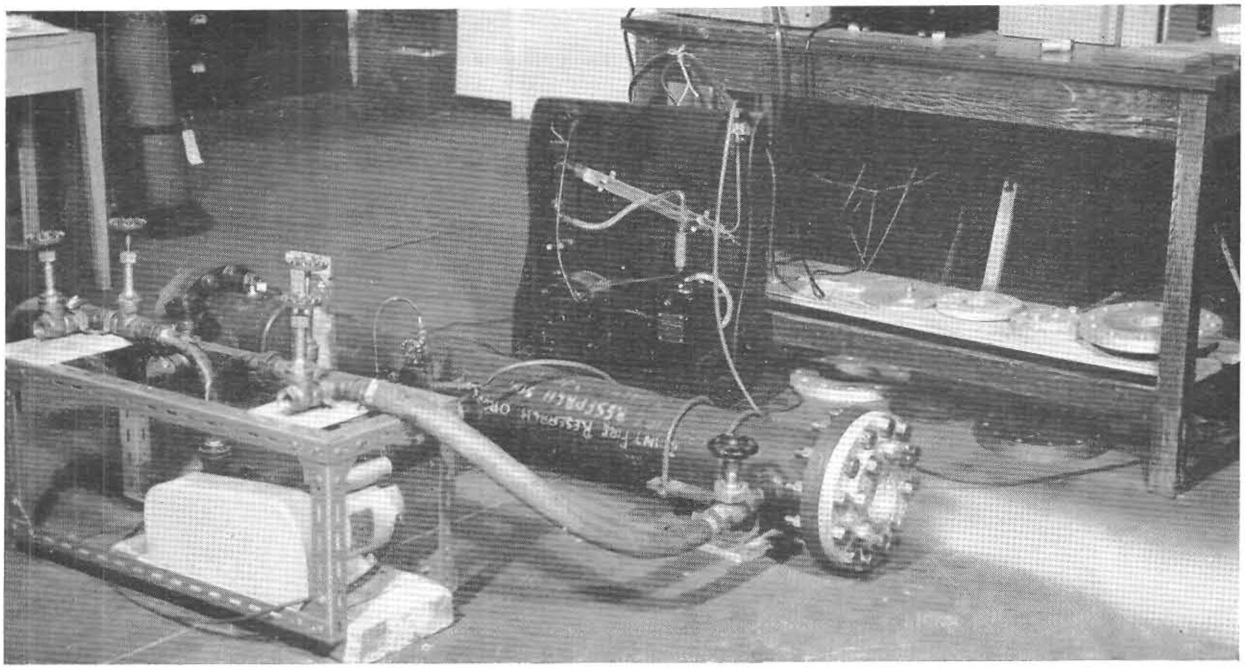


Fig. 2.—*Apparatus using 6 in. diameter duct*

to a pressure of 700 lb/in$^2$. The square duct, however, was fabricated from $\frac{1}{8}$-in. steel sheet and could not withstand high pressures. Figs 2 and 3 show respectively a length of 6 in. diameter and 1 ft square duct set up for the experiments. Pentane or propane was the flammable gas. When propane was used, the gas and the air were metered separately and the streams allowed to mix before entering the duct. Sufficient gas mixture to give seven changes was passed through the duct. When pentane was used, the requisite quantity of pentane was introduced into the duct as a vapour and the contents of the duct were circulated with a fan for a time sufficient to ensure thorough mixing. In all tests the gas was allowed to become stationary before igniting the mixture with an induction spark.

Three sets of experiments were carried out :

(1) The effect of end vents in straight ducts was investigated. The three different types of ducts mentioned above were used for this series.

(2) The effect of obstacles placed inside a duct was studied. These experiments were carried out with the 6 in. diameter duct. In most tests, the duct was 12 ft long, closed at one end and open at the other, with the obstacle at the centre. The gas was ignited 6 in. from the closed end. Tests were also carried out to investigate the effect of placing small relief vents in the end near the ignition source, and the effect of increasing the length of duct between the closed end and the obstacle.

(3) Methods of distributing relief vents along a length of duct were examined. All these experiments were carried out with a 1 ft square duct, the vents being distributed along the top of the duct either as rectangular openings or as longitudinal slots.

*Procedure and measurements*

In the first two series of experiments, the relief vent at the end of the duct was closed with a bung or cover which was

Fig. 3.—*Apparatus using 1 ft square duct*

removed after charging the duct but before the gas was ignited. In the third series, the vent spaces distributed along the duct were closed at ignition either by loose covers weighing 250 g/ft$^2$ of vent area, polythene sheeting 0·001 and 0·0015 in. thick clamped to the edges of the vent, or by light covers weighing 270 g/ft$^2$ of vent area clamped to the ducts by magnets. The purpose of the loose covers was to confine the gas mixture in the duct during the interval between charging the duct and ignition, and the results of tests with these covers are the nearest to tests with open vents that could be obtained under the experimental conditions. The two other methods of closure were such as might be used in industrial practice. The magnetically clamped covers were specially designed to give a good seal but nevertheless to be light, robust and capable of being removed at a very early stage in an explosion. Details of their design are given in Fig. 4.

conditions for both pentane and propane explosions, the maximum pressure when plotted against $K$ fell between the two lines

$$P = 0{\cdot}8K \quad \ldots \quad (1)$$

and

$$P = 1{\cdot}8K \quad \ldots \quad (2)$$

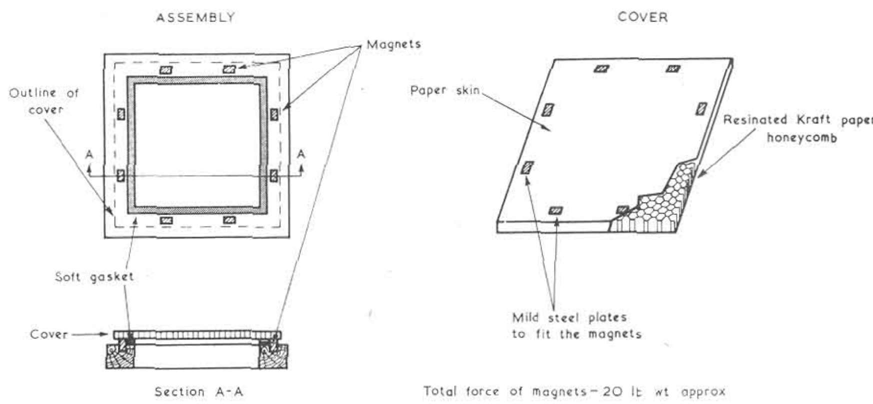
where $P$ = maximum pressure in pounds per square inch.

The limits of the conditions referred to above are summarised below :

(*a*) Vent size ($K$) = 2–32.

(*b*) Ratio of length ($L$) to hydraulic mean diameter ($D$) = 6–30.

(*c*) Mixture strength ($M$) = 1·0–1·3 where $M$ equals the concentration of flammable vapour divided by the concentration in a stoichiometric mixture.




Duct: 12 ft long × 6 in. diameter
Flammable vapour: pentane

Fig. 4.—*Design details of magnetically-held vent closure assembly*

In all experiments measurements were made of the pressure developed during the explosion and of the speed of the flame along the ducts. The experiments with the circular ducts were carried out in the laboratory and a piezo-electric sensing device was used in the measurement of the pressure. The tests with the 1 ft square duct were carried out in the open ; a capacity gauge was used for these experiments since it was less sensitive to the weather than the piezo-electric gauge. In the first series of experiments, the flame speed was measured using ionisation gaps spaced at intervals of approximately 3 ft along the duct and protruding a short distance into the duct. The use of ionisation gaps was found unsuitable for the tests in the second and third series since the obstacles distorted the flame ; the passage of the flame in these tests was, therefore, monitored by infra-red photo-electric cells.

## Results

### *End vents for straight ducts*

Details of most of the results of this part of the investigation are being published elsewhere[3] so the results will be only briefly summarised and illustrated here. In correlating the results it was found convenient to express the vent-size as the dimensionless ratio $K$, equal to the ratio of the cross-sectional area of the duct to the area of the vent. Thus $K$ was equal to 1 and to infinity when the end of the duct was fully open and fully closed respectively. Over a wide range of

(*d*) Position of ignition source = 6 in. from the closed end of the duct to one quarter of the distance along the length.

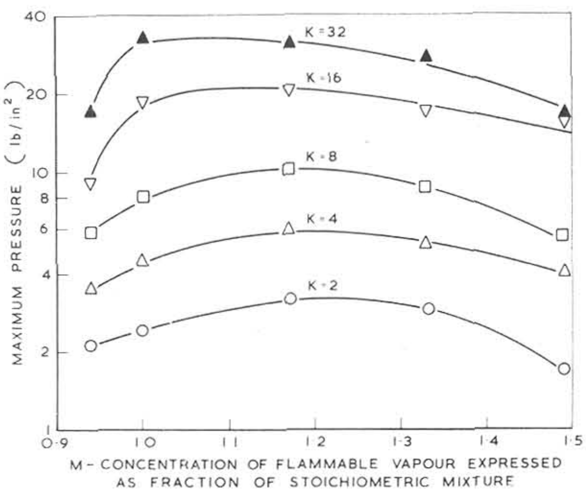
(*e*) Position of pressure gauge : any point along the duct.

When ignition took place near the vent, very much lower pressures and flame speeds were obtained than when ignition took place remote from the vent. For example, with a 30 ft length of 1 ft square duct and a vent area of 0·25 ft$^2$ ($K = 4$), the maximum pressure was reduced by a factor of 50 when the gas mixture was ignited close to the vent compared with that obtained with the ignition near the closed end.

Within the limits of equations (1) and (2) there was a complicated inter-relationship between factors (*a*), (*b*), (*c*), and (*d*) above. For example, the concentration at which the maximum pressure was obtained varied with the size of the vent ; this is illustrated in Fig. 5. The position of the ignition source that would give rise to the maximum pressure also varied with the size of the vent. Within the conditions specified, the maximum pressure was approximately independent of the length and the diameter of the duct. This did not apply, however, when the end of the duct was fully open (*i.e.* $K = 1$). Under these conditions, which are not covered by equations (1) and (2), the maximum pressure was approximately proportional to the length to diameter ratio of the duct and was given by :

$$P = {\cdot}07 \; L/D \quad \ldots \quad (3)$$
$$(6 < L/D > 48)$$

The flame speeds increased as both the length to diameter ratio of the duct and the size of the vent increased. This is illustrated in Fig. 6, which shows the speed of the flame as it approached the vent plotted against the ratio $L/D$ for different sizes of vent. When the end of the duct was fully open, flame speeds of 600–700 ft/s were reached for values of $L/D$ greater than 24.




Duct 12 ft long × 6 in. diameter
Flammable vapour: pentane

Fig. 5.—*Effect of concentration of flammable vapour on maximum pressure*

*The effect of obstacles in the duct*

The presence of obstacles in the duct increased the violence of explosions. The effect is illustrated by Fig. 7, which shows a selection of pressure records for these experiments. The flame propagated in a normal manner until it reached the obstacle but immediately downstream of the obstacle there was a rapid rise in pressure. The effect of the nature of the obstacle on the maximum pressure of the explosion is shown in Fig. 8. The maximum pressure was approximately proportional to the resistance to fluid flow caused by the obstacle. A large-radius bend, which did not give a sharp change in the fluid motion in the duct, gave a maximum pressure in the explosion that was less than that caused by the other obstacles of the same resistance to flow. Fig. 9 shows that the presence of the obstacles also gave rise to a sharp increase in the flame speed in the duct downstream from them.

An increase in length of the ducting upstream of the obstacle within the range 3–12 ft did not have a great effect on the maximum pressure reached, although there was evidence, with some of the obstacles of a maximum at a certain length of ducting. (Fig. 10.)

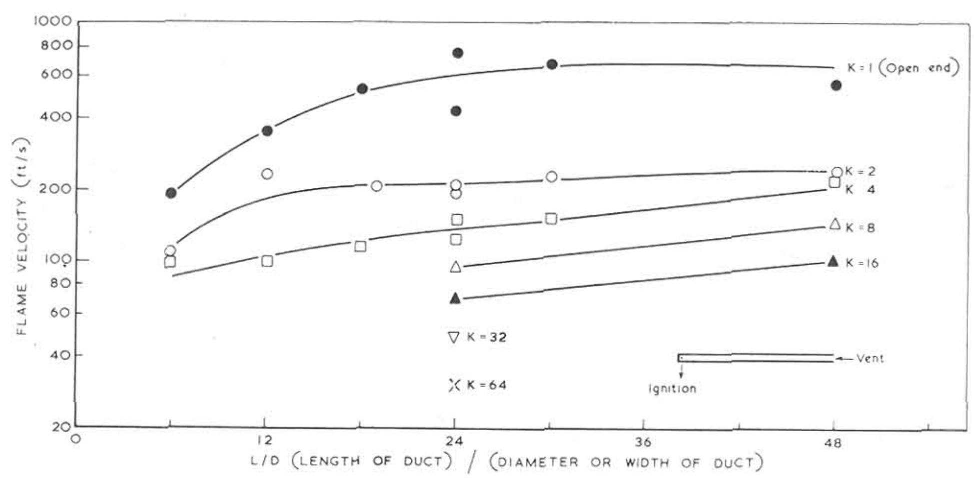
The insertion of a relief vent near the ignition source always brought about a very marked reduction in the maximum pressures and the flame speeds. Fig. 11 shows that broadly similar effects were obtained for different obstacles and different lengths of ducting upstream of the obstacle.

*Distributed vents on ducts*

EFFECT OF A SINGLE SUPPLEMENTARY VENT

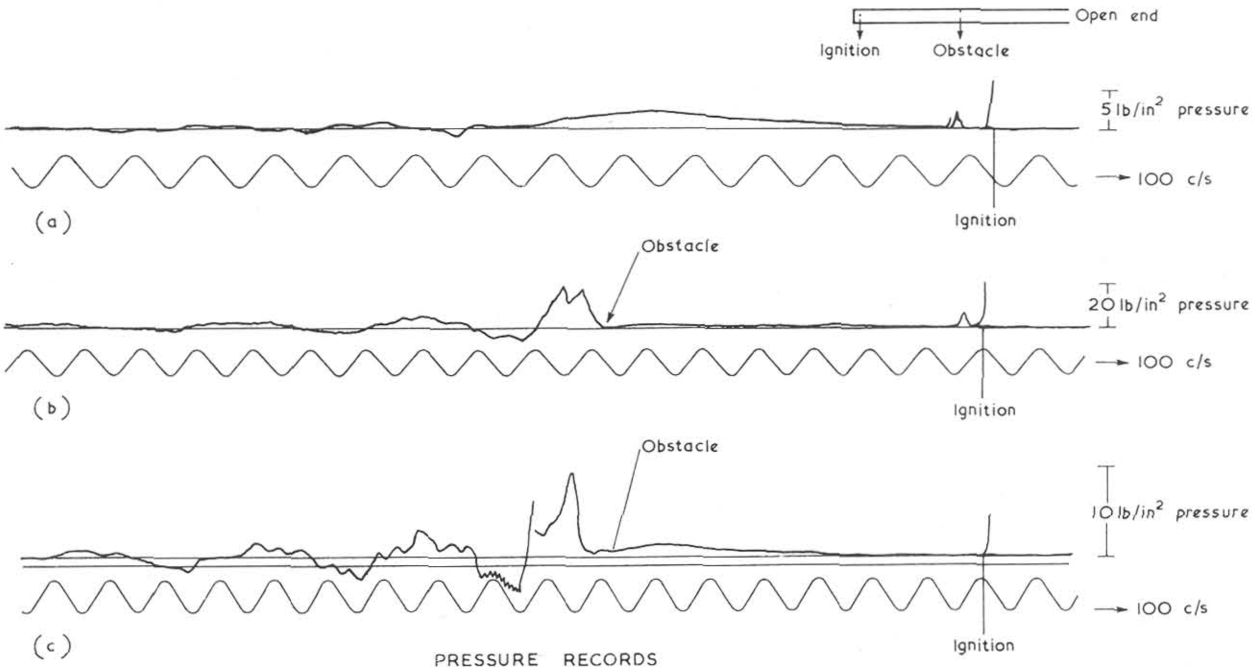
The above work showed that the presence of a relief vent close to the ignition source greatly reduced the maximum pressure and the flame speed. The reason for this effect will be discussed later. It follows that in designing relief vents for duct systems it is desirable to provide reliefs wherever ignition might take place and not only at convenient points in the system. The effect of a supplementary relief vent at different distances from the ignition source was therefore studied in some detail. These experiments were carried out on the 30 ft long 1 ft square duct, the supplementary vent being located in the top of the duct. In all the tests, the duct was fully open at one end, the gas was ignited 6 in. from the closed end and the vent was covered with a light cover weighing 250 g/ft².

Fig. 12 shows the maximum pressure obtained in the explosions plotted against the distance from the ignition source to the supplementary vent, for different sizes of this vent. The maximum pressure increased approximately as the 0·8 power of the distance between the vent and the ignition source, but decreased only as the 0·4 power of the size of the vent. This indicates that for a given amount of venting area, it is better to distribute the area along the duct as small but frequent vents rather than as fewer large vents. Thus, for example, with a venting area of 1 ft² placed 12 ft from the ignition source, the maximum pressure was 1 lb/in². If this vent were subdivided so that there was a vent 0·25 ft² at 3 ft from the ignition source, the maximum pressure would have been 0·6 lb/in.²




Flammable vapour: propane or pentane (M = 1.25)

Fig. 6.—*Effect of L/D ratio on speed of flame approaching the vent*

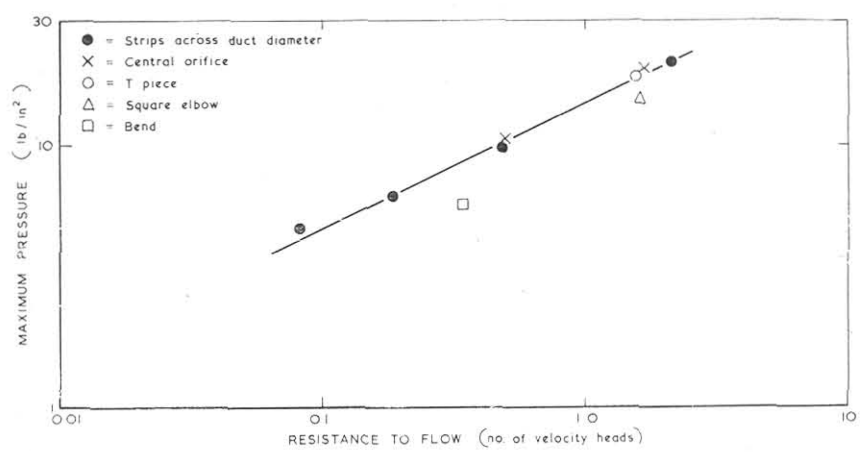



Duct: 12 ft long × 6 in. diameter
Ignition near closed end

(*a*) = no obstacle
(*b*) = obstacle (strip) 37% cross-sectional area of duct obstructed
(*c*) = obstacle (orifice plate) 18.5% cross-sectional area of duct obstructed

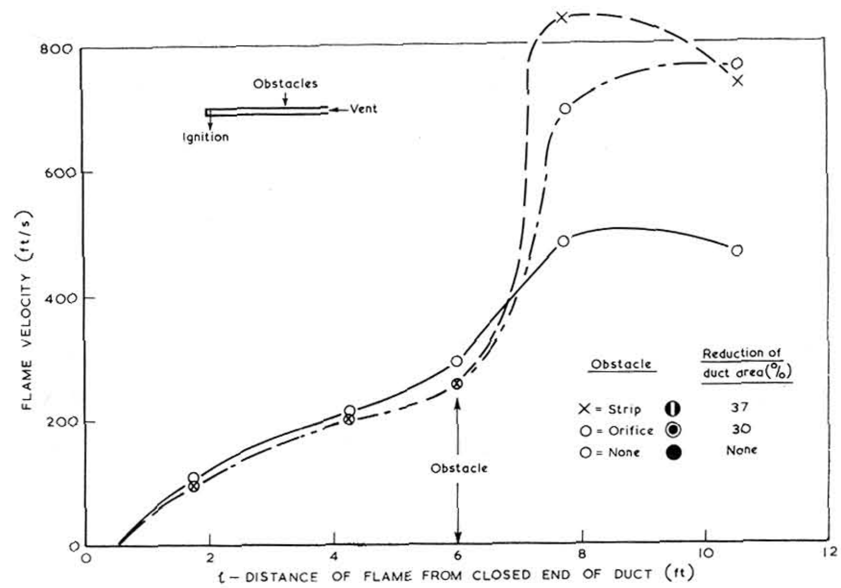
Blip on the timing wave indicates arrival of flame front at the probe

Fig. 7.—*Pressure records*



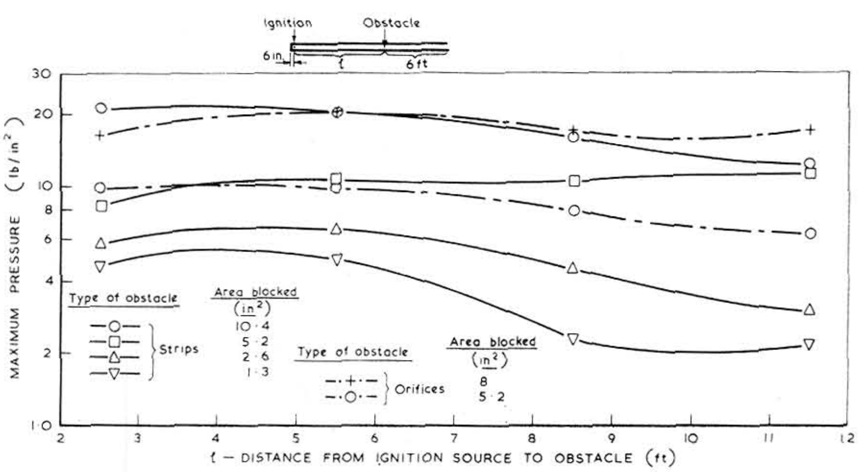

Flammable vapour: propane (M = 1.25)
Duct: 12 ft long × 6 in. diameter. Obstacle in centre

Fig 8.—*Relation between maximum pressure in an explosion in a duct containing an obstacle and the resistance to flow caused by the obstacle*




Flammable vapour: [propane (M = 1.25)

Fig. 9.—*Effect of obstacles on flame speed*




Flammable vapour : propane (M = 1.25)

Fig. 10.—*Effect on the maximum pressure of the run up distance to the obstacle*

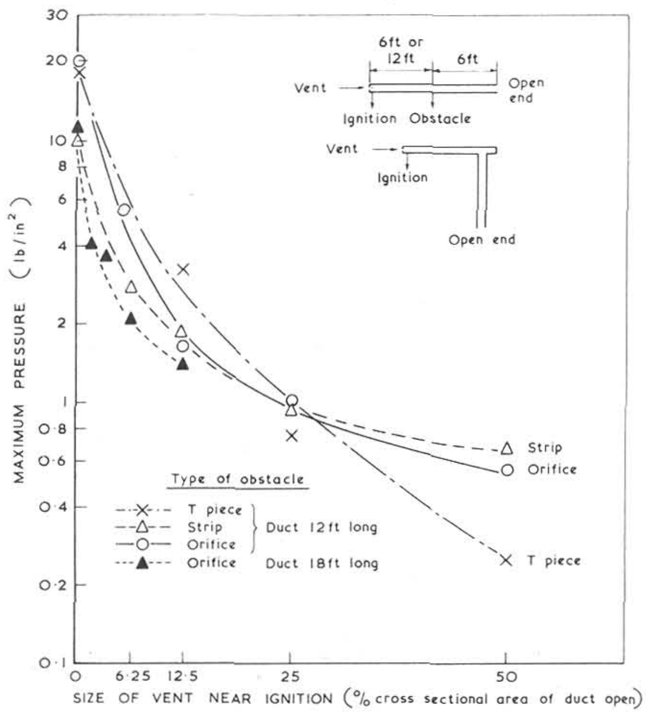
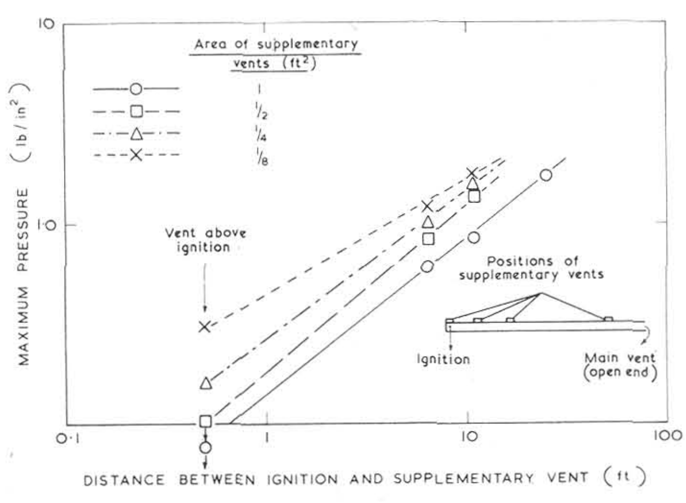
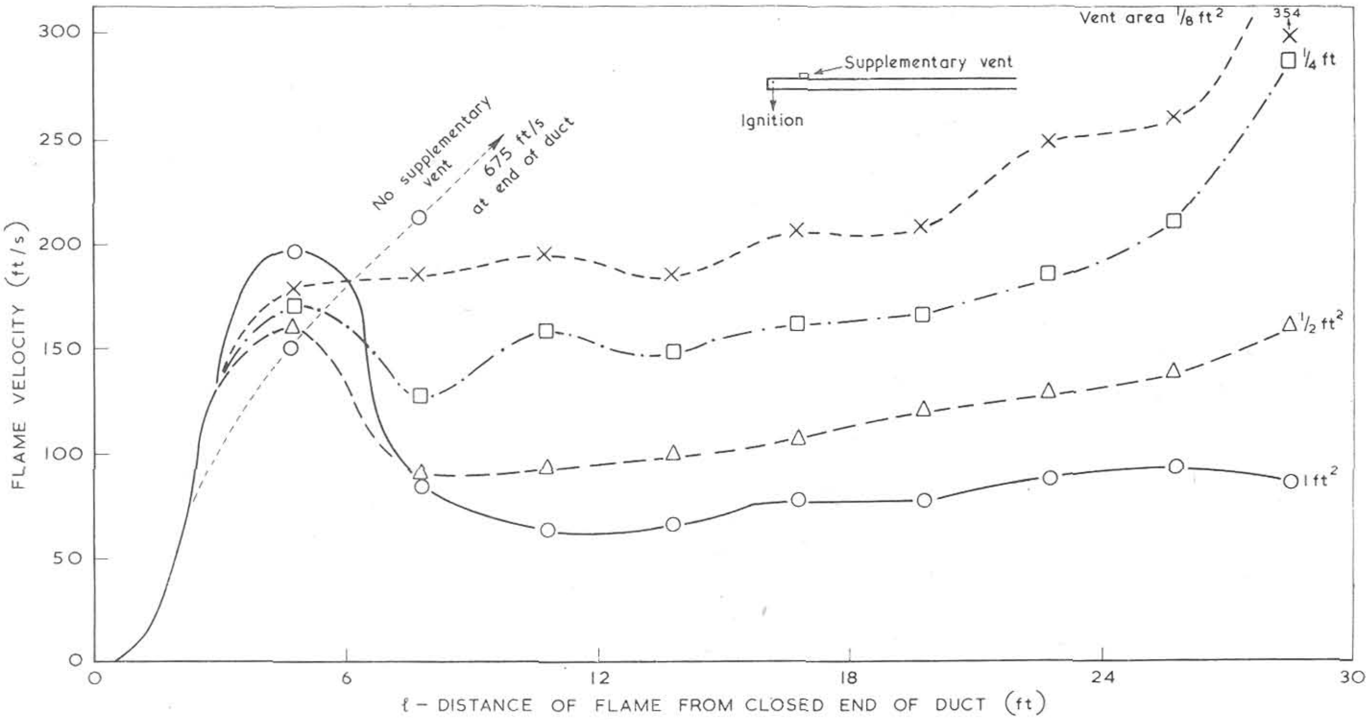



Fig. 11.—*Effect of vent near ignition on maximum pressures for different obstacles*




Duct: 30 ft long × 1 ft square
Flammable vapour: propane (M = 1.25)
↓ Pressure $<0.1$ lb/in²

*Fig. 12.—Effect of a supplementary vent on the maximum pressure*




Duct: 30 ft long × 1 ft square
Flammable vapour: pentane (M = 1.25)
Vent 6 ft 3 in. from gas source

Fig. 13.—*Effect of a supplementary vent on the flame speed*

Fig. 13 shows the flame speed along the duct plotted against the distance of the flame travel when vents of different sizes were placed 6 ft 3 in. from the source of ignition. The marked reduction in the flame speed as the flame passed the vent is clearly shown, the minimum speed decreasing approximately as the square root of the area of the vent increased.

EFFECT OF A SERIES OF SUPPLEMENTARY VENTS

These experiments were carried out with the main purpose of developing a practicable system of venting a duct containing an obstacle, that would allow maximum pressures during an explosion to be kept down to the order of 1 lb/in$^2$. The experiments were all carried out on a 24 ft length of 1 ft square-duct with one end open. The obstacles were installed halfway along the duct, and the gas was ignited at various points between the closed end and the obstacle. Three systems of distributing vents along the duct were studied as follows :

(1) Vents were placed at 6 ft intervals along the duct, one vent being close to the obstacle. The sizes of the vents tested were respectively $\frac{2}{3}$ and 1 ft$^2$.

(2) Vents in the form of slots running parallel to the axis of the duct. Each 6 ft length of the duct contained a slot 5 ft long. The width of the slots were 0·8 in., 1·6 in., and 2·4 in., giving respectively $\frac{1}{3}$, $\frac{2}{3}$, and 1 ft$^2$ of vent area for each 6 ft run of duct.

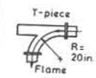
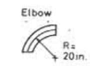
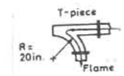
(3) The whole of the side of the duct was constructed to act as a vent. A special duct was made for each experiment by covering a framework of metal rods with polythene 0·001 in. thick.

The maximum pressures obtained in the experiments are shown in Table I, which also shows the method by which the vents were closed in the different experiments. The ducts were too weak for explosions to be carried out with obstacles and without supplementary relief venting. It was estimated that such experiments would have given maximum pressures up to 20–40 lb/in$^2$. All pressures shown in Table I are well below this value. The pressures in all experiments with loose covers intended to simulate open vents, were below 1 lb/in$^2$. Within this limit, pressures were approximately three times greater when the vents were distributed at 6 ft intervals along the duct than when using vents of equal total area in slot form. It will be noted that when the vents were distributed at 6 ft intervals the flame had to travel 3 ft from the ignition source before it reached a vent, whereas when the vent was in slot form the flame had to travel only 6 in. to the side of the duct. The loose vent covers are impracticable for most conditions likely to be encountered in industry. Replacing these covers by polythene sheet clamped to the duct, or clamping light covers to the duct by magnets, considerably increased the maximum pressure in the explosions. Most pressures, however, remained below 2 lb/in$^2$ which is the maximum that can be generally allowed in weak ducts. Relatively high pressures were obtained in some experiments with polythene closures when the gas was ignited close to the obstacle, since the flame reached the obstacle before a sufficient area of the polythene had melted.

Although slot vents were much more efficient than square vents when the vents were closed with loose covers, this advantage was reversed when the vents were closed with polythene.

TABLE I.—*Explosions in a Duct Containing an Obstacle and Provided with Distributed Vents*

Duct—24 ft long × 1 ft square    Flammable Vapour—Propane ($M$ = 1·25)

| Venting system | Vent closure | Distance ignition to closed end | Maximum Pressure (lb/in²): No Obstacle | Strips Area Blocked (in²): 6·5 | 13 | 26 | Orifice Plates Area Blocked (in²): 26 | 42 | 72 | 108 | T-piece  | Elbow  | T-piece  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2·4 in wide slots | Loose covers | 6 in. | <0·1 | <0·1 | <0·1 | <0·1 | <0·1 | <0·1 | 0·11 | 0·32 | 0·1 | — | — |
| 2·4 in wide slots | Loose covers | 9 ft | <0·1 | <0·1 | <0·1 | 0·12 | <0·1 | <0·1 | 0·11 | 0·11 | | | |
| 2·4 in wide slots | Polythene 0·001 in thick | 6 in. | 0·60 | 0·50 | 1·05 | 1·26 | 0·50 | 1·18 | 1·79 | 1·76 | 1·03 | — | — |
| 2·4 in wide slots | Polythene 0·001 in thick | 9 ft | — | — | — | — | 0·79 | 1·79 | 7·2 | — | 0·83 | — | — |
| 2·4 in wide slots | Polythene 0·0015 in. thick | 6 in. | 0·92 | 0·63 | 1·62 | 1·96 | 0·75 | 2·09 | — | — | — | — | — |
| 1·6 in.wide slots | Loose covers | 6 in. | <0·1 | <0·1 | <0·1 | 0·10 | <0·1 | <0·1 | 0·19 | — | <0·1 | — | — |
| 1·6 in.wide slots | Polythene 0·0010 in.thick | 6 in. | 0·70 | 0·65 | 1·59 | 1·81 | 0·64 | 1·56 | 2·70 | — | — | — | — |
| 0·8 in.wide slots | Loose covers | 6 in. | — | <0·1 | 0·13 | 0·27 | <0·1 | 0·29 | 0·81 | 0·84 | 0·13 | 0·10 | — |
| 0·8 in.wide slots | Polythene 0·0010 in.thick | 6 in. | 0·70 | 0·78 | 1·59 | — | 1·29 | 2·6 | — | — | — | — | — |
| Square 1 ft² | Loose covers | 3 ft | <0·1 | <0·1 | <0·1 | 0·1 | <0·1 | <0·1 | 0·11 | 0·16 | — | — | — |
| Square 1 ft² | Loose covers | 9 ft | <0·1 | <0·1 | 0·18 | 0·34 | <0·1 | 0·18 | 0·29 | 0·35 | — | — | — |
| Square 1 ft² | Polythene 0·0010 in.thick | 3 ft | 0·31 | — | — | 0·50 | 0·28 | 0·36 | — | — | — | — | — |
| Square 1 ft² | Polythene 0·0010 in.thick | 9 ft | 0·35 | 0·26 | 0·56 | 0·96 | 0·50 | 0·76 | 2·40 | 2·50 | — | — | — |
| Rectangle 2⅓ ft² | Loose covers | 9 ft | — | <0·1 | 0·23 | 0·61 | 0·17 | 0·46 | 0·77 | 0·55 | — | — | — |
| Rectangle 2⅓ ft² | Polythene 0·0010 in.thick | 9 ft | 0·52 | — | — | — | — | — | — | — | — | — | — |
| Square 1 ft² | Covers held by Magnets | 3 ft | 0·10 | — | — | — | 0·13 | 0·21 | 0·27 | — | 0·10 | — | 0·38 |
| Square 1 ft² | Covers held Magnets | 9 ft | <0·1 | — | — | — | — | — | 1·94 | — | 0·13 | — | — |
| Duct made from 0·0010 in. Polythene | | 6 in. | <0·1 | — | — | — | — | <0·1 | — | — | — | — | — |

– Not Determined    T-piece referred to in this table is a long-sweep T.

This was because the vents opened initially as a result of the action of both pressure and heat on the polythene film. The bursting pressure of the square vents was considerably less than the bursting pressure of the slot vents at a given temperature. This difference more than outweighed the intrinsically greater efficiency of open slot vents as compared with the open square vents. On the other hand, thin polythene is more likely to be a practicable form of covering for slot vents than for square vents. In all experiments with vents clamped by magnets, a vent cover close to the ignition source was removed at a very early stage in the explosion. When there were no obstructions in the duct or when the obstruction was small, some of the other vent covers were not moved as the explosion travelled along the duct. As a result, the time during which flames were projected from the vent near the ignition source was more prolonged than in experiments with loose covers or polythene sheeting ; in the latter experiments hot gases produced by the explosions tended to be expelled evenly along the whole length of the duct. No measurable pressure was obtained in the tests in which the whole duct was fabricated from thin polythene.

## Discussion

*The principles of relief venting for duct systems*

The work described above illustrates certain basic principles of the progress and control of explosions in ducts. The main initial consequence of a gaseous explosion is the heating of the gases passing through the flame to a temperature of the order of 2000°K. The rate at which gas is heated in this way is directly related to the rate of combustion *i.e.* the speed of the flame relative to the unburned gas. During the period immediately following the initiation of a flame in a stationary gas, this speed is a few feet per second. However, if the heated gas is not free to expand through a vent directly, it will quickly establish a local pressure rise that will accelerate the flame and unburned gas ahead of the flame. After a short time the moving unburned gas becomes turbulent and one of the consequences of this turbulence is that the rate of combustion at the flame front is increased. This process results in the continued acceleration of the flame up to very high speeds. Shock waves associated with the acceleration of the flame probably also play a vital part in the eventual transition from deflagration to detonation. The effect of an obstacle in the duct is to create a local pocket of intense turbulence in the moving unburned gas which brings about a very rapid increase in the rate of combustion. If the gas is initially in rapid motion the initial propagation of flame is also generally faster and, other conditions being constant, a more violent explosion occurs than when the gas is initially stationary.

It follows that, as a general principle, relief vents should be sited so that burned gas close behind a flame is expelled from the vents ; this would minimize the effect of the expansion of this gas on the motion of the unburned gas ahead of the flame. This implies placing a relief vent wherever there is likely to be a source of ignition. For duct systems it also suggests that relief vents should be installed along the whole length of the duct system to cater, firstly for the possibility of ignition at any point in the duct, and secondly for the diminished effect of a single vent as the distance between the flame and the vent increases. It is also necessary that explosion reliefs, particularly those behind and near the flame, should open at a very early stage in the explosion since otherwise high flame speeds and substantial motion in the unburned gas may quickly be established.

*Application of results to practical systems*

In view of the wide range of different duct systems that may be encountered the data above are necessarily limited in their direct application to practical systems. If the data are taken in conjunction with information given elsewhere,[1, 4, 6, 7,] they can provide an indication of the amount of venting required under different conditions. To apply the information, it is necessary to know the maximum pressure that the system can withstand. It is unlikely that many duct systems as used in practice can withstand pressures greater than 1–2 $lb/in^2$ and relief venting, if it is to be entirely satisfactory, must keep pressures down to this value under the worst conditions likely to be encountered. Indeed, even if the pressure which the duct system can withstand is substantially higher, say 10–20 $lb/in^2$, it is still desirable, in order to avoid the conditions that might lead to the building up of detonation in long and complicated duct systems, to provide vent systems that will keep the maximum pressures down to 1–2 $lb/in^2$ and maximum flame speeds down to about 100 ft/s. For short ducts, however, or for long cylindrical vessels of length to diameter ratios less than about 30, the latter consideration will not apply and the relationship given in equations (2) and (3) may be used to calculate venting requirements.

The information in Fig. 12 may be used to provide estimates of the venting requirements for long ducts with an $L/D$ ratio of 50 or greater. Thus, for example, in a duct of 1 ft square cross-section it may be desired to keep the pressure in an explosion down to 1 $lb/in^2$ by using a series of vents each of area 0·25 $ft^2$. Fig. 12 indicates that to achieve this a vent should be no further than 6 ft from an ignition source; this implies that the vents should be 12 ft apart. Moreover, the information in Fig. 6 and equation (3) indicates that, within the limits tested, maximum pressures and flame speeds with open ended ducts scale with the $L/D$ ratio of the duct. In the present context of an indefinitely long duct, the duct length $L$ might be regarded as the distance between two vents. If this is accepted, it is permissible to scale the information in Fig. 12 to ducts of cross-sectional area other than 1 ft square provided the cross-sectional area is of the same order.

An estimate for the venting required when there are obstacles in the duct is indicated in Table I. For ducts containing several obstacles as obstructive to flow as T-pieces or orifices obstructing more than 30% of the duct area, it is necessary to provide vents equal to the cross-sectional area of the duct for each duct length equivalent to six diameters.

These statements apply only to stationary gases and for a single-spark ignition source. It is unlikely that gas speeds of the order of 5–10 ft/s will produce a major difference, since unburned gas speeds of the order of 50–100 ft/s are developed after the flame has travelled the distances stipulated above between vents. However, gas speeds of the order of 20 ft/s and upwards might produce substantial effects, and further work should be carried out on this point. The information is applicable to propane and pentane air mixtures. In many systems it has been found that the venting area required is approximately proportional to the fundamental burning velocity.[2, 4] It can therefore be expected that for gases with fundamental burning velocities similar to propane-air mixtures the above estimates will apply. For acetylene and hydrogen-air mixtures, and for mixtures of most flammable gases with oxygen, the venting stipulated above will not be sufficient. For some of these mixtures, a venting area approaching the whole surface area of the duct might be necessary to keep down maximum pressures and flame speeds. This might be achieved either by constructing the whole duct of a material like thin polythene or by arranging for the sides of the duct to be constructed in the form of light panels which are clamped to a skeleton with magnets or held in place by light friction at the edges. The construction of ducts by these methods will of course incur physical disadvantages but it is a logical alternative to the construction of extremely strong ducts for systems which might be subjected to occasional explosions or detonations.

In principle, the best way of distributing a given area of venting is in the form of a slot along the whole length of the duct. Under these conditions a certain amount of venting area will always be very close to a source of ignition wherever this may occur. If the vent is closed by a diaphragm of a given thickness, then the advantage of the greater efficiency of the slot vent compared, for example, with square vents of size equal to the cross-sectional area of the duct, may be offset by the higher pressure required to burst the diaphragm closing the vent. This disadvantage should not apply to closures held in place by springs, weights, magnets, etc., where, for a given restraint on the closure, the pressure required to dislodge the latter would be independent of its shape.

It should be stressed that if vents are to be fully effective they must open at a very early stage in the explosion and before the flame has travelled more than 1–2 ft. If they are opened by pressure it is desirable that they should be opened completely before the pressure of the explosion exceeds $\frac{1}{3}$ $lb/in^2$. The magnetically clamped covers fulfil this requirement. Vent covers weighing $\frac{1}{3}$ $lb/in^2$ would not be so effective because the inertia of these covers might prevent their opening until much higher pressures were reached. If the vents are opened by melting this should occur after contact with the flame for about 1/50 s. The thin polythene sheet used in the tests does not quite fulfil this requirement as it melts in about 1/25 s following contact with the flame.

*Use of relief vents in conjunction with flame arresters*

The use of an adequate amount of relief venting distributed along a duct system not only reduces the maximum pressure of an explosion but also reduces the speeds of both the flames travelling along the duct and the flame and hot combustion products ejected through the vents. The latter reduction facilitates the design of any flame arresters that may be used either in the duct to prevent propagation of flame from one unit of plant to another, or at the vents to prevent ejection of flame into working spaces. Thus if it can be ensured that flame speeds are kept down to about 40 ft/s, a single layer of 60 mesh gauze would be adequate to stop the flame.[5] Moreover, when well-distributed vents are used, all of which open in the vent of an explosion, the heat capacity, necessary to prevent failure by melting of any flame arrester placed outside the vents during expulsion of hot products, is limited by the small length of duct that each vent serves. On the other hand, a flame arrester placed outside a single vent at the end of a long duct would have to withstand the passage of hot combustion products generated along the whole length of the duct.

*Comparison with present practice*

It is common practice at the moment for duct systems carrying flammable vapours and gases to have no relief vent at all. Occasionally, however, relief vents are placed at a number of bends in the duct work; these reliefs are usually closed with discs that burst at 2–3 lb/in$^2$. The amount of venting specified in this paper is far greater but this does not imply that such relief vent systems as are now in use have no value. Indeed, they might well be adequate for gas mixtures very near the flammability limits or for explosions in very small local pockets of flammable gas mixtures. Such systems cannot, however, rely on the relief vents as a major factor in promoting safety, and reliance must continue to be placed on keeping concentrations of the flammable constituent well outside the flammability range.

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**Symbols Used**

$D$ = hydraulic mean diameter of vessel or duct (ft).

$K$ = ratio $\frac{\text{(cross-sectional area of duct)}}{\text{(area of vent)}}$.

$L$ = length of vessel or duct (ft).

$M$ = concentration of flammable vapour present, divided by the concentration in the stoichiometric mixture.

$P$ = maximum pressure (lb/in$^2$).

**References**

1 Palmer, K. N. *J. Inst. Fuel*, 1956, **29**, 293.

2 Cubbage, P. A. and Simmonds, W. A. *Gas Council Research Communication* GC 23 and GC 43.

3 Rasbash, D. J. and Rogowski, Z. W. *Joint Fire Research Organization F.R. Note No.* 298/1957.

4 Rasbash, D. J. *Joint Fire Research Organization F.R. Note No.* 416/1959.

5 Palmer, K. N. *Joint Fire Research Organization F.R. Note No.* 417/1959.

6 Cousins, E. W. and Cotton, P. E. *American Society of Mechanical Engineers Paper No.* 51—PRI—2. 1951. (New York: American Society of Mechanical Engineers.)

7 Freeston, H. G., Roberts, J. D., and Thomas, A. *Proc. Instn mech. Engrs*, 1956, **170**, 811.

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