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RELIEFS FOR GASEOUS AND VAPOUR EXPLOSIONS

by

D.J. Rasbash

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INTRODUCTION

Flammable vapours and gases are handled in many industries and the danger of explosion exists wherever these vapours and gases may form flammable mixtures with air. A common way of protecting plant and buildings against explosions is to provide relief vents. In this note, certain aspects of the design and installation of these vents are discussed. Although no attempt is made to give a comprehensive review of the subject or to give a practical guide to venting, particular attention is paid to the correlation of the results of different investigations, to indicating those problems for which useful information is available and those for which further work is still required.

GENERAL CONSIDERATIONS

Basic steps in the design of venting systems

In the design of any venting system, the first question that arises is what is the maximum pressure that the vessel can stand. This question is largely outside the scope of this paper but it might be broadly stated that buildings and any plant which have not been specially constructed to withstand internal pressure will collapse or burst at pressures greater than one or two p.s.i. As a rule plant outside this category has been built to withstand a certain design pressure and information should be available on the maximum pressure that may be allowed during an explosion. The second question that arises is how much venting area is required to keep the pressure in an explosion down to an acceptable value and how this area should be distributed; this is the question that will receive most consideration. Lastly, a method has to be developed to close these venting areas so that there is no inconvenience to normal working.

Factors controlling the rise in pressure in an explosion

There are two sets of factors that govern the pressure reached in an explosion in a vented vessel, those that govern the rate at which the volume of the gas in the vessel might be expanded by the explosion and those that govern the rate at which gases may be discharged. The most important factor in the first group is the rate of combustion of the explosion gases although the cooling of burned gas will also be a factor. The most important factor in the second group is the restriction to flow at the vent, although the inertia and friction of both the moving gas and the device used to close the vent are also important. Attempts have been made in the past to calculate venting requirements from the fundamental principles indicated above. However, the results of these attempts have little practical application mainly because of the assumptions that are made concerning the rate of combustion. Thus it is often assumed that the rate of combustion is the same in a vented vessel as in a closed vessel. This assumption is not usually justified. Until a great deal more is known about the factors that control the rate of combustion in a vessel, empirical investigations must be relied upon to provide data for venting systems.

Expression of venting area

It has been customary in the past to express venting areas in terms of the volume of the vessel for example, the excellent N.F.P.A. guide for explosion venting(1) is based on this method. However, the ratio of area to volume is dimensionally unsatisfactory and both Cubbage and Simmonds(2) and Mansfield(3) have expressed venting areas in terms of a characteristic area of the vessel.

The most useful approach would be the one which allowed the use of simple formulae over the widest range of conditions. On this basis, the author has found a system very similar to that used by Cubbage and Simmonds to be the most satisfactory and in this paper the venting area for vessels with three main dimensions has been usually expressed as a factor K defined as:-

$$K = \frac{\text{the smallest cross sectional area of the vessel}}{\text{the area of the vent}}$$

Thus, if the whole of the smallest end of a vessel is used as a vent K is equal to 1. If there is no vent K is infinity.

There is some theoretical justification for this approach. If ignition takes place at some point inside a vessel of three main dimensions. the flame front will stretch across a maximum area, when the flame has traversed the two smaller dimensions of the vessel. Thereafter, the flame travels along the longest dimension of the vessel as either one or two flame fronts. however, it must not be expected that the above method of expressing venting areas can give a simple correlation for use under all conditions, since even if the area of the actual flame front were directly proportional to the cross sectional area of the vessel, the rate of combustion of the gas per unit area of flame front would not in general be constant. This rate of combustion depends on the turbulence encountered by the flame and depends on the shape of the vessel, the siting of the vents and the history of the explosion.

INVESTIGATION INTO VENTING REQUIREMENTS

For the purpose of this survey, investigations have been divided into two groups A and B, according to whether the ratio of the maximum main dimension L, to the minimum main dimension D, of the vessel used is respectively smaller or greater than 3. The sub divisions may be considered as referring broadly to cubical and duct shaped vessels respectively.

Group A. (L/D less than 3)

There are four main investigations in this group.

1. Cubbage and Simmonds(2) investigated venting requirements of industrial drying ovens. The vessels used were mainly cubical in shape, and ranged in size from 1 to 500 cu.ft. The vent areas tested varied over the range (K = 1 to 4) and the vent covers were held in place by gravity.

2. A Committee for explosion research in Sweden(4) conducted a number of tests in a building measuring 8.8 metres by 5.8 metres by 4.0 m. high (volume 7000 cu.ft). Propane/air and acetylene/air mixtures were exploded. Most tests were carried out with the vents in one wall and a value of K = 1.26; the vent covers were held in place by spring latches.

3. Cousins and Cotton(5) worked with vessels of comparatively small volume of size 7.6, 3.0 and 1.13 ft^3. Values of K varied from 4 to infinity. With the first two of the above vessels, explosions were carried out with open vents only and with the last, explosions with bursting discs only.

4. Burgoyne, Newitt and Wilson(6,7), studied explosions in a cylindrical vessel of 60 cu.ft capacity. Values of K used varied from 4 to infinity. The vent covers consisted of loose cards, bursting panels and spring release valves.

Cubbage and Simmonds found that in general there were two peak pressures on the pressure records. The first corresponded to the pressure (P_1) at which the vent cover was blown off and was given by the following equation.

$$P_1 \; V^{\frac{1}{3}} = S_o(0.30 \; Kw + 0.40) \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

P_1 = pressure (lb/in^2), V = oven volume ft^3, S_o = fundamental burning velocity of gas mixture (ft/sec.), w = weight per unit area of relief cover (lb/ft^2).

The second peak P_2 corresponded to the pressure required to force the gases out of the vents. For explosions in towns gas, this peak pressure was given by equation (2)

$$P_2 = K \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Cubbage and Simmonds also suggested tentatively on the basis of a few experiments carried out on an oven of volume 8 cu. ft that the second peak pressure was directly proportional to the fundamental burning velocity, thus this would give equation (3)

$$P_2 = \frac{S_o}{3.9} \; K \qquad \ldots\ldots\ldots\ldots\ldots(3)$$

Equation 3 reduces to equation 2 for towns gas.

The main conclusions reached by the authors was that drying ovens should be designed so that all or as much of the top of the oven as possible should act as a relief vent in an explosion.

With the Swedish work the highest pressure rise encountered with a propane/air mixture was 0.71 lb/sq.in. An examination of the pressure records indicated that this maximum pressure usually occurred as the second peak and indicated that equation (3) was the appropriate one to use for comparison with the previous authors. On the basis of equation (3) a pressure of about 0.4 lb/sq.in. would have been expected. Thus it appears that a thousand-fold increase in volume, gives less than a two-fold increase in pressure. Also under identical conditions of experiment an acetylene/air explosion gave a pressure 3.2 times greater than a propane/air explosion. This ratio was approximately the same as the ratio of flame speeds and also supports equation 3.

Evidence showing a wider applicability of equation 3 and also indicating some limitations of its use is also furnished by the work of Cousins and Cotton, and Burgoyne et al. This evidence is shown in Fig.1. The results of experiments by Cousins and Cotton with hydrogen explosions agree quite well with the values predicted by equation 3. The results for propane and pentane tend to the values predicted by equation 3 at low values of K. However, for high values of K higher pressures were obtained by these investigators, the deviation from the expected value being much greater with the results of Burgoyne et al who used a much larger vessel than Cousins and Cotton.

It would therefore appear that equation 3 has a wide range of applicability in determining pressures that may be reached in an explosion in an approximately cubical vessel using either an open vent or a vent covered in such a way that the vent covering is blown off at a comparatively low pressure. The main exception to this generalisation is that the equation would underestimate the pressure for small vents ($K > 4$) used in large vessels. It might be desirable also when equation 3 is used for large buildings to introduce a small correction factor to cover the scale effect suggested by the results of the Swedish work.

Equation (3) might also be expressed in a dimensionless form

$$\left(\frac{P_2}{P_o}\right) = (A \; S_o) \; (K) \qquad \ldots\ldots\ldots\ldots\ldots(4)$$

where P_o is the original pressure in the vessel and A is a constant equal to 0.017 when S_o is measured in ft/sec. and P_o is equal to atmospheric pressure. If it is assumed that A is independent of P_o then equation (4) can be applied to explosions in which the initial pressures is not atmospheric. However, a great deal more needs to be known about the nature of the factor A before this can be done with any confidence. It would be expected that an increase in the temperature of the gas at atmospheric pressure could be allowed for merely by the effect of temperature on the fundamental burning velocity S_o. However, some tests carried out by Cubbage and Simmonds with hot solvent vapours of low spontaneous ignition temperature indicate that equations 3 or 4 predict maximum pressures which are too low. It is clear that further investigation is desirable to clarify both the above points.

An important finding of Burgoyne et al was that when the vent was covered by a bursting panel which burst at a much lower pressure than the maximum pressure obtained with an open vent, the subsequent maximum pressure following the bursting of the panel was very much higher than that obtained with an open vent; this was possibly the result of an increase in combustion rate following bursting of the disc. Cousins and Cotton also obtained results for explosions in a small vessel with a range of bursting discs, and in most cases, pressures obtained were much higher than bursting pressure of the disc. However, since no comparable experiments were carried out with open vents, it is difficult to judge whether these higher pressures were due to the normal restricting effect of the vent or the effect found by Burgoyne et al. Since bursting discs are a very convenient way of closing vents, particularly if the contents of the vessel are at a high pressure, it is important to define the range of conditions where these discs do not confer a disadvantage to the system. It may be added that Burgoyne et al found that the use of spring loaded covers did not cause an increase in the maximum pressure.

Finally, in all the work referred to so far the gases have been initially stationary and the vessels have been empty. Some of the authors who have been quoted, also carried out some tests on explosions in stirred gases and Cubbage and Simmonds also investigated the effect of expanded metal shelves in an oven. In general, these changes gave a substantial increase in the maximum pressure obtained. Insufficient information is available, however, to allow any correlations to be made which can be usefully applied to practical problems.

Group B. ($\frac{L}{D}$ less than 3)

Extensive work has been carried out here (J.F.R.O.) on explosions in a number of ducts and certain duct systems. Tests with single cylindrical ducts have also been reported on by other investigators. Very little information is available for flat vessels characterised by two large dimensions and one small dimension.

It was found here, that the maximum pressure reached in an explosion in a duct shaped vessel, varied widely with the relative positions of the ignition source and the relief vent, pressures and flame speeds up to fifty times greater being obtained when the ignition source was remote from the vent than when the source was near the vent. Under the conditions which gave the most violent explosion, the maximum pressure obtained in propane/air explosions was given by:

$$P = 1 \cdot 8K \qquad \text{.............}(5)$$

This equation held approximately over the wide range of vent and duct sizes indicated in Table 1.

TABLE 1

Conditions under which Equation 5 applied

Smallest main dimension of duct D	Length to diameter $\frac{L}{D}$	Vent sizes K
3 in.	24	$2 < K < 32$
3 in.	48	$K = 2$
6 in.	12, 24	$2 < K < 32$
6 in.	36	$K = 2$
12 in. (square duct)	6, 12, 18, 24, 30	$K = 4^*$
12 in. " "	12, 18, 24, 30	$K = 2$

*No tests carried out with 12 in. duct with values of $K > 4$.

With values of $K > 32$, i.e. as the vent was reduced to zero size, the maximum pressure approached the value obtained in a closed duct; this varied between 70 to 90 lbs/sq.in. according to the duct used. For values of $L/D > 30$, i.e. for long ducts, pressures were obtained that were higher than those expected from equation 5 for values of $K > 2$. Explosions in these ducts were accompanied by violent pressure oscillations.

In Fig.2 the work carried out here is compared with work on cylindrical ducts carried out by other authors. The results of Freestone et al(8) for explosions of petroleum spirit in a vessel 18 in. diameter and 11 ft long fall only slightly above the line expressing equation 5. Results of Cousins and Cotton(5) for hydrogen and Jones et al(9), for acetone, are respectively 8 and 0.6 times greater than the J.F.R.O. results for propane. This suggests again. that the maximum pressure is approximately directly proportional to the fundamental burning velocity under a wide range of conditions. However further work is desirable on this point and is in hand.

There is one implication of these results, which should perhaps be brought out, i.e. for a duct of a given diameter and with a vent in the end of the duct, the maximum pressure has been found to be independent of the length of the duct, over a wide range of duct length in spite of the change in the volume of the duct. This point illustrates how the expression of the venting area on a volume basis might be misleading.

Experiments have also been carried out, on the effect of obstacles, bends and T pieces in the duct on an explosion. It has been invariably found that unless the explosion is well vented before the flame reaches an obstacle, a sharp peak in the pressure record and a very marked increase in flame speed is obtained directly after the flame has passed the obstacle. The maximum pressure obtained under given explosion conditions, may be broadly correlated with the resistance that the obstacle causes to fluid flow. This is shown in Fig.3 which shows the maximum pressure obtained for an open ended duct 12 ft long x 6 in. diameter, with obstacles placed halfway along the duct, plotted against the resistance of the obstacle. The obstacles were all of the kind that produced a sharp change in the flow pattern. A relief vent of area equal to the cross sectional area of the duct placed near the obstacle reduced the maximum pressure to about 25-50% of the value without a vent. However, a small relief vent placed near the ignition source had a much more marked effect in reducing the maximum pressure and substantially reduced the maximum flame speeds as well. This is illustrated in Fig.4 which shows the effect of this type of relief on the maximum pressure when a T piece was the obstacle.

Probably the majority of duct systems used for carrying flammable vapours and gases are not vented at all. Where these systems are vented the practice is usually followed of placing a bursting disc at some of the bends on the ducts. This method might be effective in cases where the bends are long radius bends, where there are no side T pieces leading from the duct into which the explosion might be diverted and if the discs burst at low pressures. However, even under these conditions distances between vents should not exceed about 30 diameters. Where there are a number of T pieces, sharp bends or other obstacles in a duct system it is desirable that relief area should be distributed along the whole length of the duct system so that there would be a vent in the vicinity wherever ignition might take place. Two systems of venting which have this aim in view have been studied here on a duct of 1 ft square section 24 ft long with an obstacle at the centre of the duct. The systems are as follows:-

(1) Vents distributed as a slot up to 2.4 in. wide along the length of the duct.
(2) Vents distributed as a series of rectangular openings up to 1 ft^2 in. area placed at 6 ft intervals along the duct, one vent being near the obstacle.

Both systems are effective in keeping pressures down to a reasonable value (less than 2 lb/in^2) if the vents at the start of the explosion are covered with only a very light cover held in place by gravity. However, such a system of covering the vents would not be acceptable in practice.

A method of covering the vent which might prove more acceptable is to use polythene which is melted by the passage of the flame but will stand up to normal pressure changes within the duct. This method of covering the slot vents has been found effective for most obstacles likely to be encountered in practice in duct systems but high pressures have been obtained with some obstacles which block a substantial area of the duct when ignition is close to the obstacles. It has also been found that the light covers such as those mentioned above may be clamped to the duct with a force of 20 lb/ft^2 by means of magnets without interfering substantially with the efficiency of the venting system. Tests are also in hand on the venting of duct systems when the gas is initially in motion and it is expected that much larger venting areas might be required to vent explosions under such conditions. There is ample scope for increasing the venting area, however, by increasing for example the width of the number of polythene slots used. In the limit the whole duct wall can be made out of polythene on a supporting framework so that the whole surface acts as a vent in an explosion. Alternatively all the sides of the duct may be made light and rigid and clamped to a skeleton with magnets.

Finally, with duct systems containing flammable gases there is a risk of detonation leading to pressures of several thousand pounds per square inch. For most flammable gases and vapours there are certain mixtures with air which can give detonation in duct systems provided these are sufficiently long and complicated. Once detonation has been established it is doubtful if any form of venting can reduce the pressure of explosions to acceptable values. However, the systems of distributed venting outlined above should be effective in preventing detonation. As a flame passes along a duct, vents would open continuously in the immediate vicinity of the flame and combustion will take place throughout the duct in a manner similar to combustion which has only just been initiated near the open end of a duct.

VENT CLOSURES

The correlations given in Figs. 1 to 4 refer to open vents. In practice it is rare that open vents can be used and some method of closing the vents is necessary. As a rule, devices to close vents rely on the initial rise in pressure in an explosion to effect the opening of the vent. Where this is the case it is very desirable that the pressure required to open the vent should be less than the maximum pressure which would be obtained in an explosion with a vent initially open. There is generally no difficulty in achieving this when the latter pressure is greater than about 4 or 5 pounds per sq.in., but when the pressure is less than one or two pounds per sq.in. some difficulty may be encountered, particularly when small vents are used. Thus discs that burst at these low pressures are generally very fragile and if they are used it is desirable to protect them from falling objects. Covers held in place by either gravity or springs are also commonly used to close vents. These have the disadvantage that to obtain a good seal it might be necessary to use either a heavy cover or a substantial spring loading and because of the inertia effect the pressure required to open the vent may be considerably greater than the pressure required merely to counter balance the weight of the cover or the force of the springs. Probably the best type of vent closure to use from the point of view of opening at a low pressure, is a very light rigid cover, held in place by some device, the force of which is removed completely very soon after the cover begins to move. Vent covers held in place by magnets, spring latches, and light friction at the edges, fall into this category. The tests carried out here with magnets are very indicative of the efficiency of this system but more quantitative information on the pressure at which other such venting devices open is also required.

Vents might also be opened by the flame itself melting a substance like polythene. This principle is generally difficult to apply because to melt rapidly the material must be so thin that with large vents it might not stand up to normal pressure variations in the system. However, for vents with a small dimension, e.g. the slot vents suggested earlier for ducts, the system is feasible provided the vents are protected against falling objects. Finally vents might be opened automatically following the detection of the explosion by a sensing device. This method rules out the necessity of using a very light cover since powerful springs or some other suitable system could be made to open the vent.

A consideration which must be borne in mind in designing vent closures is that they should cause no injury by being thrown during an explosion. If rigid vent covers are used they should either be very light or secured in a way which limits the throw. An ingenious method of overcoming this difficulty developed by Cubbage and Simmonds is to use vent covers which are disintegrated by the explosion.

SITING OF RELIEF VENTS

The most efficient places to site relief vents is near likely sources of ignition. However, it is possible with some risks that ignition may take place at any point. For these risks it is better to distribute the relief area throughout the whole system rather than concentrate it on large areas in a few places. It is also important to site relief vents so that flames and hot gases should not injure personnel.

THE ROLE OF TURBULENCE IN EXPLOSIONS

The investigations summarised above cover a wide field and are capable of application to many problems. However, it is clear that there are many practical problems for which there is insufficient information available to allow relief vents to be designed adequately. There are two ways of obtaining information for these problems, either directly by doing tests on a full-scale or indirectly by obtaining sufficient information about the factors controlling the progress of explosions to allow either small scale model experiments to be carried out or to allow direct computation of maximum pressures without recourse to experiment.

As indicated earlier, the major stumbling block to the latter approach is the lack of knowledge on the factors that influence the rate of combustion and in particular the effect of the turbulence which might be originally present in the system or caused by the explosion itself. There is ample evidence that such turbulence exerts a powerful effect on explosions. Thus, the correlation given in Fig.3 between the maximum pressure in an explosion in a pipe with an obstacle and the resistance to flow of the obstacle might also be regarded as an expression of the dependence between the rate of combustion and the turbulence encountered by the flame downstream of the obstacle. The fact also that much smaller pressures are obtained when ignition is near a vent may largely be ascribed to the fact that by venting burned gas, the unburned gas is not set into bulk motion and turbulence in this gas is reduced to a minimum. The turbulence in the unburnt gas set up by the progress of a flame along a duct closed at one end towards a vent remote from the ignition source also accounts for the difference between equation 3 giving the maximum pressure for vessels in group A. and equation 5 giving the maximum pressure for vessels in group B. This point is illustrated in Fig.5 in which the maximum pressure for different values of K have been plotted against the $\frac{L}{D}$ ratio. This figure shows how the maximum pressures given by equation 3 passes into the maximum pressures given by equation 5 as the $\frac{L}{D}$ ratio increases from about 3-10. The effect might be ascribed to turbulence becoming established in the unburnt gas moving towards the vent in an elongated vessel and the effect of such turbulence on the combustion rate.

It would, therefore, appear that if an approach is to be developed for the design of relief vents, which would eliminate the necessity of carrying out full scale empirical experiments, a more fundamental study is required on the effect of turbulence on the combustion rate in premixed gas/air systems. Much work is already being carried out in other fields of combustion on this problem; it is clearly desirable to apply information from this work as far as possible to industrial explosions. This requires a more detailed knowledge of the nature of gas motion and turbulence established during an explosion, a field which has hardly been touched upon in the past.

CONCLUSIONS

1. There is a certain amount of information on venting requirements for different systems. However, there are still many systems of practical importance for which there is insufficient data to allow the rigorous design of vents. These may be briefly enumerated as follows:-

    (a) Systems in which the gas is moving or is initially at a pressure and temperature other than atmospheric.

    (b) Systems containing obstacles.

    (c) Large vessels of $\frac{L}{D}$ ratio between 1 and 3 which can stand up to pressures greater than about 2-3 lb/in^2, particularly where the vents are to be closed by bursting discs.

    (d) Systems containing ducts of large diameter ($>$ 2 ft).

2. Expression of the venting area in the form of the factor K has certain advantages over expression in the form of venting area per unit volume, in that for a number of systems of a given shape, there is a relation between the pressure and K which is approximately independent of the volume.

3. More information is required on the pressure at which vent closures are removed in the early stages of an explosion.

4. A fundamental study of the effect of turbulence on explosions is required before it is possible to estimate venting requirements from basic principles.

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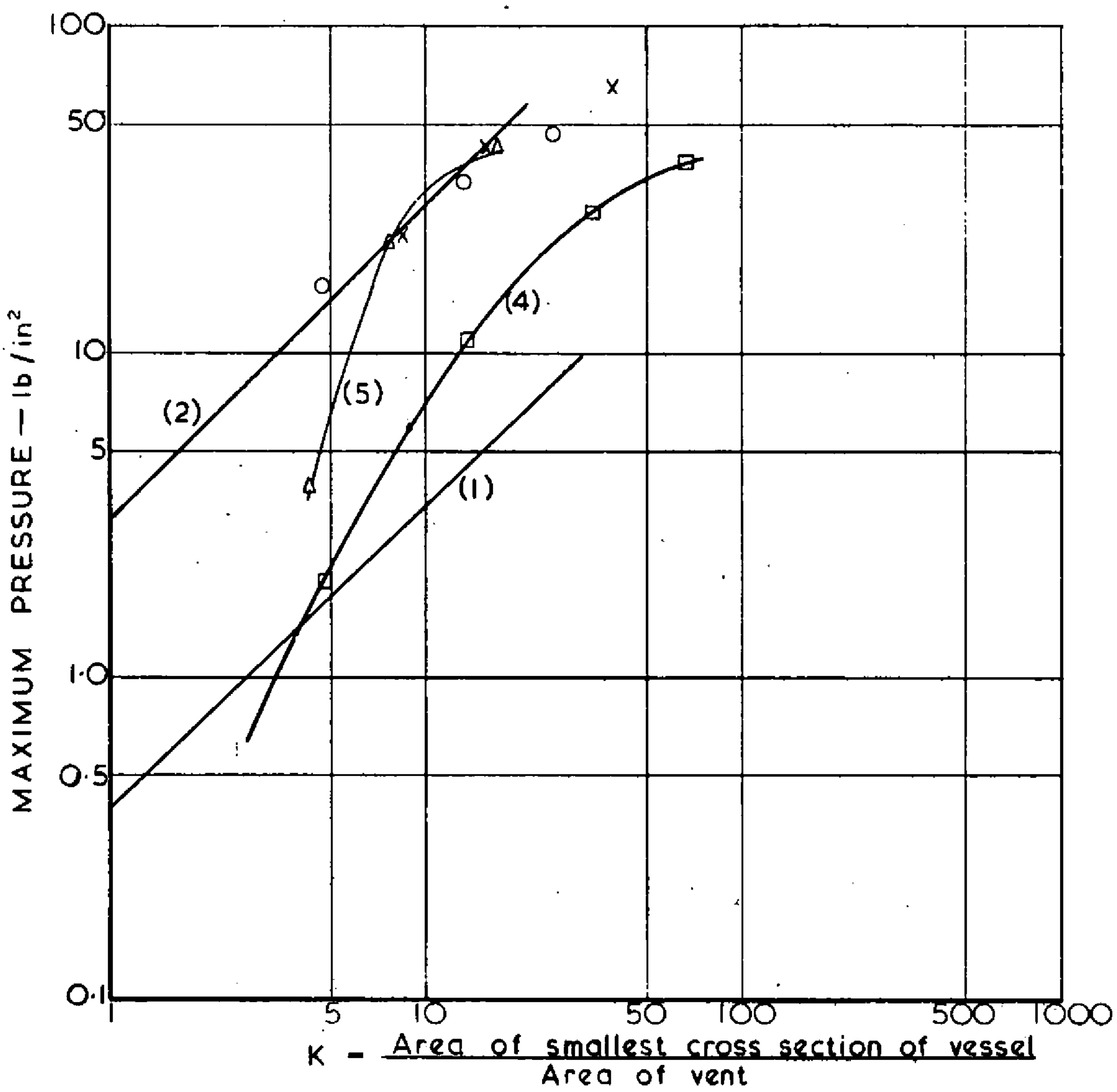


(1) Propane and pentane (equation 3)

(2) Hydrogen (equation 3)

(3) x Hydrogen (drum, volume 7·6 ft³, $\frac{L}{D}$ = 1·44, Cousins and Cotton)

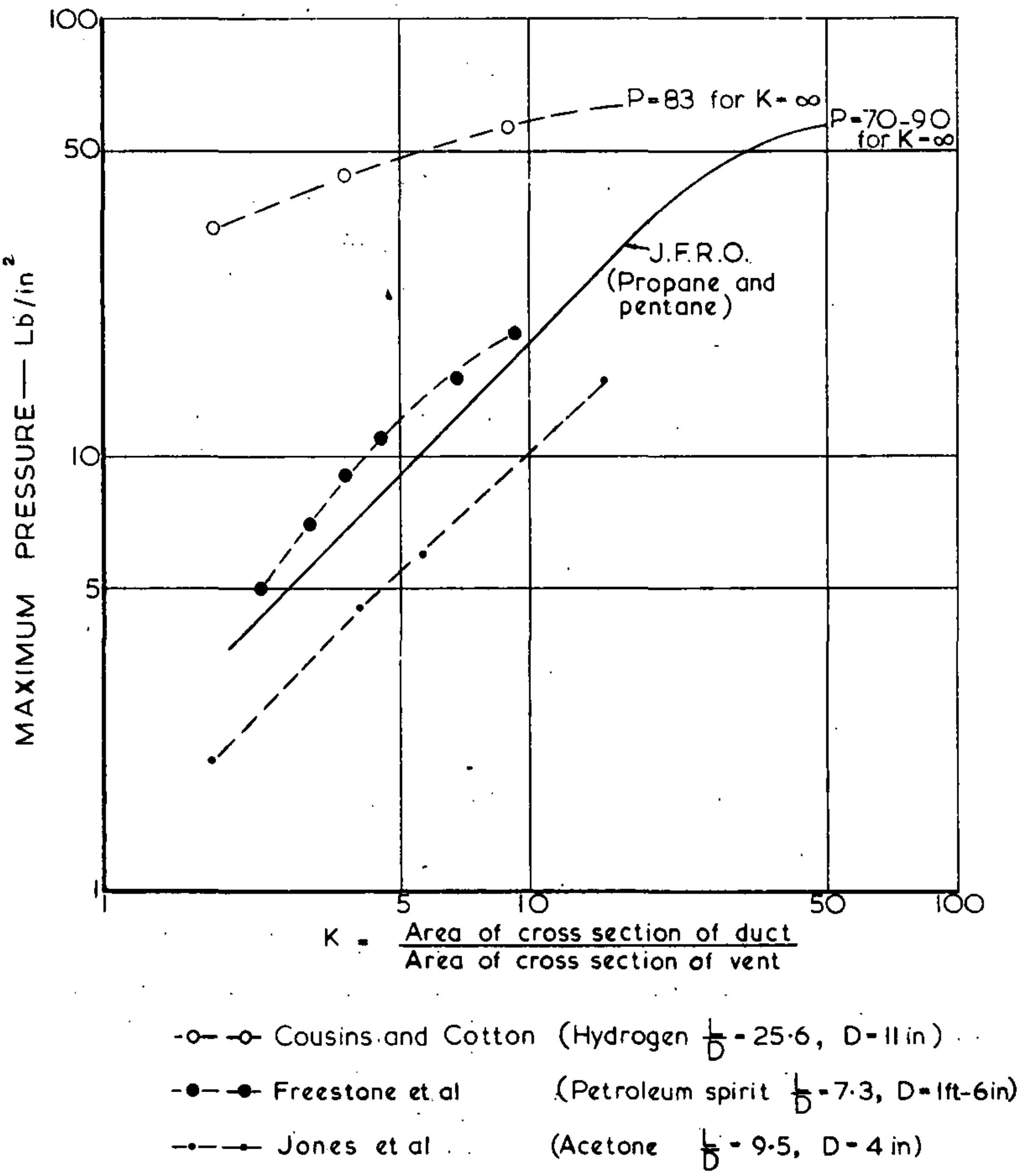
(3) o Hydrogen (tank, volume 3·0 ft³, $\frac{L}{D}$ = 2·3, Cousins and Cotton)

(4) ◻ Propane (tank, as in (3))

(5) △ Pentane (60 ft³ vessel, $\frac{L}{D}$ = 1·1, Burgoyne et al, Loose card covered vent)

Group A vessels ($\frac{L}{D}$ < 3)

FIG. 1. MAXIMUM PRESSURE OBTAINED WITH OPEN VENTS



Group B vessels ($\frac{L}{D} > 3$)

FIG.2. MAXIMUM PRESSURE OBTAINED WITH OPEN VENTS

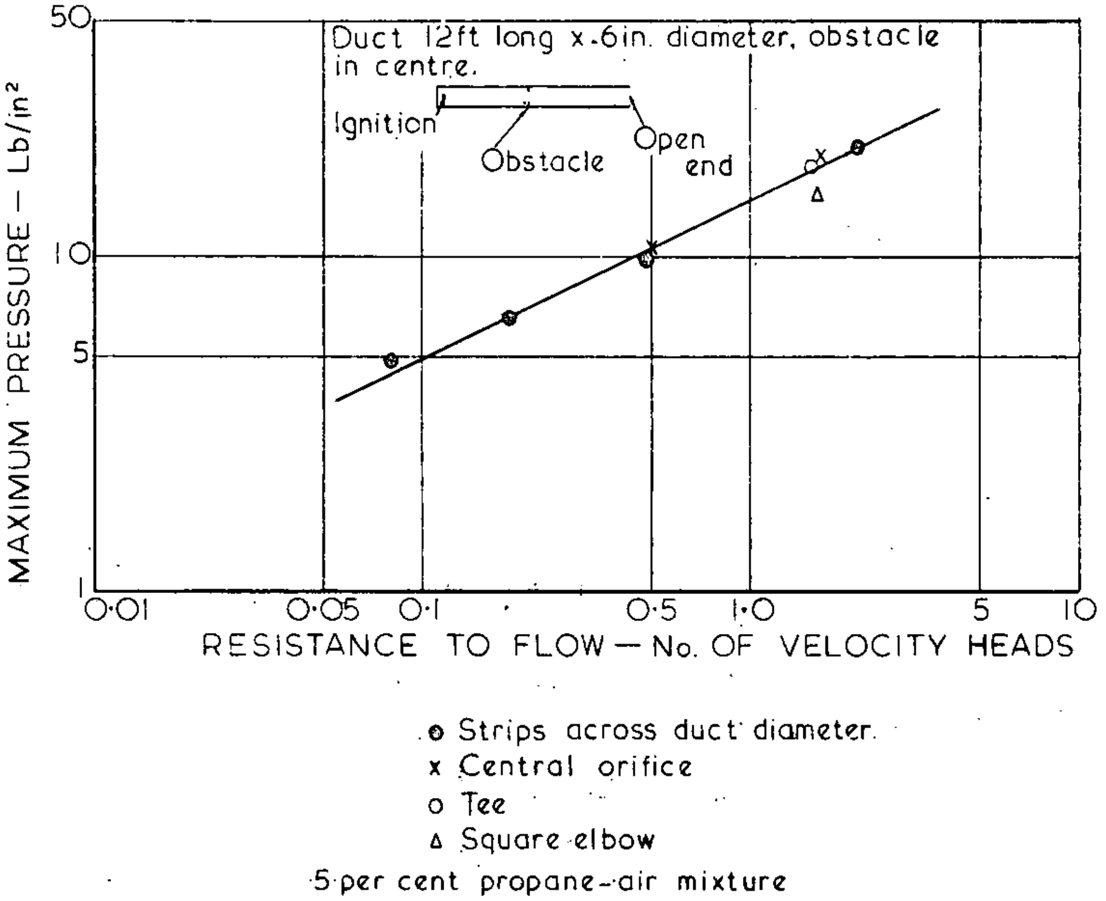


FIG. 3. RELATION BETWEEN MAXIMUM PRESSURE IN AN EXPLOSION IN A DUCT CONTAINING AN OBSTACLE AND THE RESISTANCE TO FLOW CAUSED BY THE OBSTACLE

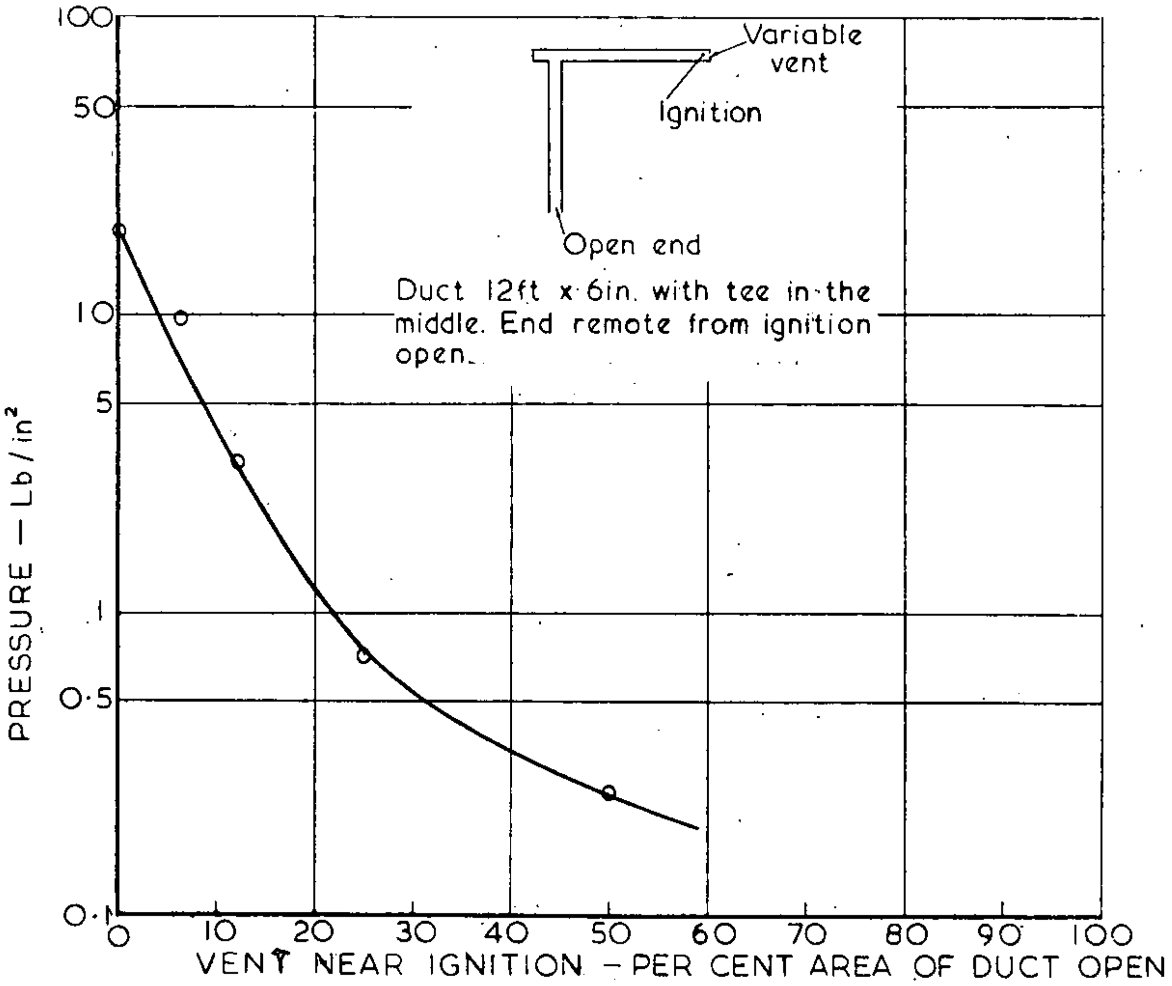
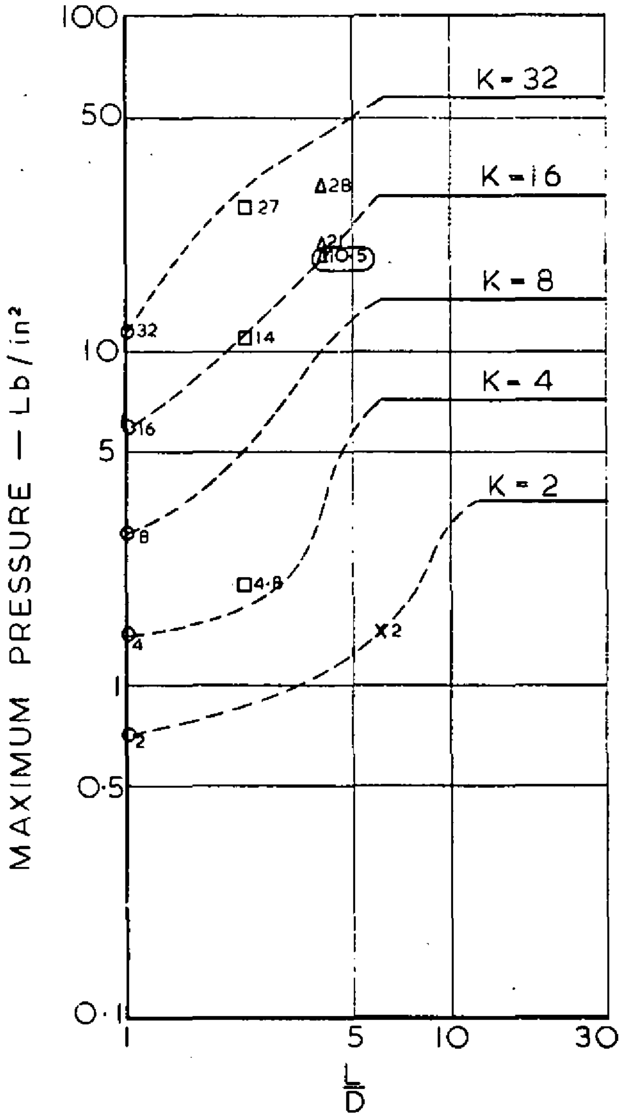


FIG. 4. EFFECT OF A VENT NEAR IGNITION ON MAXIMUM PRESSURE



○ Based on equation 3

x Point obtained at J.F.R.O. for K = 2, 6ft duct 1ft square section

□ Cousins and Cotton, vessel volume 3·0 ft^3

△ Cavalier, vessel volume 8·5 ft^3. Spring loaded covers on vents (encircled point may be high because of this)

Numbers refer to values of K

——— Based on equation 5

Propane-air mixtures

FIG. 5. RELATION BETWEEN MAXIMUM PRESSURE AND LENGTH TO DIAMETER RATIO FOR DIFFERENT VENT RATIOS