DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

# SYMPOSIUM ON FLAME ARRESTERS AND RELIEF VENTS

Held at Joint Fire Research Organization - November 1959

August, 1960.

Fire Research Station,
Boreham Wood,
Herts.

# SYMPOSIUM ON FLAME ARRESTERS AND RELIEF VENTS

## Held at Joint Fire Research Organization - November 1959

### INTRODUCTION

Flammable vapours and gases are handled in many industries and the danger of explosion exists wherever they may form mixtures with air within the flammability limits. Plant in which there is a possibility of these mixtures occurring should be designed so that the minimum amount of damage would be caused by an explosion that may result from the ignition of such mixtures. The insertion of flame arresters into the plant and the provision of explosion reliefs are two ways of reducing the damage caused by such explosions. A flame arrester acts by preventing an explosion from propagating from one part of a plant to another. The function of explosion reliefs is to reduce the maximum pressure reached in the explosion to a value which the plant can withstand.

In view of the lack of the full data necessary for the efficient design of such protective devices, the Joint Fire Research Organization were asked, by the Factory Inspectorate in 1954 to carry out research on the mechanism of operation of flame arresters and relief vents and to obtain data which would allow them to be adequately designed. This research was started in 1955 and is continuing at the present time.

While the work was in progress, visits were made by the research staff to a number of industrial premises where these devices are installed, to obtain first hand information on the practical conditions of their use. These visits, while confirming that there was a wide range of conditions of use where more design data was essential, also revealed that existing information was not being used to the fullest extent. The first stage of the research work was nearing completion in the middle of last year and it was thought desirable to discuss results at an informal Symposium with organizations concerned with the protection of plant against explosions. The Symposium was designed to serve two objects, firstly, to discuss the practical value of the work already carried out by the Joint Fire Research Organization and to obtain informed comment and criticism before the next stage of the work was planned and secondly, to put on record general principles on the use of flame arresters and relief vents for the guidance of engineers engaged in their installation.

It was intended in the first instance to hold the Symposium on one day, but owing to the large number of intended participants, similar Symposia were held on two days, 19th and 20th November, 1959, for two different groups of participants. In both groups the participants were widely drawn from industry, Government departments interested in safety and the universities. On both days sessions were allocated to discussion, and demonstrations of the experimental work in progress at the Joint Fire Research Organization. Because of the wide interest shown in the subjects under discussion both at the Symposia and subsequently by industrial concerns who were not represented, the proceedings of the Symposia are presented in this note which contains the papers presented by members of the staff of the Joint Fire Research Organization and also an account of the discussion that took place.

# FLAME ARRESTERS FOR INDUSTRIAL USE

by

K. N. Palmer

## TYPES OF ARRESTER

Most flame arresters or flame traps consist basically of a solid matrix containing a group of small narrow passages or apertures through which gases or vapours can flow, but which are intended to be too small for a flame to pass through. Thus as the flame enters the arrester it is subdivided into flamelets, and it is obvious that all of these should be quenched if the explosion is not to propagate through to the other side of the arrester. The various types of flame arrester differ mainly according to how the subdivision is obtained and the number and size of the apertures produced. A selection of the more common types of flame arrester is listed in Table 1, which shows that all the types except the hydraulic arrester contain a solid matrix. The tabulated list is not meant to be exhaustive, or to give more than a general description of each type of arrester.

The various arresters listed in Table 1 differ considerably in their resistance to gas flow. This resistance is an important consideration because in many industrial applications a flow of gas is required through the arrester and where, for instance, the gas is propelled by a fan the maximum pressure drop that can be tolerated across the arrester may be only one or two inches water gauge. On the other hand, where gas is withdrawn from a cylinder, or is pumped, a much higher pressure drop across the arrester is often permissible. The demands for high flame-quenching ability and low resistance to gas flow are to some extent incompatible, but by taking measures such as widening a duct at the arrester this difficulty can often be overcome.

TABLE 1

Types of flame arrester

| Type | Main characteristics |
|---|---|
| Wire gauze | Can be used singly or in packs. |
| Perforated sheeting or blocks. | Usually metal. Can be used in a wide range of thicknesses. |
| Crimped ribbon. | Also obtainable in a wide range of sizes. |
| Packed tower or pebble box. | Can be large items of plant, and with fillings of a wide range of sizes. |
| Parallel plate. | Assembly of closely separated plates, usually metal. |
| Sintered metal or ceramic. | Apertures can be very small and may have a high resistance to gas flow. |
| Hydraulic. | Water-sealed non-return valve, which breaks up gas flow into separate bubbles. |

Not all flame arresters contain a porous solid matrix; for instance the hydraulic arrester is basically a non-return valve sealed by a layer of water through which the gas bubbles. If properly designed there is never a continuous passage of gas through the water in the arrester; the bubbles break up the flow. The arrester can be effective as long as the flame is only propagating above the water layer and in order to ensure this the arrester is most often used in situations where the point of ignition is known, e.g. in a supply line to a burner.

A similar principle to that of flame arresters is used in the design of electrical apparatus for use in flammable atmospheres. For this apparatus to be designated "flameproof" the gaps between joint surfaces and the diametral clearance for operating rods, spindles, shafts etc. must not exceed the permissible maximum, as determined by the official standard testing procedure[1]. The main function is different from that of flame arresters and it will not be considered here in greater detail.

## USE OF FLAME ARRESTERS

Historically, the first systematic use of a flame arrester was the wire gauze in Davy's miners' safety lamp, developed early in the 19th century. This application was followed, over a century later, by the specification of a wire gauze containing at least 28 meshes to the linear inch for protection of the vent pipes of storage tanks containing petroleum. The other types of arrester were usually also developed with specific applications in mind.

The types of plant an equipment in which flame arresters are now used cover such a wide range that a complete classification cannot be attempted. The following are some of the more common uses, but they are only a selection from a much wider range.

1. In solvent vapour recovery systems.

2. In the vent pipes of storage tanks for flammable liquids.

3. Preventing flash-back in gases supplied to burners or furnaces.

4. Preventing ignition from the exhaust of internal combustion engines working in flammable atmospheres.

5. Quenching the decomposition explosions of acetylene.

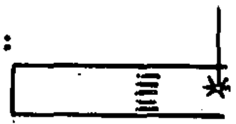
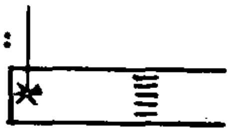
Although the types of plant and equipment using flame arresters vary widely, they tend to have certain common features. It is unusual for the system to be completely closed, so that if an explosion occurs the pressure would build up without any release, but it is far more usual for a part of the system to be open to atmosphere either through a duct opening, or a restricted opening such as a nozzle, or through a vent which opens when the gas pressure changes from the normal working range. Thus if an explosion occurs there is usually a preferential direction for the gas to move as soon as the pressure begins to increase. The existence of this preference affects the performance required of the flame arrester. Figures 1-3 show three simplified systems, represented by a duct sealed at one end and open to atmosphere at the other and containing a flammable gas mixture on both sides of the flame arrester; similar considerations would apply to more compact systems, but the behaviour in ducting is simpler to visualise.

In the case where there is no continuous flow of unburnt gas into the system the gas is stationary at the instant that ignition occurs. When ignition occurs near the mouth of the duct (Fig.1) or a flame flashes back into the duct, the flame propagates up to the arrester through a stationary or relatively slowly-moving gas. If the arrester quenches the flame the hot products of combustion are mostly discharged to atmosphere through the open end of the duct. The arrester, therefore, has to quench a flash of flame but the total amount of heat to be transferred to do this is not large, although the rate of transfer of heat must be high because the time available when the flame is in contact with the arrester is short. When ignition occurs at a position remote from the mouth of the duct (Fig.2) the expansion caused by the combustion causes the unburnt gas ahead of the flame to move down the duct through the arrester. As the flame arrives at the arrester it is propagating through a fast-moving gas mixture tending to carry it through the arrester. Because the gas is streaming rapidly an appreciable pressure drop may develop across the arrester, which must of course be sufficiently strong mechanically not to disrupt. If the flame is quenched by the arrester most of the hot products of combustion will not pass through it, but will remain between the igniter and the arrester and will cool to the walls of the duct. Thus under the conditions represented in Figure 2 the arrester must be able to quench a fast-moving flash of flame and be sufficiently strong to withstand the pressure arising from the motion of the gas. In the case where ignition occurs near the arrester, and the gas tends to exhaust through the arrester (Fig.3), the flame propagates in two directions. Soon after ignition a slowly-moving flame arrives at the arrester and should be easily quenched. Meanwhile another flame propagates towards the closed end of the duct and the hot combustion products that it generates are exhausted to atmosphere through the arrester. The arrester has to be of substantial thermal capacity to withstand the hot exhaust and must also be sufficiently strong mechanically to withstand the pressure due to the moving gas.

In most practical systems, however, the flammable gas mixture will be in motion when ignition occurs, and the gas may continue to flow during and after an explosion. If, in Figures 1-3, the gas flows from the left to right then the possibility of the flame stabilising in the duct modifies the performance required of the arrester. In the case represented by Figure 1, if the gas is flowing at a high speed the explosion may not be able to propagate back against the stream; it will then either be swept out of the duct entirely or may stabilise on the mouth of the duct, like a burner, or on a protruberance in the duct. If the gas velocity is lower, so that the flame can propagate back against the flow, the flame will stabilise on the arrester and heat it, unless the gas flow is quickly turned off. In Figure 2 the flame could stabilise either on the inlet port of the gas stream or on a protruberance in the duct; in either case a flow of hot combustion products would pass through the arrester. A similar situation can arise in the arrangement shown in Figure 3. Thus whenever a flame arrester is installed in a system in which a flowing gas stream can ignite, the possibility of the arrester heating must be studied. There are available on the market automatic detectors which will operate a valve to cut off the gas flow as soon as a flame stabilises, and these detectors can minimise damage to the arresters. The properties required in arresters installed in various systems are summarised in Table 2. The requirement of fine structure usually means that the passages through the matrix in the arrester should be small, or that the components of this matrix should be of small size, and this requirement has often to be combined with mechanical strength. The required mechanical properties and the thermal capacity are both influenced by the mass of the arrester; the thermal capacity can, however, be increased without increasing the mechanical strength by wetting or greasing the arrester.

TABLE 2

Characteristics required of arresters installed in various ducting systems

| Ducting arrangement | Requirements for arrester | | | |
|---|---|---|---|---|
| | Fine structure | Mechanical strength | Thermal capacity: Static gas | Thermal capacity: Flowing gas |
| Fig.1:  | ✓ | | | ✓ |
| Fig.2:  | ✓ | ✓ | | ✓ |
| Fig.3:  | ✓ | ✓ | ✓ | ✓ |

It should be emphasized that the systems shown in Figures 1-3 represent simplified versions of actual plant, the behaviour of which may be more complex. In particular it is often not obvious where ignition is likely to occur, so that an arrester installed in an actual plant may have to face a combination of the conditions of Figures 1-3 and Table 2.

## DESIGN AND INSTALLATION OF ARRESTERS

With the amount of information available at present, it is frequently impossible for the most economic design of flame arrester to be specified for a given installation. With arresters containing solid matrices the specification would include the cross-section and length of the passages through the arrester, and possibly also the mechanical strength and thermal capacity. If the diameter of the apertures in the arrester is too large, a flame would be able to pass through the arrester. If the apertures are unnecessarily small, then the pressure drop across the arrester will be unduly large and power will be wasted in driving the system. In addition the clogging of the arrester by dust etc. may become unnecessarily troublesome. As flame arresters of various types have been in use for a long time, knowledge of safe designs for particular systems has accumulated; but whether these designs are the most economic, or give adequate guidance for the procedure to be adopted with new installations and flammable materials, may not be clear.

Recent reviews[2,3] have given accounts of experimental work on different types of flame arrester, but in the main these experiments were aimed at studying the behaviour of the arresters in particular installations rather than discovering how the arresters functioned and the relation of the effectiveness of the arrester to the properties of flames and the dimensions of the systems in which they were produced. Accordingly, emphasis will be given here to recent work that throws light on some of these aspects, although the work covered in the reviews and the tests carried out on various types of arrester are also of considerable practical value.

First, however, it is important to realise that the cross-section of the passages through the arrester must not exceed a certain size, no matter how thick the arrester is. For circular passages this distance is known as the quenching diameter, and it is dependent upon the gas mixture composition. Values of quenching diameters for different gas mixtures are given in Table 3. If the passages are not circular, the quenching diameter can be taken approximately equal to the equivalent hydraulic diameter.

$$\left(\text{i.e. } \frac{4 \times \text{area of cross-section of passages}}{\text{perimeter of passage}}\right)$$

although with long narrow slits it is probably more accurate to take the maximum permissible width of a slit to be 0.61 x quenching diameter. A clear distinction is to be drawn between the quenching diameter in which there is a relatively slow propagation of flame and the smaller apertures required to quench fast flames, e.g. in the permissible safe gap for flameproof electrical apparatus.

TABLE 3

Quenching diameters for various gas mixtures

| Gas mixture | Quenching diameter | |
|---|---|---|
| | centimetres | inches |
| Methane-air | 0.32 | 0.125 |
| Propane-air | 0.27 | 0.105 |
| Ethylene-air | 0.19 | 0.075 |
| Hydrogen-air | 0.1 | 0.039 |
| Propane-oxygen | 0.04 | 0.015 |
| Hydrogen-oxygen | less than 0.03 | less than 0.011 |

The relationships between the structure and efficiency of various types of flame arrester are being investigated at the Joint Fire Research Organization. Work has been carried out with wire gauze, perforated sheeting and blocks, and crimped ribbon flame arresters installed in simple duct systems where overheating of the arrester does not occur (as in Figures 1 and 2). With these arresters there was a velocity of approach of the flame below which it was quenched and above which it passed through the arrester, provided that the apertures in the arrester were smaller than the quenching diameter. This critical velocity increased as the size of the aperture was reduced, and generally when the thickness of the arrester was increased. An exception to the latter was observed when packs of coarse wire gauze, having the meshes accurately aligned, were tested; the effectiveness of the pack levelled off after about 4 layers and did not increase when further layers were added. The behaviour of different types of arrester against stoichiometric propane/air flames (4 per cent by volume propane) are illustrated in Figure 4, which is intended as a rough guide to design. The relative effectiveness of the different types of arrester shows up clearly. Wire gauze and perforated metal sheeting are usually practicable against slower-moving flames; gauzes finer than about 60-mesh (mesh size 0.025 cm) are frequently ruled out for practical use due to their flimsiness and ease of blockage with dust etc. For rapidly-moving flames crimped ribbon arresters or perforated metal blocks are required. All the types of arrester represented in Figure 4 present a relatively low resistance to gas flow, and thus can be considered for installation in solvent recovery systems. Arresters with a higher resistance to gas flow, some of which are listed in Table 1, have so far not been studied in any detail at the Joint Fire Research Organization.

The results represented in Figure 4 are for arresters mounted in a 2½ in. internal diameter tube without any bends, restrictions, internal projections, or expansion at the arrester, and with ignition at either the open end (Fig.1) or the closed end (Fig.2). To a first approximation the velocity of the flame that was just quenched by a given arrester was the same for ignition under both sets of conditions. The flame velocity was altered in different experiments by varying the distance between the igniter and the flame arrester, the 'run-up'; in general the flame velocity increased with the run-up, but the increase was not in proportion, and with 20-40 ft lengths of pipe ($2\frac{1}{2}$ in. in diameter) a limiting range of flame velocities occurred. The flame velocity developing after ignition at the closed end of the system (Fig.2) was considerably greater than after ignition at the open end (Fig.1) in a tube with the same run-up distance (Fig.4). The flame velocity also depended upon variables other than the run-up, e.g. the gas composition, and the presence of bends or obstructions. Current work at the Joint Fire Research Organization on flame arresters includes a comparison of the behaviour of flames of different solvent vapours against perforated metal arresters, and the effect on the behaviour of the arrester of increasing the diameter of the duct in which it is installed. Accounts have been published of tests on wire gauze arresters(4, 5), and a correlation was obtained between the flame arresting abilities of the arresters and the heat transfer from the flame to the wires.

The behaviour of crimped ribbon arresters is being investigated by Cubbage(6) in connection with the arresting of town gas/air detonations in pipelines. These explosions are more rapidly-moving than those covered by the results in Figure 4, but it appears that suitable crimped ribbon arresters can be made.

Where a considerable amount of hot explosion products is ejected through the arrester, as in the arrangement in Figure 3, the experimental results of Mansfield(7) are available. He showed that coating gauze arresters with oil or grease increased their efficiency as arresters, but whether the action was solely that of cooling or whether some chemical effect was involved was not settled.

## CONCLUSION

As a result of work already carried out, or in progress, it should be possible to put the provision of flame arresters for ducting systems having only a low resistance to gas flow on a reasonably quantitative basis. With straight, smooth, ducts the problem of flames travelling at speeds up to detonation has been covered and arresters can be specified for these installations. If the ducts have bends or restrictions it may be necessary to instal vents to keep explosion pressures and flame speeds to safe levels. The requirements for flame arresters in ducts of 1 ft in section are being investigated, but the effect on the flame of enlarging the duct near the flame arrester still requires more study than it has so far received.

The types of arrester that cause a higher resistance to gas flow have not been investigated so fully as those of lower resistance. For instance, with sintered metal or packed tower arresters, the flame quenching ability has not been related to the particle size or thickness of the arresters. However, it may be that these arresters are not used sufficiently widely to warrant detailed examination.

The installation of flame arresters requires consideration of the layout of the containing system, as well as knowledge of the gas or vapour involved, and hence individual installations may need individual consideration. In particular it is not possible to specify an arrester that would be both safe and economic for all plant containing a given gas or vapour. The designing of a flame arrester for an installation is always likely to involve technical details if the most economic working is desired.

# RELIEFS FOR GASEOUS AND VAPOUR EXPLOSIONS

by

D. J. Rasbash

## INTRODUCTION

A common way of protecting plant and buildings against explosions is to provide relief vents. In this paper, 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 indicate 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, but 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(8) is based on this method. However, the ratio of area to volume is dimensionally unsatisfactory and both Cubbage and Simmonds(9) and Mansfield(7) 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. 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 vessels and ducts respectively.

Group A. (L/D less than 3)

There are four main investigations in this group.

1. Cubbage and Simmonds(9) 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(10) 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(11) 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(12,13), 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.

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

$P_1$ = 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 town gas, this peak pressure was given by equation (2).

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

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)

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

Equation (3) reduces to equation (2) for town gas.

The main conclusions reached by the authors was that drying ovens should be designed so that all or as much of the top or one side 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.5. 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 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

$$\left(\frac{P_2}{P_o}\right) = (A \quad S_o)\,(K) \qquad \text{.............(4)}$$

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 pressure is not atmospheric, but 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 the bursting pressure of the disc. 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. Bursting discs are a very convenient way of closing vents, particularly if the contents of the vessel are at a high pressure, and it is, therefore, 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.

<u>Group B.</u> ($^L/D$ greater than 3)

Work has been carried out at the Joint Fire Research Organization 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 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:

$$P = 1.8K \qquad \text{...........(5)}$$

This equation held approximately over the wide range of vent and duct sizes indicated in Table 4.

TABLE 4

Conditions under which Equation 5 applied

| Smallest main dimension of duct D | Length to diameter 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 lb/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.6 the work carried out here is compared with work on cylindrical ducts carried out by other authors. The results of Freestone et al[14] 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[11] for hydrogen and Jones et al[15] for acetone, are respectively 8 and 0.6 times greater than our 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.

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, smaller than the cross sectional area, 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. With a vent equal to the cross-sectional area, the maximum pressure increases with duct length and is approximately proportional to this length.

Experiments have also been carried out, on the effect of obstacles, bends and T pieces in the duct on an explosion. It has been found that unless the explosion is well vented before the flame reaches an obstacle, a sharp peak in the pressure record and a 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 shown in Fig.7. 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 per cent 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.8 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 pressure 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 or 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 pressure 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.5 to 8 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 counterbalance 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(9) 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 at 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.7 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.9 in which the maximum pressure for different values of K have been plotted against the L/D ratio. This figure shows how the maximum pressure given by equation (3) passes into the maximum pressures given by equation (5) as the 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. 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.

2. A substantial amount of information on venting requirements available for a number of different systems. Some of this information is summarised in Fig.9 which, within the range of experimental conditions it covers, may be used to estimate venting requirements for vessels with three main dimensions.

3. There is evidence that the venting requirement for a given system is approximately directly proportional to the fundamental burning velocity of the gas mixture for mixtures initially at atmospheric temperatures and pressures.

4. 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 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).

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

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

REFERENCES

1. MINISTRY OF POWER. Testing Memorandum No.4. Test and Certification of the Flameproof Enclosure of Electrical Apparatus. H.M.S.O. 1958.

2. PALMER, K. N. J. Inst. Fuel 1956 29 293-309.

3. MASSEY, B.S., LINDLEY, B. C. J. R. Aero Soc. 1958, 62 32-42.

4. PALMER, K. N. Seventh Symposium (International) on Combustion. Butterworth, London, 1959. 497-503.

5. PALMER, K. N. Engineering 1958, 185 (4804) 438.

6. CUBBAGE, P. A. Flame traps for use with town gas/air mixtures. Gas Council Research Communication GC63 1959.

7. MANSFIELD, W. P. Proc. Inst. Mech. Engrs. 1956, 170 (24) 811-62.

8. National Fire Protection Association. Code for Explosion Venting. Boston 1958.

9. CUBBAGE, P. A. and SIMMONS, W. A. An investigation of explosion reliefs for drying ovens. Parts I and II. Gas Council Research Communications. GC 23 and GC 43.

10. Report of Kommitten for Explosionsforsok. 1957. Stockholm, April, 1958.

11. COUSINS, E. W. and COTTON, P. E. Paper presented to the second Industries Conf. A.S.M.E. Paper No.51-PRI-2-p. April, 1951.

12. BURGOYNE, J. H. and NEWITT, D. M. Crankcase explosions in marine engines. Trans. Inst. Mar. Engineers, August, 1955, 67 (8) 255-60.

13. WILSON, J. G. Relief of Explosions in closed vessels. Ph.d. Thesis. London University. June 1954.

14. FREESTONE, H. G., ROBERTS, J. D. and THOMAS, A. Proc. of Inst. of Mech. Eng. 1956, 170, 811-24.

15. JONES, G. W., HARRIS, E. S. and BEATTIE, B. B. U.S. Department of Commerce Bureau of Mines Technical Paper 553. Washington, 1933.

systems where flammable gas mixtures are at high initial pressures. More information was required for the specification of arresters suitable for quenching detonations.

It was suggested that if flame arresters could be installed in flame-proof electrical equipment, more venting could be obtained than at present and as a result the weight of the equipment could be reduced. Flame arresters at present available are probably sufficiently effective for this idea to be feasible, provided that blockage and corrosion of the arrester and the interior of the equipment could be effectively prevented.

Pipes leading from vent openings

Where ducting is provided with relief vents it may be important that any gas or vapour ejected through the vent should be piped away to the outside atmosphere, and should not be allowed to discharge into the working space. The pipes should be as short and straight as possible and should preferably be of greater diameter than the vent opening. It would be a good practice to instal flame arresters in these pipes.

Secondary explosions

If an explosion occurs in the crankcase of an engine, often as the result of the formation of oil mists, there is occasionally a second explosion after the gases produced in the first explosion have cooled and drawn air into the crankcase. The secondary explosions could be avoided if the vent in the crankcase closed immediately after the first explosion. However, as a general principle it was desirable that vents should remain open, so that the largest possible area of vent was provided behind the flame and so that structural collapse caused by the cooling of the explosion products was avoided.

Application of the 'K factor'

The explosion venting requirements of compact and elongated vessels may often be stated in terms of the 'K factor' (page 11) instead of expressing the requirements as the amount of venting area per unit volume of vessel. The same value of K applied to a cubical vessel as to a double cube (dimensions 2 x 1 x 1). The correlation of the maximum pressure with the 'K factor' (Figs.5, 6 and 9) applied normally only to vessels of simple shape and to conditions where the gas is initially quiescent. If the vessel were tapered (e.g. a cyclone) or shaped (e.g. a venturi) the value of K should be obtained from the maximum cross-sectional area of the vessel, perpendicular to the axis.

Venting in difficult cases

The correlation given in Fig.9 between the maximum explosion pressure, the dimensions of the vessel, and the 'K factor' would not apply to large vessels with small vents (e.g. reaction vessels). In these vessels, explosions would generate intense turbulence near the vent, but insufficient was known about the effect of turbulence on combustion rates for assessing the possibility of limiting combustion rates developing under conditions of intense turbulence.

When the construction to be vented was very weak (e.g. a building) the required amount of venting area might appear impracticable. This difficulty could perhaps be overcome by constructing an elongated, rather than cubical, building. There was insufficient information available on the design of vents for plant where there was only a narrow margin between the working pressure of the process and the maximum safe pressure

## SUMMARY OF DISCUSSIONS ON FLAME ARRESTERS AND RELIEF VENTS

The following account contains the main points raised in the discussions and the authors' replies. The topics discussed have been grouped together under various headings and are not necessarily in the same order in which they were raised.

### The design of flame arresters

The effectiveness of most types of flame arrester depends on the thickness of the arrester and the diameter of the apertures through it, provided that these diameters do not exceed the values given in Table 3 (page 5). The values in the Table represent the maximum permissible, and were determined with slowly-moving flames; to arrest fast flames it might be necessary to reduce greatly the aperture diameters. Wetting the channels through the arrester with grease or water would not materially affect the quenching diameter, but would increase the thermal capacity of the arresters (Table 2). If the gas is hot so that the arrester is heated to say 100°C, this should not markedly reduce its effectiveness, but the velocity of the flame as it approached the arrester might be higher as a result of the higher gas temperature. However, if a flame stabilised on an arrester much higher temperatures could be reached and the installation near the arrester of a detector which could actuate a valve to cut off the gas flow would be recommended. When installing a flame arrester in a duct it was often convenient to widen the duct where the arrester was inserted; as a result the resistance to gas flow was reduced and the quenching of the flame might be assisted(6). There was a lack of design data for sintered metal and packed tower flame arresters: and although both types were in use there was relatively little quantitative information about their effectiveness, particularly as regards the size of packing to be put into the towers.

### The positioning of flame arresters

Flame arresters and explosion relief vents should be sited as near as possible to the igniting source in ducting systems. If the position of the igniting source is not known the relief vent should be distributed along the whole length of the duct, because in this way the flame velocities are kept down. The introduction of bends into the ducting system should be avoided if possible because they could increase the flame velocity by generating turbulence. If bends are unavoidable flame speeds could be reduced by using relief vents. With detonations, however, the introduction of bends causes retardation of the flame(6).

In solvent vapour extraction systems different types of solvent might be used successively, and it was important that flame arresters should be tested against a range of fuels. In this type of system arresters causing low resistance to gas flow would be required.

### Storage tanks for flammable liquids

The provision of flame arresters to the breather valves of tanks containing flammable liquids, particularly petroleum, was causing concern. If a 28-mesh gauze were fitted it could become blocked by ice or, in tropical climates, by sand; when the tank was pumped out there was a danger of collapse. It was often not practicable to fit a heater to prevent freezing. The problem might be overcome by installing a supplementary relief valve that would come into operation at a predetermined pressure difference, together with an expendable filter on the breather valve to prevent blockage. Alternatively, to avoid icing, the supply of an anti-freeze to the arrester by a wick could be arranged.

### Flame arresters for special systems

Although values for the quenching diameters of hydrogen/oxygen mixtures were available (Table 3) there was hardly any information available for the design of flame arresters for these mixtures, for oxygenated mixtures in general, or for permissible. If a vessel had only a limited area available for the provision of vents the maximum possible amount of venting should be provided, as this might at least cope with mild explosions.

The design of vents

The usual design of vent was a simple square-edged orifice in the wall of the vessel or duct. An increased rate of discharge of gas could be obtained if the orifice were shaped, although in the shaping some of the effective area of the vent might be lost. If the vent were large there was a possibility that noise generated by normal working processes inside the vessel would be transmitted and would become a nuisance.

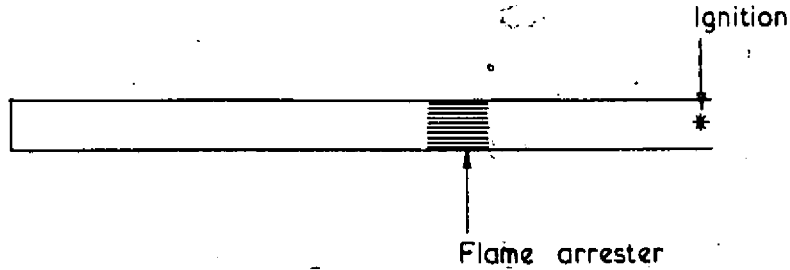



FIG. 1. IGNITION AT OPEN END OF DUCT

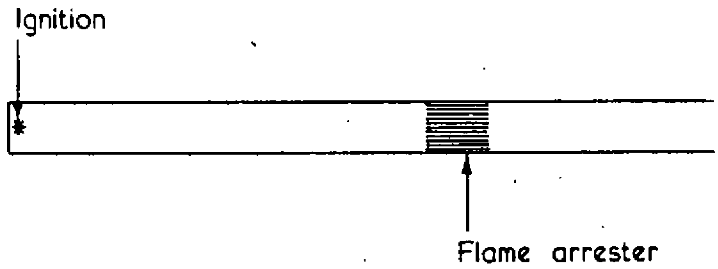



FIG. 2. IGNITION AT CLOSED END OF DUCT

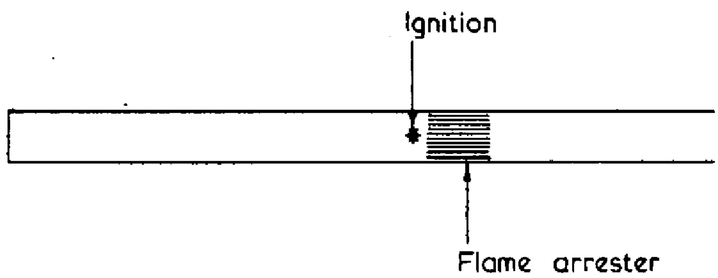
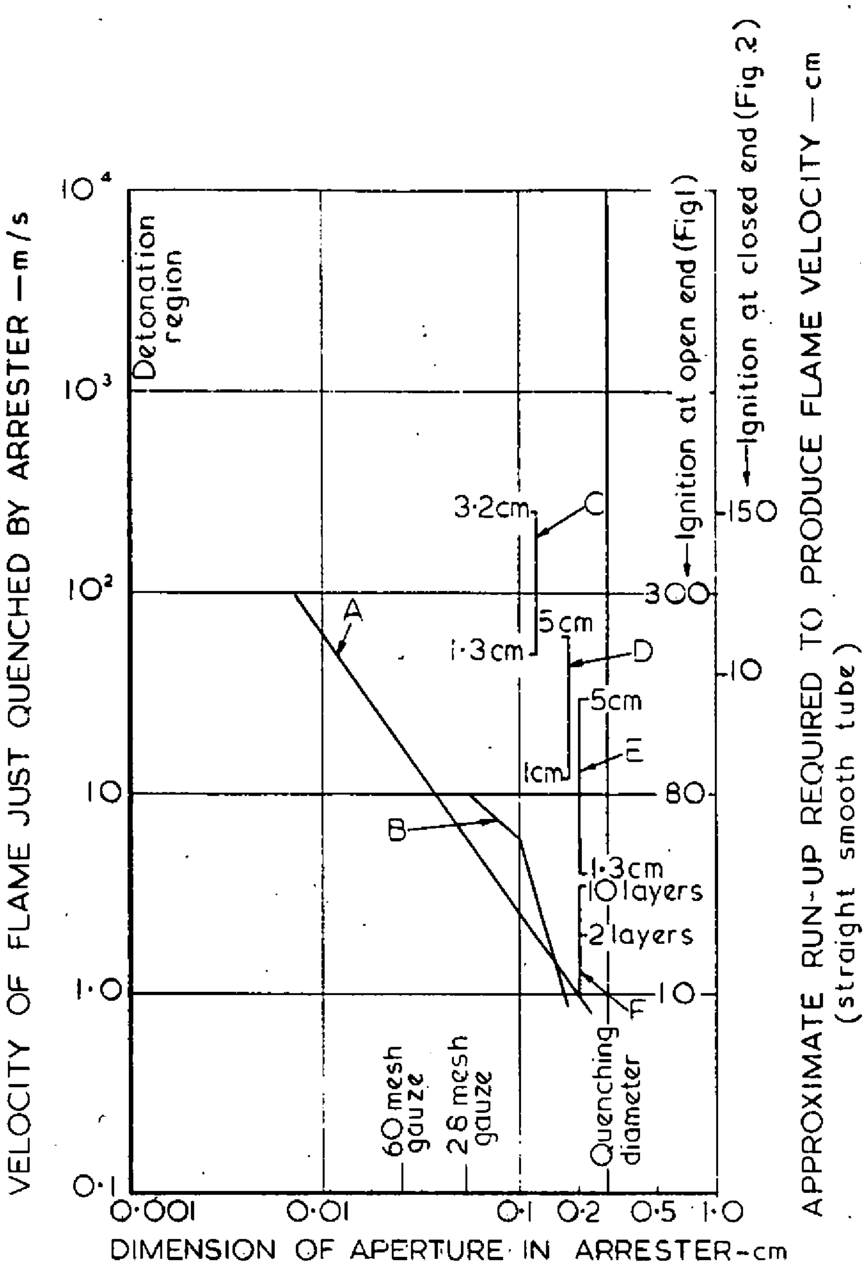



FIG. 3. IGNITION NEAR FLAME ARRESTER

F.R. 441

1/3829




A–Single layers of wire gauze
B–Perforated metal sheet
C–Crimped ribbon
D–Perforated metal block
E–Crimped ribbon
F–Gauze pack

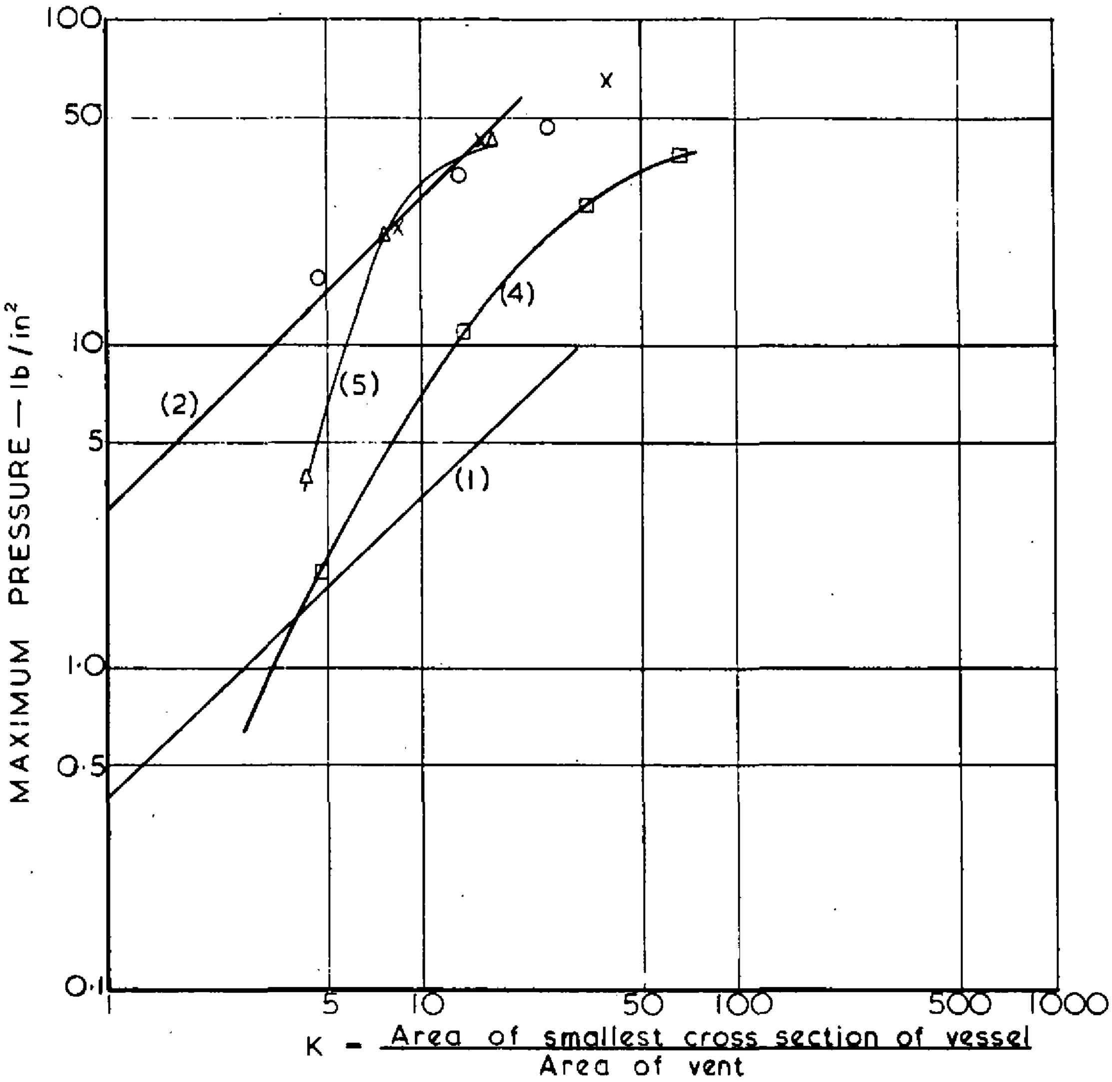
DETAILS OF PERFORATED SHEET

| Diameter of hole cm. | Thickness of sheet cm. | Area of hole in unit area of sheet |
|---|---|---|
| 0·175* | 0·073 | 0·37* |
| 0·100 | 0·072 | 0·31 |
| 0·055 | 0·046 | 0·24 |

* These values also apply to the perforated metal block

FIG. 4. FLAME ARRESTERS FOR FOUR PER CENT PROPANE–AIR MIXTURES

F.R. 417




(1) Propane and pentane (equation 3)

(2) Hydrogen (equation 3)

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

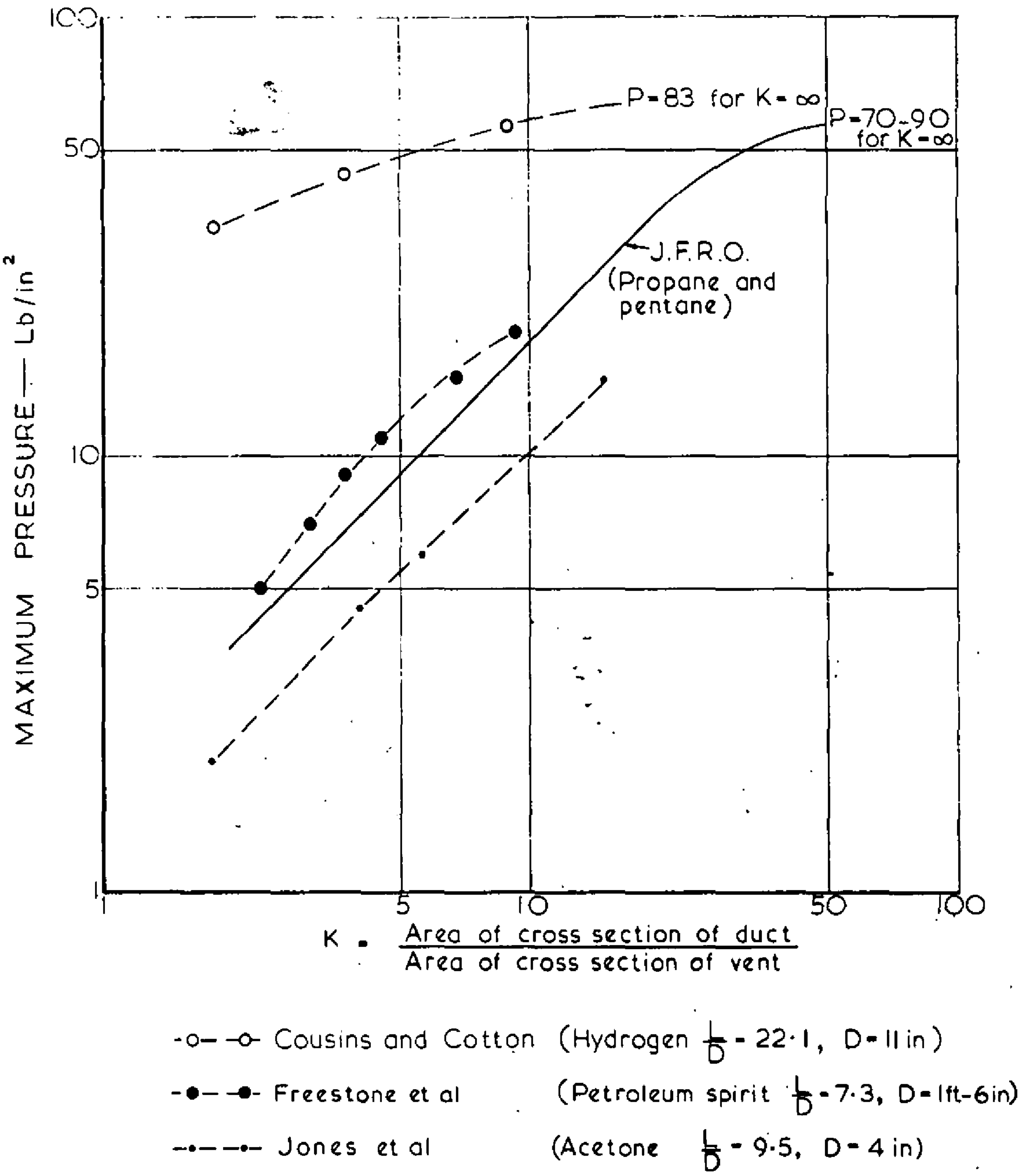
(3) o Hydrogen (tank, volume 3·0 ft$^3$, $\frac{L}{D}$ = 2·3, Cousins and Cotton)

(4) □ Propane (tank, as in (3))

(5) △ Pentane (60 ft$^3$ vessel, $\frac{L}{D}$ = 1·1, Burgoyne et al, Waxed paper covered vent)

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

FIG. 5. MAXIMUM PRESSURE OBTAINED WITH OPEN VENTS




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

FIG. 6. MAXIMUM PRESSURE OBTAINED WITH OPEN VENTS

1/3453 F.R.441

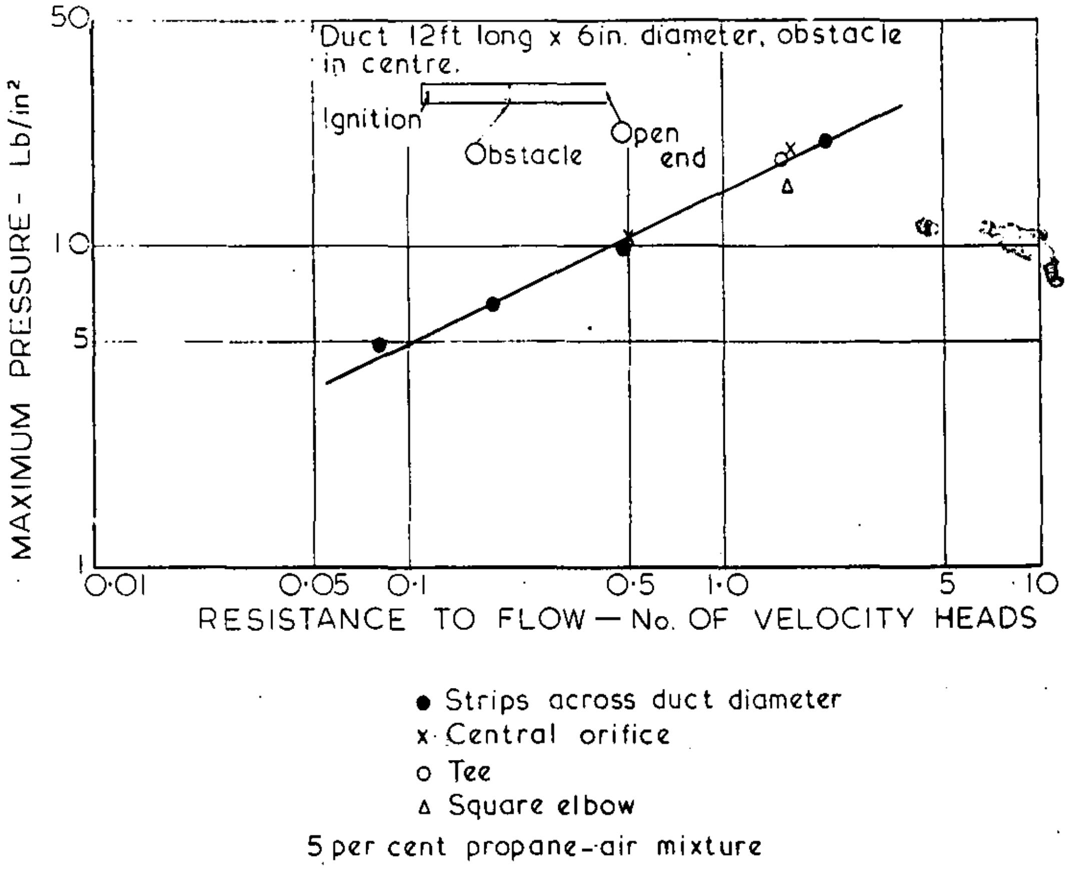



FIG. 7. RELATION BETWEEN MAXIMUM PRESSURE IN AN EXPLOSION IN A DUCT CONTAINING AN OBSTACLE AND THE RESISTANCE TO FLOW CAUSED BY THE OBSTACLE

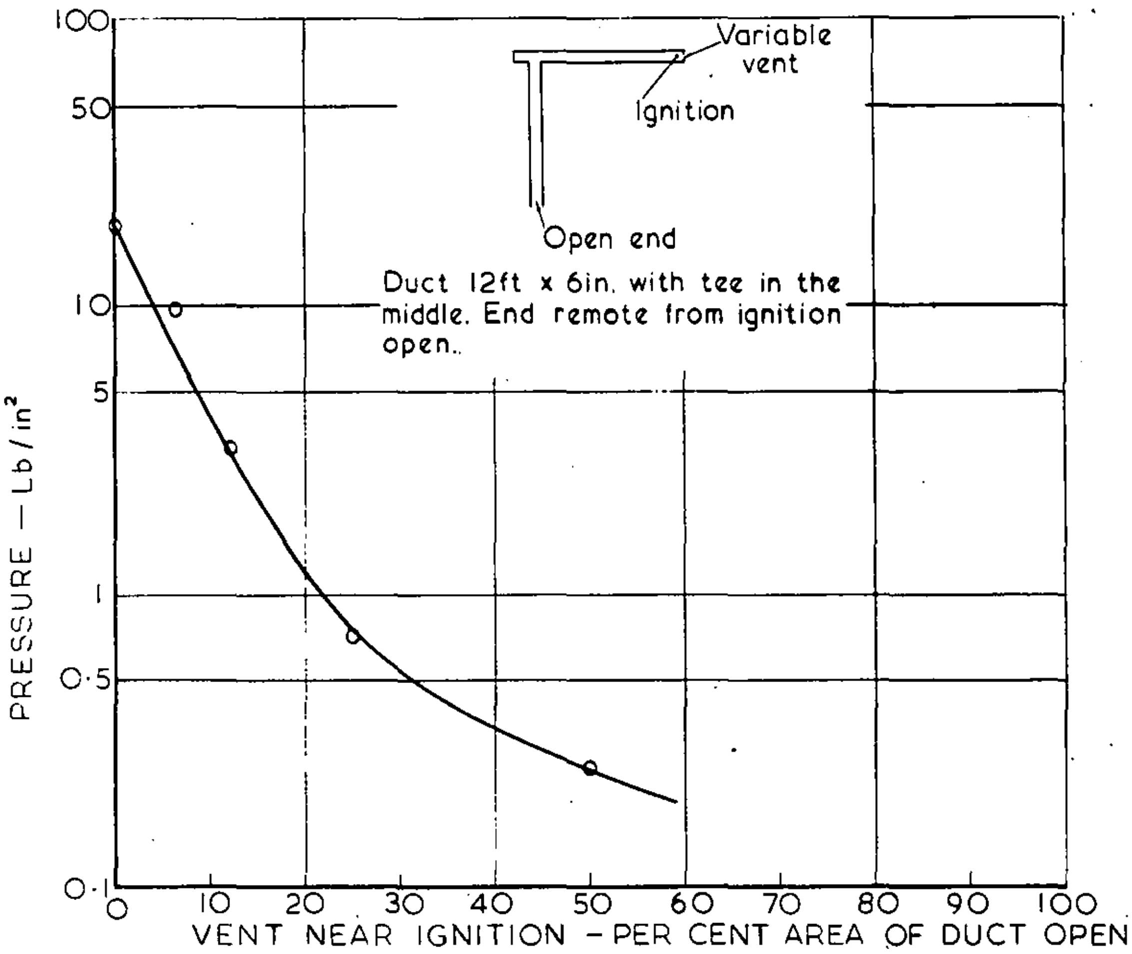



FIG. 8. EFFECT OF A VENT NEAR IGNITION ON MAXIMUM PRESSURE

F.R. 441

1/3454

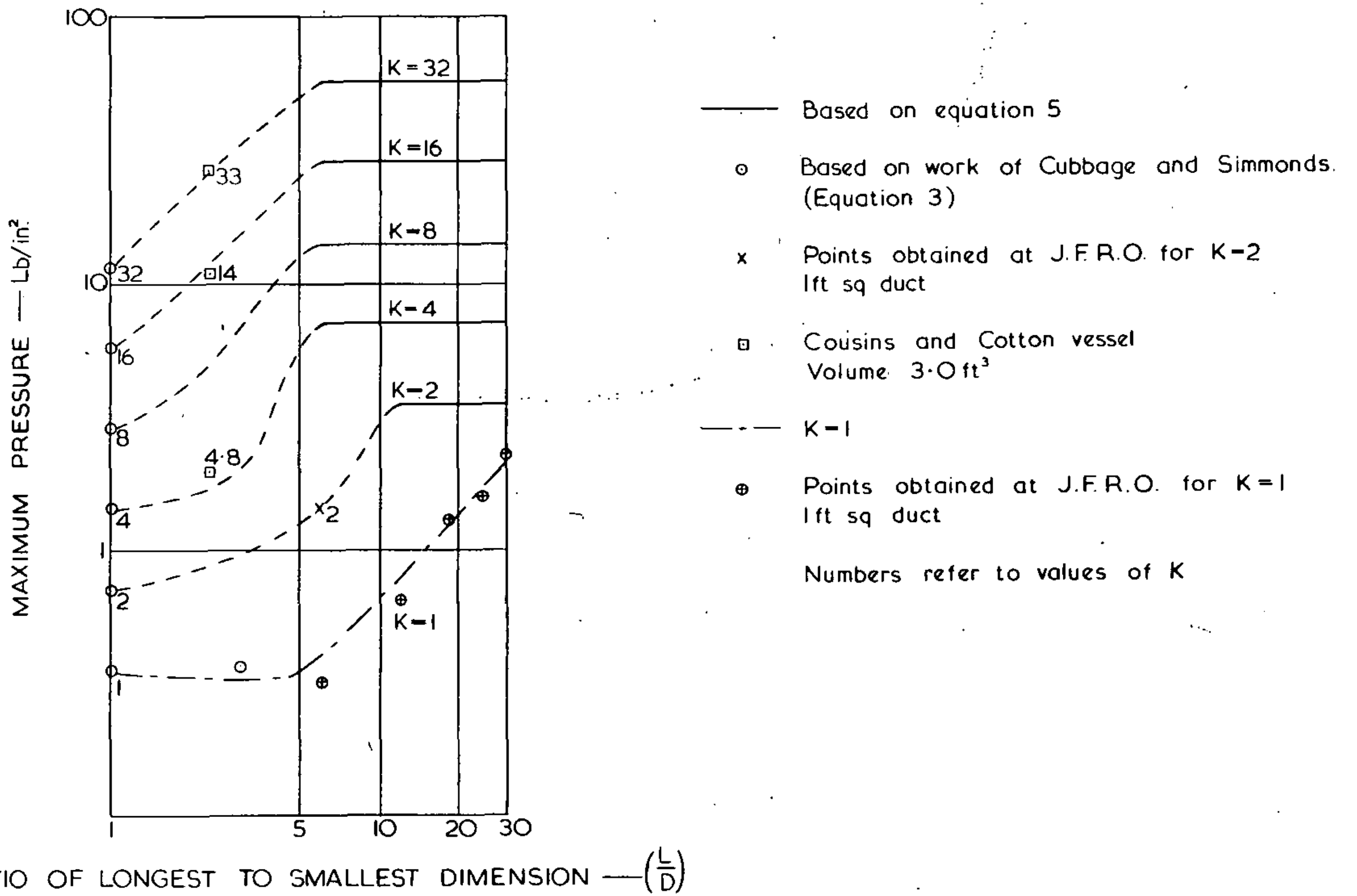



FIG. 9. RELATION BETWEEN MAXIMUM PRESSURE AND LENGTH TO DIAMETER RATIO FOR DIFFERENT VENT RATIOS (OPEN VENTS). PROPANE-AIR MIXTURES