EXPLOSION RELIEF PROTECTION FOR INDUSTRIAL PLANT OF INTERMEDIATE STRENGTH

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SYNOPSIS — Design data for explosion reliefs to protect relatively weak structures are available as are data on the design of bursting discs for protecting high pressure plant. Between these extremes there is a range of industrial plant for which guidance on the provision of explosion relief has not been formulated. This paper presents information on the protection provided by explosion reliefs in the form of rigid panels. Experimental results for enclosures fitted with such reliefs are presented and an empirical correlation is deduced. The use of explosion reliefs on industrial plant of different strengths is considered and practical problems involved in their installation are discussed.

INTRODUCTION

Fuel-fired plant, and chemical plant processing flammable feedstock, are used throughout industry and generally present no hazard. In the gas industry manufacturers, installers and users endeavour to provide gas-fired plant and equipment that is efficient, reliable and, above all, safe. Extensive studies by British Gas on the most critical phase of plant operation, i.e. start-up, have culminated in the publication of standards [British Gas (1970a)] and codes of practice, [British Gas (1970b)] the observance of which has done much to ensure the safe operation of gas-fired industrial plant and equipment. However, it cannot be guaranteed that a hazardous situation will never arise; system malfunction, operator error or interference with the prescribed operating procedures may occur, leading to the accumulation of a flammable gas-air mixture within a plant, or even within the building in which the plant is situated. Should the mixture become ignited, possibly through an attempt to start up the plant, the severity of the incident will depend on the relative magnitudes of the explosion pressure developed and the strength of the confining structure, be it the plant or the building.

Most common fuel gases when mixed with air at atmospheric pressure can produce on ignition a maximum pressure rise of approximately 700 kN/m^2 in a closed space. This order of pressure rise is much greater than that which ordinary plant, and buildings, can withstand and would probably result in their total destruction. However, most plant has some, albeit fortuitous, degree of explosion relief built into it; even the strongest appliance will have on it attachments such as doors and inspection hatches that would be broken or blown off at an early stage during an explosion, thus creating openings through which combustion products can escape. Whether or not this is effective in preventing damage to the rest of the plant depends largely on

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its construction; often this type of relief is too small and thus not very effective. A further consideration is what may happen in the immediate vicinity of the plant when a vent is created by explosion pressure. If the relief is fortuitous rather than purposely designed, the flying debris could cause injury to personnel and damage to the building housing the plant additional to that which would result directly from the pressure developed in the explosion.

Thus, in order to minimise the effects of an explosion in a plant, the pressure generated should be reduced as much as possible. Probably the most effective method of achieving this objective is to provide adequate explosion relief on the plant. Design data for explosion reliefs to protect relatively weak structures such as conventional box ovens are available [Simmonds and Cubbage (1955 and 1957), Rasbash (1960)] as are data on the design of bursting discs for the protection of high pressure plant [British Standards (1957)]. However, there is an intermediate range of plant for which no guidance on the topic has yet been formulated and the paper is mainly concerned with this range.

MECHANISM OF EXPLOSION RELIEF

Although in theory, the ignition of a mixture of any common fuel gas with air could produce a maximum pressure rise of approximately 700 kN/m^2, in a closed chamber, in commonly used plant and structures the pressure developed will be much lower because of pressure relief through vents already present, or created by the pressure itself, in the confining enclosure. Whether or not such pressure relief is effective in preventing serious damage being caused will depend mainly on whether the vents are effective in reducing the pressure developed to a safe value. This is not normally likely to be the case if the venting is adventitious and is only likely to be effective if weak sections designed to give way at a low pressure, are deliberately included in the plant.

Pressure relief is a consequence of the relatively slow rate of propagation of a flame front through a gas-air mixture during an explosion; the slow rate of flame propagation means that the time required to reach the peak pressure varies from tens to a few hundred milliseconds, depending on the properties of the gas-air mixture ignited and the characteristics of the confining structure. Because of this relatively slow build-up of pressure, there is time available to allow some of the combustion products formed, together with unburnt mixture, to escape through any opening that may be available. If no such opening exists, the pressure generated will create one by breaking the weakest part of the structure, again allowing combustion products and unburnt mixture to escape. It is of course, the action of the pressure wave, travelling at the velocity of sound, and therefore ahead of the combustion wave, that is responsible for this and thus for creating a vent before a substantial volume of gas-air mixture has been burnt. Whether or not this is effective in minimising further damage is dependent on the design of the whole structure. Explosion relief, therefore, consists of providing sufficiently large openings in the walls of an enclosure to allow the combustion products to vent rapidly and safely. Obviously, it is not always practicable to provide open spaces in the walls but relief in these cases can be afforded by constructing relatively weak sections which will give way, or open, at an early stage in an explosion.

During the time interval between ignition of the gas-air mixture and the removal of the explosion vent, the rate of pressure increase is determined by the rate of production of hot combustion products, which in turn is determined by the burning velocity of the gas-air mixture. The greater the burning velocity the greater is the rate of increase in pressure and hence the shorter is the time taken to reach a specific value of pressure rise. Consequently a proportionately shorter time period is available for the removal of an explosion relief. Because of inertia, a further finite time interval is required, after the pressure necessary to break an explosion relief is reached, in order to move the explosion relief sufficiently for a significant flow of gases out of the enclosure to be established. Up until this time, the pressure inside the enclosure will continue to increase at approximately the same rate as if the enclosure were unvented. To be effective, therefore, an explosion relief should have as low a breaking pressure as possible and be as light as possible (whilst remaining compatible with the rest of the structure), in order that the pressure attained in the enclosure prior to the establishment of an outward flow of gases is kept to a minimum. The magnitude of the pressure reduction that can be obtained upon the removal of the explosion relief will depend on the open area created. The larger the vent area, the more easily will combustion gases escape and the sooner will the rate of loss of gases, through the vents, equal the rate of production of gases, by the explosion process; consequently, the lower will the maximum pressure developed be.

It will be apparent that it is a misconception to assume that an explosion relief designed to break or open when the pressure reaches P_v will, in fact, limit the maximum pressure generated in a plant to that value. An effective explosion relief must have a breaking pressure, weight and area such that it will operate at a pressure much lower than that required to damage the structure it is designed to protect in order that the maximum time is available for the escape of combustion products during the explosion process.

Significant influences on the maximum pressure generated are exerted by other factors. For example, the degree of turbulence in a gas-air mixture before its ignition has an effect on the pressure developed through its influence on the burning velocity. Turbulence increases the rate of combustion thereby leading to a more rapid rise in pressure than is produced by the ignition of a similar non-turbulent mixture. However, if a static gas-air mixture is ignited within a well-vented enclosure, the ensuing explosion will not generate appreciable turbulence, provided that there are not too many obstructions to impede the passage of the combustion products towards the relief vent [Rasbash (1969)].

The size and shape of the confining structure will also influence the final pressure generated; for instance, higher pressures will be generated in long narrow enclosures than in more nearly cubical ones, but in practice it is the characteristics of the explosion relief that will determine whether or not a plant is damaged by an internal explosion.

STRENGTH OF INDUSTRIAL PLANT

To determine the need for fitting explosion reliefs of a particular design it is necessary to know to what extent the plant or structure under consideration could withstand the effects of an explosion. This presupposes that the nature of the explosive medium and other related factors have already been assessed and the maximum explosion pressure that could be generated determined.

If the explosive medium is likely to be a gaseous hydrocarbon then the maximum explosion pressure would be about 700 kN/m^2 ; clearly, any plant having a strength capable of withstanding this pressure does not need reliefs.

However, all plant with lesser strength or having weak sections will require explosion reliefs designed to keep the pressure generated to below a safe level. This might be well below the strength of the structure. For instance, in the case of box ovens for paint drying, experiments showed that the oven might be capable of withstanding 30 kN/m^2, but to prevent minor internal damage the explosion relief was required to keep the pressure to under 7 kN/m^2. Most industrial plant is of a greater strength than this and does not require such an effective relief.

In some industrial processes, the plant, working chamber and/or combustion chamber operate at a pressure above ambient. For these types of plant the design of relief fitted to box ovens would not be appropriate and a less effective relief could be fitted.

The type of relief described in this paper is aimed at all those classes of plant, e.g. cast iron air heaters and boilers, furnaces, kilns, etc. which either are stronger than the simple box ovens used for paint drying, stoving, etc, or have combustion chambers that are designed to operate at a pressure in excess of 0.6 kN/m^2 (0.2 - 0.3 in w.g.)

EVALUATION OF EXPLOSION RELIEFS

The effectiveness of a variety of materials, available in the form of rigid panels, as potential explosion reliefs has been investigated. Explosion pressure measurements have been obtained on two structures; a cubical steel box, having a volume of 0.95 m^3, with a facility for varying the area of the explosion vent (Fig. 1) and a large, rectangular enclosure, having a volume of 31 m^3, of which the vent area was fixed. A wide range of venting conditions has been investigated in the two structures, by varying the areas, weights and breaking pressures of the vent coverings. Both manufactured gas-air and natural gas-air mixtures have been used, the mixture to be ignited being present either as a pocket of stoichiometric composition or as an approximately homogeneous layer.

The use of pockets of stoichiometric gas-air mixture, contained in balloons, in order to generate explosion pressures, is an extension of a laboratory technique used previously [Cubbage and Marshall (1972)] to study pressure rises in a small chamber (0.14 m^3) under various open vent conditions. Although it pertains to an idealised situation, the technique has certain advantages; it is simple and repeatable and, for a given volume of gas, the pressure generated can be predetermined. Furthermore, using this technique in a closed chamber results in a simple relationship between the volume of gas present and the pressure developed

$$P = 1.013E + 0.016E^2 \quad (E \leq 30) \qquad \text{..........} \ (1)$$

where P is in lbf/in^2 and E is in Btu/ft^3 enclosure volume.

For values of $E \leqq 5$ the data conform equally well to the relationship $P \approx E$. This numerical equivalence of pressure and energy density was used to advantage in the determination of the breaking pressures of the various materials used as vent covers, when, initially, very low explosion pressures could be engineered and then the pressure developed could be gradually increased until the material under test failed.

In order to determine the effectiveness of a material as an explosion relief, pressures greater than that required merely to break the relief were generated. The difference between the maximum pressure developed and that required to remove the relief is then a measure of the effectiveness of the explosion relief.

Typical results from the studies conducted in the two experimental enclosures are presented in Figs. (3) - (6), which illustrate the points made in the discussion on the mechanism of explosion reliefs. The importance of relief area, weight and breaking pressure are clearly demonstrated, as is the influence of the burning velocity of the gas-air mixture on the pressure developed. The data presented in Fig. (2) [from Cubbage and Marshall (1972)] clearly demonstrate the importance of the area of the explosion relief vent. (These data refer to measurements, carried out on a chamber having open vents, of the pressure developed on ignition of pockets of stoichiometric gas-air mixtures.) As the area of the relief vent decreases, resistance to the outward flow of combustion products formed during the combustion of the pocket of gas-air mixture increases, until at very small vent areas, i.e. $K > 50$, all the mixture has reacted before gases begin to vent from the enclosure. In this situation, the enclosure approaches the unvented condition and pressure rise (lbf/in^2) can be equated to energy density (Btu/ft^3). Figure (3) refers to a similar situation except that in this instance the explosion vent was initially covered, and the influence on the pressure generated of the vent cover can be clearly seen — the pressures developed were much higher than was the case in the enclosure with open vents. The reason for the increase in the pressure developed is of course that the pressure required to break the explosion vent cover must first be developed in the enclosure and then the vent cover has to be removed before products can be vented, thereby relieving pressure.

For the materials investigated, breaking pressure was found to be inversely proportional to the area of the vent cover. Hence, as the area of an explosion relief is decreased, the pressure required to remove it is increased. Furthermore, the smaller the explosion relief area, the smaller is the vent area available upon its removal and the less rapid, therefore, is the egress of combustion products. Thus, as the area of an explosion relief is decreased, two distinct factors combine to produce higher maximum pressure rises. This is clearly illustrated in Fig. (3); it is apparent that very little pressure reduction is obtained at the small vent area, corresponding to $K = 9$, because the vent covering has a high breaking pressure and its area is too small to allow rapid egress of combustion products once it has been removed, whereas at a larger vent area, e.g. $K = 2.94$, the explosion relief controls pressure very effectively, although the material used for the vent cover is identical.

The weight per unit area of the vent cover is also important; because of inertia a finite time interval is required, after the pressure necessary to break an explosion relief is reached, in order to move the relief material sufficiently far from the enclosure for the flow of gases out of the enclosure to be established and, therefore, for pressure relief to occur. This is illustrated in Fig. (4), where data are presented on two reliefs of different materials (plasterboard and insulating board) which, although having the same areas and breaking pressures, are of different weights per unit area. The heavier vent cover (plasterboard) is not as effective as the lighter material in minimising the pressure developed.

An explosion relief of given characteristics — area, breaking pressure, weight per unit area — will not be equally effective for all fuel gas-air mixtures, because of the influence of the burning velocity of the mixture on the time available for the operation of the explosion relief. Figure (5) represents explosion pressure data for pockets of stoichiometric manufactured gas-air and natural gas-air mixtures ignited under identical venting conditions. It is immediately apparent that the lower burning velocity of the natural gas-air mixture and, therefore, the lower rate of production of combustion products, leads to establishment of an outward flow of gases at a pressure not much in excess of that required simply to break the vent cover and thus allows more time for the escape of products and results in a more effective control of the pressure rise. In order to obtain a similar reduction in the pressure developed when using manufactured gas-air mixtures a larger relief, having a lower breaking pressure, would be required. The influence of the air-gas ratio of the mixture ignited on the explosion pressure developed is demonstrated in Fig. (6), in which the mixture ignited was contained as a near-homogenous layer. The data were obtained under the same venting conditions as those presented in Fig. (5) and it is worth noting that the maximum pressure obtained (for a layer of stoichiometric proportion corresponding to an energy density of $E \approx 820$ kJ/m^3 enclosure volume) is the same as that predicted by extrapolation of the lower curve in Fig. (5).

The evaluation of possible explosion relief materials for plant of intermediate strength has not only shown that a variety of suitable materials are available but has also illustrated how the characteristics of the gas-air mixture ignited and the explosion reliefs themselves affect the maximum pressure developed.

PREDICTION OF PRESSURE RISE

It is obviously desirable, for design purposes, to be able to assess the effectiveness of an explosion relief in a given situation by calculation rather than by experiment. A formula has been derived [Cubbage and Marshall (1973)] which will correlate the data presented above and may be used to predict the pressure developed on the explosion of gas-air mixtures in simple vented enclosures. It relates the pressure developed to characteristics of the confining enclosure and the gas-air mixture ignited and is of the form:

$$P_m = P_v + 0.5\,(Kw)_{av} S^2 / V^{1/3}\ \left[1 - \exp - \left\{\frac{E - E_o}{E + E_o}\right\}\right] \qquad \text{...........(2)}$$

where the parameter $(Kw)_{av}$ is given by:

$$1/Kw)_{av} = 1/(Kw)_i + 1/Kw)_j + \text{.....}$$

Explosion vents are regarded as paths of conductance and, by analogy with the electrical situation, the parameter (Kw) is averaged in the manner of resistance in parallel. The averaging of (Kw) in this manner is valid only if the pressures required to break or remove the various explosion reliefs are approximately equal i.e. $P_{vi} \approx P_{vj}$, etc.

Hence, using the formula, the effectiveness of an explosion relief of given characteristics when fitted to a particular plant/appliance can be assessed prior to its installation.

From the experimental evidence accumulated to date, the formula may be used with some confidence in any structure fulfilling the following conditions:

(a) maximum and minimum dimensions of confining structure have a ratio equal to or less than 3:1 ;

(b) the breaking pressure of, or pressure necessary to remove, the explosion vent cladding does not exceed about 50 kN/m^2 ;

(c) the vent area coefficient K is between 1 and 10 ;

(d) the weight of the vent cladding lies within the range 2.5 - 25.0 kg/m^2 ;

(e) the parameter (Kw) does not exceed 75 kg/m^2.

It is considered that the characteristics of many types of industrial plant fall within the limits imposed by the above conditions.

PRACTICAL IMPLICATIONS

It is apparent that, in order to provide effective pressure relief on plant the characteristics of the explosion relief fitted (e.g. weight per unit area, breaking pressure, area) must fall within certain well defined limits which will depend on the type of plant. Probably the most difficult requirement to meet in practice is that of a sufficiently large area; on some types of plant the replacement of inspection doors and hatches alone may not provide a sufficient area of explosion relief to allow rapid egress of combustion products, and therefore a significant reduction in pressure, should an explosion occur. Furthermore, even if enough area for explosion relief could be obtained in this matter, it may not be completely effective because it is imperative that an explosion relief should vent directly that part of the plant in which an explosion initially occurs. Thus, although replacement of metal doors may be practicable, unless they communicate directly, and not via flueways for example, with the space in which the explosion is initiated, pressure relief could be minimal. In order to meet the requirements of large area and sufficiently low breaking pressure for an explosion relief it may be necessary to modify the structure of a plant, rather than to utilise existing door and hatch ways.

However, even though enough pressure reduction to prevent some damage to plant may not be possible simply by the replacement of metal doors by weak panels, other factors need to be considered — in particular the possible injury to personnel and to property caused by flying debris in the vicinity of an explosion. Obviously it is preferable that an explosion in a plant should scatter debris consisting of pieces of broken explosion reliefs (which will be light in weight and therefore have only a small momentum) rather than pieces of metal (e.g. a broken — or even a whole — door or hatch cover) which can cause severe injury to personnel and extensive damage to property.

A further consideration, perhaps not as widely appreciated as it should be, is the effect of a plant explosion on the building in which it is contained. Preliminary studies have indicated that as a result of an explosion in a plant significant pressures can be developed in buildings, even when they are vented (e.g. by a window). With plant or appliances occupying only 1/40 of the volume of the building housing it, it is not impossible because of the relative strengths of the structures for an explosion that would cause only minimal damage to the plant or appliance to destroy completely the building in which it is housed. It is desirable therefore to limit the pressures generated in the appliance by an explosion, not necessarily to protect the appliance from excessive damage — although this should be the first consideration — but also to protect the confining structure. A suitable manner in which this can be accomplished is by the provision of explosion relief on appliances so that the pressure generated in the buildings housing them will be limited to a magnitude sufficient to blow out only the vents incorporated in the building (i.e. windows and doors) and not to damage walls.

Materials for use as explosion reliefs on low temperature appliances are available and their physical properties suggest that they may be suitable for high temperature plant as well. In general they are good heat insulators and, therefore, their installation should not reduce plant efficiency because of heat losses. In some cases it is acknowledged that the fitting of explosion reliefs could cause some difficulty in that they may not be compatible with plant operation. This could be the case for instance with plant working under positive pressure, or with plant in which small pressure transients are liable to occur under normal operation; in both cases, the breakage of explosion relief panels caused in this way during normal plant operation has been cited as a disadvantage of their use. It is considered however, that materials with breaking pressures significantly higher than any pressure encountered in normal plant operation, but low enough to provide pressure relief in the event of an explosion, are available for use in most circumstances.

CONCLUSIONS

Data are available from which it is possible to design explosion reliefs for most types of industrial plant. The application of rigid panels as explosion reliefs has been demonstrated and their effectiveness proved. Practical problems of implementation, resulting from plant design, may however limit the effectiveness of reliefs in preventing damage to some types of plant. Nevertheless, any reduction of the pressure generated as the result of an explosion in an appliance is desirable as this will not only protect the plant itself but also reduce the likelihood of damage to the building housing it. There is, therefore, a need for the effects of explosions in industrial plant on the structures housing them to be examined.

LIST OF SYMBOLS

E = energy density per unit volume of enclosure [kJ/m^3 (Btu/ft^3)]

E_o = energy density at which the explosion relief is removed [kJ/m^3 (Btu/ft^3)]

K = vent coefficient defined as: cross sectional area of enclosure in plane of vent/area of vent.

P = pressure generated [kN/m^2 (lbf/in^2)]

P_m = maximum pressure generated [kN/m^2]

P_v = breaking pressure of explosion vent [kN/m^2 (lbf/in^2)]

V = volume of enclosure (m^3)

w = weight per unit area of vent cover (kg/m^2)

Subscripts

$_{av}$ = average

$_{i, j}$ = refer to separate vents in the same enclosure

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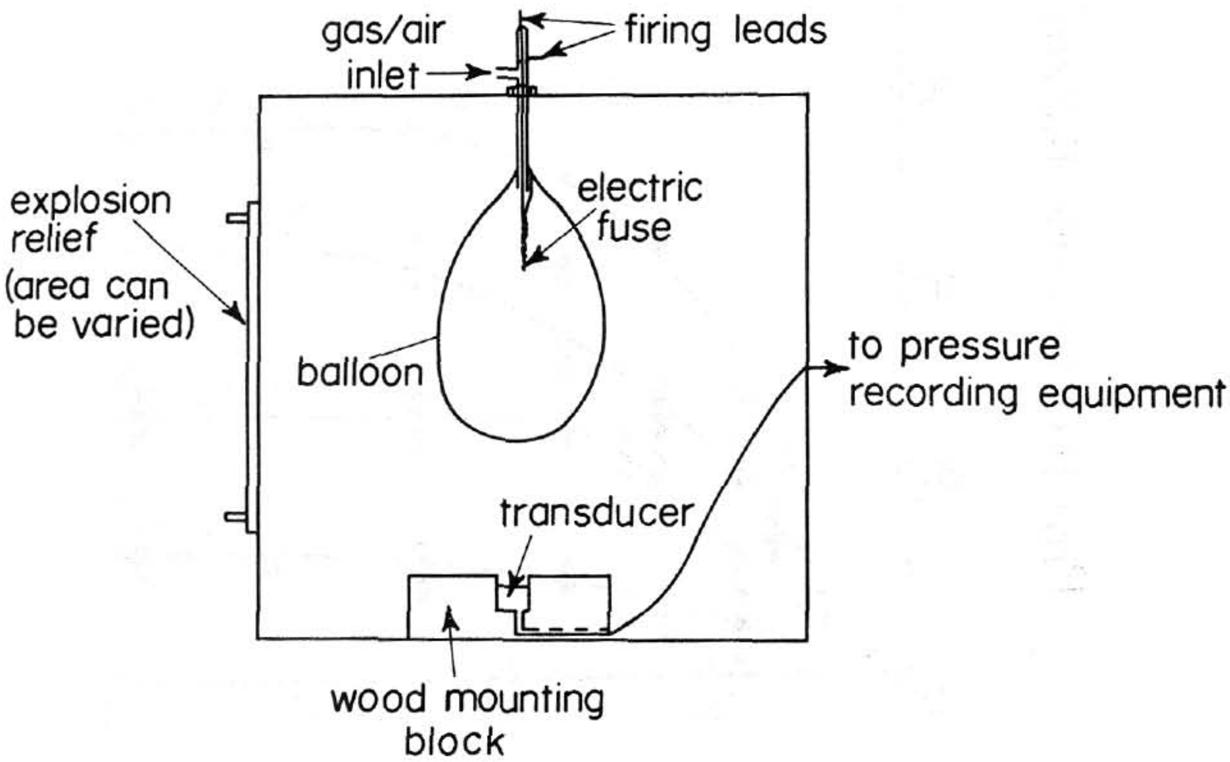

Fig. 1 Diagram of 0·95 m³ explosion chamber illustrating the experimental arrangement

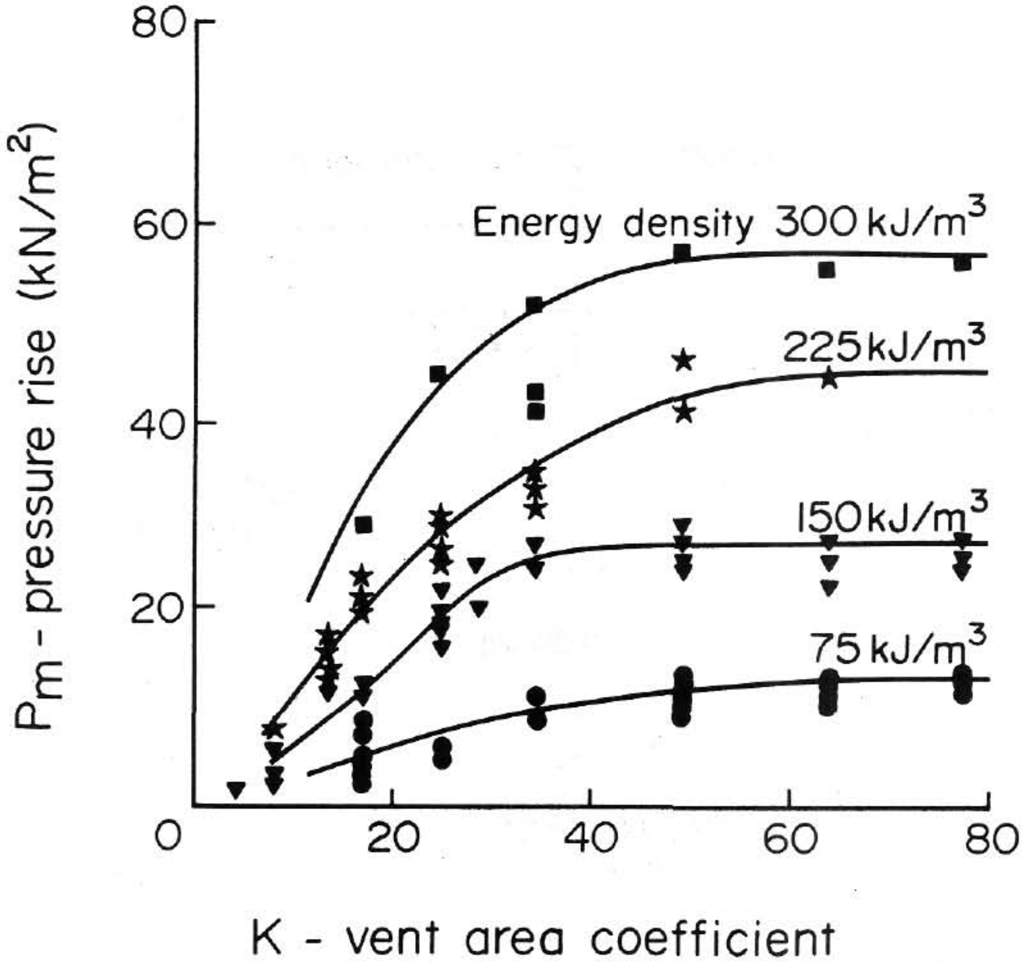

Fig. 2. Graph of pressure generated as affected by the area of open vent

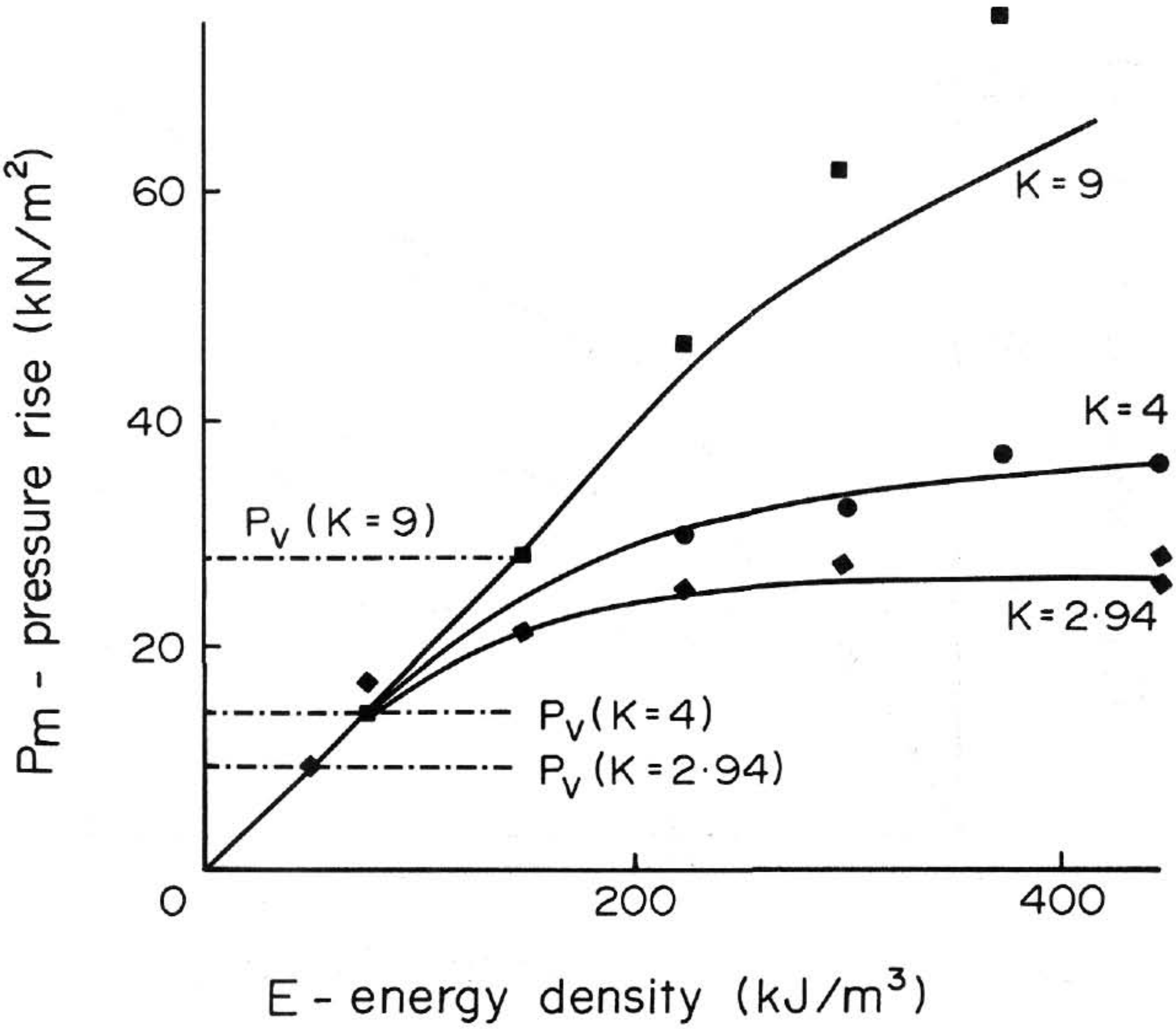

Fig. 3. Graph of pressures generated on ignition of pockets of stoichiometric manufactured gas-air mixture in a vented enclosure of 0·95 m^3 volume against energy density

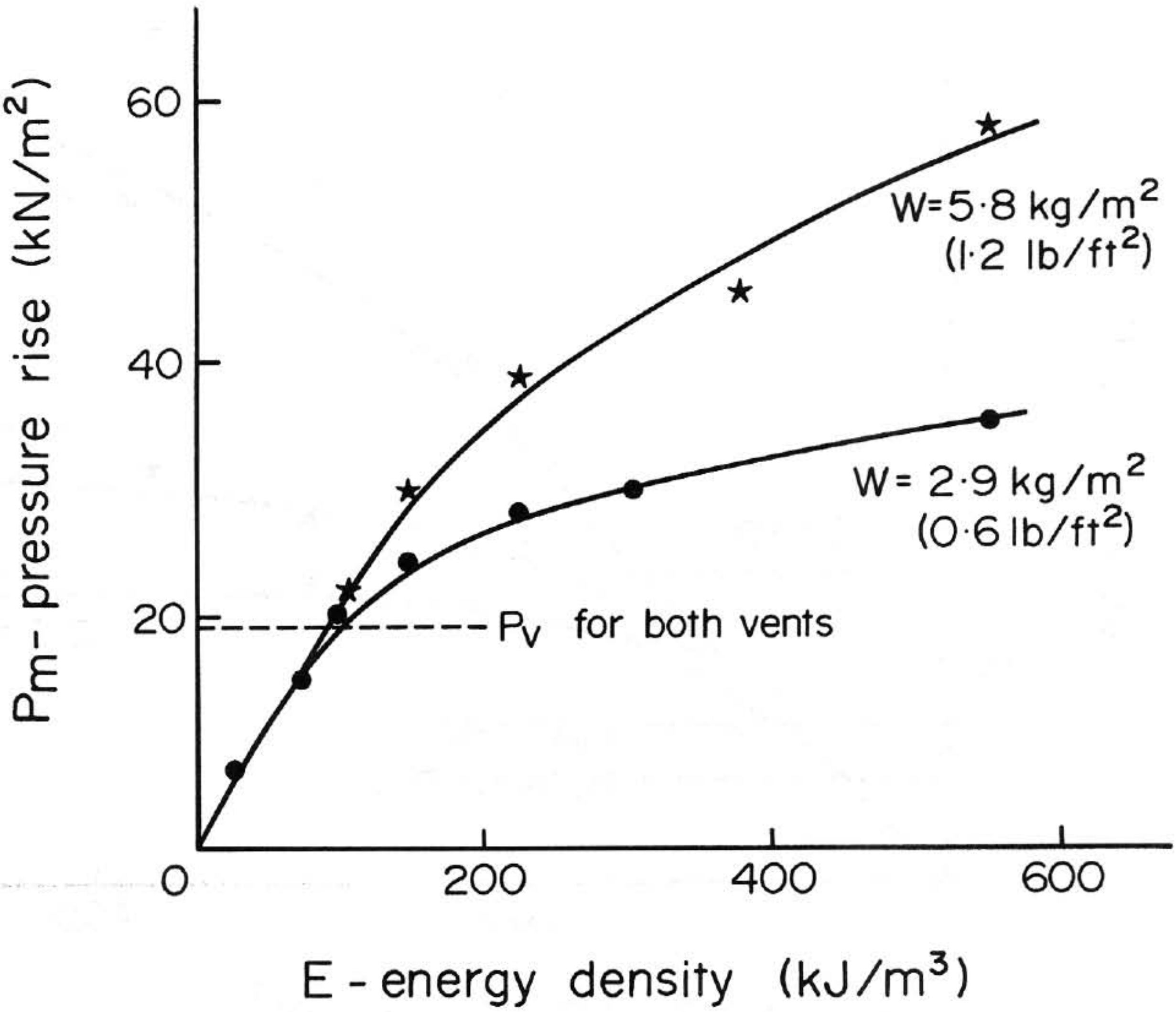

Fig. 4. Graph of pressure generated as affected by weight/unit area of vent cover against energy density

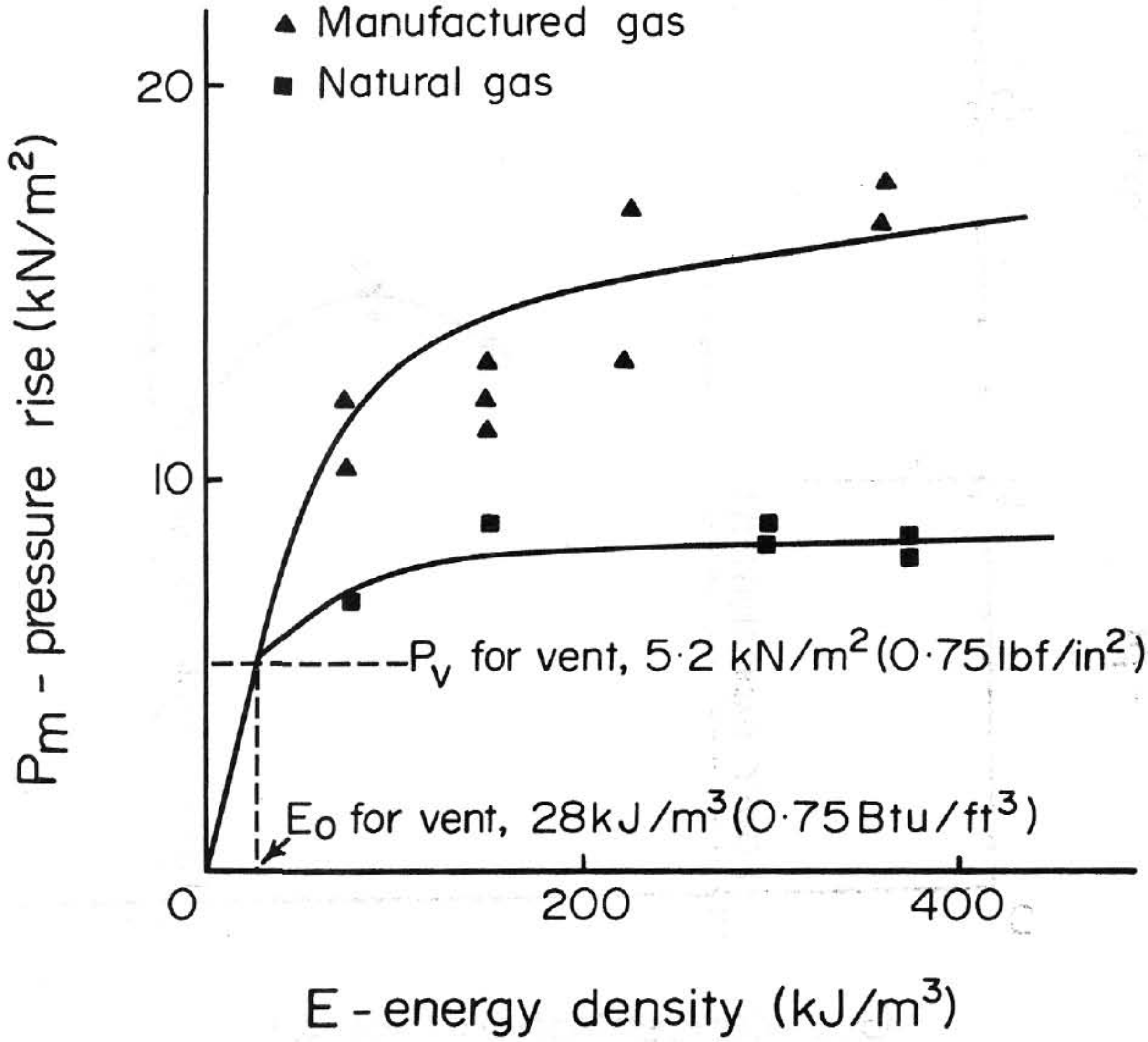

Fig. 5. Graph of pressures generated on ignition of pockets of stoichiometric gas-air mixture in a vented enclosure of 31m^3 volume against energy density

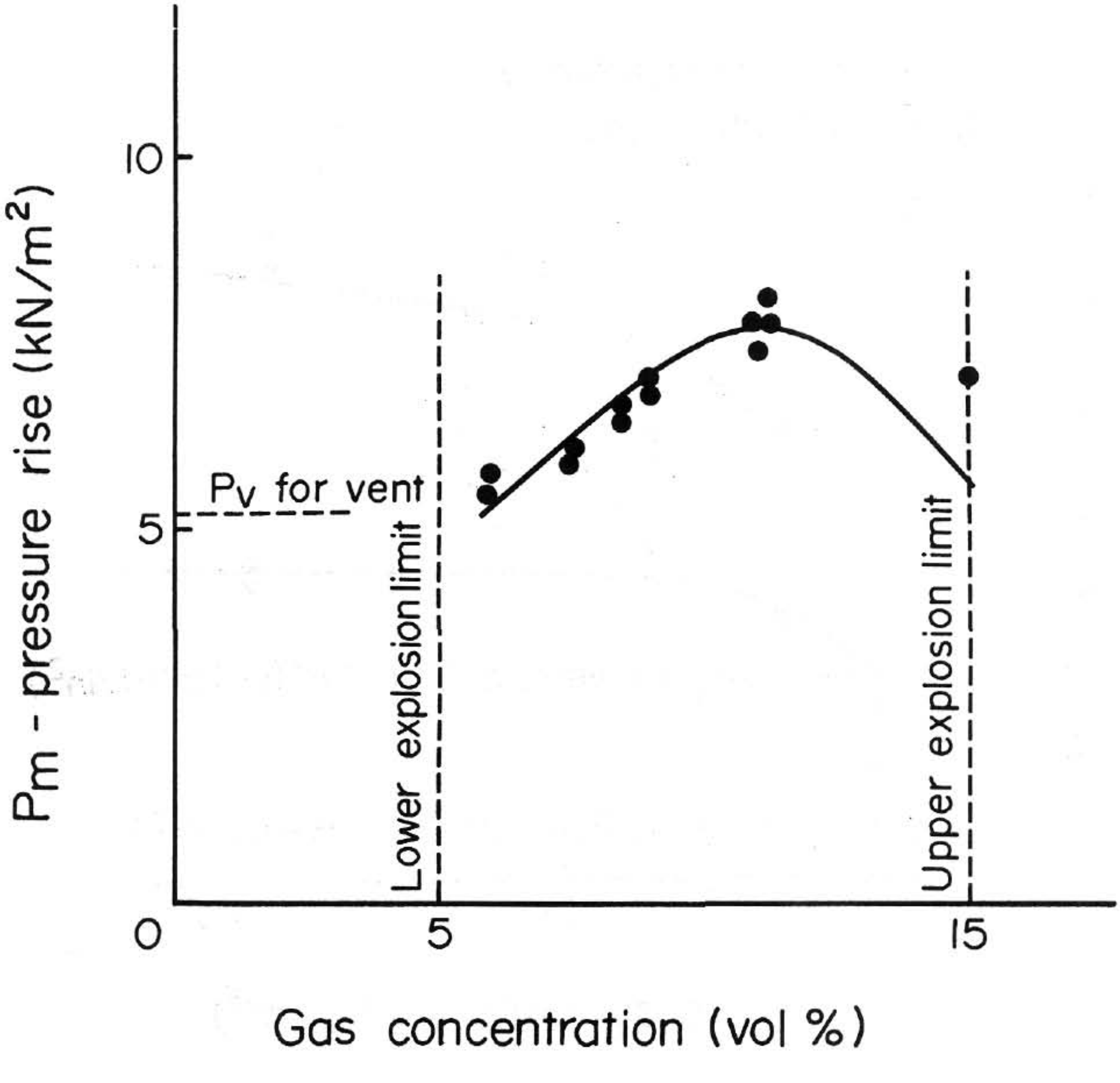

Fig 6. Graph of pressures generated on ignition of layers of natural gas-air mixture in a vented enclosure of $31 m^3$ volume (layer volume $7 m^3$) against gas concentration