EXPLOSIONS OF GAS LAYERS IN A ROOM SIZE CHAMBER

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The effect of layer depth, vent diaphragm size and strength, and ignition source on pressures produced by deflagrations of buoyant layers of stoichiometric mixtures of methane in air in a 27 m^3 cubical chamber are reported and their practical application discussed.

INTRODUCTION

The piping of flammable gas under pressure into both industrial and domestic structures introduces the possibility of escape of this gas into the structure, with the possible formation of explosive mixtures with air.

It is not the intention of this paper to quantify this risk, but it may be helpful to refer to some recent statistics from Fire Brigade reports of gas explosions. In 1976 there were 202 mains (natural gas) explosions in industrial and domestic buildings in the UK (excluding Northern Ireland). In the last 11 months of 1977 the figure was 159. On the basis of previous statistics, Chandler 1 , at least 50 per cent caused structural damage to the room of origin, of which 20-30 per cent cause damage outside the room and 10-20 per cent of these damage outside the building.

The fact that explosions do occur clearly demonstrates that natural gas does mix with air to form explosible mixtures; but whether these mixtures completely fill the rooms of origin, exist as layers extending down from the roof or ceiling or are sandwiched between fuel rich and lean mixtures depends upon many factors which are discussed in section 2.

This paper presents work carried out at the Fire Research Station to determine the pressures generated by explosions of explosible natural gas/air mixtures present as buoyant layers on air in an average room-sized structure (27 m^3). The work forms part of a larger programme studying explosions of hydrocarbon gas/air mixtures in single and interconnected rooms, the explosible gas mixture either completely filling the room, or partially so as a layer.

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This paper concentrates on the effect of vent area and vent covering material; and the number and position of ignition sources on the explosion pressures resulting inside the chamber, partially filled with different volumes and concentrations of quiescent explosible methane gas mixtures.

FEASIBILITY OF EXPLOSIBLE GAS MIXTURE LAYER FORMATION

This can be approached by considering the main possible types of accidental leaks of pressurised gas that can occur, these are:

a. Leak at roof level

b. Leak at floor level

Clearly these are the two extreme possibilities and leaks between the roof and floor levels will display characteristics of both types discussed below.

a. Leak at Roof Level

This will be considered initially, as it is perhaps the simplest to understand. The buoyant gas, methane leaking into a room will mix with and/or displace air depending on the flow rate of the gas. For example, in work reported by Birch et al 2 , the leakage rate from an open ended 13 mm dia gas pipe was taken as 2.4×10^{-3} m^3/s. Work by Leach and Bloomfield 3 enables an estimation to be made of the methane concentration for this leakage rate, depending upon the cross sectional area of the room. Taking a typical room area of 10 m^2, a layer will be formed at the ceiling of about 100 per cent methane, its depth dependent on the duration of the leak. The interface between 100 per cent methane and pure air would however remain constant at about 600 mm, of which about 50 mm will be in the flammable region (5-15 per cent).

A lower leakage rate will lead to the formation of deeper flammable regions. For example a flow rate of 0.25×10^{-3} m^3/s, over 10 m^2 roof area gives a 100 mm deep explosible methane/air layer.

b. Leak at Floor Level

The leak can be considered to be initially a momentum plume, as the gas is under pressure, but it will eventually become buoyant. Work by Long 4 allows the estimation of the distance from the leak when this occurs and Birch's calculation 2 of the concentration of methane at this transition point.

Considering methane gas discharging from a 13 mm dia pipe at 18 m/s, transition from a momentum plume to a buoyant plume is complete 2 m from the source of the leak. The maximum concentration at this point is 3.8 per cent by volume (average 2.3 per cent over the plume cross sectional area 0.3 m^2).

According to the model proposed by Baines and Turner 5 a buoyant plume, in this case methane/air, will spread out at the ceiling, displacing air and in time this layered methane/air mixture will be entrained into the plume, increasing the concentration of methane. A layer of explosible methane/air mixture will therefore be formed, although the depth is not easily forecast as it will vary as the input of gas continues and is a function of the gas leak velocity.

In the two cases discussed, it can be postulated with some certainty that explosible methane/air mixtures can exist in rooms as layers assuming draught-free conditions. However it is likely that in practice draughts will be present. These will promote mixing of the gas mixture tending to produce a homogeneous mixture, the draughts of air also acting as a diluent for the methane. For example a domestic fan will produce a homogeneous mixture in an average sized room (20 m^3) in less than half an hour.

Draughts of air into a room will be balanced by the exit of air or a gas/air mixture from the room, if it is not to become pressurised. If the diluent effect of the air draughts balances the gas leak a steady state will be reached. The presence of any opening in the room, eg air bricks, 'open' windows and doors can facilitate the formation of a gas/air mixture layer with a sharp cut off from the air below 3 .

Which of the many situations described predominates is for the purposes of this work unimportant, as they are all possible. The possibilities for the formation of explosible gas layers are clearly established. The experiments described in this paper were intended to investigate the most onerous conditions in respect of methane concentration, hence layers of stoichiometric (10 per cent by volume) mixtures were used.

PRELIMINARY EXPERIMENTAL WORK

The explosion characteristics of layers of methane/air mixtures have not apparently been studied before in detail, although there is a limited amount of work reported by Astbury et al 6. A series of preliminary experiments were therefore carried out in order to define the most onerous conditions in terms of explosion pressures developed.

The explosion experiments were carried out in a single chamber 3.7 m long x 3.0 m wide x 2.4 m high, provided with a full width opening, extending downwards from the roof, in one of the 3 x 2.4 m walls. A weak vent covering of 0.05 mm thick polyethylene film was hermetically sealed around the edges of the wall containing the vent for all vent sizes examined.

The gas/air mixture at the selected concentration was introduced at roof level at a rate that allowed a layer to be formed displacing air through valves situated 0.5 m above the bottom of the chamber. Layering was accomplished by use of four 900 mm diffusers which allowed a fairly large gas/air volume input rate to be used, their large surface area ensuring a low linear velocity which favours layer formation. Table 1 gives the typical volume input rates and their respective linear velocities for the various layer depths used and indicates that 0.31 m below the nominal layer depth the methane concentration is approaching its lower explosible limit (LEL) value (5 per cent by volume). The nominal layer depth is defined as the lowest depth from the roof to which 95 per cent of the desired methane concentration extends. Samples of the gas mixture were remotely drawn from various depths in the chamber and analysed automatically by gas chromatography. The analysis system has been fully described by Butlin et al elsewhere 7 .

The layers of explosible gas/air mixtures were ignited by a number of different ignition sources described below and the resultant pressure pulses both inside and outside the chamber measured as gauge pressures (not absolute) by piezo-electric pressure transducers. The signals from these were amplified and recorded as a voltage time function by (i) photographing an oscilloscope trace and (ii) direct magnetic recording using an FM tape recorder.

The explosion tests were grouped into sets examining the effect of the variation of one of the following parameters:

a. Ignition source (type and position)
b. Vent size and explosible gas mixture layer depth
c. Concentration of gas/air mixture.

a. Ignition Source (type and position)

Previous workers, for example Cubbage and Simmonds 8 , found that ignition at the centre of an homogeneous explosible gas/air mixture produced the highest pressures in a vented cubical chamber. In this situation the flame travels the furthest distance before quenching occurs at the chamber walls. However explosions of buoyant layers of gas/air mixtures were found to generate the highest pressures when ignited, at the bottom of the layer, at the centre of the wall most remote from the vent, by a single spark of theoretical energy 30 mJ. The reasons for this behaviour are not fully understood, but it is due, in part at least, to the fact that cooling of the flame by that part of the secondary layer of methane/air mixture whose value is below the LEL, but nevertheless may contribute towards the heat of combustion, would be substantially less than that caused by solid walls. Initiation of the explosion at a location most remote from the vent enables the flame to accelerate over a greater distance to the vent than is possible with ignition in the centre of the layer.

The variation of pressures for different locations of the single spark ignition source is shown in Table 2, where Pv is the pressure at which the chamber was vented and Pm the maximum pressure recorded. Ignition close to the vent gave lower pressures, partly due to the thermal destruction of the vent covering material allowing premature discharge of hot burnt gases through the vent, thus abating their contribution to the explosion pressure. The other cause of low pressure from ignition close to the vent has been discussed by Rasbash and Rogowski 9 : the venting of burnt gas behind the flame front minimizes the effect of the expansion of burnt gas on the motion, and compression, of the unburnt gas ahead of the flame front.

The use of multiple ignition sources, including igniferous fuses* resulted in lower pressures than those achieved with a single spark at the location most remote from the vent. However, the use of multiple ignition sources in the geometric centre of the layer (middle of the layer, equi-distance from the walls of the chamber) resulted in higher pressures than were recorded with a single spark at that location: at 1.22 m (L = 0.5) from the roof 7.6 kN m^{-2} compared to 5.5 kN m^{-2} and at 0.61 m (L = 0.25) from the roof 6.2 kN m^{-2} compared to 3.5 kN m^{-2}. The use of multiple ignition sources at the geometric centre of the nominal layer also produced higher pressures than use of these sources remote from the vent.

It is generally considered from cine records of explosions that high energy and/or multiple ignition sources will cause turbulent combustion, which in homogeneous mixtures results in higher flame speeds, rates of pressure rise and maximum pressures. Although this appears to be the case for central ignition in layers, it is considered that the local turbulence created by multiple ignition sources at the bottom of a nominal layer causes some mixing with the lean and sub LEL mixture below that layer, tending to slow down the rate of combustion. This effect will tend to be greater the further the flame has to

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*These are commercially available devices which scatter a number of minute burning particles, each capable of igniting a flammable gas/air mixture, substantially within an included angle of sixty degrees up to a distance of about half metre.

travel to the vent; mixing will be minimal with a small single spark ignition source.

b. Vent Size and Explosible Gas/Air Mixture Layer Depth

Decrease in the vent area gave rise to higher pressures when all other experimental parameters were held constant. The pressure at which the chamber vented, Pv , remained constant due to the method of fitting the vent covering material. The increase in maximum pressure, Pm was found to be linear with decrease in vent area (defined as K values) from K=2 to K=8 for constant volumes of explosible gas/air mixtures as buoyant layers (Fig.1). This agrees with other workers as reported by Rogowski 10 and further work that has been carried out at FRS with homogenous explosible gas/air mixture-filled chambers.

The effect of increasing the explosible gas mixture layer depth for a particular vent factor K was also investigated (Fig.2). The physical model of this relationship cannot be proposed at this stage, but an empirical correlation can be developed which must satisfy a number of conditions - it should reasonably predict the 'full' chamber pressure (although there are difficulties with ignition location) and should predict zero pressure at zero L . The correlation would be expected to be of the form

$$Pm(L) = f(Pm(F),\ L,\ \phi)$$

where Pm(L) is the maximum pressure from a given layer

Pm(F) is the maximum pressure from the full chamber and is itself a function of Pv and K

ϕ is related to the stoichiometry.

One can write a simple correlation for 10% v/v gas in air mixtures

$$Pm(L) = Pm(F)\ L^{n} \tag{1}$$

for the data (Fig.2) the best fit is given by

$$Pm(L) = 11.4\ L^{0.5} \tag{2}$$

the equation predicting the data within 10%.

Subsequent work to be reported elsewhere, carried out with a chamber filled with a homogeneous stoichiometric methane/air mixture indicates that this relationship is valid, though can overestimate the pressure for any particular layer depth by up to 10%. The equation presented is for pressures obtained with the ignition source located at the nominal layer depth remote from the vent, but it can reasonably be used to predict pressures at whatever depth the ignition source is located provided it is remote from the vent.

c. Explosible Gas/Air Mixture Concentration

This area of work was carried out with an igniferous fuse located remote from the vent at the nominal layer depth. The igniferous fuse was required to ensure ignition of the non stoichiometric gas mixtures. The results presented in Table 3 and Fig.3 show that a marked reduction in maximum explosion pressure occurs when the concentration of natural gas (methane) in a mixture with air departs from the stoichiometric value (ie 10 per cent). Note that the pressures are less for 10 per cent by volume methane in air than those recorded with a single spark ignition due to the reasons discussed in section a.

The differences in explosion pressures resulting from different methane/air concentrations indicate the large variations that can be expected in forces generated by explosions in buildings. From the statistics of gas explosions quoted earlier in this paper and elsewhere 1 , it would appear that the majority of explosions (c.70 per cent) that do not cause structural damage but only minor damage such as broken windows and plasterboard, are due to explosions of either fuel rich or lean mixtures, some of which must exist as layers. However it should be noted that fuel rich mixtures burn for relatively long periods, ie several seconds, which can cause the ignition of certain combustible items, eg wood, fabric and synthetic foam. The wood surround of the vent was actually ignited in experiments carried out with fuel rich mixtures.

EXPERIMENTAL WORK WITH HEAVIER VENT COVERING MATERIALS

Most industrial and domestic structures can withstand only fairly low pressures without structural damage. Typical pressures which have been found to cause actual structural damage to different building components are given in Tables 4 and 5.

It is not only the magnitude of pressure that is important, but also the ratio of the frequencies of the pressure fluctuations to the natural frequency of the structural element; this ratio determines the response of the element to a pressure pulse and the pressure it will actually experience. This has been discussed by Dragosavic 12 who describes the following categories:

i) if the frequency of the pressure pulse is less than the resonance frequency of the structural element, the amplitude of the loading is effectively equivalent to static loading

ii) if the frequency of the pressure pulse is about equal to the resonance frequency the structural element will experience an equivalent static loading greater than the actual pressure pulse. If the frequencies are equal, the static pressure loading is equal to π times the pressure pulse

iii) if the frequency of the pressure pulse is greater than the resonance frequency, the pressure wave is partially absorbed, the structural element experiencing a lower static pressure loading than the amplitude of the pressure pulse.

Some typical resonance frequencies of structural elements are given in Table 6, though clearly some variation can be expected, along with the frequency of pressure pulses from methane/air explosions and blast waves, indicating that the former falls into Dragosavic's category (i) and the latter in category (iii). This indicates that the pressures given for structural failure in Table 4 should be less for methane/air deflagrations.

From the pressure values shown in Tables 4 and 5, it can be seen that structures can be damaged by relatively low pressures. Therefore there is a need to equip structures in which explosions may occur with vents which fracture at a pressure lower than that which will cause structural damage and offer a vent area sufficient to prevent subsequent pressure peaks capable of causing structural damage.

It is apparent that, for most structures, maximum pressures should be held below about 21 kN m^{-2}, therefore practical vent covers should fracture at pressures that do not allow the explosion pressure to exceed this figure and are not so fragile that they fracture by wind pressure. The preliminary experiments reported above were carried out with 0.05 mm thick polyethylene vent coverings. Maximum pressures were low < 14 kN m^{-2}, but the vent covering was much too fragile, fracturing at 0.7 kN m^{-2}, to be considered for industrial and domestic use.

In the second stage of the work, vent coverings were used that burst between 7 and 14 kN m^{-2}. The study was not exhaustive, being limited to selected layer depths, but it does illustrate, quantitatively, the use of such materials as vent covers for practical explosion reliefs.

The experimental conditions, cell dimensions, mode of layer formation and measurement transducers etc were the same as for the preliminary work (section 3) except that the vent covering material was held in a frame covering only half of the wall area containing the vent. From the preliminary work, the most onerous conditions had been found to arise with nominally stoichiometric methane/air mixtures, ignited by a small spark (about 30 mJ)in the centre of the wall most remote from the vent, and at the bottom of the layer.

It was therefore decided to employ these conditions to study the effect of layer depth on maximum explosion pressures with different size vents and vent covering materials.

Pressures from the ignition of buoyant 1.5 m ($L = 0.63$) deep layers of stoichiometric methane/air mixtures in the chamber equipped with $K=2$ vent,were quite similar for all vent materials tested (Table 7).

It is interesting that the second pressure peak was not the maximum for the two materials having the highest bursting pressures tested and one can conclude that with this layer depth and type of ignition the vent covering materials that burst about 7 kN m^{-2}, with a vent area ($K=2$) will prevent the pressure rising substantially above 7 kN m^{-2}.

Subsequent experiments with these vent materials were carried out with a $K=4$ vent and a buoyant 0.91 m ($L = 0.38$) layer of nominally stoichiometric methane/air mixture, the results of which are summarised in Table 8. The results show the expected increase in maximum pressure compared to those pressures recorded using a $K=2$ vent. However the differences in pressure recorded for different materials (and layers of material) for vent covering, although statistically significant, were not so in terms of their likely effect as pressure pulses on concrete and brick structural elements.

Further work carried out with a buoyant 1.2 m ($L = 0.5$) layer of explosible gas mixture again did not show any significant difference in the explosion pressure resulting from the use of different vent covering materials (Table 9). However, there are indications that with completely filled compartments that this may no longer be the case. For example, work carried out at FRS (to be reported elsewhere), showed significant differences in explosion pressures when different vent covering materials were used, particularly with central ignition.

Increasing the stoichiometric methane/air mixture layer depth gives an increase in explosible gas/air mixture volume with a corresponding increase in explosion pressures. The basic form of equation (1) has been found to hold for this work. For example using the data in Tables 8 and 9, the ratio of $Pm(L)/L^n$, where $n = 0.5$, for a given vent covering material and vent size, predicts substantially the same $Pm(F)$. Using this equation it is possible to predict the maximum explosion pressures for a completely filled chamber (Pm(F)), equipped with a K=4 vent and those vent covering materials reported in Tables 8 and 9, to be between 14 and 20 kN m^{-2}. Assuming it also applies to K=2 vents covered by those materials reported in Table 7, the expected maximum pressures (Pm(F)) will be between 8 and 11 kN m^{-2}. These figures are in agreement with subsequent FRS work (to be reported elsewhere), the higher pressures being produced when the higher bursting pressure vent covering materials were used.

From this work it is possible to conclude that rooms equipped with vents that open between 7 and 11 kN m^{-2} and are not less than 25 per cent of the area of one wall, should not suffer serious structural damage in the event of a methane explosion. However, FRS has found indications that for completely filled chambers, central ignition results in pressures about 1.5 times greater than those expected using remote ignition.

Structural damage could therefore be expected with a K=4 vent, although providing the building was constructed to withstand 35 kN m^{-2} [13], it is unlikely that its collapse would result.

Glass windows are often the only lightweight pressure relief vents to be found in domestic and industrial buildings. It is therefore on the efficiency of these in relieving explosion pressures that the likelihood of the building remaining substantially intact depends. As glass by virtue of its presence in buildings, will almost invariably fulfil a secondary venting role, many research workers have used it as a vent covering material in their studies of the effect of gaseous explosions on building structures. The pressure at which approximately square glass panes of a given thickness breaks is inversely proportional to its area, but because of manufacturing and mounting tolerances quite large variations, (in the order of ± 35 per cent) can be expected. The data scatter is shown in Figs 4 and 5 summarising the work of FRS and other workers on the breaking pressure of glass when subjected to a gaseous deflagration.

Although the total glazed areas may be large, they are often composed of individually mounted panes, which require correspondingly higher pressures to break. The work reported here involved the use of three glass panes, the middle one equal in area to the other two, held in place by a wooden frame and beading. In terms of the vent factor K, the total areas were 2.5 and 5.0, but it is more significant to quote the actual glass sizes (Table 10) as it is on these individual panes that Pv and also Pm for deep layers, depend.

For the particular glass configuration used (K=2.5) pressures were in the order of 11 kN m^{-2}, the shape of pressure pulse indicated in Fig 6, showing the effect of progressive venting on the pressure pulse. The expected maximum pressure for a chamber completely filled with a stoichiometric methane/air would be of the order 13 - 15 kN m^{-2} and is unlikely to cause serious structural damage.

The glass configuration used for K=5 resulted in pressures between 20 and 27 kN m^{-2} (Fig 7) which would be sufficient to cause structural damage to single and cavity brick walls. The maximum pressure to be expected in a chamber completely filled with stoichiometric gas/air mixture could exceed 30 kN m^{-2} and again it should be stressed that this is for ignition remote from the vent, central ignition elevating the pressure by a factor of about 1.5.

It should be remembered that there is also a safety hazard with the glass when it breaks as it produces many fragments, in our work travelling over 60 m from the chamber, and could cause, for example, severe facial injuries to personnel.

CONCLUSIONS

1. The explosion pressures generated by ignition of buoyant layers of flammable methane/air mixtures indicate that providing they are vented at relatively low pressures in the order of 7 to 14 kN m^{-2} and the area of vent is sufficiently large ie about 25 per cent of the area of one wall, the resultant maximum pressures should not cause substantial damage to buildings.

2. Using the empirical relationship (equation 1) presented above to estimate the maximum explosion pressure in a compartment filled with a quiescent homogeneous stoichiometric methane/air mixture also indicates that *structural damage should not be severe providing that, when glazed units* are used, they comprise at least 50 per cent the area of one wall.

3. The results presented in this paper, including the pressures at which structural elements fail and breakage pressures of glass can be used to estimate the explosion pressures at actual incidents. Clearly it is possible to obtain estimates within quite wide limits, but a skilful and sensible approach, considering damage to a number of structural elements and glass panes in different locations will give a fairly accurate indication of maximum pressure.

SYMBOLS USED

Pv = pressure at which vents open (kN m^{-2})

Pm = second, after maximum, pressure peak (kN m^{-2})

L = dimensionless unit, referring to layer depth in chamber (max value 1.0) given by $\frac{\text{depths of layer}}{\text{height of chamber}}$

K = $\frac{\text{area of wall containing vent}}{\text{area of vent}}$

P external = maximum pressure at an external location (kN m^{-2})

P internal = maximum pressure inside the chamber (kN m^{-2})

Pc = pressure at which centre glass pane breaks (kN m^{-2})

P_L = pressure at which left (to observer) glass pane breaks (kN m^{-2})

P_R = pressure at which right glass pane breaks (kN m^{-2})

V = volume of compartment (m^3)

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TABLE 1 - Typical 10% Gas in Air (v/v) Input Rates for Different Layer Depths

Layer depth (m)	Gas/air input rate (m^3/s)	Gas/air velocity (m/s)	Concn 0.31 m below layer depth (%)	Concn 0.61 m below layer depth (%)
0.31	4.7×10^{-3}	1.9×10^{-3}	6.3 SD 0.88	1.3 SD 0.34
0.61	9.4×10^{-3}	3.7×10^{-3}	5.5 SD 0.95	1.4 SD 0.41
0.91	1.4×10^{-2}	5.5×10^{-3}	6.4 SD 1.13	1.7 SD 1.04
1.22	1.9×10^{-2}	7.5×10^{-3}	5.8 SD 0.28	1.1 SD 0.5
1.52	2.4×10^{-2}	9.4×10^{-3}	7.5 SD 1.3	0.9*SD 0.5
1.83	2.8×10^{-2}	1.1×10^{-2}	2.6*SD 1.4	0*

NB Theoretical fill time 12 min, actual fill time between 15 and 18 min.

*The lower concentrations at these locations are due to the proximity of the cutlet values

TABLE 2 - Effect of position of single spark ignition source on the explosion pressures of a 1.2 m layer of 10 per cent methane/air in chamber (K=8)

Ignition source location	Pv (kN/m^2)	tv (ms)	Pm (kN/m^2)	tm (ms)
0.5 H back of chamber	0.7	300	6.3	500
0.25 H back of chamber	1.0	280	7.6	480
0.5 H centre of chamber	0.7	200	5.5	340
0.25 H centre of chamber	0.7	200	3.5	320
0 H centre of chamber	0.7	260	2.5	320
0.5 H front of chamber	ND	220	0.9	280
0.25 H front of chamber	ND	220	0.5	270

ND = not determinable
H = dimensionless height of chamber (from roof)

TABLE 3 - Effect of Methane concentration on pressures of a layer (L=0.5) ignited by igniferous fuse (K=8)

Methane/air (%)	Pv (kN/m^2)	tv (ms)	Pm (kN/m^2)	tm (ms)
7	0.1	500	0.6	1000
10	0.4	270	5.5	400
13	0.1	700	0.9	1300

TABLE 4 - Structural Damage due to Gas Explosions (6)

Structural Element Damaged	Over Pressure (kN/m^2)
19 mm thick Chipboard (held in place with nails) blown out	3
19 mm thick Chipboard shatters	7
114 mm (4.5 in) Brick wall displaced (restrained)	23
228 mm (9 in) Double Brick wall displaced (restrained)	>49
Room communication door blown off hinges	3

NB Unrestrained walls fail at between 30 to 40% lower pressures. These are failure pressures for newly built brick walls, where the mortar has not weathered.

TABLE 5 - Structural Damage due to Blast Waves (11)

Structural Element Damaged	Over Pressure (kN/m^2)
Glass windows	About 7
Corrugated asbestos	7 - 14
Corrugated steel or aluminium	7 - 14
Up to 300 mm Concrete or Cinder Block walls	14 - 21
Up to 300 mm thick Brick Wall	49 - 56
114 mm Brick Wall with Cavity	35

TABLE 6 - Resonance Frequencies (Hz) of Structural Element and Pressure Pulses

Concrete Floors	30 - 100	(Ref 12)
0.2 m thick concrete walls	70 - 100	
Brick Walls	60 - 70	
Methane/air deflagration	In order of 4 (a)	
Blast wave	In order of 10^6 (Ref 11)	

(a) Typical Value calculated from experiment

TABLE 7 - Pressures from layer (L = 0.63) of 10% methane in air $(^{v}/v)$ K = 2

Vent material*	Thickness (mm)	Pv (kN/m^2)	tv (ms)	Pm (kN/m^2)	tm (ms)
P	0.13	1.7	220	6.6	500
P.T	0.13	6.6	280	6.2	510
P.T	0.05	5.7	250	10.9	490
J.M	0.79	6.3	280	5.0	490

TABLE 8 - Pressures from layer (L = 0.38) of 10% methane in air $(^{v}/v)$ K = 4

Vent Material*	Thickness (mm)	Pv (kN/m^2)	tv (ms)	Pm (kN/m^2)	tm (ms)
One P film	0.13	1.7	220	9.8	480
One P.T film	0.13	9.0	320	6.6	500
Two P.T films	0.13	7.0	300	7.0	480
Two J.M sheets	0.79 0.40	7.5	290	13.0	480

TABLE 9 - Pressures from layer (L = 0.5) of 10% methane in air $(^{v}/v)$ K = 4

Vent Material*	Thickness (mm)	Pv (kN/m^2)	tv (ms)	Pm (kN/m^2)	tm (ms)
One P film	0.13	1.9	220	10.9	480
One P.T film	0.13	7.6	280	10.1	470
Two P.T films	0.13	7.9	280	10.2	470

* P = polyethylene

P.T= polyethylene terephthalate

J.M= jointing material

TABLE 10 - Pressures resulting from ignition of a 1.8 m (L=0.75) deep layer of stoichiometric methane/air mixture in chamber equipped with glass windows (K=2.5 and 5.0)

Glazed	Glass breakage pressure (kN/m^2)						Pm	tm
area	P_R	tr	P_L	t_L	Pc	tc	(kN/m^2)	(ms)
2.5 x 1.2 m 5 mm thick (Fig.6)	7.2	310	11.0	340	8.3	320	11.0	340
2.5 x 1.2 m 3 mm thick	3.9	234	Did not break		10.1	438	11.0	450
2.5 x 0.6 m 5 mm thick (Fig.7)	21.6	577	11.5	332	14.3	356	21.9	485
2.5 x 0.6 m 3 mm thick	15.5	553	12.4	510	8.6	320	22.1	612

NB Right and left window panes are half width of the centre pane

ACKNOWLEDGEMENT

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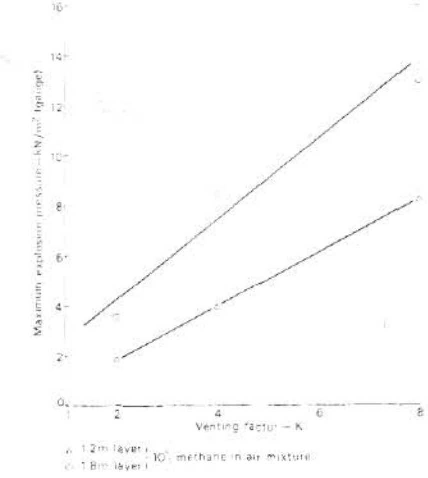

Figure 1 Variation of pressure (P_m) with vent area for different layer depths

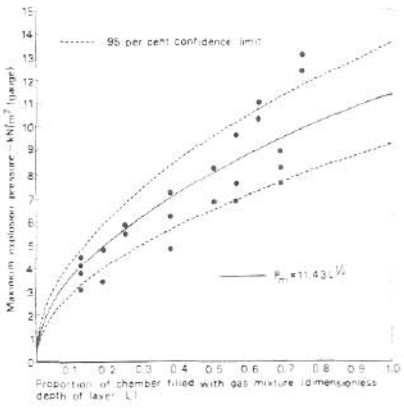

Figure 2 Effect of layer depth of 10% methane in air mixture on explosion pressure in a vented chamber (K = 8)

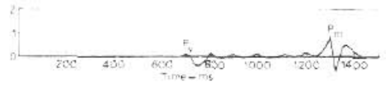

Figure 3a 13 per cent natural gas / 87 per cent air mixture

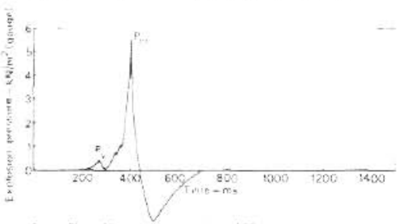

Figure 3b 10 per cent natural gas / 90 per cent air mixture

Figure 3c 7 per cent natural gas / 93 per cent air mixture

Figure 3 Pressure from explosions ignit at back of chamber. Effect of explosible gas composition. $L = 0.5$, $K = 8$

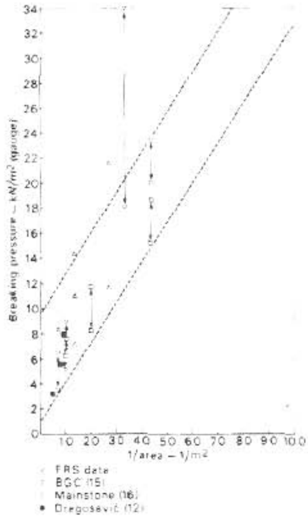

Figure 4 Relationship of the breaking pressure of 5 mm thick glass panes and their area

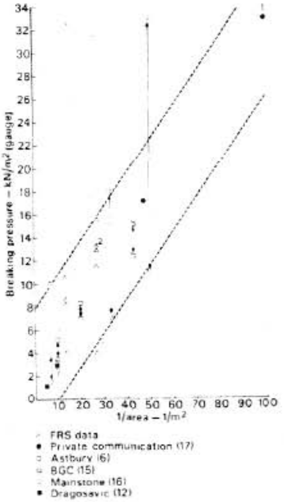

Figure 5 Relationship between the breaking pressure of 3 mm thick glass panes and their area

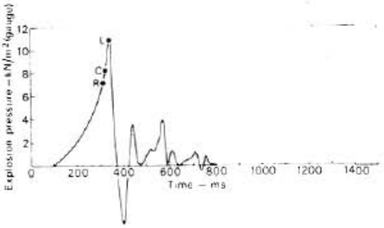

Figure 6 Pressure curve obtained with glazed vent. L = 0.75, K = 2.5

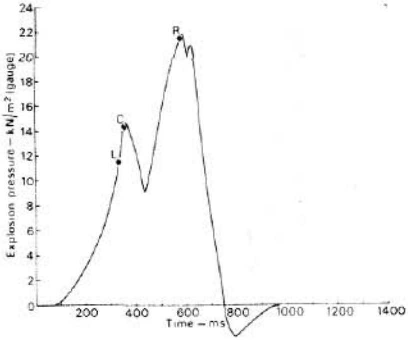

Figure 7 Pressure curve obtained with glazed vent. L = 0.75, K = 5