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A REVIEW OF INFORMATION ON EXPERIMENTS
CONCERNING THE VENTING OF GAS
EXPLOSIONS IN BUILDINGS

by

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SUMMARY

A review of previous experimental investigations on the venting of gas explosions is presented. Relevant factors are listed, and the extent to which they have been considered and were under positive control in past experiments is discussed. Some of the limitations of previous work are discussed in the conclusions and the points to be considered in future work are outlined.

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1. INTRODUCTION

As a result of the disastrous explosion at Ronan Point¹ changes were made in the Building Regulations requiring that high-rise dwellings of the type at Ronan Point should not give progressive collapse, (The Building (Fifth Amendment) Regulations, 1970). Strengthening of the structure was found necessary and undertaken in many cases and in some buildings the gas supply was removed.

These measures did not solve the long-term problem of the design of buildings to withstand explosion pressures safely, with or without explosion venting, and discussions were held to decide what research needed to be done to provide the required data. One of the recommendations was an assessment of previous tests on explosion venting in buildings, and of other relevant experiments. The present note presents a critical assessment of published experimental measurements and methods and includes some indications as to where the main emphasis of future experimental work should be.

This review will be restricted to the relatively small number of investigations which are considered to be the most pertinent, mainly with respect to the scale and geometric factors. The many experimental investigations on record for explosion venting in systems (ducts for example), where the characteristics of the explosion behaviour are typical of one dimensional behaviour are excluded from consideration. Also the closed spherical bomb type of investigation, from which much basic data on closed-system explosions has been derived, is not relevant, mainly because large-scale explosion systems do not exhibit the theoretically predictable behaviour of the laboratory scale experiments where the variables, apart from being fewer, are under much closer control. Wall effects may also influence the results from experiments using small enclosed vessels.

2. SUMMARY OF EXPERIMENTAL INVESTIGATIONS

As each of the investigations referred to has been the subject of one or more publications and reports, only the main features are presented in this note. Further information on methods of measurement and detailed results may be sought from the original publications. A brief summary of the main investigations to be considered in this review is to be found in Table 1.

3. IMPORTANT FACTORS

In order to facilitate a critical description of each individual piece of research work it will be helpful first to list the variables which the author considers important in such work and then to consider which have been taken into account, which have been under control and which experimental parameters have been measured (directly or indirectly). These variables are listed in an order which is not that of any priority.

Compartment/vent

Effect of explosion on the structure of the experimental compartments/buildings. Shape, size, material of construction of vent covers and the means whereby vent is opened.

Natural frequency of structure.

Gas

Type of flammable gas, and composition of explosible mixture.

Location of gas (eg layer).

Method and geometry of gas containment.

Control of gas mixture composition and distribution.

Emission of unburnt gas from cell during venting of explosion.

Ignition

Nature, number and extent of source (s).

Flame speed

Measurement of average and localised flame speed.

Turbulence/fluid dynamics of explosion

Measurement of turbulence generated by gas movement, obstacles, and vent opening.

Turbulence generated by bursting of initial container (balloon).

Development of inherent flame instability with respect to flame size.

Movement of unburned gas ahead of flame.

Pressure

Internal pressure generated during explosion

External pressure generated during explosion and its attenuation with distance.

Effect of pressure oscillations and acoustic vibrations.

Measurement of actual relief pressure of vents.

General

Measurement of noise.

Effect of scaling.

4. REVIEWS OF PREVIOUS WORK

4.1. Some of the more important earlier work is that of Cubbage and Simmonds^{2,3}. The basic data from this work is given in Table 1 and will be considered here in more detail.

The work was undertaken specifically to provide a design basis for explosion relief for industrial drying ovens. To this end it was successful, but it must be borne in mind that the scope of the investigation was deliberately restricted. The investigation was concerned mainly with the explosion of town gas in ovens, although some work was done on other vapours, and the use of different vents was investigated thoroughly. An empirical formula for the pressures developed during an explosion in a compartment provided with explosion relief was derived. The phenomenon of a second pressure peak was observed and interpreted qualitatively. The effect of turbulence on such explosions was studied in a limited number of experiments. Turbulence, induced into the gas mixture by vigorous stirring before ignition, or by the presence of shelves, resulted in an increase in the pressures generated over those from non-turbulent explosions. Preliminary experiments showed that the maximum pressures occurred with central ignition. No attempt was made to investigate the effect of multiple ignition sources. The position of the vent relative to neighbouring walls and ceilings was also examined. The investigation achieved its desired objective but to provide data for complex compartmentation, as in dwellings, additional information is needed including:

- a) Measurements of pressure and other parameters for a wider range of geometrical configurations.
- b) Measurements of the scale and intensity of turbulence and its effects.
- c) Justification of empirical equations on a theoretical basis assuming their applicability to other results on explosion venting.
- d) Measurement of overall flame speeds by more precise methods, additional to long distance cine photography.

4.2. An investigation carried out by Harris⁴ was on a generally smaller scale than that of Cubbage and Simmonds. In this investigation a cylindrical vessel of 1.7 m^3 (60 ft^3) containing pentane - air mixtures was used. Certain important phenomena are described which

arose during the venting of turbulent explosions, particularly the existence of oscillatory and multiple pressure peaks under certain experimental conditions. Central ignition was used, as this was shown in preliminary tests to give the highest pressures.

The experiments were carried out using bursting discs as vents, and the production of turbulence by the bursting process was examined and interpreted together with the nature of the flow of gas through the vent during an explosion. The operating pressure of the bursting discs was found to vary with rate of application of pressure, and under explosion conditions all the discs used burst at a higher pressure than their static rating.

A variable speed fan was used to produce turbulence, and investigations were carried out to determine the maximum explosion pressure in the vessel for different vent sizes as a function of fan speed. The important concept of expressing the bursting pressure of a disc as a function of the impulse (taken as the area under the pressure/time trace for an explosion) is considered in this work. The pressure produced during an explosion was recorded, together with the actual time and bursting pressure of each disc. No direct measurements of the turbulence generated in the gas before ignition were made.

Limited variations in mixture composition were also examined. Drawings of flame behaviour to indicate the effect of vent opening on flame shape under different venting conditions are given but flame speeds were not measured nor was the effect of multiple ignition investigated. Harris carried out measurements of pressure with a sensitive transducer at various points inside the vessel. In a previous, related investigation of the effect of turbulence on explosion pressures in cylindrical closed vessels⁵ of 1.7 m³ volume a linear correlation was found between turbulence, expressed as the root mean square of the amplitude of the pressure fluctuation, and increasing fan speed. Some idea of the flow of gas in the vessel was also obtained.

4.3. Large-scale explosions in Sweden

A comprehensive set of realistically large-scale experiments on explosion venting was performed in Sweden in 1957 by a group representing several organisations. The work was carried out in a frame and panel building of approximately 200 m³ which was essentially oblong with a roof sloping from the front to the rear across the lesser plan dimension. The walls, ceiling, floor, doors and detachable panels

were built to withstand 105 kN/m^2 (15 psi) over pressure, and 64 kN/m^2 (9 psi) under pressure. Facilities were provided on the long vertical open face on the side where the roof was of maximum height for the support of a series of explosion relief panels across the spaces, between narrow vertical supports, which reached from top to bottom of the front opening. The areas used for venting (varied by differing the number of relief panels) were 26 m^2 , 21.7 m^2 , 17.4 m^2 and 13 m^2 . These corresponded to venting area: volume ratios of 13.1, 10.9, 8.8 and $6.5 \text{ m}^2/100 \text{ m}^3$ respectively. Two types of relief panels were used, the one of corrugated aluminium sheet lined with plastic insulation, and the other of hardboard sheets strengthened with wooden battens. The panels were fixed so that they were effectively hinged at one vertical edge, with the other locked with one of a variety of retaining devices designed to fail at different pressures.

Meteorological balloons were used to contain explosive gas mixtures of volume 15, 25, 40, and 70 m^3 within the cell, the volume 200 m^3 being provided when the whole test cell was filled with the gas mixture. Modified electrical percussion caps were used as igniters. In the balloon experiments two igniters in series were used and four in series in the 200 m^3 tests. Standard and high-speed cine cameras were used at different orientations to the cell to monitor events externally. Six transducers were used for pressure measurement, five inside the cell and one some distance from it. Approximate temperatures were measured using colour-sensitive indicators. The indicators were hung on brass strips both inside and outside the cell. Other effects of physiological significance (blast etc) were also monitored. Mechanical mixing was used in the first group of tests, but because this sometimes resulted in premature explosions diffusive mixing was used - acknowledging that mixing might be incomplete.

It had been realised at the outset that the scaling of results would have to be considered. Consequently theoretical relationships were derived which related the flame speed to the volume of the enclosure, the actual flame speed being calculable either from the observed rate of flame spread from photographs, or from the measured rate of pressure rise. The derivations used are probably applicable to ideal conditions (radial spread of flame) and although allowance is made for the acceleration of gases, no allowance is made for the natural development of turbulence in a flame greater than a threshold size, or to the effects of the bursting of the initial container (balloon) on the rate of and nature of the subsequent flame propagation. A very

important point is made concerning the use of multiple ignition sources or sources of ignition which are effectively multiple or extended (percussive line-fuses). The rate of pressure rise for multiple sources was greater than for a point source. This phenomenon of the development of flame at several points simultaneously was taken into consideration in the Swedish work when flame speeds in the cell were derived from rates of pressure rise.

The tests were carried out using propane and acetylene, with and without explosion panels, ie some experiments were free-venting; 4.5 per cent and 6 per cent propane/air mixtures and 12 per cent acetylene/air mixtures were used in the experiments. Free-venting tests with 25 m³ of 4.5 per cent propane resulted in a very low rate of initial spherical flame spread in the balloon, such that the pressure generated in the room was not measurable, followed on rupture of the balloon by a more rapid spread inside the room and out of the cell. The experiments using acetylene gave rise to similar pressure-time effects except that the rate of pressure rise and flame speed were much greater. The maximum pressure for propane was approximately 2 kN/m² (0.3 psi) and for acetylene approximately 8 kN/m² (1.1 psi). It is interesting to note that in both cases strong rarefaction waves were recorded. This is a problem not always considered when the stability of structures to explosions is investigated. Another important observation made early in this series of tests was that turbulence was generated when the flame passed a wire which was part of the ignition system. This observation indicates the necessity for careful mounting of instrumentation to avoid the development of turbulence.

A useful summary of the tests is given in the report of the Swedish work. In tests with panels as vents, the now well-established phenomenon of the double pressure peak was observed². It was also demonstrated in these tests that the panels were effective vents; for example, with 200 m³ of 6 volume per cent propane mixture all the panels had opened 195 ms after ignition, when 2 per cent of the gas mixture had burned. The phenomenon of oscillatory burning was also observed. The initial flame speed (and hence pressure) was shown to be a function of the fundamental burning velocity of the mixture but the subsequent generation of turbulence gave rise to much higher flame speeds and associated pressures. Using an open fronted cell, the explosion pressure was proportional to the flame speed over the range 2 m/s to 20 m/s. A decrease in the area of the open front of the building by

20 per cent (from 10.8 to 8.7 m²/100 m³) increased the pressure by about 50 per cent. With explosion relief panels fitted to the building the lowest explosion pressure was 1.3 kN/m² (0.19 psi) and the highest 4.5 kN/m² (0.64 psi), values which were independent of flame speeds from 1 to 7 m/sec. The different relief panels, locking systems and explosion pressures resulted in the first relief panel opening at between 1.1 and 5.2 kN/m². For the higher flame speeds (those corresponding to turbulent propagation of flame), the explosion pressure was found to increase in proportion to the flame speed up to about 20 m/s. A decrease of vent area by 25 per cent increased the pressure by about 40 per cent. The linear increase in pressure with flame speed was considered unusual by the Swedish workers, as they had expected a square law relationship between pressure and flame speed. Explanations of the relationship between pressure and flame speeds corresponding to initially laminar and subsequently turbulent flame spread are attempted in the report, but as some of the phenomena arise from an artificial situation (eg the generation of turbulence upon bursting of a balloon full of gas mixture) the explanations are not generally applicable to other situations. One interesting point made in the discussion of results is that the combustion at high pressures happens chiefly outside the cell, ie much of the flammable gas is expelled during venting and subsequently burns outside. This is a factor which should be considered in the interpretation of the results for, and in the instrumentation of, future work.

Further experiments were concerned with the effectiveness of various lock mechanisms and the venting efficiency of the panels, approximate temperature measurements on surfaces and the physiological effects of blast and heat. The results from these tests are not of immediate significance to the problem of structural behaviour but may indicate limiting values applicable to cladding in buildings.

This pioneer work in Sweden has therefore provided extremely useful pointers to the important phenomena to be taken into consideration, orders of magnitude of the pressures to be expected, some idea of the flame velocities involved and the effectiveness of a particular type of venting, all under realistic conditions of scale. Given the considerable time interval since the Swedish work has done, and the increase in knowledge of combustion generally, and more particularly the degree of sophistication in measuring instrumentation now available, these experiments could be extended gainfully with more attention to detailed measurement (of turbulence for example) of the parameters

responsible for some of the slightly unexpected observations made at the time. Despite the initially stated intentions of the work in Sweden, no directly applicable data was derived concerning the behaviour of the structure of the building under explosive loading.

4.4. Tests at Potters Marston

The most recent work on a realistic scale concerning gas explosions in dwellings has been that jointly undertaken by the Brick Development Association, the BCRA, British Gas and the Fire Research Station of the Department of the Environment. The experiments were carried out on a remote site at Potters Marston in Leicestershire. The prime objects of these tests were to investigate the ability of structural brickwork in different configurations to withstand pressure of the magnitude written into the Building Regulations after the Ronan Point disaster and also to investigate the behaviour of explosible natural gas and town gas layers and homogeneous mixtures when involved in explosions in domestic premises. This research has been organised in several phases and is far too extensive to be dealt with in any great detail. Reference to the reports now available^{8,9} must be made for precise information on instrumentation, configuration, etc. Basically two types of structure were employed. First, existing bunkers each of approximately 35 m³ volume were used for testing the ability of brick walls and other structures to withstand various explosion pressures. Secondly a much more elaborate brick structure was built with four rooms as two inter-communicating pairs, above ground level as part of a 3½-storey structure, with windows, doors, and with the facility for venting areas to be varied. The volume of each room was approximately 25 m³.

The objectives of Phase I of the work (quoting from the report⁸) were

- (a) to determine the effectiveness of venting or explosion relief, provided by the cladding and windows, and to measure the pressures involved.
- (b) to determine the pressure necessary to damage a load-bearing brick wall,
- (c) to test the competence of the structure to withstand progressive collapse following the failure of a main structural wall.

The objectives of Phase II⁸ were

- (d) to determine the pressure profiles of different types of explosions, and
- (e) to determine the effect of 'cascade' explosions ie explosions proceeding from one room to another through a doorway when both rooms contain gas.

In Phase I, balloons filled with stoichiometric gas/air mixtures were ignited electrically and in Phase II layered gas/air mixtures were used as well as gas filled balloons. Pressures were recorded using piezo-electric transducers with the output recorded on a tape-recorder transfer system. Cine records were also taken over a wide range of recording speeds. For the layer work, an analysis system based on gas chromatography was used to follow the build-up of a layer. Both natural gas and town gas were used in each phase of experimentation.

From the results of the Phase I and II tests it is maintained⁸ that because the impulse (taken as the integral of the pressure-time profile, $\int_0^t p dt$) was found to be similar for layered town gas and balloon-contained town gas then the use of balloons to simulate layer explosions is justified. Some doubt must be cast on this assertion because there was some lack of control over the layering of gas, evident from the method of forming the layer and from the resultant gas concentration profiles in the rooms concerned. It was noted in some of the preliminary experiments that the rate of pressure rise was greater and that the rate of rise was greater for higher pressures for town gas than natural gas. High frequency vibrations on pressure traces are attributed to the mixing of hot combustion products with cold gases. In subsequent work elsewhere such vibrations have been attributed to the acoustic parameters of the enclosures involved¹⁰. In a comparison of the pressure-time profiles for vented layered natural and town gas explosions under identical geometrical conditions using two rooms, the rise time from zero to maximum over-pressure for town gas appeared to be a third of that for natural gas, and the maximum over-pressure was greater by a factor of 1.7. The consequences of these observations in terms of dynamic loading on a wall are discussed in the report.

The effects of venting (different vent covers) in Phases I and II for both bunker and main building experiments are shown by comparisons of the pressure/time profiles for vented and non-vented conditions. Generally speaking, in the bunker experiments where rapid venting was provided with low-pressure relief at 7 kN/m (1 psi) over-pressure, a rapid rise to a maximum pressure in about 60 ms was followed by an equally rapid fall in pressure, then by a rarefaction and subsequently by a series of low amplitude, low frequency pressure and rarefaction waves. In the non-vented condition a slow pressure rise to a peak pressure in 200 ms was followed by a very slow fall in pressure over a

period of 800 ms to ambient. Where venting did not occur until a high pressure was attained, 36 kN/m² (5.1 psi), in a bunker experiment with a 4.5 in brick wall as cover, the high pressure was sustained for 100 ms until the brick wall cracked. It was found that in all the balloon experiments in the building, the pressure in the room containing the balloon was much greater than the pressure in the adjoining room. However, where layers were used the higher pressure always occurred in the room in which ignition had not been initiated. An empirical relationship for the pressures in the two rooms was derived viz:

$$P_2 = 0.59 P_1 + 1.14 P_1^2 \quad \dots(1)$$

where P_1 is the pressure developed in the first and P_2 in the second, connecting, room. It should be pointed out however that this relationship was based on three experiments only together with an estimate of the similar effect in the Ronan Point explosion. No attempt was made to justify this kind of relationship theoretically.

A summary of the conclusions from this work includes the following:

- a) effective venting can be achieved by glass windows which typically fail at 2 - 5 kN/m² (0.3 - 0.7 psi) or by cladding which in general fails at 7 kN/m² (1 psi).
- b) An 11 inch cavity wall, (with limited loading or pre-compression) in the experimental building, was found to withstand up to about 23 kN/m² (3.3 psi), whereas one fully restrained 9 in wall withstood 49 kN/m² (7 psi) without damage and another, between 98 - 112 kN/m² (14 - 16 psi) with only minor damage.

In ambitious and expensive programmes such as described above, and later, it is not economic to carry out long series of experiments, in which the effects of single variables can be fully examined. It would seem therefore that future large-scale work should be less ambitious and have narrower terms of reference, at least in the early stages.

4.5. Further tests at Potters Marston

A further set of bunker experiments (Phase III) were undertaken at Potters Marston by the Fire Research Station, BCRA and the British Gas Council in order to assess the development of high pressures in a building divided into interconnecting compartments, due to turbulence generated by the passing of flame and unburnt gas past obstacles and through restricted openings. It was considered that the situation in the two-room experiments precluded high pressure generation in the room

into which the explosion moved through a doorway, because 'back-relief'¹¹ was always provided in the room in which ignition took place. Further, it was thought that more precise control of the production of gas layers was necessary before fully comparable results could be obtained. Accordingly experiments with controlled layers of town and natural gas were performed so that after ignition at the blank end of the first chamber, the flame travelled about one-third of the way along the bunker towards the 'mouth' up to and through a wall containing two symmetrically placed vertical openings 1.53 m high and 0.61 m wide, and thence to a wall centrally symmetrical in the bunker with gaps 0.76 m (2.5 ft) at each side adjoining the bunker wall, about two-thirds of the distance towards the 'mouth'. The open end of the bunker (the 'mouth') was covered with polythene sheet in a wooden frame to provide a low-pressure relief. During experiments, pressure and flame speed were monitored (the latter by high speed photography and by ionisation gap records). Some difficulty was experienced during the tests from the effect of flame impingement on the piezo-electric transducers. The explosible gas layers were ignited using a set of three safety fuses in series across the gas-air mixture/air interface. Although the use of multiple ignition sources is justified in layer work, on the grounds of increasing the chance of ignition, it should be emphasized that, as was shown in the Swedish work, this can lead to high rates of pressure rise compared with those produced by single ignition sources.

The maximum pressures measured in the tests were 35 kN/m^2 (5 psi) for town gas-air and 21 kN/m^2 (3 psi) for natural gas-air mixtures. In general the flame speeds in the compartments beyond that in which ignition took place were approximately an order of magnitude higher than that in the ignition compartment, but reproducibility was not good. Pressures in the second compartment could also be much higher than in the ignition compartment. The flame speed in the ignition compartment for town gas appeared to be that expected under low turbulence conditions. Extra-high pressures, perhaps expected due to the generation of turbulence, were not observed and the conditions under which these might be generated are discussed in the report.

The conditions include the size and bursting pressure of the vent cover, the effect of the wall orifices, the use of a homogeneous gas/air mixture throughout the volume compared to a layer, the effect of gas concentration and the possible effects of the presence of other turbulence-generating obstacles such as furniture. The results are discussed with reference to a modified version of an empirical formula

derived previously¹². No attempt was made to measure the generation of turbulence in this work.

A further set of experiments at Potters Marston (Phase IV)⁹ sought to reproduce some of the effects and pressures observed in layered town gas/air mixtures where the explosion moved from one room with vent(s), to an adjacent room with vent(s), via an opening (doorway) and also involved the measurement of the relative resistances of single and double glazed windows in the bunkers. Minor modifications were made to the building before the tests commenced. Other experiments in the main building in this series investigated the effect of layer thickness, gas concentration and position of ignition on the pressure-time profiles for town gas and natural gas-air mixtures and examined the two-room situation with the dividing door closed, with ignition in the room where the door would only open on rarefaction.

Considerable difficulties were encountered in Phase IV in obtaining acceptable layering of gas mixtures with the result that, due to time limitations, many of the experiments originally intended were abandoned. As in previous phases different types of pressure gauge were used and discrepancies appeared at times not only between the readings of different gauge types but also between pressures monitored by gauges of the same type and in the same room. Because of the unforeseen problems encountered it was not possible to make positive conclusions from the results of many of the experiments. The following, however, were felt to be generally proven, namely:

- (i) A relationship between gas concentration and pressure developed was established for 0.61 m (2 ft) thick, albeit unstable, layers, of neat gas.
- (ii) Much higher pressures were obtained with a 0.61 m (2 ft) layer of town gas than for natural gas
- (iii) When two rooms are connected via a doorway with the door closed (the door being a 'one-way' device) ignition in the room into which the door opens produces a different effect to that of ignition in the other room, because in the former case the gas is sucked into the room by a rarefaction wave after an explosion and where venting has already occurred, leading to low pressure, whereas in the latter the flame enters a room which has not vented, leading to higher pressure.

- (iv) The repeat of the experiment with an effectively stoichiometric town gas-air layer in two rooms, both with vents, with an inter-communicating open door confirmed the previous results:

that a higher pressure was observed in the non-ignition room than in the room in which ignition took place (this is generally attributed to a 'cascade' effect, the significance of which will be referred to later). Three pressure peaks were observed, comprising the expected double-peak for a vented enclosure plus an extra peak corresponding to the vented explosion in the adjoining room. The actual pressures attained were similar to those in the previous test, but the observed damage to the building was less marked.

The existence of multiple vents in such experiments possibly over-complicates interpretation of the results in the absence of results for explosions in single chambers for comparison.

- (v) The experiments which compared single with double-glazing showed generally that the double glazed windows failed at pressures about 30 per cent higher than for the equivalent single sheet of glass.

Recurrent problems manifest in the Potters Marston experiments were firstly uncertainty in the accuracy of pressures indicated by different transducing and recording methods and secondly the uncertain significance of the transient pressure pulses observed. These have been the subject of much discussion and the latter considered theoretically¹⁶.

In contemplating future experimental work, the transducer problem should be given early attention.

4.6. Large-scale gas explosion experiments in Holland

The last piece of large-scale experimental work to be discussed in this review is that carried out by the TNO organisation in Holland¹⁰. A one-storey building has been used for this work, comprising two adjacent rooms, (2 m x 4 m and 3.5 m x 4 m) separated by a wall containing a doorway, each room having an open front on a common side onto which cladding and vent covers (glass) could be fixed. Tests were carried out using homogeneous stoichiometric natural gas-air mixtures throughout the volumes. The use of different thicknesses of glass on the windows in the smaller room enabled tests to be carried out for different vent relief pressures. A characteristic pressure-time profile comprised two major peaks. The first was that expected for the breaking of glass,

(with a slight overshoot for small windows with thick glass) and after a relatively prolonged period (about 300 m sec) at ambient pressure a second overall pressure rise occurred, superimposed on which were high frequency vibrations (200 Hz). In an experiment in which the explosion was allowed to progress from a smaller room through an open door into a larger room, very low overall pressures were obtained. In this case the vent in the smaller room opened first. This indicated no large-scale development of turbulence. In all tests ignition was by an electrical spark at the centre of the room, as ignition at the wall did not give such high pressures. Membrane strain gauges were used as well as a commercial piezo-electric gauge and the results appeared to be similar. The pressure gauge records were in phase at various measuring points during an explosion, with the exception of the period of high frequency vibration when out of phase readings were observed. Empirical relations for the two pressure peaks p_1 and p_2 were derived, assuming (intuitively based on the duration of the pulse) $0.8 p_1$ and $0.8 p_2$ as the static equivalent of the dynamic pressures measured. If p_0 is the pressure at which venting begins to take place, it was found that,

$$p_1 = 3 + p_0 \quad \dots (2)$$

from a plot of $0.8 p_1$ versus p_0 , in kN/m^2

and

$$p_2 = 3 + 0.5 p_0 + \frac{0.04}{\psi^2} \quad \dots (3)$$

where $\psi = \frac{\text{ratio of area of broken panes in experiment}}{\text{cubic volume of room in m}^3}$

from a plot of $0.8 p_2$ versus p_0 , in kN/m^2

Only pressure and cine records were taken in this experimentation. The high frequency vibrations were attributed to resonance of the gas between parallel walls of the room or between ceiling and floor (an 'organ-pipe' effect) during the second pressure maximum.

4.7. Maximum

Reference is made for the sake of completeness to two other pieces of work, one by Burgoyne & Wilson¹² and the other by Yao et al¹⁴, the former involving the venting of pentane-air mixtures and the latter being a commissioned programme into explosions in glove boxes used in atomic energy laboratories in the USA. The glove box work includes some

useful theoretical derivations used in the interpretation of results. A further mathematical model has been presented recently¹⁷ and some correlation has been obtained between experimental pressure/time curves and the theoretical treatment. The effects of turbulence are included in the theoretical treatment, using a turbulence factor, which accounts for behaviour over a limited range. The experimental significance of the factor is not understood.

5. CONCLUSIONS

The material reviewed in this note has collectively provided an overall picture of the current knowledge of the venting of gas explosions. Some of the information concerning empirical relationships between various parameters from some of the earlier work on explosion has been reviewed and correlated by Maisey¹⁵ but the limitations of the results and experimental methods were not considered in that review. The following list of conclusions is intended to provide guidance as to where the emphasis should lie in future work. Some extra comments are added at appropriate places.

- (i) Empirical formulae have been derived by the research workers which relate pressures obtained in vented gas explosions with vent area and the volume of the container. In general however, they are based on very limited experimental data and as yet have not been shown to have any theoretical justification.
- (ii) No completely successful attempt appears to have been made which explains theoretically the events which take place during the venting of a gas explosion. To facilitate theoretical analysis a deeper understanding of the flow processes is required: this may come from small scale experiments.
- (iii) The problem of scaling does not seem to have received a great deal of attention. Most of the existing work has been done on too small a scale to be applicable to explosions in buildings, or on a scale which is realistic but without sufficient control over variables. Future work should therefore include derivation of the scaling laws.
- (iv) The phenomenon of the double pressure peak in vented gas explosion experiments has been well established, but has not as yet been explained on a satisfactory theoretical basis.
- (v) The design of experiments has generally been intuitive. Given that in the large numbers of experiments required for statistically meaningful results in compartments of a realistic scale are not economically feasible some thought should be given to this problem. The use of 'extreme value theory' may prove useful in this context.

- (vi) Because in some of the more recent experiments the validity and interpretation of pressure records is still open to some doubt (particularly where rapid transient peaks and oscillations are involved) it is imperative to use transducers which can be shown to reproduce faithfully the pressure changes during an experiment.
- A comparison of the results from different transducers under identical conditions and the extraneous factors likely to affect their performance (thermal radiation, conducted heat transfer, structure, vibration) is therefore needed to clarify the situation.
- (vii) The existence of high-frequency acoustic phenomena has been established and requires further study of cause and effect.
- (viii) The actual number of points at which pressures have been measured in large-scale experiments was insufficient to describe the overall explosion process in detail. In particular, the pressure developed outside the enclosure and the significance of strong rarefaction waves call for attention.
- (ix) Little detailed attention has been given to the properties of ignition sources, both in terms of location and more especially nature. The use of effectively multiple sources (such as electrical safety fuses) gives rise to much higher rates of pressure rise than a single source (point source). This behaviour needs further detailed investigation.
- (x) In some experiments where layers have been used, control over layering has not been demonstrated, because the horizontal and vertical gas distributions have not been measured extensively. Furthermore discrepancies in the accountable gas compared to the gas introduced into the explosion chamber were large in some instances. Much closer control is necessary in future experiments. The effect of layer stability on explosions also requires some investigation.
- (xi) Although the effect of turbulence is generally acknowledged as being a major factor in the development of gas explosions, vented or otherwise, no quantitative measurements have been attempted to assess the extent of this effect in venting experiments. Turbulence should be studied in future work.
- (xii) The phrase 'cascade effect' has come into prominence to describe the increase in pressure and rate of pressure rise in the progression of an explosion from one compartment to another. As the total effect will comprise the combined effects of turbulence and 'pressure-piling' or pre-compression of gas prior to ignition in the second compartment the phrase is a little misleading. However the effect warrants further investigation..

(xiii) One of the main points of interest in work on venting is the effect on the containing structure. Apart from gross observations on behaviour, more detailed measurements on the response of structures during the venting of explosions are necessary.

(xiv) The factors mentioned at the beginning of this article should serve as a useful guide to the kind and extent of measurements to be undertaken in future work.

6. FUTURE WORK

It is clear from this review that a research programme needs to be carried out in which the venting of gas explosions is examined systematically with particular reference to unresolved problems outlined above. To this end the Fire Research Station has initiated a programme of research in which firstly the production of reproducible layers of gas/air mixture has been examined followed by a systematic examination of the pressures generated inside and outside a single vented compartment of 28 m³ volume. It has of course been necessary to develop and prove the required instrumentation facilities before the commencement of systematic studies. After further work on the effect of different forms of pressure relief vent in the single chamber a second phase of research will commence using a multi-compartment explosion chamber with variable geometry. The main emphasis in this second phase will be to determine the effect of turbulence (generated by the movement of gas ahead of the flame from one compartment to another) on the pressures generated.

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Table 1. Data from experimental work on gas explosions (venting)

Ref. Nos	Scale and geometry (volume)	Gas	Configuration and method of containment	Venting	Parameters measured	Empirical relations	Turbulence	
							Existence	Measurement
Cubbage and Simmonds Ref.2,3	Cubical ovens (industrial) size range up to 14.1 m ³	Mainly town but also methane, carbon disulphide, diethyl ether, acetone, and acetylene	Cubical, mixture with air, main container	Sheet metal or plywood panels, weighted	Pressure, 'flame spread' (expansion of flame volume outside vessel)	a) $p_1 V^{\frac{1}{3}} = 1.18 Kw + 1.57$ b) $p_1 V^{\frac{1}{3}} = s_0 (0.3 Kw + 0.4)$ c) $p_2 = K$ <u>Units</u> $p_{1,2,3}$ psi V cu.ft s_0 ft/sec w lb/sq.ft	Yes (deliberately induced) in some experiments	No
Harris Ref.4,5	Near spherical, 1.7 m ³ (60 ft ³)	Pertane	Spherical, main container, mixture with air	Cellophane, 'Klingerit' gas-getting, metal discs range of sizes	Pressure, flame speed (average) calculated from vessel radius and time between ignition and time to P_{max}	None	Yes (induced by fan in some experiments)	Yes (indirect)
Potters Marston Phases I and II Ref.8	Bunker (see original for plan and elevation) 34.55 m ³ (1220 ft ³)	Natural, town	Mixture with air, layers, mixtures in polythene bags and Met balloons	Glass, chipboard, brick	Pressure, some idea of flame spread outside by photography		No	No
Potters Marston Phases I and II Ref.8	4 rooms as part of 3-storey building. Expts generally in 2 adjacent rooms with door between and external venting.	Natural, town	Layers, premixed - config. of room, some in Met balloons	Cladding, glass	Pressure	$P_2 = 0.590 P_1 + 1.141 P_1^2$ for experiments where door between 2 rooms open <u>Units</u> P_2, P_1 psi	Yes	No
Potters Marston Ref.11	Bunker, subdivided with devious path by gaps in internal dividing walls (not diametrical)	Natural, town	Layered mixture in roof	Polyethylene sheet	Pressure, arrival time of flame at bunker mouth	No	Yes	No
Swedish work Ref.7	Bunker, see original for details 199 m ³ volume (7000 ft ³)	Propane, acetylene	Various mixtures with air in balloons (met.) and also of whole bunker config.	Separate panels gave variable area over one long side	Pressure, approx. temp. Distance of vent ejection. Flame spread.	Pressure and flame speed	Yes	No
TNO Ref.10	2 rooms, with adjoining door, 2 m x 4 m, 3.5 m x 4 m. Both rooms have provision for explosion relief	Natural	Mixture in whole of room	Glass window held by simple catch and bolt	Pressure. Cine records	d) $p_1 = 3 + p_0$ $p_2 = 3 + 0.5 + \frac{0.04}{\psi^2}$ <u>Units</u> $p_0, 1, p_2$ kN/m ² ψ m ⁻¹	Possibly	Out of phase pressure peaks measured by separate transducers

Symbols

p_0 Pressure at which vent opens
 p_1 First maximum pressure
 p_2 Second maximum pressure

P_1 Maximum pressure in 1st room of 2 adjoining rooms
 P_2 Maximum pressure in 2nd room of 2 adjoining rooms

s_0 Fundamental burning velocity of gas mixture
 V Volume
 K Vent area coefficient

w weight per unit area of vent cover, in lb
 ψ Ratio of area of broken pane (m²) to volume of room in m³

