THE EXTERNAL EXPLOSION CHARACTERISTICS OF VENTED DUST EXPLOSIONS.

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SYNOPSIS: The quantification of the external effects of blast and fire generated by vented dust explosions is important for the siting of explosion reliefs and the safety of personnel. In this study the external effects of vented explosions of Kellingley coal dust and maize starch in 20 m^3 and 40 m^3 chambers have been investigated. The characteristics of the external explosions are considered and the results of this study are compared with predictions of external blast and flame length based on empirical equations derived from previous experimental work [5].

KEYWORDS: Explosions, vented, external effects, coal dust, maize starch

INTRODUCTION

Explosion relief venting is a commonly used form of explosion protection, employed in a wide range of industries, to protect vessels and production units from the overpressures generated by dust or gas explosions. Considerable research has been undertaken on the control of the internal explosion pressure by relief venting and this has resulted in the production of a number of guidance documents for the use and sizing of explosion relief vents [1,2,3].

The development of a dust explosion in a vented vessel can be described by a sequence of four events:

1. the generation of a flammable dust/air mixture inside the vessel,
2. ignition and propagation of the explosion inside the closed vessel (primary explosion),
3. the bursting of the relief vent and subsequent creation of a combustible cloud of dust outside the vessel,
4. the ignition and explosion of the combustible mixture outside of the vessel as the flame emerges through the relief vent (secondary explosion).

In this description the secondary explosion can arise from two routes:

A. the ignition of material which has accumulated outside the vented vessel prior to the explosion and which is dispersed and ignited as a result of the event, or

B. through the ignition of unburnt material ejected from the vessel during the course of the explosion.

Historically, guidance on venting dust explosions has recognised the importance of route A, and considered its prevention through good house-keeping, eg by the prevention of unnecessary accumulations of dust through regular cleaning and good maintenance practices. Only comparatively recently has some attention been paid to route B, and the consequences of the external blast and fire effects that may be generated as an inherent function of the venting process.

Van Wingerden, reviewing the published experimental data [4] from vented explosions, suggested that the most appropriate available methods for estimating the external effects of vented dust explosions was that of Schumann and Wirkner-Bott [5]. They developed four empirical relationships which allow the maximum external pressure, maximum flame length, location of maximum external pressure and pressure at given distances from the maximum external explosion to be calculated. Equation (1) determines the maximum external overpressure,

$$P_{s,\max} = (0.2 \, . \, A_v^{0.1} \, . \, V^{0.18}) . \, P_{red,\max} \tag{1}$$

where, $P_{s,max}$ = Maximum external explosion overpressure, bar g
A_v = Vent area, m^2
V = Vessel volume, m^3
$P_{red,max}$ = Maximum overpressure within the test chamber.

Equation (2) determines the maximum flame length in metres, $L_{f,max}$, emitted from the vent by the explosion:

$$L_{f,\max} = 8 \, . \, V^{1/3} \tag{2}$$

where, V is the vessel volume, m^3.

Equation (3) determines the distance, R_s, from the vent at which the maximum external overpressure occurs :

$$R_s = 0.25 \, . \, L_{f,\max} \tag{3}$$

Equation (4) calculates the pressure, P_r , at any distance, r, from the vent, where r is greater than R_s,

$$P_{r,\max} = \left(\frac{R_s}{r}\right)^{1.5} . \, P_{s,\max} \tag{4}$$

These empirical relationships are presented with the following stringent constraints which limit their application :

- The method should only be applied to St.1 dusts
- Vessel $P_{red} \leq 1$ bar g and,
- $P_{stat} \leq 0.1$ bar g.
- Volume ≤ 10000 m^3

This paper describes part of an experimental study in which the characteristics of vented dust explosions, involving maize starch and Kellingley coal dust, have been compared with values predicted using Equations (1) to (4) above. The results of these experiments are discussed and some modifications to the equations suggested. The experimental study has also considered the effects on the external explosion characteristics of target structures as well as the consequences of the explosion on the structures themselves, this work is discussed in a later paper [6].

EXPERIMENTAL WORK

Test Arrangement and Instrumentation

Figure 1 shows the steel chamber used for the experimental work. It comprised two chambers, each with a volume of 20 m^3, which could be combined into a single chamber of 40 m^3 volume by the removal of a central dividing wall. Explosion relief vents were fitted into the upper half of the front wall of each chamber (the 40 m^3 chamber had two vents of identical dimensions to the 20 m^3 chamber). The explosible powders were injected directly into the test chamber from pressurised containers through rapid acting valves and `pepper pot' dispersion nozzles positioned in the roof of the chamber. The resultant dust cloud was ignited by two 5000 J chemical igniters positioned at either the centre or rear of the chamber.

The ignition delay time and dust dispersion pressure were used to control the initial level of turbulence (a critical factor in the development of the explosion) in the chamber. These two parameters were adjusted so that the internal reduced explosion pressure, P_{red}, obtained under the experimental conditions and central ignition, were in accordance with the VDI 3673 (1984) [1] nomographic approach for the sizing of explosion reliefs.

Pressure measurements were made both inside and outside the explosion chamber. The internal transducers were located in the centre of the roof, one side wall and in the front wall, below the relief vent. The external transducers were positioned on the centre line of the 40 m^3 chamber at distances of 0.5 m, 2.5 m, 3.75 m, 5.0 m, 7.5 m, 10.0 m, 15.0 m and 20.0 m from the relief openings, Figure 2.

Standard speed video (25 frames per second) together with high speed video (1000 frames per second) records were made of each test to assist in the analysis and interpretation of the explosion characteristics. An overhead video record (25 frames per second) was also taken to measure the flame emitted from the test chamber.

Explosible powders

The materials used to generate the explosible mixtures were :

- Maize starch, supplied by Tunnel Refineries, Greenwich, London, and
- Kellingley, single seam coal, supplied by Standard Pulverised Fuels Ltd, Staffordshire.

A standard 20-litre sphere test [7] was carried out on each powder to determine the explosion characteristics of maximum explosion overpressure, P_{max}, and maximum rate of pressure rise, K_{st}. The 20-litre sphere test was repeated for each successive batch of powder to confirm that there was no major deviation in the materials K_{st} value. These results were then used, in conjunction with the initial turbulence control measures described previously, to establish the experimental conditions required for the large-scale tests.

Experimental conditions

The experimental conditions used are summarised below:

- Chamber Volume - 20 m^3 or 40 m^3
- Dust Concentration - 0.25 kg/m^3 - 1.25 kg/m^3 (maize starch)
  - 0.125 kg/m^3 - 1.25 kg/m^3 (coal)
- Ignition Location - Centre or rear of chamber, 1.2 m from the floor.
- Vent Area - 1.0 m^2 or 1.44 m^2 (20 m^3 chamber)
  - 2.0 m^2 or 2.88 m^2 (40 m^3 chamber)
- Vent Opening Pressure 0.05 bar g, 0.1 bar g, 0.2 bar g (nominal values)
- Ignition delay - 500 ms - 950 ms
- Dispersion pressure - 10 bar g or 20 bar g

RESULTS

Material Classification

The physical properties and explosion characteristics determined in a 20-litre sphere for the maize starch and Kellingley coal used in this study are summarised in Table 1.

Table 1. Explosion characteristics of powders.

Powder	Median Particle Size (micron)	Moisture content (% w/w)	Maximum rate of Pressure Rise, K_{st} (bar m/s)	Maximum Explosion Overpressure, P_{max} (bar g)
Coal	32.2	6.4	155	8.2
Maize Starch	25.6	10.8	139	9.5

External Explosion Characteristics

The experimental results from this study identified two types of external explosion behaviour:

- *Type 1* : the largest external explosions were generated when the relief vent area was large and/or the relief vent opening pressure low, and when the ignition source was remote from the vent. These explosions produced large clouds of unburnt material outside the vent which were subsequently ignited by the emerging flame front as shown in Photograph 1; ignition of the dust cloud occurs in frame 8.

- *Type 2* : this type of explosion was distinguished by the formation of a strong jet of flame emerging from the vent with little preceding unburnt material to form a fireball as shown in Photograph 2; ignition of the dust cloud occurs in frame 5. These external explosions were observed particularly when the vent area was reduced and the initial turbulence increased; these conditions tended to promote rapid burning inside the chamber.

Figure 3 is a typical pressure time history taken from a Type 1 explosion showing the internal explosion pressure and the corresponding maximum external explosion overpressure. Figure 4 gives the internal and corresponding external pressure time histories form a Type 2 explosion. Although the magnitude of the internal pressure is higher for the Type 2 explosion, in the example shown, the external pressure was less than that for the Type 1 explosion. Both Figures 3 and 4 show a negative phase in the external explosion pressure time history. This negative phase tended to be more marked in the Type 1 explosions.

Figure 5 shows for a Type 1 and a Type 2 external explosion the decay in pressure with distance. To take account of the differences in the magnitude of the pressure for both events the plots have been normalised relative to the external pressure ($P_{s,r}/P_{s,max}$) and the distance from the vent at which the maximum pressure was measured. ($r/R_{Ps,max}$). The Type 1 explosion follows closely the acoustic decay curve, while for the Type 2 explosion the decay is much less than acoustic.

Explosion Pressures

Figures 6 to 9 show plots of the maximum external pressure versus the maximum internal pressure for all the experiments undertaken, and under all experimental conditions. To identify the important parameters the results are plotted so as to highlight the influence of particular experimental variables.

The influence of powder type, is shown in Figure 6. The results show that for a given internal pressure slightly higher external pressures were found using coal, although the effect is not particularly significant.

The influence of changing the ignition position from the centre to the rear of the explosion chamber is presented in Figure 7. This shows that stronger external explosions were observed when ignition was remote from the relief vent, ie at the rear of the chamber.

The influence of vent coefficient, K_v, on the P_{red} is shown in given in Figure 8, where, K_v has been defined as:

$$K_v = \frac{V^{2/3}}{A_v} \qquad (5)$$

where A_v = the vent area
V = the volume

Figure 8 shows that generally the smaller the vent area (larger K_v) the higher the internal pressure, but the lower the external pressure.

The effect of the vent operating pressure on the internal and external explosion is shown in Figure 9. There is no clear trend, but it was noted that in some experiments with low vent failure pressure a high external pressure was obtained for relatively low values of internal pressure.

Figures 10 and 11 compare the experimental results with the value of external pressure calculated from Equations (1) - (4), using the experimentally observed P_{red} in each case. Comparisons are presented for the maximum external pressure, and the external pressure at distances of 10 m, 15 m, and 20 m from the chamber. Figure 10 shows the calculation of pressure at given distances of 10 m, 15 m and 20 m from the chamber using Equation (4), ie a rate of pressure decay the exponent equal to 1.5. Figure 11 are the same graphs re-plotted but using a value for the exponent in Equation (4) of 1, equivalent to an acoustic decay in pressure with distance.

Figure 10 shows that the empirical equation for the estimation of maximum external pressure (plot a) is reasonable with the majority of data below or close to the line of 100% correlation. However, the external pressure at a given distance from the chamber (plots b, c and d) is under predicted particularly as the distance from the vent increases.

In Figure 11, assuming an acoustic pressure decay with distance in Equation (4), the agreement between the calculated and experimental data is significantly improved, particularly as the distance from the relief vent increases.

Flame Length

Table 2, summarises the data for the measurement of flame length emitted by the vented dust explosions. The table presents the maximum measured flame length and the average value for all experiments where the dust concentration was at the optimum or higher concentration. It also shows the predicted flame length calculated using Equation (2). Note, the 40 m^3 chamber was always fitted with two relief vents; the horizontal distance between the centres of the vent openings is given in Table 2 as the vent separation.

Table 2. Comparison of flame lengths for the 20 m^3 and 40 m^3 chamber.

Vessel Volume (m^3)	Vent Separation (m)	Predicted Flame Length (m)	Experimental Flame Length (m)	
			Maximum	Average
20	Single Vent	22	>30	26
40	0.5 m	27	>30	25
	1.2 m		27	21
	2.4 m		21	21

The flame lengths predicted by Equation (2) for the 20 m^3 chamber, with a single vent opening, underestimate both the maximum and average values observed. For the 40 m^3 chamber the table shows that when the two vents were close together the flame length was close to or slightly exceed that expected from Equation (2). However, when the separation between the vents was increased the length of flame emitted decreased, The trend was consistent although only a few tests were carried out at the widest separation.

DISCUSSION

It is clear from this and previous studies that two consequential hazards can arise even from a correctly vented dust explosion, namely:

- the effects of pressure, which may cause injury to personnel and damage to neighbouring buildings and installation, and
- the effects of flames and hot particles, which may cause injury to nearby people and possibly fires as a result of the secondary ignition of flammable materials.

It is important that an estimate of the magnitude of these external effects be made so that appropriate safe discharge areas can be specified. Such calculations would also make a useful contribution in a hazard analysis, risk assessment or consequence analysis

The equations of Wirkner-Bott were a significant development in this area and from the comparison of the experimental data from this study with calculated pressures based on these Equations (1) - (4) it has been found that Equation (1), which determines the maximum external overpressure, provides a reasonable estimate of the external pressure of explosions which are vented into an open area.

$$P_{s,\max} = (0.2 \; . \; A_v^{0.1} . \; V^{0.18}). \; P_{red,\max} \qquad (1)$$

This comparison has been based on the experimentally observed values for the internal pressure, P_{red}. In practice, however, the value of P_{red} would normally have to be estimated; one means of doing this is through the K_{st} Nomographs which can be found in references 1, 2 and 3. Figure 12 shows an analysis of the experimental data using the P_{red} calculated from Nomographs for the experimental conditions.The analysis is presented as a plot the ratio of experimental and calculated values of $P_{s,max}$ against the ratio of experimental and calculated values of P_{red}. The majority of data lies in quadrants 3 and 4 of the plot, (ie the maximum external pressure is lower than the calculated value even when the experimental P_{red} is higher than the calculated value). Importantly, little data lies in the first quadrant which would indicated that higher than expected external pressures were obtained from lower than expected values of $P_{red,}$ and relatively little data is found in Quadrant 2. This implies that an estimate of external pressure based on a value of P_{red} obtained using the K_{st} and the Nomographs would be satisfactory for the majority of cases .

Equation (2), which determines the maximum emitted flame length in metres, $L_{f,max}$, underestimated the observed maximum flame length emitted from the vented explosion. This difference may arise because in many of the Schumann and Wirkner-Bott experiments venting was in most cases vertically upwards. In this study venting was always horizontal and ground effects may be acting to extend the distance travelled by the flame. To encompass the results of this study Equation (2) would need to have the following form:

$$L_{f,\max} = 10 \;.\; V^{1/3} \qquad (2a)$$

While Equation (2a) is appropriate for the single vent conditions it tends to overestimate the maximum flame length from multiple vents with large separation distances. However the separation of the vents increased the lateral flame spread and this should not be ignored when assessing vent separation as a potential means of reducing the hazard associated with the length of flame emissions. The extent to which vent separation might be used to reduce potential flame lengths requires further investigation.

Equation (3) determines the distance, R_s, from the vent at which the maximum external overpressure occurs. This equation uses the value of the flame length calculated in Equation (2a), therefore, to maintain the continuity of the original equations, Equation (3) must to be modified to take the following form:

$$R_s = 0.2 \;.\; L_{f,\max} \qquad (3a)$$

In estimating the decay in pressure with distance the Wirkner-Bott equations indicate a stronger than acoustic decay in the pressure; this is contrary to the results of this study. The decay in pressure in this work was found to be acoustic (for a Type 1 explosion) or less (for a Type 2 explosion). In this respect, the Type 1 explosion represents one extreme, where at the time of ignition the external dust cloud has little forward momentum and explodes as a large fire ball which moves away from the vent at relatively low velocity. For the Type 2 explosions, the external dust cloud itself is either moving rapidly away from the vent or is ignited by a strong flame jet. Thus as the pressure wave is generated it is moving rapidly away from the vent, and the decay is therefore less than acoustic.

Despite the above, the results for both Type 1 and Type 2 explosions are enveloped by assuming an acoustic decay in pressure with distance. Thus, Equation (4), which calculates the pressure, P_r, at any distance, r, from the vent, where r is greater than R_s, has been modified to:

$$P_{r,\max} = \left(\frac{R_s}{r}\right) . \; P_{s,\max} \qquad (4a)$$

CONCLUSIONS

- A series of simple empirical equations can be used to estimate the external effects of dust explosions vented into an open area,
- These empirical equations have been derived from equations for predicting external effect from vented dust explosions of Schumann and Wirkner-Bott but which, in their original form, are not wholly supported by the results of this study.
- The original equations provide a reasonable estimate of the maximum external pressure, based on a measured reduced internal pressure P_{red} or on a value of P_{red} estimated from the VDI Kst Nomographs [1].

- The rate of external pressure decay with distance did not correspond well to the measured values. An acoustic decay in pressure with distance was found to more appropriate to the experimental data.
- The original equation for the calculation of maximum flame length from a single vent appears to under estimate the maximum flame lengths observed in this study. Flame length of up to approximately 10 times the cube root of the volume of the chamber were observed.
- The use of multiple explosion relief vents may reduce the flame lengths from vented explosions although the, potential increase in the, lateral spread of flame should also be considered.

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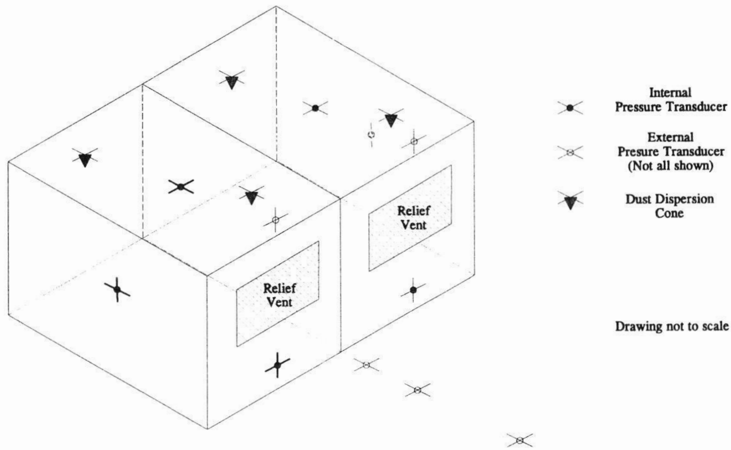


Figure 1. Schematic of Explosion Chamber

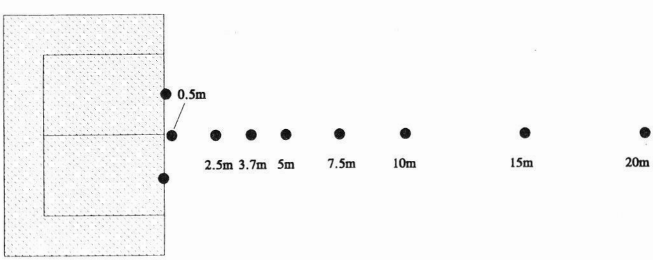


Figure 2. External pressure transducer locations (plan view)

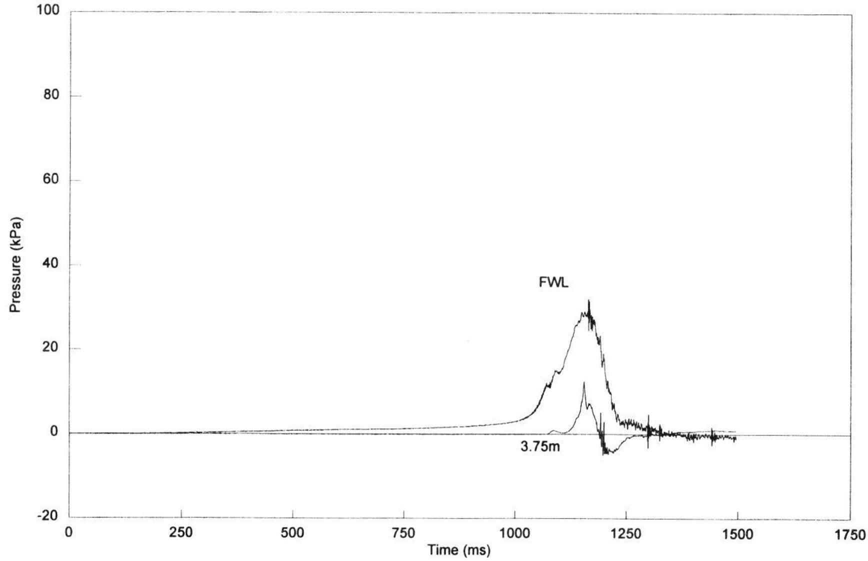


Figure 3. Test 137 - internal and external pressure/time histories
Type 1 external explosion

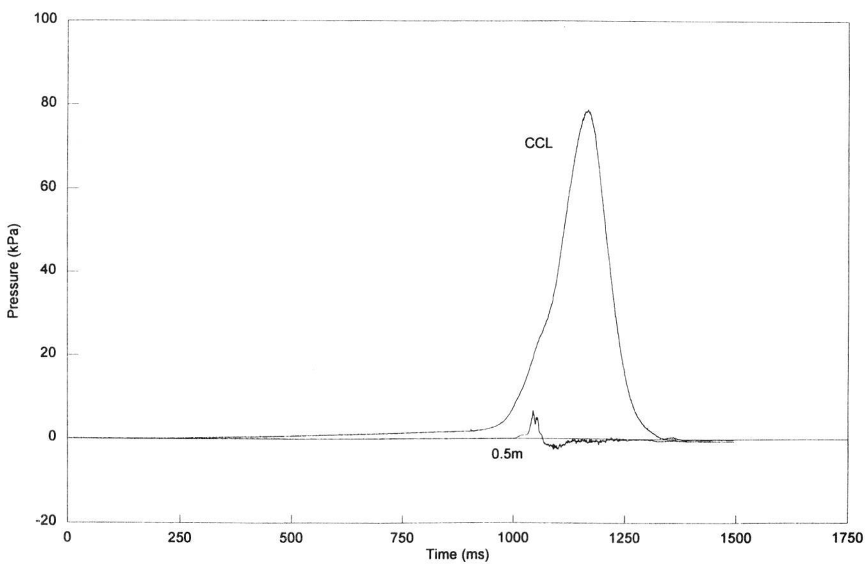


Figure 4. Test 103 - internal and external pressure/time histories
Type 2 external explosion

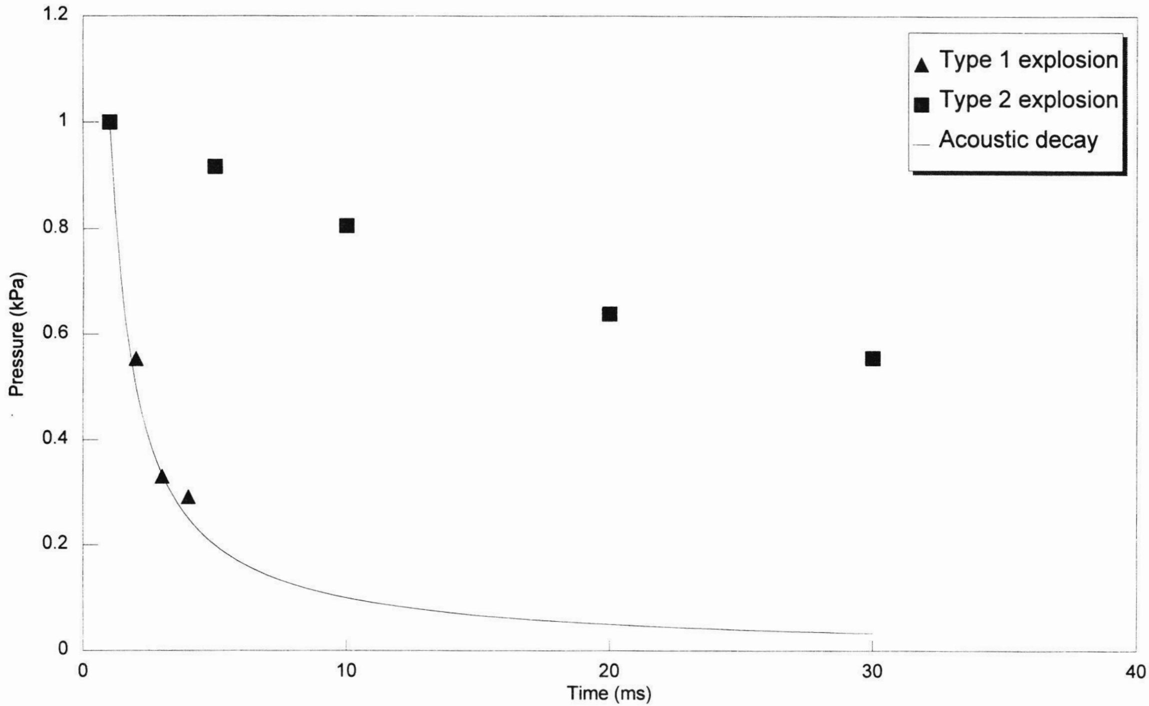


Figure 5. Normalised maximum external pressure vs. normalised distance for the two types of external explosion

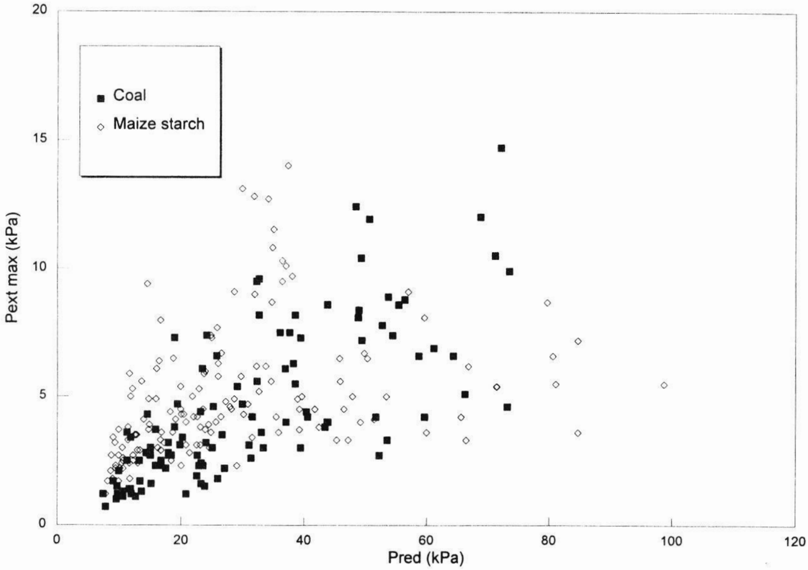


Figure 6. Pext max vs. Pred for coal and maize starch

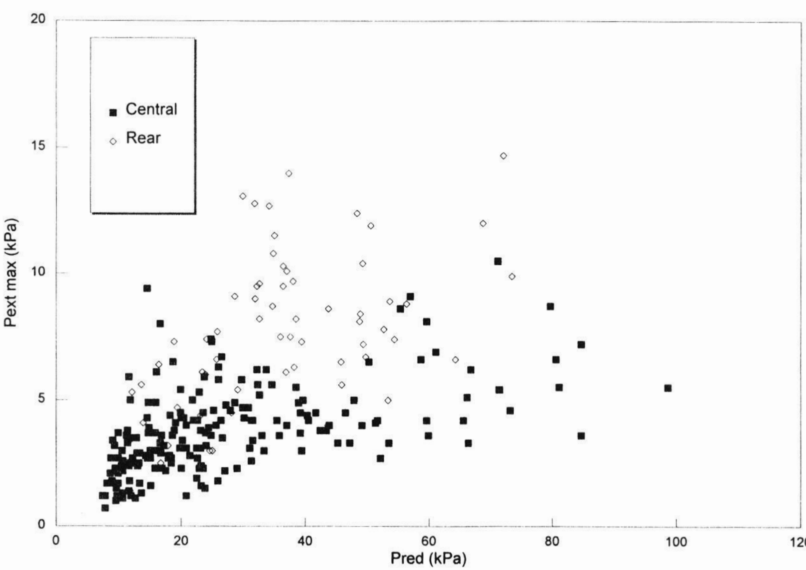


Figure 7. Pext max vs. Pred for central and rear ignition

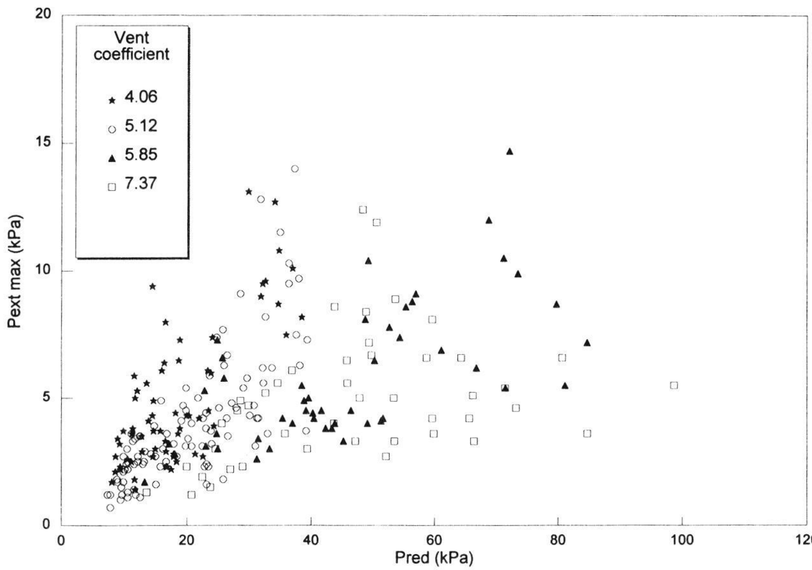


Figure 8. Pext max vs. Pred for all vent coefficients

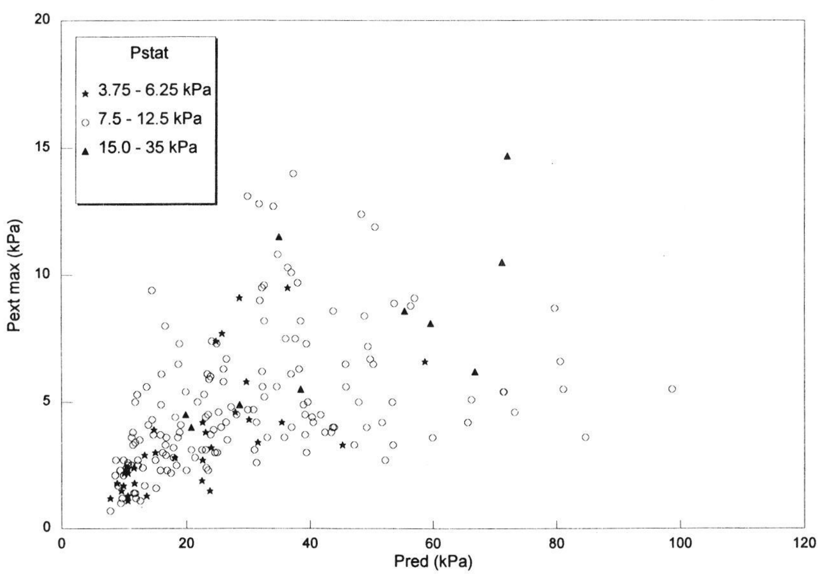


Figure 9. Pext max vs. Pred for various Pstat ranges

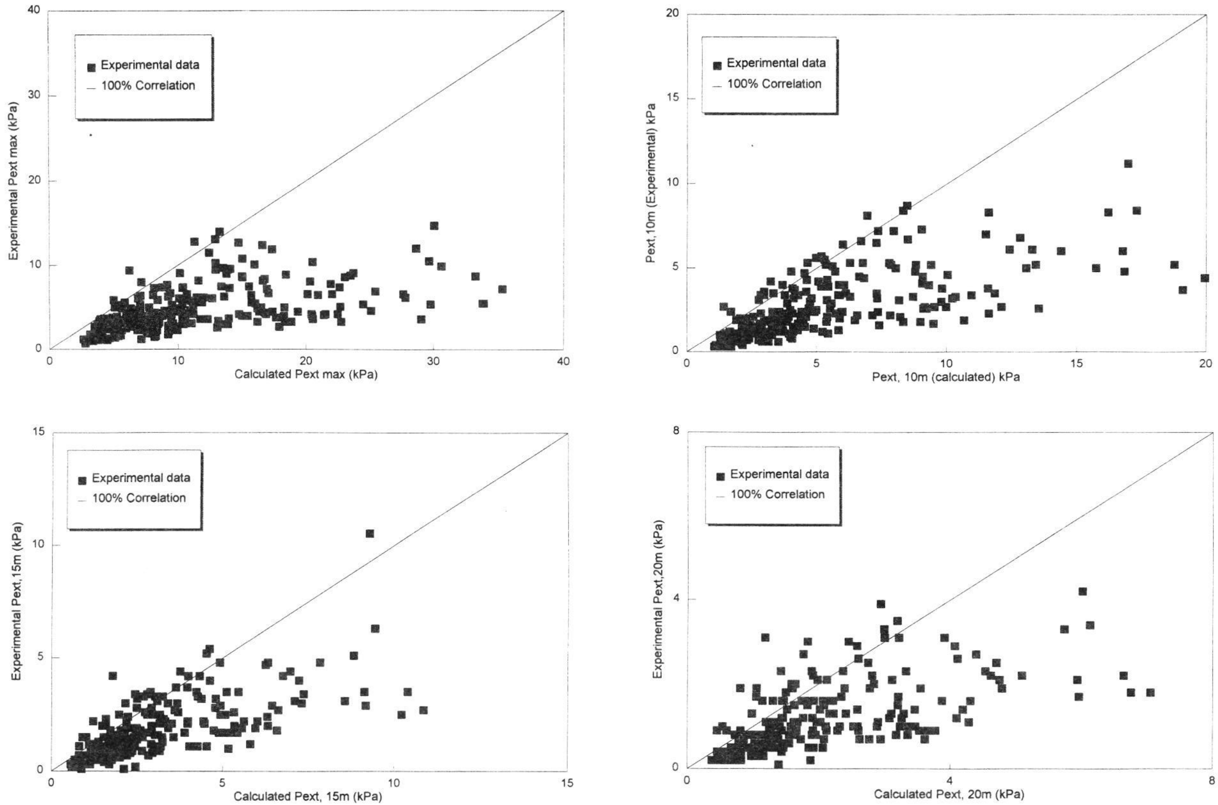


Figure 10. Experimental data vs. theoretical data predicted using a decay rate exponent of 1.5

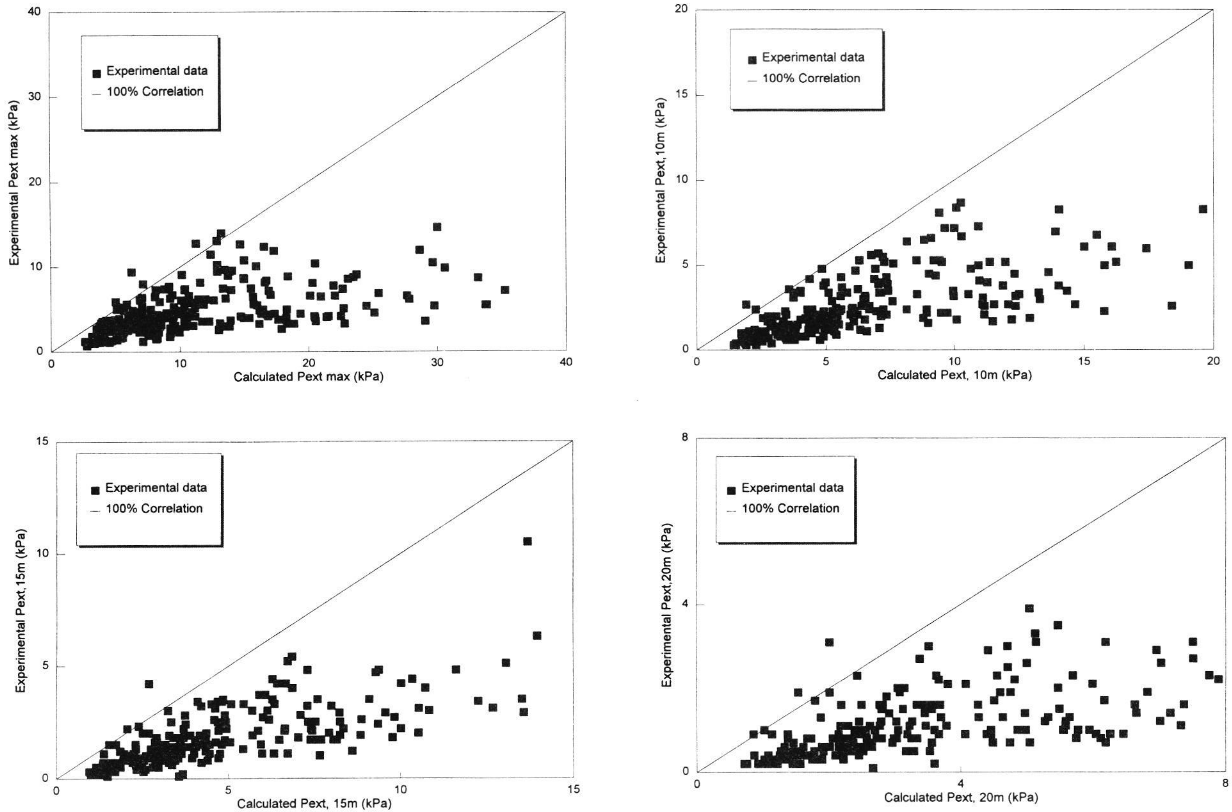


Figure 11. Experimental data vs. theoretical data predicted using a decay rate exponent of 1.0 (acoustic)

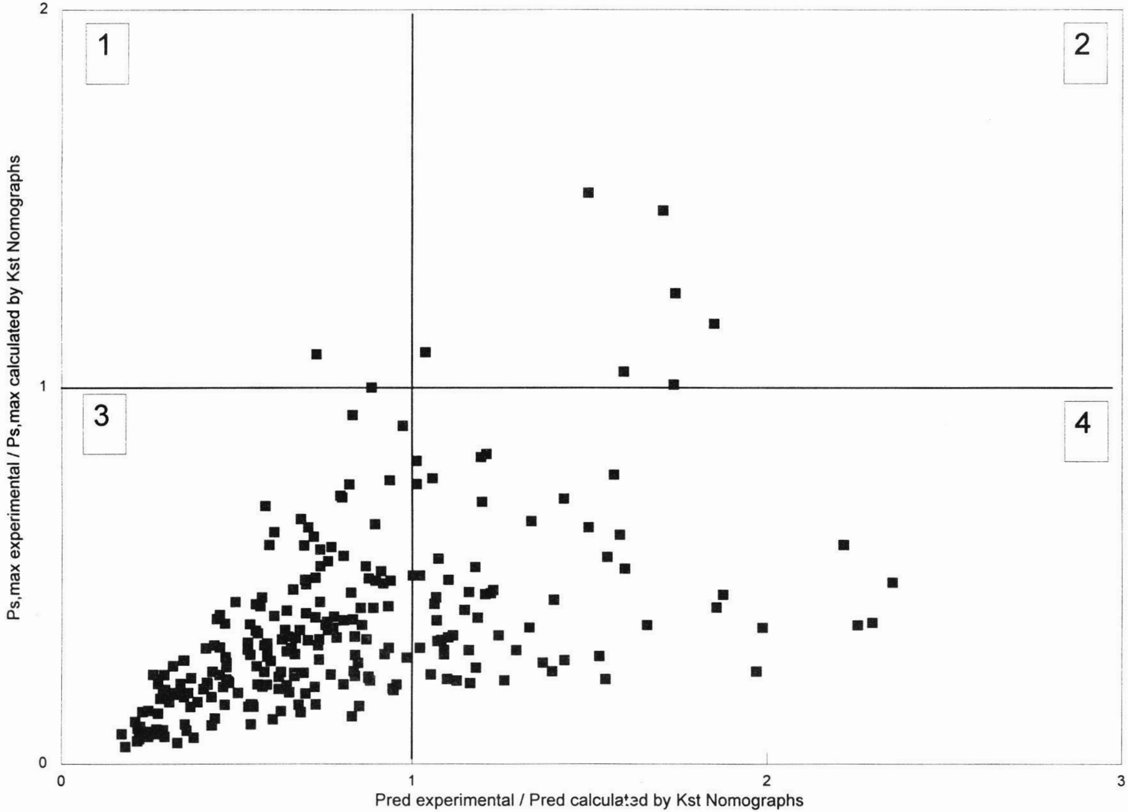
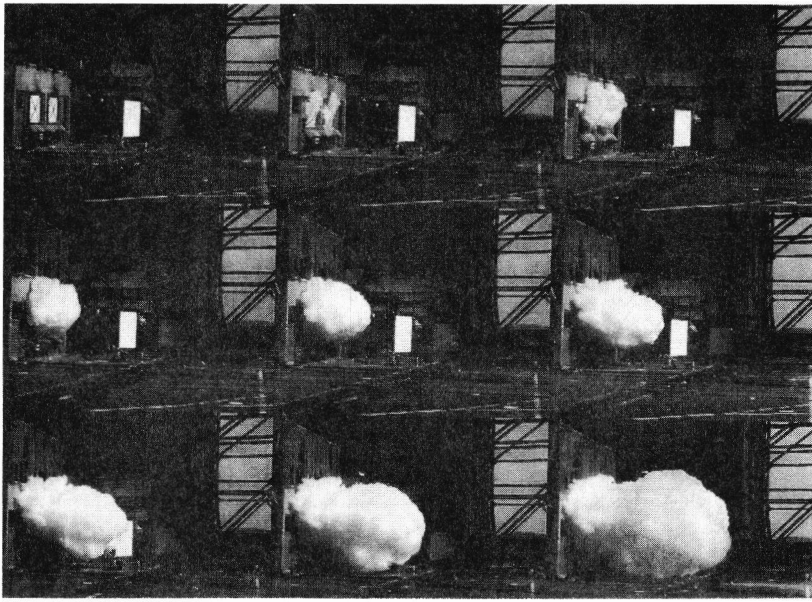
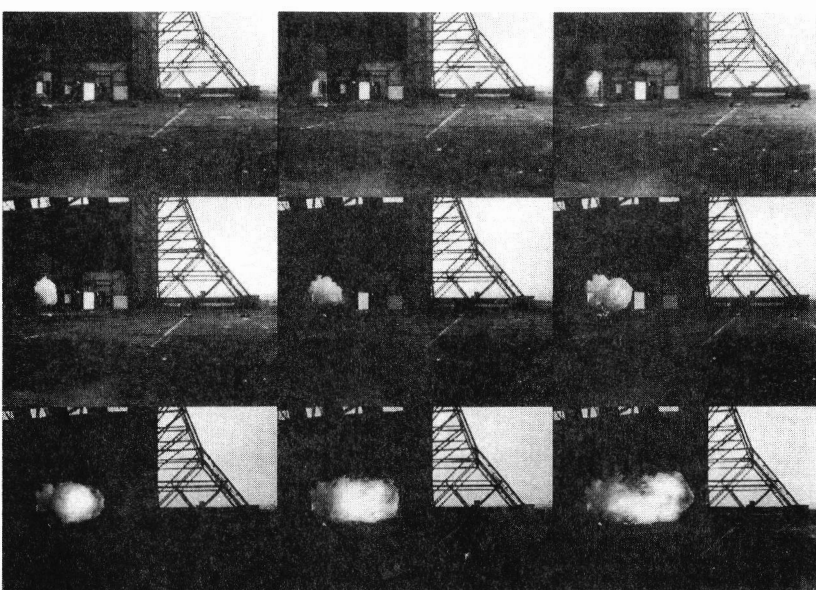


Figure 12. Ratio of experimental to calculated Pred and Ps,max - Kst Nomographs



Photograph 1. Type 1 Explosion (ignition of dust cloud in frame 8)



Photograph 2. Type 2 Explosion (ignition of dust cloud in frame 5)