Fire Research Note No. 830

DUST EXPLOSION VENTING - A REASSESSMENT OF THE DATA

by

K. N. PALMER

August 1970

FIRE RESEARCH STATION

Fire Research Station,
Borehamwood,
Herts.
Tel. 01-953-6177

F.R. Note No.830
August 1970

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SUMMARY

The published data on the pressures developed in vented dust explosions has been reassessed in an attempt to bring it together and form a basis for discussion.

Nine basic assumptions are listed, the most important being that at some instant in a severe explosion the combustion could be taking place throughout the whole volume of the vessel. The assumptions have led to the derivation of equations relating the explosion pressure to the area of vent, the volume of vessel, and explosion parameters of the dusts. Calculated explosion pressures have been compared with the published data. Only unrestricted vents have been considered.

The severe conditions of explosion would be of most interest in practice, to the design engineer, but modified calculations could be made for less severe conditions.

The present ad hoc procedure for stipulating vent area has been compared with calculation, and appeared to be reasonable.

The gaps in the published data were listed, and attention drawn to those aspects where further information is particularly required.

KEY WORDS: Dust explosion, explosion venting

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

SYMBOLS

A	Area of relief vent
C	Discharge coefficient
$(dp/dt)_{av}$	Average rate of pressure rise in the closed standard explosion vessel
$(dp/dt)_{max}$	Maximum rate of pressure rise in the closed standard explosion vessel
g	Acceleration due to gravity
K	Constant
p	Maximum pressure in vented explosion
p_o	Atmospheric pressure
p_1	Pressure in closed standard explosion vessel when rate of pressure rise was a maximum
p_{max}	Maximum pressure in the closed standard explosion vessel
V	Volume of vessel
V_o	Volume of apparatus for which $(dp/dt)_{max}$ was measured
γ	Ratio of specific heats
ρ	Density of combustion products at pressure p
ρ_o	Density of combustion products at pressure p_o
ρ_c	Density of unburnt dust suspension at pressure p_o and of combustion products at pressure p_1

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INTRODUCTION

"The literature of dust explosion relief may be fairly described as chaotic. Efforts to distil any general relationships between relief area and maximum explosion pressure from the empirical data available are not particularly rewarding. The essential difficulty probably lies in producing and igniting fully dispersed dust clouds in vessels of various shapes and sizes, in order to get a range of data on any comparable footing"[1].

There is no consistent approach, combining experiment and theory, to relate the principal variables. The main requirement is to relate the maximum pressure in a vented explosion to the explosibility characteristics of the dust as measured in small scale tests, the area of vent, and the size and shape of the plant. The venting has often been characterised, on an empirical basis, in terms of the vent ratio, i.e. area of vent per unit volume of plant. The vent ratio has the dimensions of $(\text{length})^{-1}$ and when the maximum pressure is related to the vent ratio in the design of plant, there is doubt about the validity of applying empirical relationships to plant of different scale.

The venting of explosions in gases and vapours has been put on a reasonably systematic basis, both experimental and theoretical, and it has been suggested that the same treatment should be applied to dust explosions[1,2]. Correlation of the explosion parameters of dusts, vapours and gases, measured in the same apparatus, would enable this approach to be used. Final judgement of its validity must await a fuller understanding of the mechanism of propagation of the dust flames because, if this is different from that in vapours and gases, reliable prediction of venting requirements may not necessarily be obtained.

The absence of an agreed method for the calculation of venting requirements has important practical consequences, because venting is a relatively cheap method of obtaining protection of plant handling explosible dusts. As a result it is commonly used, and the degree of safety obtained cannot be adequately judged at present. The situation is steadily worsening because the scale of industrial processes involving dusts is increasing rapidly, but the amount of design information for safety precautions is not increasing correspondingly.

Extrapolations are therefore becoming greater, and causing increasing uncertainty in the effectiveness of the explosion protection measures applied. The situation can only be remedied by a better understanding of the principles involved, for example in dust explosion venting, coupled with confirmatory experiments on larger scale equipment than that customarily used.

This note is an attempt to reformulate the problems in the venting of dust explosions, and is put forward as a basis for discussion. It considers data published elsewhere and attempts to systematize some of the information. The assumptions which have been made are described in more detail below; equations have been derived based on these assumptions, and are compared with the published data.

OBSERVATIONS AND ASSUMPTIONS

In order that realistic assumptions shall be made it is useful to consider firstly some of the properties of dust explosions which have been reported, from various sources, following experiments. The principal observations included:

1. Dust flames were longer or thicker than gas flames. If the equipment containing the explosion was of sufficient size the dust flame thickness could be of the order of metres[3].

2. In explosions in closed compact vessels (i.e. all three dimensions of the same order) of volumes 190 l and 1900 l the duration of the explosion, using an unspecified plastics dust, was approximately proportional to the cube root of the vessel volume[4].

3. In sugar dust explosions in closed compact vessels, of volumes 1.2 l and 1000 l, the maximum rates of pressure rise were of the same order[5]. The ratios of maximum rates varied between 2.0 and 0.4, for the two vessels respectively, depending on particle diameter.

4. In vented dust explosions the maximum pressure increased with the size of the ignition source. The pressure could be particularly high if the dust had been ignited by a large external source projected into the suspension.

5. The maximum pressure in vented explosions also depended on the method of dispersion of the dust and on its concentration. By suitable adjustment of the variables, explosions could be graded from mild to strong[6].

Using these observations as a basis, certain tentative conclusions can be drawn regarding the mechanism of dust explosion venting. The thick flame implies that the dust particles became ignited relatively rapidly, and subsequently burned relatively slowly. Thus in a vented explosion in a compact vessel, initially completely filled with a dust suspension, the enclosure may be completely filled with flame when the pressure reaches a maximum. This would particularly be the case when the venting is generous, so that maximum explosion pressures are kept low as is required for many industrial applications, being assisted by the expansion due to the formation of combustion products with ignition remote from the vent. Because of the expansion, the majority of the dust initially in suspension in the enclosure may be ejected before it is completely burned, and would form a flame outside the vent. The emission of large volumes of flame from the vents during dust explosions is a common observation.

The relatively rapid ignition of dust throughout the enclosure, and its continued burning throughout the volume, would be assisted by turbulence of the suspension which is often generated during the dispersion of the dust. In experimental dust explosions in compact enclosures the dispersion of the dust is usually by some form of vigorous mechanical action, and this can be expected to lead to an intensely turbulent suspension. In such a suspension, the existence of pockets of unignited mixture would not be favoured, again leading to the conclusion that simultaneous burning of the suspension throughout the entire volume of the enclosure would be likely.

For enclosures with little or no venting, so that pressures are high, mass flow to the exterior would not be dominant. Flame speeds within the enclosure, assisted by expansion of the combustion products, would be lower than for well vented explosions but the distribution of flame due to the turbulence arising during the dispersion of the dust would still be present. For very small enclosures with a vigorous dispersion technique, such as the Hartmann apparatus for determination of maximum explosion pressure and rate of pressure rise, in a 1.2 l closed vessel[7], ignition throughout the volume is likely to be rapid. Hence the measurements of rate of pressure rise would correspond to combustion simultaneously throughout the volume. It is likely that these conditions would not apply in larger volumes, with a relatively small source of ignition and dust dispersion from the centre of the vessel, for example with the tests in the vessels of 190 and 1900 l volume[4]. Under such conditions dependence of the duration of the explosion on the vessel volume is reasonable as in (2) above.

In the sugar explosions in (3) above, the dust was dispersed vigorously from near the 1000 l vessel walls, with the source of ignition at the centre[5]. These conditions apparently gave rapid ignition throughout the volume.

When the size of the ignition source is increased, there will clearly be a tendency for the dust to be ignited throughout the volume of the enclosure quickly, even in large enclosures. Further, the introduction or generation of a large ignition source is likely to increase turbulence, which again favours the rapid ignition of the dust. As a first step, it has been assumed that an ignition source was large if its dimensions were of the same order as the enclosure containing the dust suspension. A typical example would be injection of a flame from explosion in an attached vessel. A small ignition source would be of dimensions of order(s) smaller than the enclosure, such as an electric spark or a wire coil. The ignition source was also taken as effectively large if the dust suspensions were intensely turbulent throughout its volume. This would be the case when the dust was dispersed by the action of detonators.

Where enclosures are not compact, as in ducting or galleries, some modifications of the above conclusions may be required. Even if the ducting were filled with a turbulent dust suspension, ignition from a single point is unlikely to propagate flame along the whole length of the ducting sufficiently rapidly for the assumption to be valid that combustion is taking place simultaneously throughout the volume. The assumption may be reasonable only if the ducting is relatively short, and the ignition source is large. In other cases the flame would take a relatively long time to propagate along the ducting, particularly if the length were markedly greater than the thickness of the flame. The rate of generation of combustion products would then be less than if the flame were present throughout the ducting simultaneously. A further complication is that in some reported experiments only part of the length of the ducting was filled with dust suspension at the commencement of the explosion. To obtain full understanding of the problem a detailed analysis would be necessary, and unfortunately there are relatively few experimental results with which to compare. As a first step two limiting cases have been taken. The first was that the dust suspension was ignited throughout the whole length of the ducting, and was burning at all points, and the estimated pressures would give an upper limit. The second case was that only the part length of ducting containing the dust suspension was involved, and that the combustion products were generated only from this volume of ducting throughout the explosion. This would give a lower limit to the explosion pressure, because in the explosion the dust suspension would be heated and occupy more than its original volume. The true pressure should thus lie between those calculated for these limits. As and when further information becomes available, both theoretical and experimental, it may be possible to make a more accurate estimate of the pressures to be expected. The above considerations have led to the following basic assumptions being used.

1. In small compact volumes, with vigorous dispersion, and in large compact volumes with vigorous dispersion and large ignition source, in vented explosions, combustion would take place throughout the whole of the volume either before or when the maximum pressure was obtained, depending upon the vent ratio.

2. The maximum rate of generation of combustion products, derived from the standard test apparatus for measurement of explosion pressures[7], would be generally applicable where combustion was taking place throughout the enclosure volume.

3. In explosions in large compact closed volumes, with small ignition source, combustion would take place in only part of the volume when the maximum pressure was obtained. The maximum rate of pressure rise would be inversely proportional to the cube root of the volume.

4. For elongated enclosures, such as ducting, under vented conditions, simultaneous combustion throughout the volume would generally not be obtained, the nearest approach being ignition in a short length by a large source.

5. Where only part of the length of the ducting was filled with dust suspension, modified calculations were necessary.

6. For all enclosures, where vents were large, so that explosion pressures were low, the maximum pressure was obtained when the rate of generation of combustion products reached a maximum.

7. Where vents were very small, so that explosion pressures were high, the maximum pressure may not have been obtained when the rate of generation of products reached a maximum.

8. The main effect of turbulence of the suspension was to promote ignition throughout the stirred volume. Once ignited, the burning rate of a unit volume was calculated from that measured in the standard pressure test apparatus.

9. The maximum burning rate of a dust suspension in the standard pressure test apparatus, per unit mass of dust, was independent of the pressure.

SELECTION OF AVAILABLE DATA

Some selection of the published data is inevitable. In general the aim has been to use information obtained from the most severe conditions of test for a given venting arrangement, as any relationships thus derived should cover the conditions of interest in practice. In no case has information been rejected solely on the basis that the observed pressures were not in agreement with others reported elsewhere. Where a range of experimental conditions has been reported usually only the most severe has been considered. In some cases results have been used although they were not obtained under the most severe conditions that could have been employed in the experiments, providing that data for the severe case was not available, and special notes to this effect are provided.

Apart from these exceptions, the data used was obtained from experiments in which the following criteria could be applied.

1. The ignition source selected was the most severe, where choice existed. Ignition by a large flame was preferred to that by small flame, hot wire coil, or electric spark.

2. The ignition source was remote from the vent. This would encourage the rapid movement of flame throughout the enclosure, and strengthen the assumption that in compact enclosures the flame was present throughout the whole volume.

3. The dust was uniformly distributed throughout the volume, preferably assisted by intense turbulence. In elongated enclosures, such as ducting, where the suspension was initially present in only part of the volume, account was taken in the calculations.

4. The dust concentration was stoichiometric, or richer, to avoid using pressures obtained in explosions of reduced severity due to lack of fuel.

5. All vents were open, and not obstructed by covers, or by any form of external restriction.

6. For explosions in ducting, only straight lengths were considered, with venting at the end.

THEORETICAL

CRITICAL PRESSURE RATIO

In the venting of explosions two flow regimes must be considered. The relationship between the mass rate of gas discharge through a vent and the pressure difference across the vent changes when the ratio of absolute pressure downstream to that upstream of the vent reaches the critical value. For practical purposes the venting of dust explosions the downstream pressure may be taken as atmospheric and for high explosion pressures (low values of the pressure ratio) the linear velocity of gas through the vent is sonic. For low explosion pressures (the pressure ratio being above the critical) the gas velocity is subsonic and depends on the explosion pressure.

The critical pressure ratio[8] is given by $\left(\frac{2}{\gamma + 1}\right)^{\gamma/\gamma-1}$, where γ is the ratio of specific heats. A value of 1.27 has been taken for γ, assuming the gas discharged through the vent is diatomic and at 2300°K. This temperature has been calculated for a dust giving a maximum explosion pressure (gauge) of 100 lbf/in^2 (690 kN/m^2) in a closed vessel. The critical pressure ratio was calculated as 0.55. If the pressure downstream of the vent is atmospheric, the critical value upstream would be 12 lbf/in^2 (83 kN/m^2) gauge.

Thus in considering dust explosions vented to atmosphere, different relationships are obtained between vent area and maximum explosion pressure for pressures greater or less than 12 lbf/in^2 (gauge).

DERIVATION OF EQUATIONS

The conditions considered were for the maximum explosion pressure (p) developed by a dust explosion in a vessel of volume V, having a relief vent area A. The products of combustion discharged through the vent were of density ρ_o at atmospheric pressure p_o. Because the combustion products were at high temperature the dust is likely to have vaporized, and the products were taken to be in the gas phase.

Unless stated otherwise, all pressures were absolute.

Maximum explosion pressures below critical (12 lbf/in^2, 83 kN/m^2) gauge

It is assumed that the maximum explosion pressure would be generated when the rate of formation of combustion products within the vessel reached a maximum.

Mass rate of flow of combustion products through vent[8], assuming isothermal conditions, was

$$CA\ (2\ p_o \rho_o \ln p/p_o)^{\frac{1}{2}}$$

where C was a discharge coefficient.

The mass rate of generation of combustion products is not measured directly in dust explosions, but an estimate of the maximum mass rate may be obtained as follows. In the measurement of maximum explosion pressures, by standardized techniques in a closed explosion vessel[7], a value is found for the maximum rate of pressure rise $(\frac{dp}{dt})_{max}$ which occurs at an intermediate stage in the explosion. If the explosion pressure is p_1 at the instant the rate of rise is a maximum, then the volume rate of generation of combustion products per unit volume of reactants would be $^1/p_1\ (\frac{dp}{dt})_{max}$. That is, each volume of dust suspension would generate, in unit time, $^1/p_1\ (\frac{dp}{dt})_{max}$ volumes of products, measured at the same pressure. The maximum volume rate of generation of products could develop at a pressure slightly below, but not above, that at which the maximum rate of pressure rise occurs (p_1). The error involved is not likely to be serious because $\frac{dp}{dt}$ is usually near its maximum for a narrow range of pressure, and any error would be further reduced because p_1 is measured on an absolute basis.

Considering now an explosion in a vented vessel it is assumed, see 9 above, that the maximum volume rate of generation of products per unit volume of reactants would be unaltered, provided reactants and products were measured at the same pressure. Alternatively, this assumption may be expressed as the maximum rate of reaction, per unit mass of reactants, being independent of the pressure. However, the combustion products discharged through the vent enter an atmosphere at constant pressure, p_o, and their specific heat will be greater than in the closed explosion vessel[7] by the factor γ. In a vented vessel each volume of dust suspension would generate, in unit time, $\frac{1}{\gamma p_1}\ (\frac{dp}{dt})_{max}$ volumes of products having density ρ at pressure p.

The maximum mass rate of generation of products in unit volume of a vented vessel would be

$$\rho/\gamma p_1\ (\frac{dp}{dt})_{max} \quad \text{or} \quad p/p_o\ \rho_o/\gamma p_1\ (\frac{dp}{dt})_{max}$$

The maximum mass rate of generation in a vessel of volume V would be

$$^{p}/_{p_o} \frac{\rho_o V}{\gamma p_1} (\frac{dp}{dt})_{max}$$

This mass rate of generation would apply to the severe conditions of explosion considered in assumptions 1 and 2 above. For the less severe cases, as in assumption 3, the maximum rate of pressure rise would be reduced by a factor inversely proportional to the cube root of the vessel volume. Alternatively, if values of rate of pressure rise are available from direct determinations in a closed vessel of the same volume as that to be vented, these values can be used directly. The severe conditions are most likely to be of industrial importance and are considered here. The less severe cases are considered later.

Then at maximum explosion pressure

$$^{p}/_{p_o} \frac{\rho_o V}{\gamma p_1} (\frac{dp}{dt})_{max} = CA\ (2\ p_o \rho_o \ln {}^{p}/_{p_o})^{\frac{1}{2}}$$

$$(^{p_o}/_{p})^2 \ln {}^{p}/_{p_o} = \frac{\rho_o}{2\ C^2 \gamma^2\ p_o} (\frac{V}{A} \frac{1}{p_1} (\frac{dp}{dt})_{max})^2$$

ρ_o/ρ_c = $^{p_o}/_{p_1}$ approximately, where ρ_c is density explosion products at pressure p_1 and ρ_o is their density at p_o.

$$(^{p_o}/_{p})^2 \ln {}^{p}/_{p_o} = \frac{\rho_c}{2\ C^2 \gamma^2} (\frac{V}{A} \frac{1}{p_1{}^{3/2}} (\frac{dp}{dt})_{max})^2 \quad \text{.........} (1)$$

For situations of most practical interest the maximum explosion pressure (gauge) is low, so that $(p-p_o)$ is small compared with p_o, and as pressures are absolute $^{p}/_{p_o}$ is approximately unity. Equation (1) can be approximated to

$$(p-p_o) = \frac{\rho_c p_o}{2\ C^2 \gamma^2} (\frac{V}{A} \frac{1}{p_1{}^{3/2}} (\frac{dp}{dt})_{max})^2 \quad \text{.........} (2)$$

As p_o is atmospheric pressure, $(p-p_o)$ would be the maximum explosion pressure (gauge) obtained in a vented dust explosion.

The explosion pressure at the instant of maximum rate of rise, p_1, is not measured in the standard test[7] and neither are values available from the literature. Direct measurements can, however, be made easily. An analysis of the results on 23 dusts tested recently at JFRO has shown that there was an approximate proportionality between p_1 and p_{max}, the maximum explosion pressure (absolute) in a closed vessel (see Appendix). The proportionality constant was 0.57, with a standard deviation of 0.12. Thus approximately

$$p_1 = 0.6 p_{max}$$

Equations (1) and (2) then respectively approximate to

$$(p_o/p)^2 \ln p/p_o = \frac{2.3\rho_c}{c^2\gamma^2}\left(\frac{V}{A}\frac{1}{p_{max}^{3/2}}\left(\frac{dp}{dt}\right)_{max}\right)^2 \quad \ldots\ldots\ldots (3)$$

$$(p-p_o) = \frac{2.3\rho_c p_o}{c^2\gamma^2}\left(\frac{V}{A}\frac{1}{p_{max}^{3/2}}\left(\frac{dp}{dt}\right)_{max}\right)^2 \quad \ldots\ldots\ldots (4)$$

For the less severe explosions, where the ignition source was small compared with the vessel volume, the values of $\left(\frac{dp}{dt}\right)_{max}$ in equations (3) and (4) should be multiplied by a factor $\left(\frac{V_o}{V}\right)^{\frac{1}{3}}$, where V_o is the volume of the apparatus from which $\left(\frac{dp}{dt}\right)_{max}$ was obtained.

<u>Maximum explosion pressures above critical (12 lbf/in^2, 83 kN/m^2) gauge</u>

Mass rate of flow of combustion products through vent[8], assuming non-isothermal conditions, was

$$CA\left(\gamma p\rho\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}\right)^{\frac{1}{2}}$$

Now $\rho = \rho_o\,p/p_o$ hence mass rate of flow of products was

$$CAp\left(\frac{\gamma\rho_o}{p_o}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}\right)^{\frac{1}{2}}$$

or, KA p where

$$K = C\left(\frac{\gamma\rho_o}{p_o}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}\right)^{\frac{1}{2}}$$

and is approximately constant for dust flames discharging to atmosphere.

Where the vent is relatively small, so that high explosion pressures are developed, the maximum explosion pressure can occur after the rate of formation of combustion products has reached the maximum. For instance, with no vent, the maximum rate of pressure rise clearly precedes the development of the maximum explosion pressure. In a vented explosion, with a small vent and high explosion pressures, different conditions obtain as compared with large vents and low pressures where the maximum explosion pressure would be generated when the rate of formation of combustion products reached a maximum as was assumed in the derivation of equations 3 and 4.

The approach taken for the high pressure/small vent system has been to calculate the loss of combustion products from the vent during the explosion, to compare the loss with the amount of dust suspension originally present, and hence to calculate the maximum pressure in terms of the maximum explosion pressure in a closed vessel with no vents.

Mass rate of flow of combustion products at maximum explosion pressure p was KA p.

Mean mass rate of flow during increase of explosion pressure to maximum was $\frac{KA}{2}$ $(p-p_o)$, approximately. The approximation arises because whilst the pressure is still below the critical (12 lbf/in^2) the flow rate is proportional to a fractional power (about 0.5) of the pressure (see above). The approximation overestimates the mass of combustion products vented.

The duration of the explosion, from the ignition to the maximum pressure, has been taken as

$$(p_{max} - p_o)/(\frac{dp}{dt})av$$

where $(\frac{dp}{dt})av$ is the average rate of pressure rise in the closed standard explosion vessel[7]. This introduces a further approximation because, in the vented explosions under consideration, the maximum pressure is probably developed slightly more rapidly than with a closed vessel. A more accurate estimate cannot be easily made, and the approximation has therefore been accepted. The value of $(\frac{dp}{dt})av$ would be reduced by the same factor as previously when the ignition source was small compared with the vessel volume. The less severe case is considered later.

The total mass of combustion products delivered through the vent was

$$\frac{KA}{2}\ (p-p_o)\ (p_{max} - p_o)/(\frac{dp}{dt})av$$

The total mass of dust suspension originally present was $V\rho_c$. Hence, fraction of mass vented was

$$\frac{KA\,(p-p_o)\,(p_{max}-p_o)}{2\,V\rho_c\,(\frac{dp}{dt})av}$$

Fraction remaining was

$$1-\frac{KA\,(p-p_o)\,(p_{max}-p_o)}{2\,V\rho_c\,(\frac{dp}{dt})av}$$

$= {}^{p}/p_{max}$, neglecting adiabatic cooling of the mass remaining in the vessel.

Rearranging,

$$\frac{1}{(p-p_o)} = \frac{1}{(p_{max}-p_o)} + \frac{KA\,p_{max}}{2V\rho_c\,(\frac{dp}{dt})av} \quad \text{.........} \quad (5)$$

With some dusts, values of $(\frac{dp}{dt})av$ may not be available. An analysis of 130 published values[2] for agricultural and plastics dusts, and Pittsburgh coal, obtained by the U.S. Bureau of Mines, has shown that the mean ratio of the average to the maximum rate of pressure rise was 0.40, with a standard deviation of 0.11.

$$\text{i.e.}\quad (\frac{dp}{dt})av = 0.4\,(\frac{dp}{dt})_{max}$$

Equation (5) then became

$$\frac{1}{(p-p_o)} = \frac{1}{(p_{max}-p_o)} + \frac{KA\,p_{max}}{0.8\,V\rho_c\,(\frac{dp}{dt})_{max}} \quad \text{.........} \quad (6)$$

For the less severe explosions, where the ignition source was small compared with the vessel volume, the values of $(\frac{dp}{dt})_{max}$ in Equation (6) should be multiplied by a factor $({}^{V_o}/V)^{\frac{1}{3}}$.

APPLICATION OF EQUATIONS TO AVAILABLE DATA

Maximum explosion pressures below critical ($12\ lbf/in^2$, $83\ kN/m^2$)

It is convenient to use Equations (3) and (4). As all the available explosion pressures were published in British units, these have been retained for practical simplicity. Dust concentrations were usually published in g/l or oz/ft^3, and all have been quoted here in g/l. The conversion is $1\ oz/ft^3 = 1\ g/l$.

In Equations (3) and (4) the right hand side must be divided by the constant 144 g, because the practical pressure units were lbf/in^2 and the equations were derived using pdl/ft^2 as the British units. The following values were taken for the constants:

$$C = 0.6^{8}$$
$$\rho_c = 0.081\ lb/ft^3$$
$$g = 32\ ft/s^2$$
$$p_o = 14.7\ lbf/in^2$$
$$\gamma = 1.27$$

Details of the explosion parameters of the dusts, and of the experimental arrangements are summarised in Table 1. In Fig.1 the measured explosion pressures are plotted against calculated values from Equations (3) and (4).

<u>Table 1</u>

Dusts and explosion vessels for which data is available
(maximum explosion pressures below critical)

Ref.	Dust	p_{max} lbf/in^2 (absolute)	$(\frac{dp}{dt})_{max}$ lbf/in^2.s	Explosion vessel: Shape	Explosion vessel: Volume (V) ft^3	Notes	Symbols on Fig.1
9	Cornstarch	150	8700	Cubical	1, 64 and 216		O, X, ●
10	Cork	102	2900	Gallery 4 ft diameter, 55 ft length	691	Gallery open at one end, ignition near closed end	▲Ⓐ and ▲Ⓑ
						Gallery open both ends, ignition at centre	▼Ⓐ and ▼Ⓑ
				Gallery 10 in diameter, 10 ft length	5.5	Gallery open at one end, ignition near closed end	□
	Phenol formaldehyde resin	122	6500				■
6	Cellulose acetate	125	5000	Cubical	1		◇
12	Coal	96	2600	Coal pulverising mill	183	External ignition, from 50 ft^3 cylinder, connected by ducting 23 in. diameter, length 20 ft	+ Ⓐ and + Ⓑ

The following notes apply to Table 1:

The values of explosion pressure and vent ratio, given in Ref.9, were obtained in earlier work. The explosion parameters of the cornstarch, given in Ref.9, have been used here; the maximum rate of pressure rise was obtained at a dust concentration of 0.6 g/l and the value of maximum explosion pressure was also taken at this concentration. The dust concentration in the venting experiments was not stated but was varied to obtain the severest conditions[6]. The explosion parameters for cork dust were not given in Ref.10, so values obtained at the Fire Research Station were taken[7]. Values for phenol formaldehyde resin were taken from the same source. The explosion pressures measured in the vented explosions in Ref.10 were produced by dispersing dust over a 20 ft length of the 55 ft long gallery. In calculating explosion pressures from the equations, the volume of gallery generating combustion products was taken to be either that corresponding to the 55 ft length or to the 20 ft length; the alternatives are marked with superscripts A and B respectively in Fig.1 and in Table 1. Dust was dispersed over the whole length of the 10 ft gallery. The explosion parameters for cellulose acetate were estimated from Fig.8 of Ref.6, and from Ref.11. In Ref.12 two coals were used, Silkstone and Beamshaw, of similar volatile and ash contents but the explosion parameters were not stated. The values of p_{max} and $(\frac{dp}{dt})_{max}$ obtained at the Fire Research Station for Silkstone coal have been used. The coal mill was fitted with four 'trash doors', of total area 3 ft^2, which were open but which may not have participated fully in the venting. Calculations were made assuming either no participation or full participation; the alternatives are marked with superscripts A and B respectively in Fig.1 and in Table 1. In all the experimental arrangements given in Table 1, except for the 1 ft^3 cubical gallery, the dust was dispersed by detonators. In the 1 ft^3 gallery compressed air was used, as this procedure was found to be fairly efficient[6]. The dust suspensions were ignited by a flame in all cases. Because of the intense turbulence present the ignition sources have been taken as effectively large, and the explosions to be severe.

Figure 1 is concerned with explosion pressures below critical, and calculations of pressures above this value using Equations (3) and (4) are not valid. Two such calculated pressures, at 25 lbf/in^2, are included for comparison and are discussed below.

Maximum explosion pressures above critical (12 lbf/in^2, 83 kN/m^2)

The calculated pressures for vented explosions are given by Equation (6). In calculations, to obtain practical British units, the second term on the right hand side of Equation (6) was multiplied by the constant 144 g.

The explosion vessels, and dusts used, are detailed in Table 2, and in Fig.2 the reciprocals of the measured explosion pressure are plotted against the calculated values from Equation 6.

Table 2

Dusts and explosion vessels for which data is available
(maximum explosion pressures above critical)

Ref.	Dust	P_{max} lbf/in^2 (absolute)	$(\frac{dp}{dt})_{max}$ lbf/in^2.s	Explosion vessel: Shape	Explosion vessel: Volume (V) ft^3	Notes	Symbols on Fig.2
12	Coal	96	2600	Two cylinders 2 ft 6 in diameter, 10 ft length, connected by pipe 10 in diameter, 30 ft length	50 (Vol of 1 cylinder)	Vent area distributed unequally between the two cylinders. Vent area of vessel with majority of area and with pressure gauge used in calculations	△
				Coal pulversising mill	183	External ignition, from 50 ft^3 cylinder connected by ducting 23 in diameter, length 20 ft	+ Ⓐ and + Ⓑ
13	Cornstarch	116	6500	Cylinder	0.13	Ignition near vent	○
15	Phenol formaldehyde resin with wood flour filler	122	6500	Gallery 50 ft length 2 ft 6 in diameter	246	Ignition from 10 ft length 10 in diameter pipe	■
16	Lead stearate	63	3400	Cylinder	0.046		▽

The following notes apply to Table 2:

In Ref.12 two coals were used, Silkstone and Beamshaw, of similar volatiles and ash contents but the explosion parameters were not stated. The values of p_{max} and $(\frac{dp}{dt})_{max}$ obtained at the Fire Research Station for Silkstone coal have been taken. In tests with cylindrical explosion vessels connected by a long narrow ducting in which coal was not initially present only the vent area and volume of one vessel was used in calculation because the ducting would restrict movement of combustion products. The external ignition source for the coal pulverising mill was a cylinder 10 ft in length, connected by 20 ft of ducting in which coal was not initially present. The mill was fitted with four 'trash doors' which were either closed or open (not stated) of total area 3 ft^2; the alternatives are marked with superscripts A and B respectively in Fig.2 and in Table 2. The value of $(\frac{dp}{dt})_{max}$ was not stated in Ref.13 for cornstarch, so an estimate was made by taking a value from Ref.14 for a cornstarch having the same p_{max} as that in Ref.13. The explosion parameters for phenol formaldehyde resin, Ref.15, were taken from Table 1. The explosion pressures measured in the vented explosions were produced by dispersing dust over only a 20 ft length of the 50 ft long gallery; in calculating explosion pressures from Equation 6, the volume of gallery generating combustion products was taken to be two fifths of that corresponding to the full length and the maximum explosion pressure (gauge) and rate of pressure rise were also multiplied by the same factor.

In the small cylindrical vessels listed in Table 2, of volumes 0.046 and 0.13 ft^3, the dusts were dispersed by compressed air. With the other, larger vessels detonators were used. The ignition sources for the dust suspensions were either flames from attached vessels or, with the small cylindrical vessels, were hot wires. Because of the intense turbulence, or large ignition sources, or both, the explosions were taken to be severe.

DISCUSSION

COMPARISON OF MEASURED AND CALCULATED PRESSURES

In the majority of applications of dust explosion venting the maximum explosion pressures must be reduced to a few lbf/in^2, frequently less than 2 lbf/in^2, and these pressures are well below critical (Fig.1). Any treatment of available data which can be applied to this range of pressures is of practical interest. The data, as plotted in Fig.1, show that for cubical enclosures up to 216 ft^3 volume (Table 1) the measured explosion pressures varied approximately linearly with calculated values, with some scatter. The data for cornstarch had been published originally with the pressure/vent ratio plotted on a log/linear graph[9]; the straight line relationship broke down at pressures below 4 lbf/in^2.

The data for the experiments in the 691 ft^3 gallery were plotted against two calculated pressures, as explained in the notes to Table 1 above. The calculations were based on two extreme conditions, aimed at bracketing the actual case. The need for the alternative calculations arose because of the uncertainty due to only part of the length of the gallery initially containing dust. As far as Equation (4) is concerned Fig.1 indicates that explosion pressures are under-estimated if it is assumed that combustion products are generated from only that part of the gallery which initially contained dust. On the other hand, assuming that all the gallery generated combustion products simultaneously leads to a great overestimation of the explosion pressure, sometimes giving values outside the range of validity of the equations. An alternative approach would be to assume that as the burning suspension expanded it accelerated the column of gas ahead of it, and the force required would cause the pressure to rise. The maximum pressure would be reached when the flame velocity relative to the gallery attained a maximum; data on flame velocities would be required and few are available. Some flame velocities were reported for cork dust in the 691 ft^3 gallery[10], which was 55 ft in length (Table 1). The average flame velocities over the half of the gallery containing the vent were 520 and 1090 ft/s for dust concentrations of 0.25 and 0.5 oz/ft^3 respectively. As the average velocities were only 160 ft/s in the adjoining quarter length of the gallery, the rises in flame velocities were probably about 1000 and 2000 ft/s respectively. The forces required to accelerate a column of gas, half the length of the gallery, from rest to the maximum velocities give calculated explosion pressures of 4.4 and 17.6 lbf/in respectively. The measured pressures were 3.2 and 5.4 lbf/in respectively, and so agreement was not good. This approach would only be fruitful if flame velocities in galleries could be predicted from routine tests. Further work is needed to decide which approach is the more useful.

The lines in Fig.1 representing Equations (3) and (4) show that for explosion pressures up to 2 lbf/in^2 the difference between calculated values was small, and that Equation (3) gave higher estimates as the vent area was reduced. Except where pressures were calculated on a bracketing basis, Equation (4) gave a reasonable representation of the data over a relatively wide range of pressures, up to 8 lbf/in^2. Equation (3) gave overestimates when pressures exceeded 3 lbf/in^2. Likely sources of error include the approximations in the derivation of the equations, the numerical values taken for the dust suspension parameters, and experimental difficulties associated with measurements of vented dust explosions. Some doubt attaches to the value which should be taken for the discharge coefficient, C, in Equations (3) and (4). Here a value of 0.6 has been used, but other workers[17,18] have taken $C = 0.8$. Use of the latter value would lower the calculated explosion pressures, in Equation (4), by nearly 50 per cent.

Inserting values for the constants in Equation (4) gives

$$(p-p_o) = \frac{10^{-3}}{p_{max}^3} \left(\frac{V}{A} \left(\frac{dp}{dt}\right)_{max}\right)^2 \qquad \ldots\ldots (7)$$

where $\frac{V}{A}$ is measured in feet and all pressures are absolute and measured in lbf/in^2. For practical purposes Equation (7) can be used for relating venting requirements to dust explosion parameters, for pressures below critical, and for plant of similar design to that considered in Fig.1. In practice $\left(\frac{dp}{dt}\right)_{max}$ varies much more widely than p_{max} so that for many dusts p_{max} can be regarded as a constant, of order 100 lbf/in^2. Equation (7) can then be further simplified as a rough guide. This step is only acceptable if p_{max} does not have an extreme value.

When the vents were small, so that explosion pressures were above critical, Equation (6) was used. Figure 2 shows that the reciprocal of the measured explosion pressure was never less than the calculated value, for the results available. Thus Equation (6) consistently overestimated the explosion pressure. The equation gave reasonably close estimates of explosion pressure for the majority of results obtained with cylindrical explosion vessels of volumes

0.046 and 50 ft^3, and for a gallery of 246 ft^3 volume with powerful ignition source (Table 2). Because of the difficulty experimentally of obtaining severe explosion conditions in vessels with small vents, where dispersion of the dust and rapid spread of ignition receive relatively little assistance from expansion of combustion products, the measured explosion pressures would tend to be lower than the maxima that might be obtained. Equation (6) thus appears to give the pressures which might be obtained under the worst possible conditions, i.e. the severest case. Particularly low explosion pressures were reported for a 0.13 ft^3 vessel, using corn starch, Table 2, and the reason may be that the ignition source was near the vent; the results were included in Fig.2 for comparison. Because of the approximations used in the derivation of Equation (6), it is likely to be most reliable at higher explosion pressures, say 50 lbf/in^2 and above, and particularly inaccurate for pressures of 30 lbf/in^2 down to the critical pressure.

Other attempts have been made to correlate explosion venting data. Straumann[17] derived expressions for pressures below and above critical, and applied them to a limited range of data. The rate of generation of combustion products was taken directly from the average rate of pressure rise, i.e. was assumed constant, and estimates were needed for their molecular weight and temperature. When tested against the data for corn starch[9], Table 1, the calculated pressures were about half those measured. Heinrich[18], presented a nomogram based on an equation which took into account the adiabatic compression during the explosion, but the nomogram was not compared with available data. The equation contained vent area to the power of unity and vessel volume to the power two-thirds.

IMPLICATIONS REGARDING EXPLOSION PROPERTIES

The extent of the correlation between experimental data and the calculated pressures, shown in Figs 1 and 2, gives support to the assumptions made in the derivation of the equations. It is useful to consider the implications arising if these assumptions were to be accepted, because they could influence the design of future experiments, and also focus attention on variables of particular importance.

The crucial assumption was that in severe explosions, even in large volumes, combustion would be taking place throughout the whole of the volume when the maximum pressure was obtained. Explosion parameters obtained in the standard small scale tests were also used in the calculations, and gave the correlations shown in Figs 1 and 2. Evidence has thus been provided for a link between the small scale tests and the explosion venting data obtained in experiments up to full industrial scale, provided these explosions were severe. This link could be important in practice, to enable estimates of the behaviour of large scale plant to be made, under the worst conditions of explosion. The available data is limited to volumes up to 700 ft^3 (Tables 1 and 2) and there is no evidence as to whether important discrepancies between experiment and calculation might appear with larger volumes. Such discrepancies might be expected on several grounds. The vessel could be so large that combustion throughout the entire volume simultaneously could not take place. The turbulence of the dust suspension may never be sufficient to ensure that dust in all parts of the vessel could become ignited as rapidly as has been assumed. Finally, even if the source of ignition were injected into the vessel from a duct it might be of such small size relative to the volume of the vessel that a severe explosion could not be produced. The practical difficulties involved in this type of experiment may be demonstrated by reference to tests in a vertical cylindrical vessel, of volume 2650 ft^3, using various provender dusts[18]. The top of the cylinder had vent areas ranging from 1/9th to the whole area. The dust was dispersed by tipping it from shelves at the top of the vessel, and allowing it to fall under gravity into a gas flame near the base. The dust was not likely to become uniformly distributed throughout the volume and dispersion was not assisted by intense turbulence, the experimental conditions could not be regarded as severe and the results were not included in Figs 1 and 2. It is of interest that with large vents the explosion pressures were very low but they increased rapidly as the vent area was reduced. Apart from increased restriction due to smaller vents, increased turbulence due to the explosion may also have occurred leading to a more uniform dispersion of the dust, to more rapid flame propagation, and to more severe explosion conditions. It is unlikely that this design of experiment would give the most severe conditions that could arise in practice.

Some indications of limitation on the assumptions, as plant size is increased, may be gained from the data on gallery tests. The nearest approach to combustion throughout the whole volume of a gallery appeared to be when the gallery was short and a large external ignition source was used. Otherwise the observed pressures were well below those which could have arisen if the whole volume of the gallery were involved. The available information is relatively scanty, and further work with galleries would be especially valuable. In all gallery tests the dust suspension, although intensely turbulent when formed, had no mass flow along the duct before ignition. In industrial situations, where dusts are frequently conveyed through ducting, the velocity may be high and the residence time of the dust within the ducting correspondingly short. Thus, if burning dust, or an ignition source, were introduced the ignition could be carried rapidly along the ducting by the normal working processes. A situation might then arise in which dust burning at its most rapid rate was simultaneously present throughout the entire volume and this could give more severe conditions than any of those so far reported experimentally. Higher explosion pressures would then be expected. In other plant units within which dust is in turbulent suspension during normal working, the conditions in the event of a dust explosion should be taken as severe, particularly if the explosion is caused by the introduction of burning dust. Milder explosions would be expected from small sources within the plant, coupled with weak agitation of the suspension.

So far it has been assumed that providing the dispersion within the vessel is highly turbulent, then even distribution of the suspension throughout the volume would be favoured. Whilst this may be correct for the vessels listed in Tables 1 and 2, it is unlikely to be so for other plant units such as cyclones or fabric filters. The equations that have been derived cannot be used directly for such plant units; experiments on the venting of a cyclone are in progress at the Fire Research Station.

The majority of plant units which require venting against dust explosions are relatively weak, and capable of withstanding up to 2 lbf/in^2 and the pressures of interest are below critical. The form of equation 7 will now be examined in more detail. For a given dust, the explosion pressure varies inversely with the square of the vent ratio $(\frac{A}{V})$. The use of the vent ratio, even though it has residual dimension, appears justified and explosion pressures would be expected to fall rapidly as vent area on a given vessel was increased. Comparison may also be made between the vent ratio requirements of Equation (7) and the ad hoc values used in practice. Typical values of the explosion parameters for dust, of moderate, intermediate and high explosibility are given in Table 3 together with the calculated vent ratio assuming explosion pressures were not to exceed 2 lbf/in^2. The vent ratio increased from 1/12.5 to 1/5.0 as the explosibility of the dusts increased.

Table 3

Vent ratio required to give explosion pressures of 2 lbf/in^2 calculated from Equation (7)

p_{max} lbf/in^2 (absolute)	$(\frac{dp}{dt})_{max}$ $lbf/in^2.s$	Vent ratio $(\frac{A}{V})$ ft^{-1}
100	3000	1/12.5
110	6000	1/7.1
120	10000	1/5.0

The ad hoc ratios required in practice would be 1/20, 1/15 and 1/10 respectively, giving less vent area than that calculated. In both cases at least twice as much vent area would be needed for the highly explosible than for the moderately explosible dust. In practice other factors would be involved which would reduce the likelihood of the most severe conditions being obtained throughout the plant unit to be vented. Thus part of the volume could be occupied by deposited dust and the concentration needed for the most severe explosion is unlikely to be present, by chance, throughout the whole volume. The calculated vent ratios are thus reasonably in accord with the requirements found from practice, but also indicate that these requirements cannot be safely reduced.

Further examination of Equation (7) shows that with a given value of vent ratio the explosion pressure varies directly with the square of the maximum rate of pressure rise and inversely with the cube of the maximum explosion pressure. As rates of rise tend to vary much more widely between dusts than do maximum pressures, the pressure in a vented explosion depends strongly on the value for the rate of pressure rise for the dust. The fundamental reason why the maximum explosion pressure appears in the denominator is that for a given rate of rise, the duration of the explosion would increase as the maximum pressure rose. Additional time would be provided for the venting process, and the explosion pressure developed would be less than in a more rapid explosion.

The explosion pressure in a vessel of fixed vent ratio has been found empirically to be approximately proportional to the average rate of pressure rise determined in the standard pressure test apparatus[6], and comparison can be made with Equation (7). The average rate of pressure rise has been shown above to be directly proportional to the maximum rate $(\frac{dp}{dt})_{max}$. Because p_{max} would tend to increase with $(\frac{dp}{dt})_{max}$ (Table 3) although much less rapidly, the effect in

Equation (7) would be to reduce the square law dependence to that for a power between one and two. There is sufficient scatter in the quoted results[6] for an index between one and two to give reasonable agreement.

REQUIREMENTS FOR FURTHER DATA

Although use of the equations derived above may be justified on the available data, there is a great need for additional information. This would give further testing of the equations, and the assumptions on which they were based, as well as illustrating other factors which may have been overlooked. Further information is particularly needed on the following topics.

1. Data along lines already available, but covering a much wider range of dusts. The results for a series of dusts tested in the same explosion equipment would be particularly valuable.

2. Explosions in larger volumes than so far reported, with dust concentrations as uniform as possible.

3. Explosions of flowing dust suspensions, in plant units, including dispersion of ignited dusts.

4. Explosions in plant items which produce non-uniform dust distribution.

5. Effect on explosion pressures of vent closures and ducting to carry away combustion products. For simplicity, these problems have not been considered here, but they are of practical importance.

CONCLUSIONS

1. On the basis of certain listed assumptions, equations have been derived which related explosion pressure, in a vented explosion, to area of vent, volume of vessel, and explosion parameters of dusts measured in small scale test apparatus.

2. When compared with published data for vented explosions, over a wide range of plant scale, the equations and the assumptions by which they were obtained received support.

3. Because of the variation in experimental conditions, and also for practical requirements, only data for severe explosions were analysed in detail. For published data the severe conditions involve vigorous dispersion of the dust, intense turbulence of the dust cloud, and a large ignition source.

4. Some allowance could be made in the equations for less severe conditions, but there was insufficient data for adequate checking.

5. The relation between vent ratio and calculated explosion pressures up to 2 lbf/in^2, which is of major practical interest, was explored for dusts of differing explosion parameters. The present ad hoc procedure for specifying vent ratio appeared to be reasonable.

6. Further experimentation is necessary to analyse the assumptions more rigorously, and to provide additional explosion data. Particular attention should be given to obtaining results for a wider range of dusts, with plant of greater volume, and with uniform and non-uniform suspensions. More information is needed on dust explosions in flowing suspensions. Dust which is ignited before dispersion would appear to be particularly hazardous. Analysis should also be made of the effect of vent closures on explosion pressures.

ACKNOWLEDGMENT

Mrs Wendy Evans made the statistical calculations.

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APPENDIX

Dust explosion parameters used in establishing relationship between p_1 and p_{max}

Dust	$\left(\frac{dp}{dt}\right)_{max}$ lbf/in^2.s	p_1 lbf/in^2 (absolute)	p_{max} lbf/in^2 (absolute)
Phenol formaldehyde resin	6500	63	122
Cork	2900	54	102
Sugar	2100	39	108
Tea	1700	42	108
Esparto grass	7300	54	109
Rubber crumb	3300	65	99
Dinitroaniline on β-naphthol	12300	53	145
Provender	1800	45	98
Distillers dried solubles	700	36	79
Wood	5700	46	105
Caprolactam	1650	61	94
Aluminium	19300	65	107
Calcium propionate	1850	66	105
Benzoic acid	10250	59	110
Polypropylene	450	53	74
Diphenylol propane	8200	55	99
Glass fibre reinforced polyester	11650	61	107
Milk, spraydried	1600	73	113
Protein concentrate	5750	76	123
Sodium acetate	100	29	35
Polyethylene	600	57	81
Grass	350	39	71
Linoleum	450	59	82

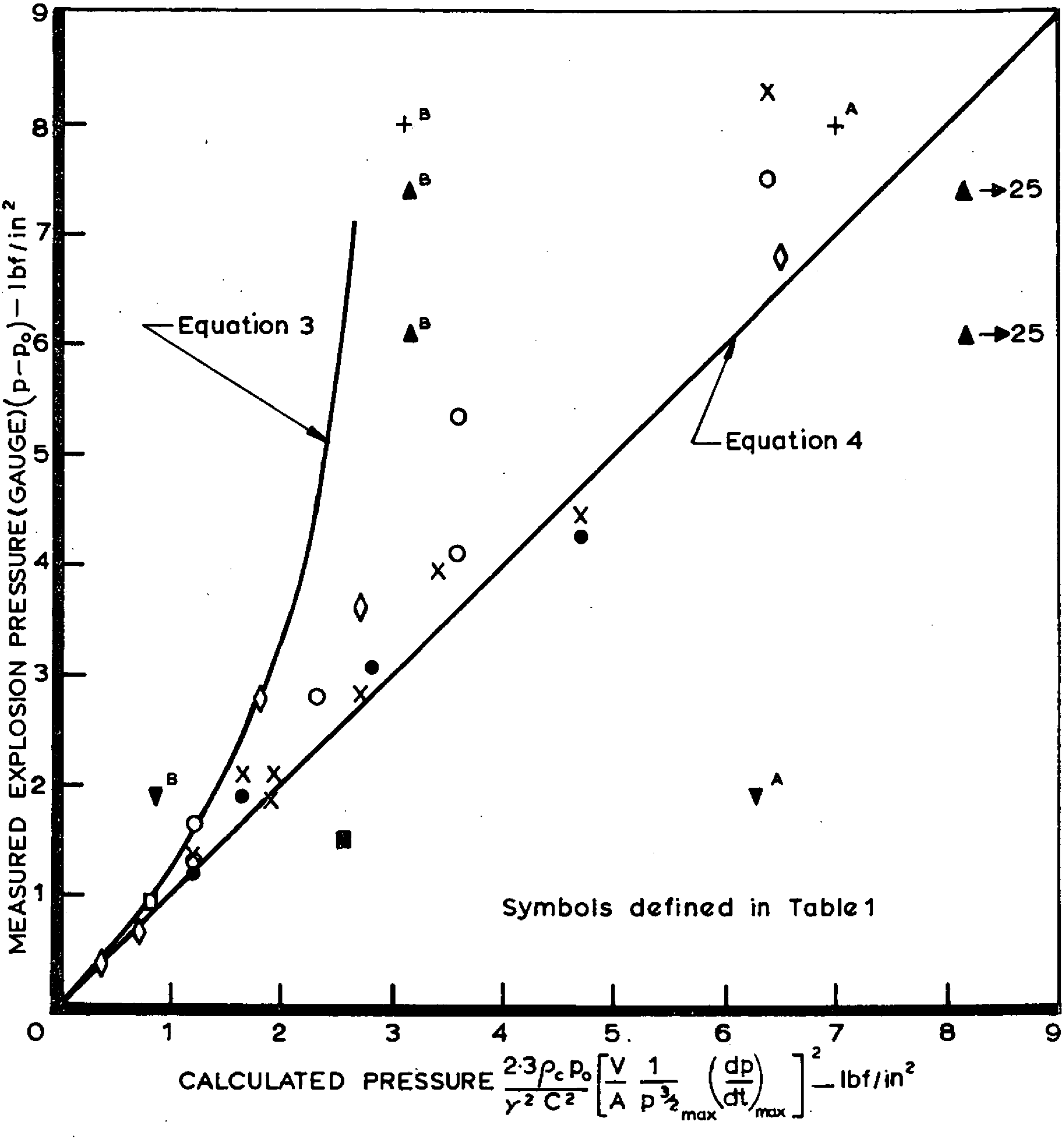

FIG.1 COMPARISON OF MEASURED AND CALCULATED EXPLOSION PRESSURES, BELOW CRITICAL

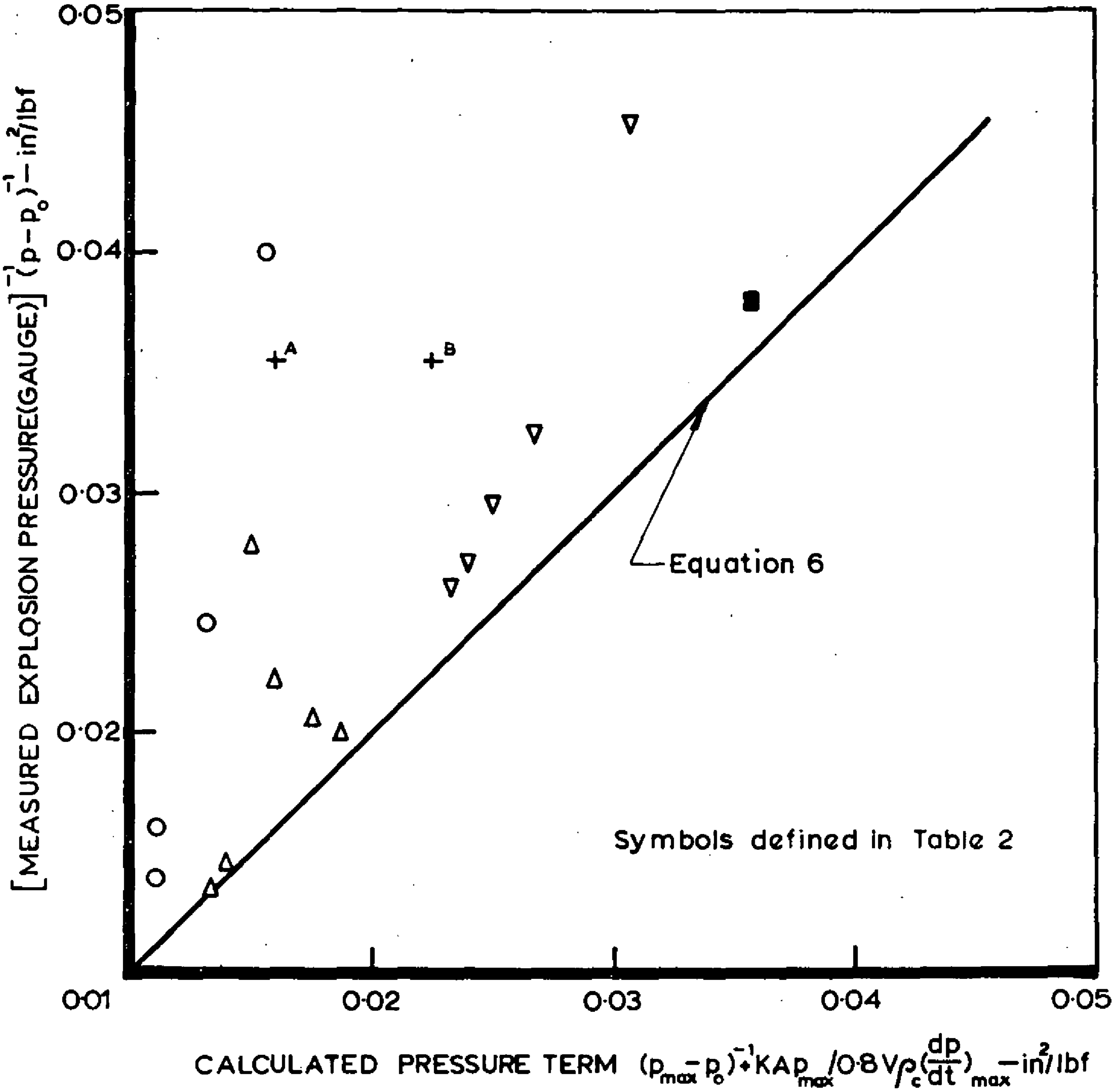

FIG.2 COMPARISON OF MEASURED AND CALCULATED EXPLOSION PRESSURE, ABOVE CRITICAL