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DUST EXPLOSION VENTING - CONSIDERATION OF FURTHER DATA

by

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SUMMARY

Equations developed previously, which related the maximum pressure in a vented dust explosion to the properties of the dust and the geometry of the explosion vessel, have been checked against further experimental data, and their theoretical basis has been extended. The following industrial plant systems were considered: vent ducting, a cyclone, and relatively large vessels with small vents. Attention was also paid to maximum rates of pressure rise in closed vessels of different volumes.

The application of the equations to the plant systems was generally adequate and gave further insight into the processes involved in vented dust explosions. There is still a serious shortage of experimental data for dust explosion venting, requiring the continued use of unconfirmed basic assumptions.

KEY WORDS: Dust explosion, explosion venting

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INTRODUCTION

Explosion protection of industrial plant handling explosible dusts is often obtained by means of relief venting. The function of the venting is to reduce the explosion pressure within the plant from the maximum obtainable in a closed vessel, commonly about 700 kN/m^2 (100 lb/in^2), to a level that the plant can withstand without mechanical damage. For plant of sheet metal construction the maximum pressure permissible is often about 15 kN/m^2 (2 lb/in^2) although higher pressures may be acceptable in plant which is constructed more strongly, often for other reasons. The dependance of the maximum pressure upon the size of vents, the volume of the plant, and the explosibility parameters of the dust were discussed in a previous note[1] in which it was made clear that the available data was insufficient for adequate generalisations to be made with confidence and also that the theoretical background to the problem had been given insufficient attention. Some further experimental data has now come to hand and is considered in this note, from the viewpoint of checking earlier ideas against additional facts.

In the previous note some reported observations of the properties of dust explosions were listed and, from these, some assumptions were made concerning the processes involved in the venting of explosions. Equations were then derived relating the explosion pressure to the vent ratio (area of vent/volume of vessel) and the maximum explosion pressure and the maximum rate of pressure rise of the dust in a standard apparatus. The most important assumption was that at some instant in a severe explosion the combustion could be taking place throughout the whole volume of the vessel. 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. Only unrestricted vents were considered.

Two equations were derived, dealing with relatively low and high pressure systems. The former case is of interest to much dust handling plant, for which the design explosion pressures should not exceed 15 kN/m^2 (2 lb/in^2), and for which conditions the combustion products can be treated approximately as a non-compressible fluid. The low pressures imply that the venting is generous and that hot combustion products will be flowing through the vent at the time the pressure reaches a maximum. The following equation was derived

$$(p-p_o) = \frac{10^{-3}}{p_{max}^3} \left(\frac{V}{A} \left(\frac{dp}{dt}\right)_{max} \right)^2 \qquad \ldots\ldots(1)$$

where A is area of relief vent

p is maximum pressure in vented explosion

p_O is atmospheric pressure

p_{max} is maximum pressure in the closed standard explosion vessel

$(dp/dt)_{max}$ is maximum rate of the pressure rise in the closed standard explosion vessel

V is volume of vessel

and where

V/A is measured in feet and all pressures are absolute and measured in lb/in^2.

When the vents were small so that the explosion pressures were above critical, the gases flowed through the vent at sonic velocity. This high pressure venting arrangement is of practical interest where plant is of inherently strong construction, although not able to withstand the full explosion pressure in a completely enclosed vessel. The gases flowing through the vent at the instant of obtaining maximum explosion pressure were again assumed to be hot combustion products and the following equation was derived

$$\frac{1}{(p-p_o)} = \frac{1}{(p_{max}-p_o)} + \frac{K\,A\,p_{max}}{0.8\,V\rho_c(dp/dt)_{max}} \qquad \ldots\ldots(2)$$

where K is constant

ρ_c is density of unburnt dust suspension at pressure p_o and of combustion products at pressure p_1 (pressure in closed standard explosion vessel when rate of pressure rise was a maximum).

All pressures were again absolute and all quantities were measured in consistent fps units. Because of approximation in its derivation equation 2 was considered to be most reliable at high explosion pressures, say 350 kN/m^2 (50 lb/in^2), and above, and less accurate for pressures of 200 kN/m^2 (30 lb/in^2) down to the critical pressure of 83 kN/m^2 (12 lb/in^2)gauge.

Equations 1 and 2 are considered in this report in terms of data on explosion pressures in ducting attached to relief vents, explosions in a cyclone plant, and results of tests in large compact vessels. The extent to which equations 1 and 2 can be used for practical situations is further assessed in the light of the information now available.

EXPERIMENTAL SYSTEMS

Vent ducting

As explained previously[1], even if ducting were filled with a turbulent dust suspension, ignition from a single point within the duct is unlikely to lead to flame propagation along the whole length sufficiently rapidly for the assumption to be valid that combustion is taking place simultaneously throughout the volume. The assumption of simultaneous burning would represent the most severe conditions, yielding the highest explosion pressure, and if only part of the volume were involved at any given instant the explosion pressure within the ducting would be reduced.

However, one situation in which simultaneous burning could occur in practice is that where the combustion of a dust suspension in a vessel is vented through ducting to a safe discharge point. An explosion in the vessel could, if the volume is substantially greater than that of the ducting, generate sufficient burning suspension to fill the ducting. The contents of the ducting would be flowing rapidly, with intense turbulence, and the most severe conditions for explosion in the ducting are likely to be approached, if not met.

As the suspension in the ducting is undergoing mass flow, there will be some increase in pressure due to pipe friction and this will also cause the pressure in the attached vessel to be higher. If the vessel is initially closed from the ducting by a bursting panel, its pressure may be increased further, even though the panel may burst at a relatively low pressure. Equation 1 was derived on the basis of the pressure drop across the vent, not on friction losses along the length of the ducting. In the present Note the pressure differential along the ducting, due to the mass flow, has been disregarded. This is a simplifying assumption which should be relatively less serious as the length of ducting is increased, the situation of major practical interest, because in equation 1 the pressure drop across the vent due to the combustion within the ducting would increase with the square of the length. The consequences of the approximation are discussed again below.

Information is now available from two experimental investigations during which ducting was attached to a vent on a relatively large vessel, in which cork dust explosions were generated, and where maximum explosion pressures were reported. The first investigation involved explosions in a dust handling plant, which incorporated a cyclone, and details are available elsewhere[2]. The ducting was attached to a vent on the top of the cyclone, and was varied in length between 0.86 m (2.8 ft) and 4.5 m (14.8 ft). A 45° long sweep elbow was included in some of the arrangements. The actual lengths of duct have been used in calculations, rather than values based on equivalent lengths from pipe friction data. The internal diameter of the ducting was 41 cm (16 in), and its area of cross section was approximately equal to that of the vent. Explosion pressures were measured in the ducting, part way along its length, and in the cyclone. For immediate purposes the pressures measured in the former position have been taken. The cyclone vent was initially closed by a panel which burst at 4 kN/m^2 (0.6 lb/in^2), but the outlet from the ducting to atmosphere was always open. The relevant explosion parameters of the cork dust were the same as previously[1], namely:

$$p_{max} = 704\ kN/m^2\ (102\ lb/in^2)\ \text{absolute}$$

$$(dp/dt)_{max} = 20\ 000\ kN/m^2\ s\ (2900\ lb/in^2\ s)$$

In applying equation (1) to ducting the value of $V/_A$ is that of L, the length, and is measured in feet. The experimental results are shown in Fig.1, where the observed pressures to the power one half are plotted against the ducting length.

In the second investigation[3] ducting of diameter 25 cm (10 in) was attached to an explosion vessel, of volume 1.4 m^3 (50 ft^3). The vent to which the ducting was attached was also 25 cm (10 in) in diameter and was open. Cork dust was used at a concentration of 0.4 g/l (0.4 oz/ft^3), which was found to give the most violent explosions, under the conditions of test. The explosion parameters given above for cork dust have been taken for purposes of calculation. In the tests the explosion pressure was measured in the vessel, and direct values are not available for pressure in the ducting, but a value was quoted for the explosion pressure in the vessel with no ducting attached. From analogous experiments with ducting attached to a cyclone[2], in which pressures were measured in both, it was seen that the total pressure in the cyclone was the sum of the pressure differentials across the vent (i.e. between cyclone and ducting) and between the ducting and atmosphere (Fig.2). The pressure in the ducting can thus be derived from the total pressure in the cyclone, minus the pressure in the cyclone with no ducting attached. The pressure in the attached ducting described in ref.3 has been taken as the measured pressure in the explosion vessel minus that obtained with the explosion vessel alone. The results are plotted in Fig.1.

A line showing the values obtained from equation 1, using the explosion parameters for cork dust given above, is included in Fig.1. The results show an approximate proportionality between $(p - p_o)^{0.5}$ and L , as would be expected from equation 1, although the pressures are generally higher than those calculated from the equation. The increased pressures could be due, at least partly, to the approximation involved in neglecting pipe friction in the ducting, particularly with the lower values of L. However, it is shown that the maximum explosion pressures developed in the ducting can be calculated approximately from knowledge of parameters obtained in the routine small scale tests and from the geometry of the ducting.

Several considerations of practical interest arise from the application of equation 1 to vent ducting. As the maximum pressure in the ducting increases with the square of the length, the use of long lengths becomes impracticable because the pressure in the vessel being vented becomes excessive. For example, with a dust having the explosion parameters of cork, the addition of a 10 ft length of ducting to a vent would increase the pressure in the vessel by about 1 lb/in^2, whereas a 20 ft length would increase the pressure by about 4 lb/in^2.

As many vessels can only withstand a pressure of 2 lb/in^2 without damage, and there will be some pressure differential across the vent, a practicable length for vent ducting would not greatly exceed 10 feet. It is of interest that this conclusion has already been arrived at in practice, largely by rule of thumb. If a dust that was more vigorously explosible than cork were concerned, then for the same maximum pressure in a vented explosion, the length of vent ducting would need to be reduced inversely with $(^{dp}/dt)_{max}$ subject to a minor adjustment because p_{max} in equation 1 would probably be slightly higher. The explosions in both vented vessels were not of maximum severity, because the pressures were relatively low for the vent ratio provided, but in the vent ducting severe conditions were undoubtedly obtained. An ill-considered design of vent ducting could thus convert a moderate explosion into a severe one. If an attempt is made to reduce the explosion pressure by widening the ducting to a uniform diameter greater than that of the vent, success is likely only if the diameter is increased sufficiently to prevent the whole volume of the ducting from being filled with burning suspension. From equation 1, in order to halve the explosion pressure the volume of the ducting would need to be increased by widening so that about 30 per cent of it did not contain burning suspension. Alternatively a truncated conical ducting could be used. The severe conditions of explosion arising in vent ducting could also be present in other industrial ducting if a dust which was already burning were introduced into an air-stream provided for pneumatic conveying. This possibility was suggested previously[1] and the results in Fig.1 support it. Direct confirmation in a practical system would be valuable.

Cyclone

The experimental programme with the cyclone plant, of industrial scale[2], included tests using several dusts with widely differing explosion parameters, in addition to the cork dust considered above. The parameters are summarised in Table 1, and the polypropylene used was of such reduced explosibility that ignition could only be obtained by switching off the circulating fan in the plant, to reduce turbulence, before injecting the igniting flame. With each dust the igniter was in the ducting attached to the inlet of the cyclone, 1.4 m (4.5 ft) upstream. Direct determination was made of the effect of vent

TABLE 1
Explosion parameters of dusts used in cyclone plant, measured by standard test

Dust	Per cent weight passing 240 BS mesh	Pmax (absolute) lb/in^2	$(dp/dt)_{max}$ lb/in^2 s
Cork	46	102	2900
English flour	74	113	1800
Phenol formaldehyde	100(approx)	122	6500
Polypropylene	3	77	350

area on the explosion pressure developed in the cyclone, with all dusts; a single vent was used in each case and it was closed with a brown paper bursting panel. This panel was intended to burst at a constant pressure of 4 kN/m^2 (0.6 lb/in^2) irrespective of the area of the vent, but in some of the slower explosions it may have ruptured by burning and could have opened the vent at a lower pressure. In the great majority of tests the vent was a sector of the roof of the cyclone, remote from the position of the inlet duct, but in a few tests with cork dust the vent was on the vortex pipe (i.e. the air outlet) and was then circular. The bursting pressure of the vent panel was slightly higher than with the sector vents.

An obvious conclusion, obtained with all the dusts, was that the explosion pressures developed in the cyclone were far lower than would be predicted from equation (1), based on the area of vent and volume of the cyclone. For instance, with a sector vent of area 0.12 m^2 (1.3 ft^2) the explosion pressures obtained with cork, flour, and phenol formaldehyde were respectively 7, 6.5 and 6 kN/m^2 (1, 0.95 and 0.9 lb/in^2). Pressures calculated from equation (1) would be respectively 61, 11, and 175 kN/m^2 (8.7, 1.6 and 25 lb/in^2). The calculated pressures were based on the vent being permanently open, and the effect of the bursting panel used would be to raise explosion pressures that were below or in the region of the bursting pressure of the panel. It was thus clear that a premise on which equation (1) was based, namely that combustion would take place throughout the whole of the volume of the cyclone, may not apply even though the dust suspension would have been highly turbulent due to the action of the fan circulating dust round the plant. Because the cyclone is designed as a separator, the distribution of dust throughout the volume would be far from uniform. Once dust had reached the wall of the cyclone it was not likely to burn as rapidly as when in a cloud, and particles were unlikely to travel to the centre of the cyclone after being introduced at high velocity tangentially near the wall. The explosible cloud was thus likely to be limited to a zone near the wall of the cyclone, and the volume of suspension would be only a fraction of that of the cyclone.

Before pursuing this argument, attention will be paid to the possibility that the low observed pressures were the result of feeble explosions caused by poor dispersion of dust within the plant. This was not considered likely because ready dispersability was one of the qualities looked for in the original selection of the dusts, but there is quantitative evidence that can also be considered. In addition to the peak explosion pressure, measurement was made in many cases of the maximum rate of pressure rise in vented explosions. The relationship between peak pressure ($p-p_o$) and the rate of pressure rise (dp/dt) is shown in Fig.3, for the four dusts listed in Table 1, irrespective of vent area. The dependence of explosion pressure on rate of rise was marked, was fairly linear, and varied between dusts, even though the presence of the bursting panel over the vent probably interfered with the development of the lower pressures. The relation between the maximum pressure in a vented explosion and the maximum rate of pressure rise during that explosion has not been explored in detail, and in any case they are separated in time. But the ratio $(p-po) / (dp/dt)$ may be regarded as a burning time characteristic of a dust in the cyclone, and compared with $(pmax - po) / (dp/dt)_{max}$ which is a burning time characteristic for the closed standard explosion vessel[1]. The comparison may be expressed as

$$(p-po) / (dp/dt) = b(pmax - po) / (dp/dt)_{max} \quad .....(3)$$

where b is a constant.

A graph of (p-po) against $(dp/dt)_{max}$ for the results in Fig.3 is shown in Fig.4, and included a line drawn by eye. The presence of the bursting panel was again disregarded. The results approximately followed equation 3, but with considerable random scatter, and the value of b was about 1.7. The clear differentiation between the dusts, observed in Fig.3, was lost in Fig.4 giving a measure of correlation between all the dusts in Table 1, even though their maximum rates of pressure rise differed widely. The explosion parameters of the dusts in the cyclone could thus be related to those in the standard test in which high pressure air is used to ensure good dispersion (Table 1).

In Fig 3 the results for different dusts increased in gradient as the explosibility decreased (Table 1). Poor dispersion of a dust would decrease its explosibility, and so the gradient in Fig 3 for a poorly dispersed dust would be expected to be greater than if it were well dispersed. On incorporation in Fig.4 the results for a poorly dispersed dust should have a consistently greater gradient than those for the well dispersed. None of the dusts shows this behaviour, indicating that the low pressure in the cyclone were not due to poor dispersion of the dust, unless all dusts had been affected to the same extent, which was unlikely. It would be useful to confirm this conclusion by direct observation, by experimenting with different efficiencies of dispersion of the same dust.

A more probable explanation of the low pressures in the cyclone would be limitation of the size of the explosible dust cloud. The distribution of dust in a cyclone has a complex pattern due to centrifugal action and to vortex formation, and also depends on the individual mass of the dust particles. In order to propagate an explosion, the concentration of dust in suspension must exceed the minimum explosible concentration, and for the suspensions used the precipitation of 80-90 per cent of the dust initially in suspension would reduce the concentration below the minimum for explosion. The variation in concentration of the dusts as they passed through the cyclone was not examined in detail, but some broad indications may be given. Direct observation with the polypropylene, which was a relatively coarse material (Table 1), showed that most of the suspension had been precipitated within the first third of the initial revolution in the cylindrical portion of the cyclone. The efficient separation obtained with all dusts indicated that a negligible quantity was in suspension in the conical part of the cyclone, where it could have been entrained by vortices and delivered through the outlet. The height of the cylindrical part was such that a suspension would on average undergo two complete revolutions before reaching the conical portion. For the dusts listed in Table 1, other than polypropylene, it is estimated that an explosible concentration would not be present for more than two revolutions of the cylindrical portion of the cyclone, tapering over this distance from a width equal to that of the inlet duct (300 mm, 1 ft) to zero width. This conclusion is an approximation, and would be affected by variation in mass of the dust particles, but has been taken as a basis for calculation.

The volume of explosible suspension in the cyclone was therefore 4π ft^3 (0.11π m^3). Explosion pressures calculated using this value of V in equation (1) are plotted against the observed values for three dusts in Fig. 5. Over the pressure range for which equation (1) is valid (up to 83 kN/m^2, 12 lb/in^2), and particularly the lower part of this range where the equation is more accurate[1], the results for cork dust were in approximate agreement with calculation, those for flour were greater and for phenolformaldehyde were less. The calculated pressures were in considerably better agreement with the experimental results than when equation (1) was applied directly, using the entire volume of the cyclone, and indicated that even an approximate estimate of the actual volume of explosible suspension was helpful.

If the volume of suspension was an important factor governing the explosion pressure, the effect of vent position and shape on the pressure can be explained. For a vent of a given area, on the roof of the cyclone, a change in shape could affect the distribution pattern of dust and hence the volume of explosible suspension. Minor differences in explosion pressure were observed between radial and circumferential (i.e. near cyclone wall) slot vents[2]. A substantial increase in pressure was found when the vent was on the vortex pipe. This arrangement requires the explosion products to be drawn to the centre of the cyclone, and would increase the volume of dust suspension and hence the explosion pressure.

Because of practical imitations only one design of cyclone could be used and the calculated volume of explosible suspension was about 30 per cent of the total volume of the cyclone. Other designs of cyclone, and other dusts, are likely to give different percentages and for purposes of design of explosion venting direct testing may be necessary. Such testing need not involve explosion pressure measurements but could employ a non-explosible dust of similar particle size and density to that for which the plant is to be designed. The flow pattern of the test dust in the cyclone could be established either by direct observation through windows or by using sampling probes. It is possible that a modelling technique could be developed, enabling the necessary information to be obtained from small-scale tests, but such a technique has not yet been applied to this problem.

For the three dusts represented in Fig. 5, the area of vent in the roof of the cyclone required to keep explosion pressures below 15 kN/m^2 (2 lb/in^2) would correspond to a vent ratio of about 1 $m^2/18\ m^3$ (1 $ft^2/60\ ft^3$) which is considerably less than that customarily advised for plant of relatively small volume[1], but it does not include any safety margin. The reduced vent ratio implies that the dust distribution pattern established in the cyclone during normal working is not greatly disturbed before the arrival of burning dust. There are some conditions in industrial plant where disturbance could occur. For instance, if a filter unit is installed downstream of the cyclone and explosion developing in the filter propagates back into the cyclone, a large volume of burning suspension could be injected into the cyclone. With these conditions the whole of the volume of the cyclone could be filled with burning suspension, equation (1) in its original form would then apply, and a larger vent ratio would be required.

In plant design, provided adequate attention is paid to the consequences of ignition on the flow of dust suspension, the venting requirements for cyclones can be put on a firmer numerical basis than hitherto, although further measurements on controlled explosions in other designs of cyclone would be especially valuable.

1 m^3 and 30 m^3 vessels

Results have been reported for pressures developed in explosions of several dusts in compact vessels[4], approximately equi-dimensional, of volumes 1 and 30 m^3. The vessels were of sufficient strength to withstand the full explosion pressure, without relief venting, and the maximum explosion pressures for the closed 1 m^3 vessel were quoted together with the maximum rates of pressure rise for the closed 30 m^3 vessel (Table 2). The range of explosion pressures found when relief vents were used covered that for the validity of equation (2), and extended to lower values. The data can thus be used as another check on the validity of equation (2). The relation between the observed maximum rates of pressure rise, and those obtained in the small-scale standard pressure test apparatus[1] will be discussed later.

TABLE 2

Dust explosion parameters from ref 4

Dust	Vessel volume m^3	Maximum explosion pressure		Maximum rate of pressure rise	
		atm (gauge)	kN/m^2	atm/s	kN/m^2 s
Coal	1	6.9	690	–	–
	30	–	–	27	2700
Dextrin	1	9.2	920	–	–
	30	–	–	66	6600
Organic pigment	1	10.4	1040	–	–
	30	–	–	92	9200
Aluminium	1	12.0	1200	–	–
	30	–	–	195	19500

A clear conclusion in this and allied work[5] was that for explosions in closed vessels, of volumes between 1 m^3 and 30 m^3, the maximum rate of pressure rise was inversely proportional to the cube root of the vessel volume. The rate of pressure rise was higher with a powerful ignition source (pyrotechnic chemical) than with a weaker one[5] (electric spark) and increased with the explosibility of the dust from coal to aluminium (Table 2). The variation of maximum rate of pressure rise with vessel volume indicated that combustion was taking place in only part of the vessel volume at that instant, and hence that the dispersion of ignited dust was not sufficiently vigorous for the whole volume of the vessel to be simultaneously involved. When vents were provided it was assumed that the cube root relationship would still hold[4], so that for a given explosion pressure, the vent ratio required would be inversely proportional to the vessel volume. This assumption implied that combustion was still taking place in only part of the volume of the vessel, although the action of the vent would encourage movement of burning suspension throughout the volume.

In applying equation (2) to these results it is necessary to establish the time during the explosion at which the pressure reaches a maximum, which is likely to be at about the time that the flame has arrived at the vent. Before this time the flame is still expanding towards the wall of the vessel, and the volumeof combustion products would be increasing. Afterwards, burning material would be ejected from the vent, and the volume within the vessel would tend to decrease. The value of the constant K in equation (2) depends on the density (i.e. temperature) and specific heat of the material being vented. When equation (2) was derived originally it was assumed that combustion was taking place throughout the whole volume of the vessel, and that the vented material was hot. In applying the equation in the present case, the explosion pressure could reach a maximum when either hot or cold material was being vented. In the absence of direct evidence, values of K corresponding to the cold and hot conditions were tried and better agreement was found for the former condition. Thus the explosion pressure was assumed to have reached a maximum just before the flame arrived at the vent. This assumption involves an approximation because the flame front would be elongated towards the vent and spherical symmetry would be lost.

Curves calculated from equation (2) for the four dusts and two vessel sizes in Table 2 are shown in Figs 6 – 13, with the pressures and vent areas converted to the units used in the original work[4]. The values of maximum explosion pressure in Table 2 were taken for both volumes of vessel, and the maximum rates of pressure rise in the smaller vessel were calculated from the given values by using the cube root factor. The calculated curves are only valid down to 83 kN/m^2 (0.8 atm). Curves representing the experimental results[4] are included in Figs 6 – 13, as the original individual results were not given. For experimental purposes the relief vents were closed with bursting diaphragms, and the results for the weakest diaphragms of bursting pressure 10 kN/m^2 (0.1 atm) have been used. The derivation of equation (2) assumed that the vents were open, and the weakest diaphragm would be the best approximation. The effect of bursting pressure on the final explosion pressure remains to be considered.

From inspection of Figs 6 – 13 it may be seen that equation (2) is in general agreement with the experimental findings, and that the relatively large decrease in explosion pressure resulting from even a small vent is apparent. Equation (2) accounted for the explosion pressure in terms of the explosion parameters of the dusts, the vessel volumes and vent areas, for most of the conditions tested. The most serious discrepancy was for aluminium dust in the 30 m^3 vessel, where the pressures for smaller vents were higher than those calculated. Further experimental data would be valuable, particularly measurements of the position of the flame when the pressure was at its maximum.

Use of equation (2) for practical systems requires knowledge of $(dp/dt)_{max}$ for the dust in the volume of vessel concerned; this point is considered further, below. For low explosion pressures (but above 83 kN/m^2) the vent ratio (A/V) is approximately proportional to $(dp/dt)_{max}$ which may be dependent on $V^{-1/3}$. A method is then possible for the calculation of venting requirement as the scale of the plant is increased. Such plant would need to be relatively massive to withstand the pressures developed in explosions relieved through the vents, which are small when compared with those appropriate to equation (1). The influence of the power of the ignition source on the explosion pressure[4] requires that the venting should be related to the practical risk. Increased pressure could be expected from a large source, such as injection of an explosion flame from attached ducting or from more vigorous dispersion of the dust.

Closed vessels of different volumes

Attention has already been drawn to the reported findings[4,5] that for closed vessels of volumes between 1 m^3 and 30 m^3 the maximum rates of pressure rise of the dusts listed in Table 2 were inversely proportional to the cube root of the vessel volume. When the rates were extrapolated to a vessel of volume 1.2 l , that of the closed standard test vessel, the predicted values were several times greater than those measured[5]. This finding does not prove that the standard test, which is small-scale, is not valid for larger scale application, because an alternative explanation can be given.

On physical grounds it is unlikely that the maximum rate of pressure rise of a dust would continue to increase indefinitely as the volume of vessel is reduced. With larger volumes, where the 'cube root' function obtains, only part of the volume of the vessel is involved in combustion at a given instant, whereas with smaller volumes the assumption given previously[1] that all of the vessel volume was involved could be expected to apply. The changeover in behaviour, occurring at a vessel volume of V_o, would depend upon the type of dust, the method of dispersion and the ignition source. For volumes less than V_o, the maximum rate of pressure rise would be $(dp/dt)_{max}$, and for volumes greater than V_o would be reduced in accordance with the 'cube root' function. The value of V_o depends on the relative rates at which a well mixed volume of suspension would burn and at which ignited and unburnt suspension would mix. For a given mixing process, i.e. method of dust dispersion, V_o would decrease as $(dp/dt)_{max}$ was increased. The following relation is suggested

$$V_o = BV_s \, (dp/dt)_{max}^{-n}$$

where B and n are positive constants, and V_s is the volume of the closed standard test vessel (i.e. effectively a constant).

Then, for vessels of volume V, greater than V_o, the maximum rates of pressure rise (dp/dt) are given by

$$(dp/dt)/(dp/dt)_{max} = (V_o/V)^{1/3} = (BV_s/V)^{1/3} / (dp/dt)_{max}^{n/3}$$

$$(dp/dt) \, V^{1/3} / (dp/dt)_{max} \, V_s^{1/3} = B^{1/3} / (dp/dt)_{max}^{n/3} \qquad .....(4)$$

The lefthand term in equation (4) represents the ratio of the calculated to the experimental maximum rate of pressure rise in the standard test vessel. It has been plotted against $(dp/dt)_{max}$ on linear scales in Fig. 14 of Ref. 5 and showed an inverse dependence. The points have been re-plotted on logarithmic axes in Fig. 14 of this Note, and are for tests using the more powerful ignition source (pyrotechnic chemical) in the explosion vessels, and an electric spark in the standard test vessel. There is considerable scatter of the points, and the line (drawn by eye) can only give an approximate representation. From this n = 2.0 and values of B for different pressure units are given in Table 3. The line in Fig. 14 also gives approximate representation of results quoted for ignition with the less powerful source (electric spark) in the explosion vessels[5], indicating that the values of n and B would be as above. From a measurement of $(dp/dt)_{max}$ in the standard test vessel, equation (4) enables the relation between (dp/dt) and V to be calculated, for vessel volumes greater than V_o, i.e. where the 'cube root' function operates. The relation appears insensitive to the choice of ignition sources, provided they are relatively small, but may depend on the method of dust dispersion.

Further experimental evidence is needed. It is of interest that with polyacrylonitrile dust in a 5 m^3 vessel, using a slightly different dispersion technique[6], the value of $(dp/dt)_{max}$ was 1300 bar/s and that of (dp/dt) was 160 bar/s. The calculated value from equation (4) for the latter, based on the former was 177 bar/s. The extent of agreement may be fortuitous, when the scatter of points in Fig. 14 is considered, but further testing would be warranted.

TABLE 3

Values of B for different units of pressure

Pressure	B
atm	1.8×10^7
kN/m^2	1.8×10^{11}
lb/in^2	3.8×10^9

CONCLUSIONS

1. The equations derived in an earlier report, which related dust explosion pressures to the explosibity parameters of the dusts and the geometry of the containing vessels, have been tested against further data. Some extensions of the theoretical concepts were necessary.
2. Explosion pressures in vent ducting, which for practical reasons are relatively low, have been related to dust parameters and were shown to vary as the square of the length of the ducting.
3. Data from experiments with a vented cyclone have shown that provided the dust concentration is predominantly near the walls, as in the normal working of a cyclone, the explosion pressures were considerably less than for a homogeneous suspension. An approximate method of calculation of the reduction has been derived.
4. The explosion pressures in relatively large vessels, with small vents, were calculated from the original equation, with modification to cover the observed reduced rate of pressure rise in these vessels.

5. The relation between the maximum rate of pressure rise in the small-scale standard closed test vessel, and in much larger vessels, was discussed and a method of extrapolation proposed.

6. There is still a serious shortage of experimental data for dust explosion venting, which must be remedied if confirmation is to be obtained of the assumptions still necessary.

ACKNOWLEDGMENT

Dr W D Woolley programmed the calculator and graph plotter for Figs 6 - 13.

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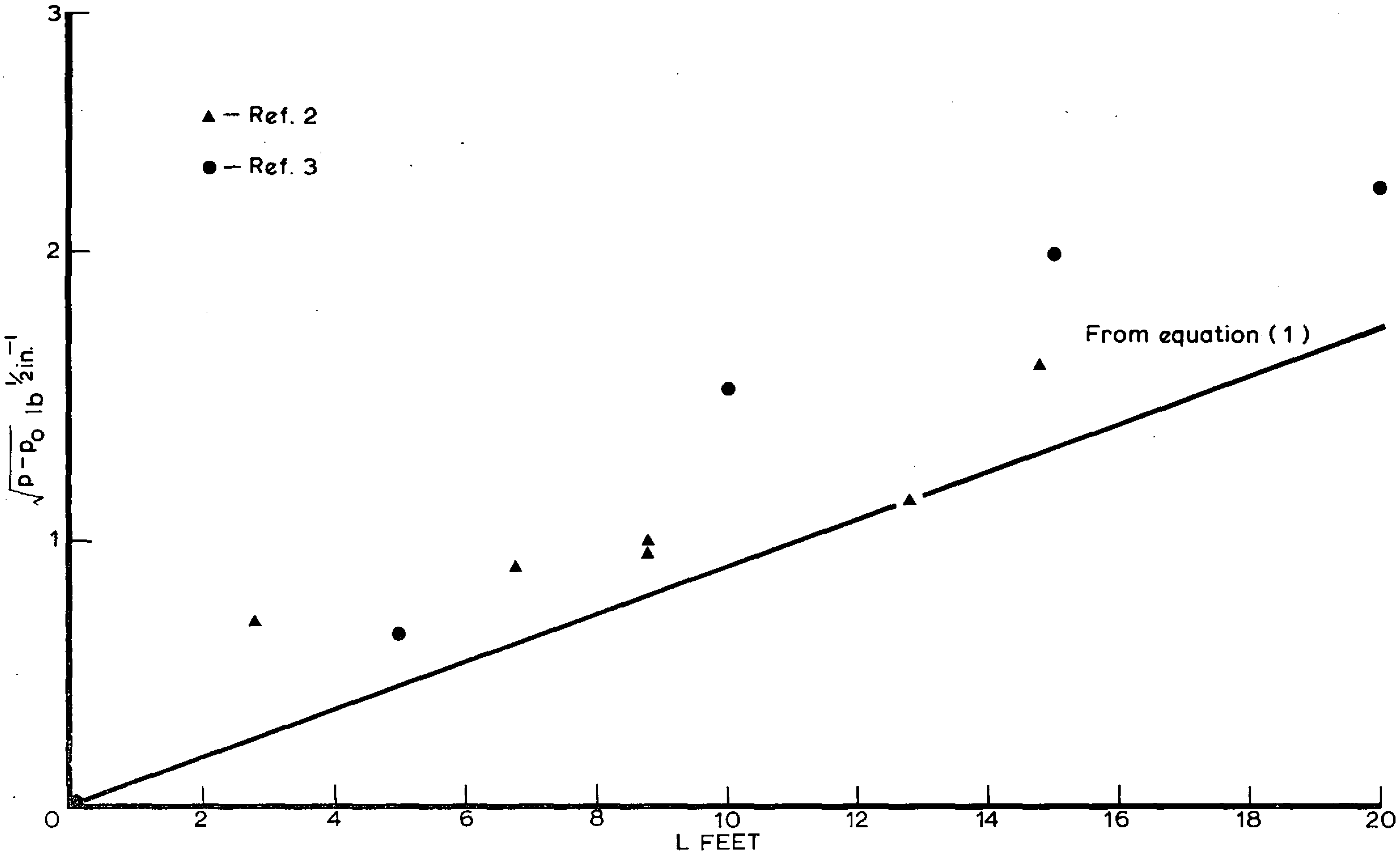

FIG. 1 DEPENDENCE OF PRESSURE IN CORK DUST EXPLOSIONS ON LENGTH OF VENT DUCTING

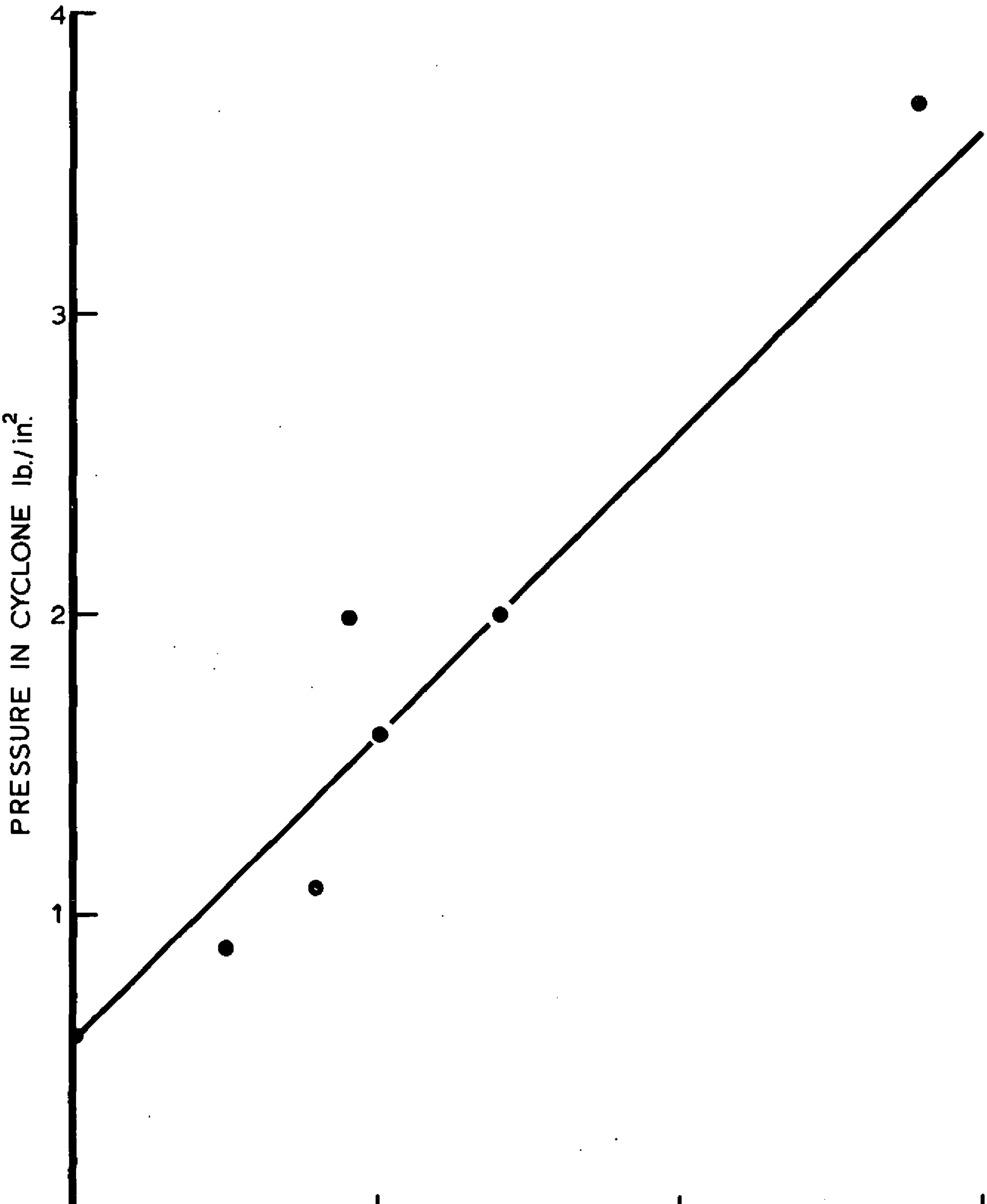

FIG. 2 CORK DUST EXPLOSION PRESSURES IN CYCLONE AND IN ATTACHED DUCTING (Ref. 2)

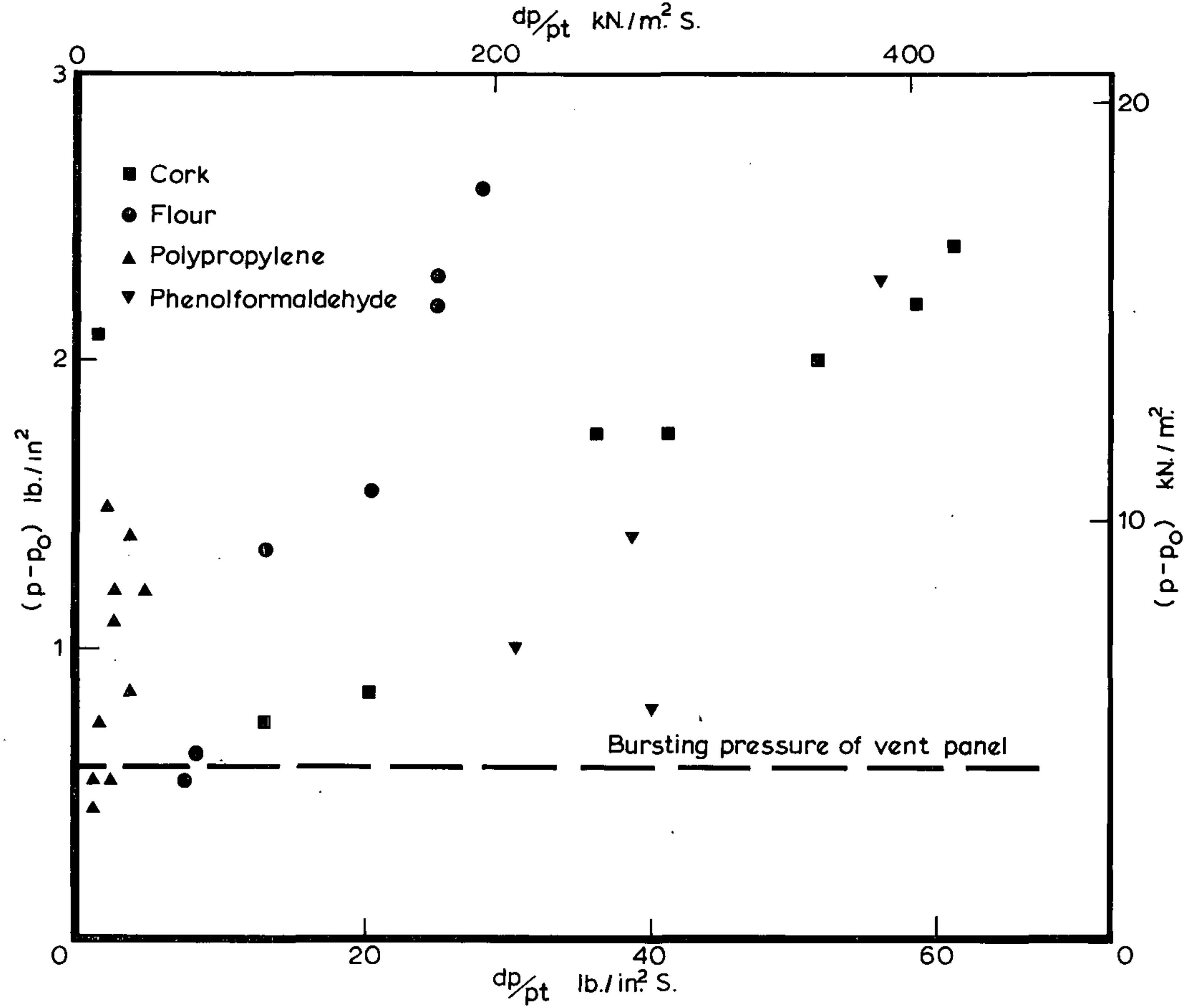

FIG. 3 RELATIONSHIP BETWEEN EXPLOSION PRESSURE AND RATE OF RISE IN VENTED EXPLOSIONS IN CYCLONE (Ref. 2)

12076 FR NOTE 961

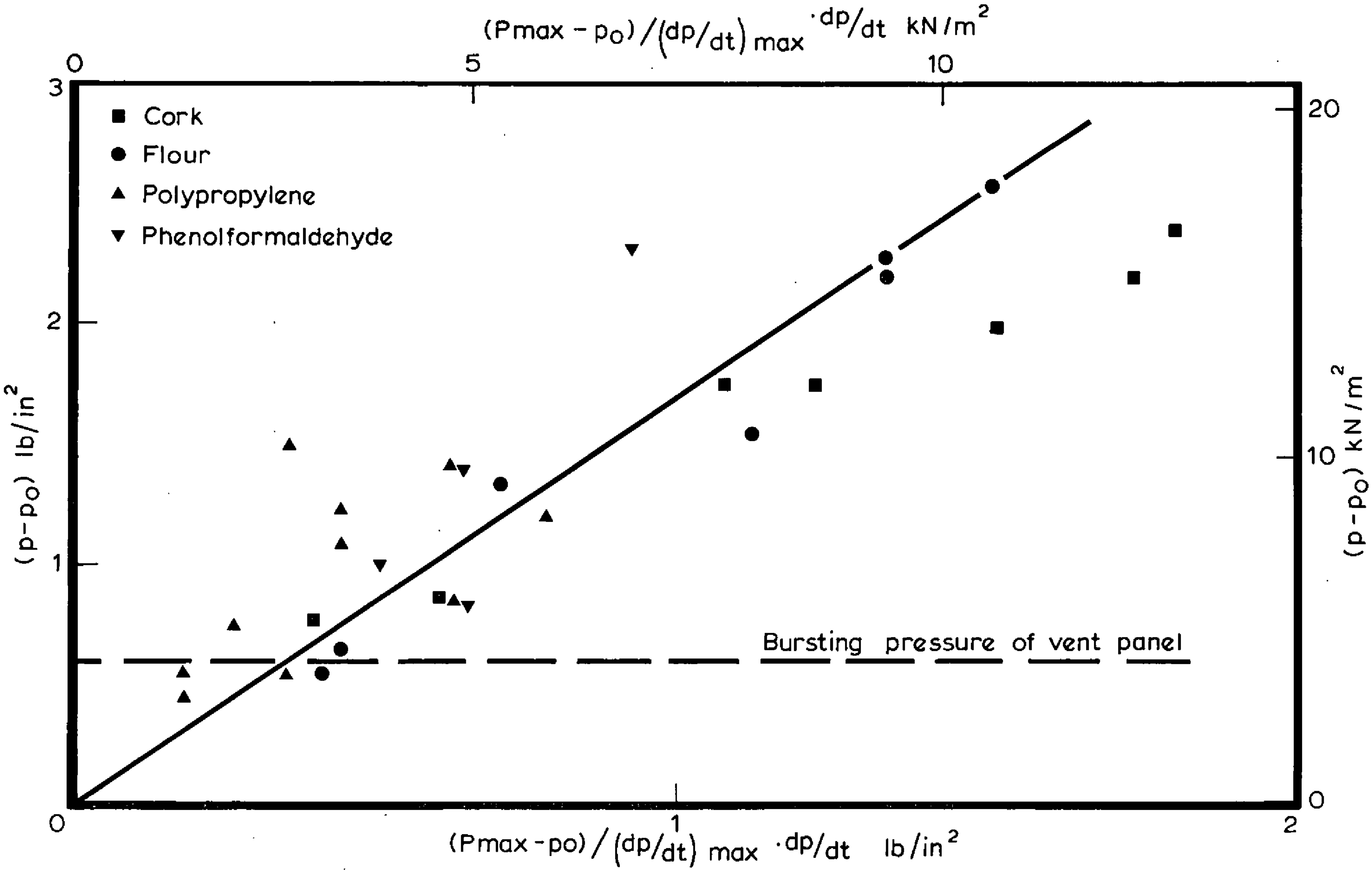

FIG. 4 BURNING CHARACTERISTICS OF DUSTS IN CYCLONE AND TEST APPARATUS COMPARED USING EQUATION 3

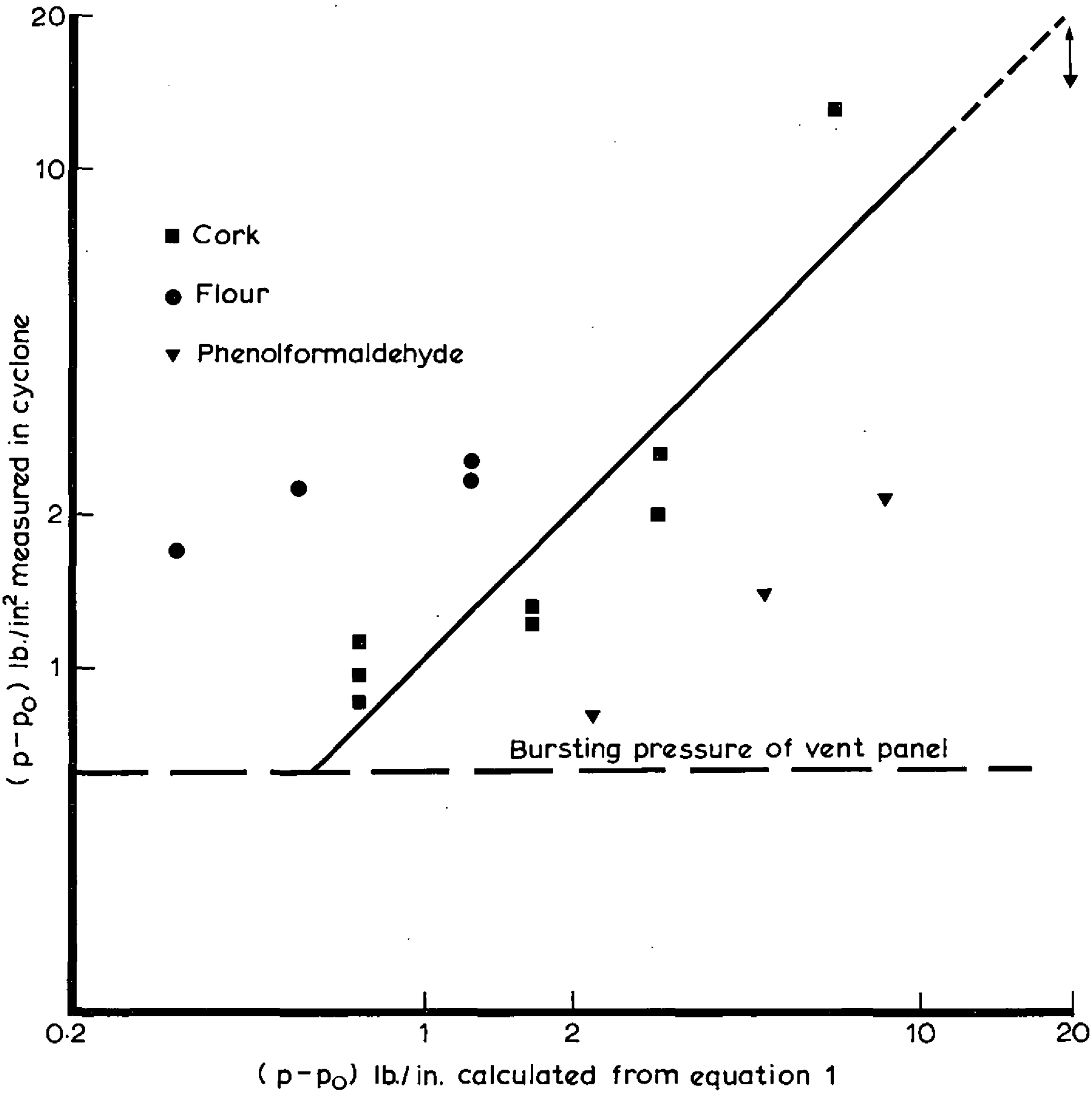

FIG. 5 RELATION BETWEEN MEASURED & CALCULATED EXPLOSION PRESSURES FOR THREE DUSTS IN EXPERIMENTAL CYCLONE PLANT

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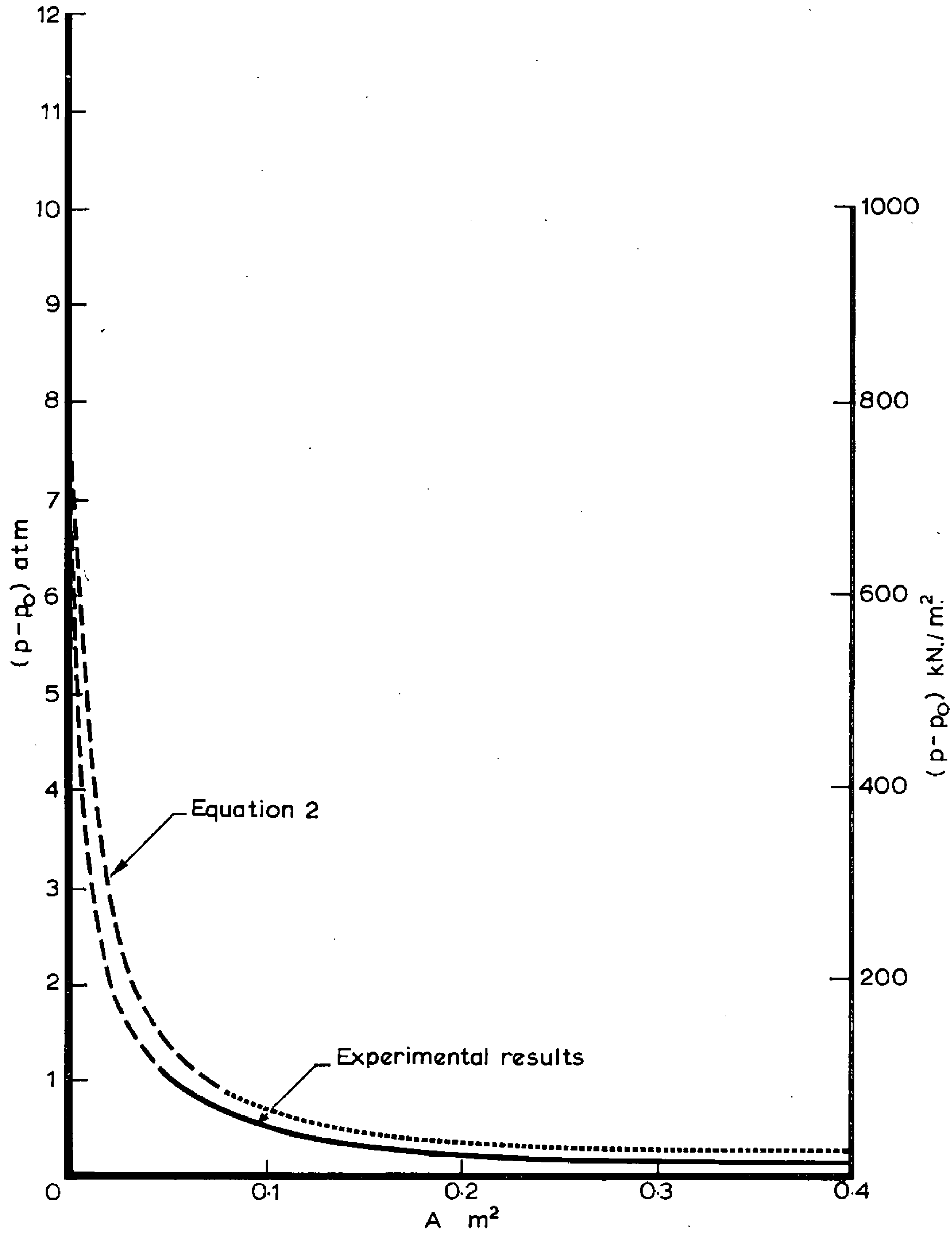

FIG. 6 COAL DUST EXPLOSION PRESSURES IN $1 m^3$ VESSEL (Ref. 4)

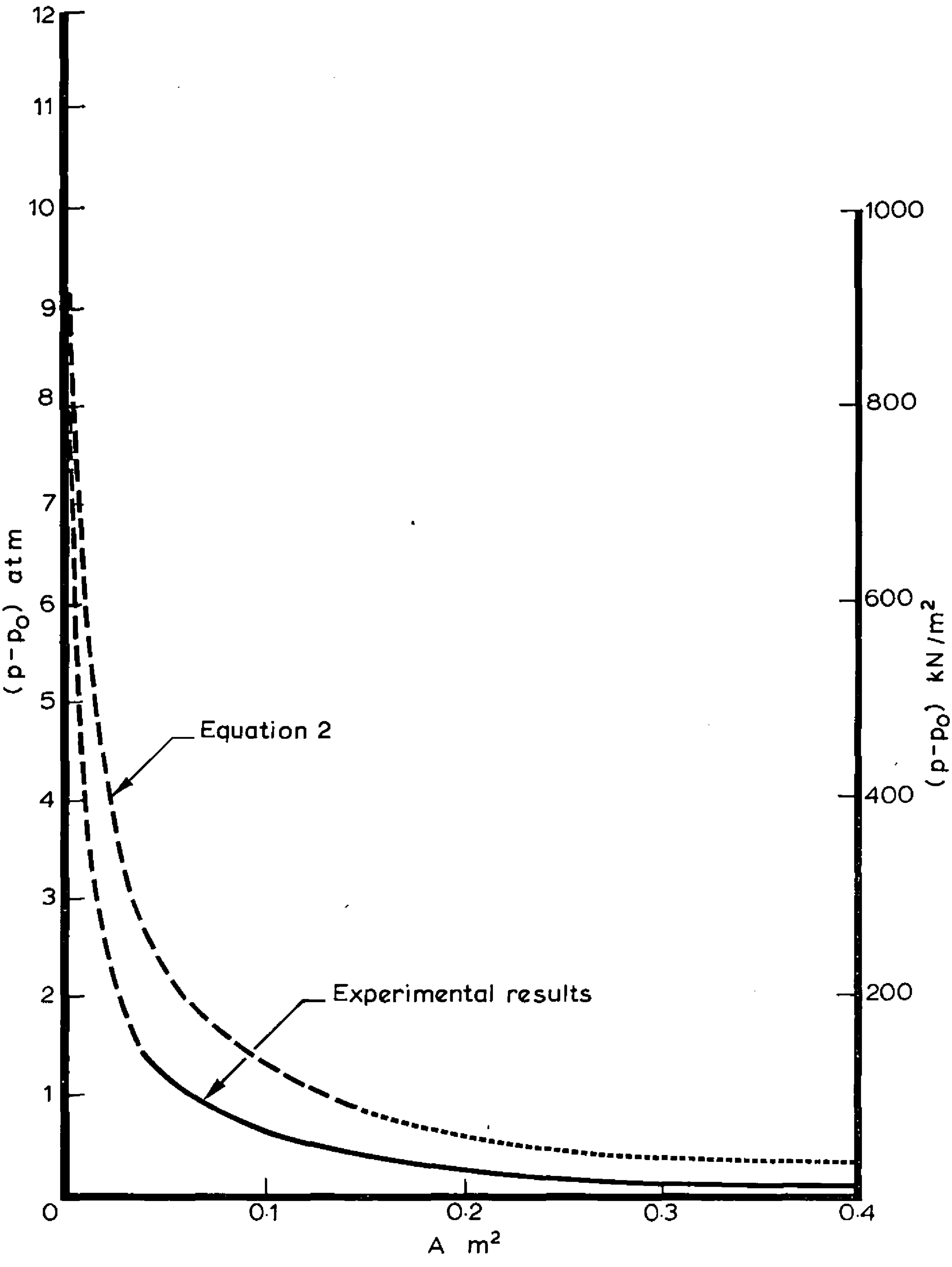

FIG. 7 DEXTRIN EXPLOSION PRESSURES IN 1m^3 VESSEL (Ref.4)

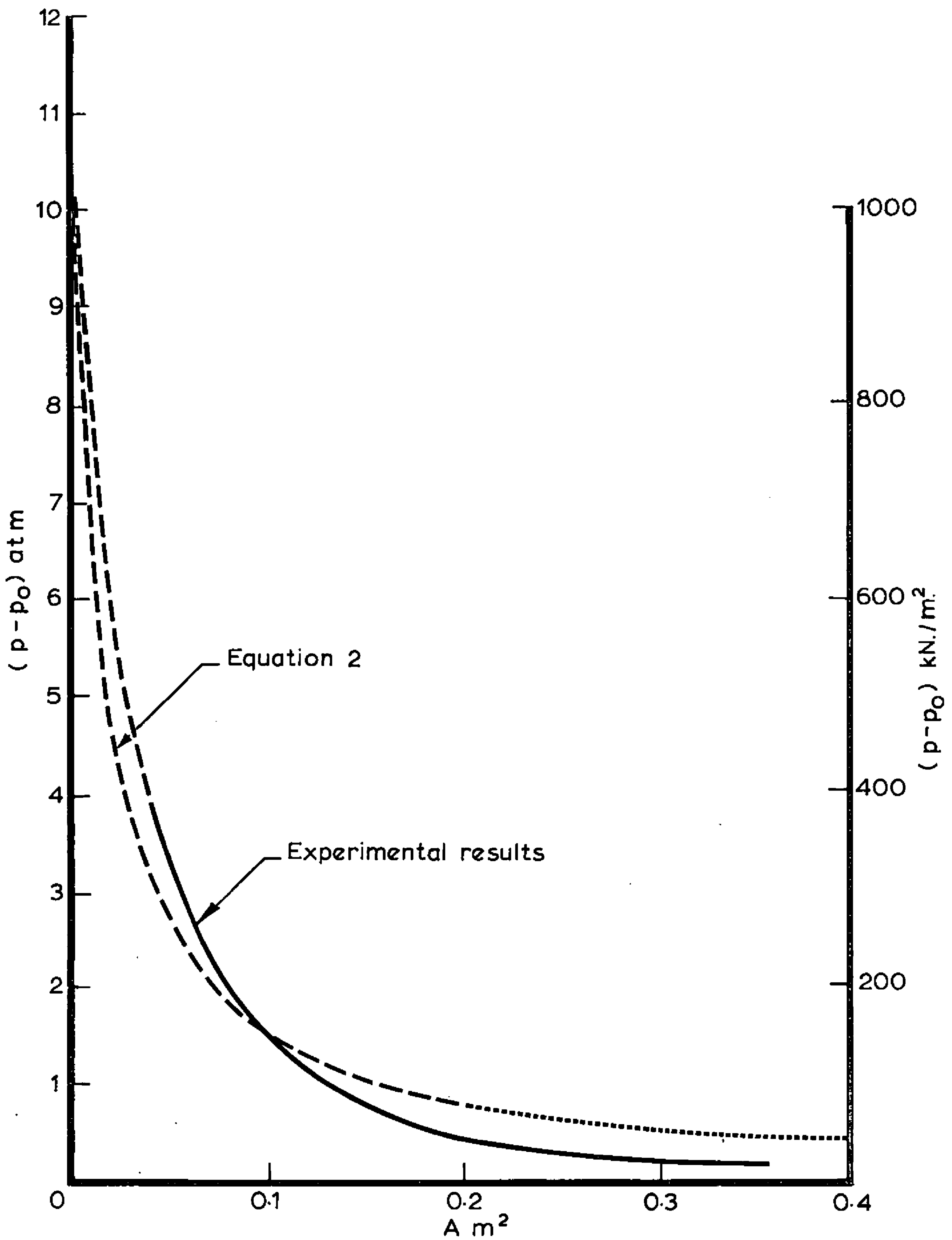

FIG. 8 ORGANIC PIGMENT EXPLOSION PRESSURES IN 1m^3 VESSEL (Ref. 4)

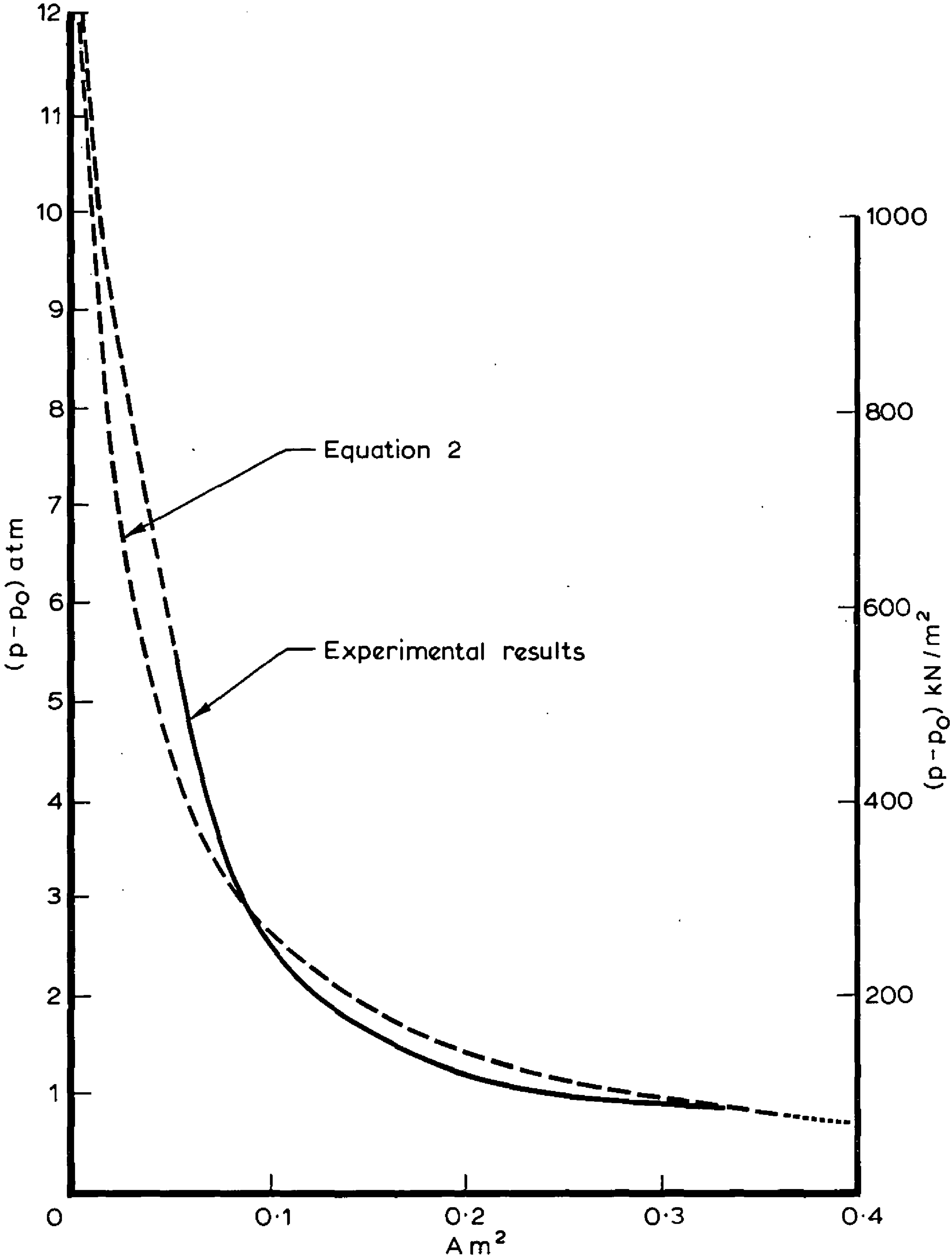

FIG. 9 ALUMINIUM DUST EXPLOSION PRESSURES IN $1m^3$ VESSEL (Ref. 4)

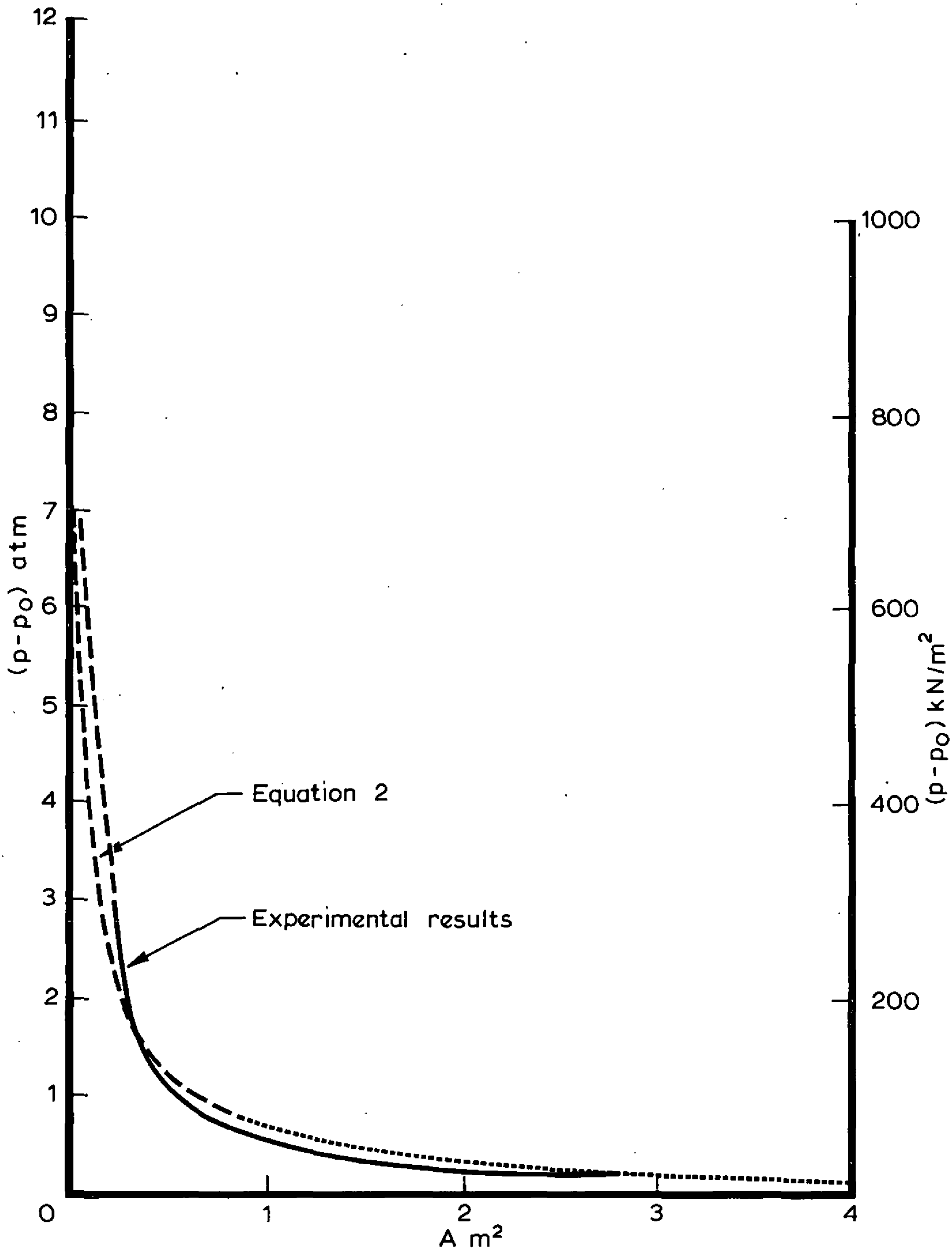

FIG. 10 COAL DUST EXPLOSION PRESSURES IN 30m³ VESSEL (Ref. 4)

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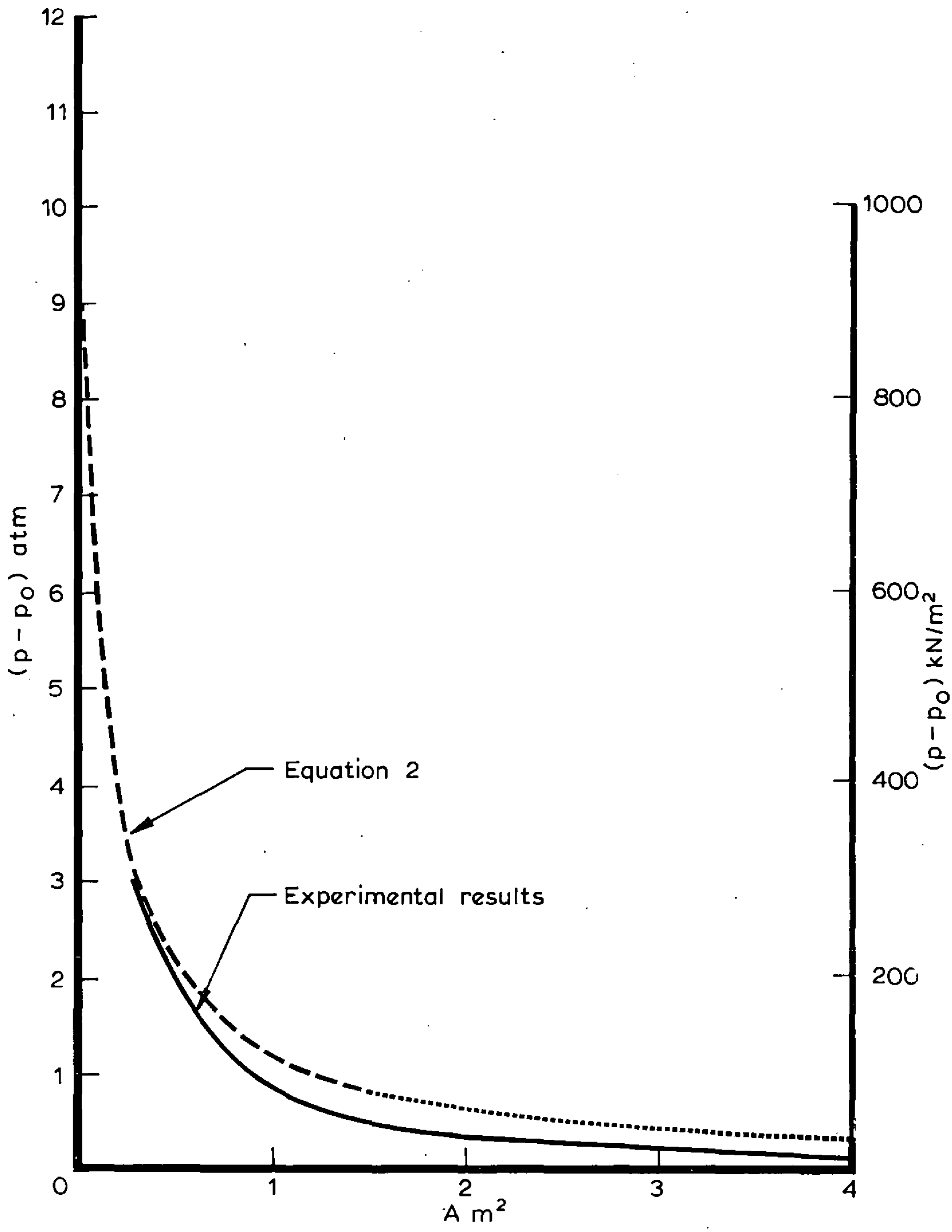

FIG. 11 DEXTRIN EXPLOSION PRESSURES IN $30 m^3$ VESSEL (Ref. 4)

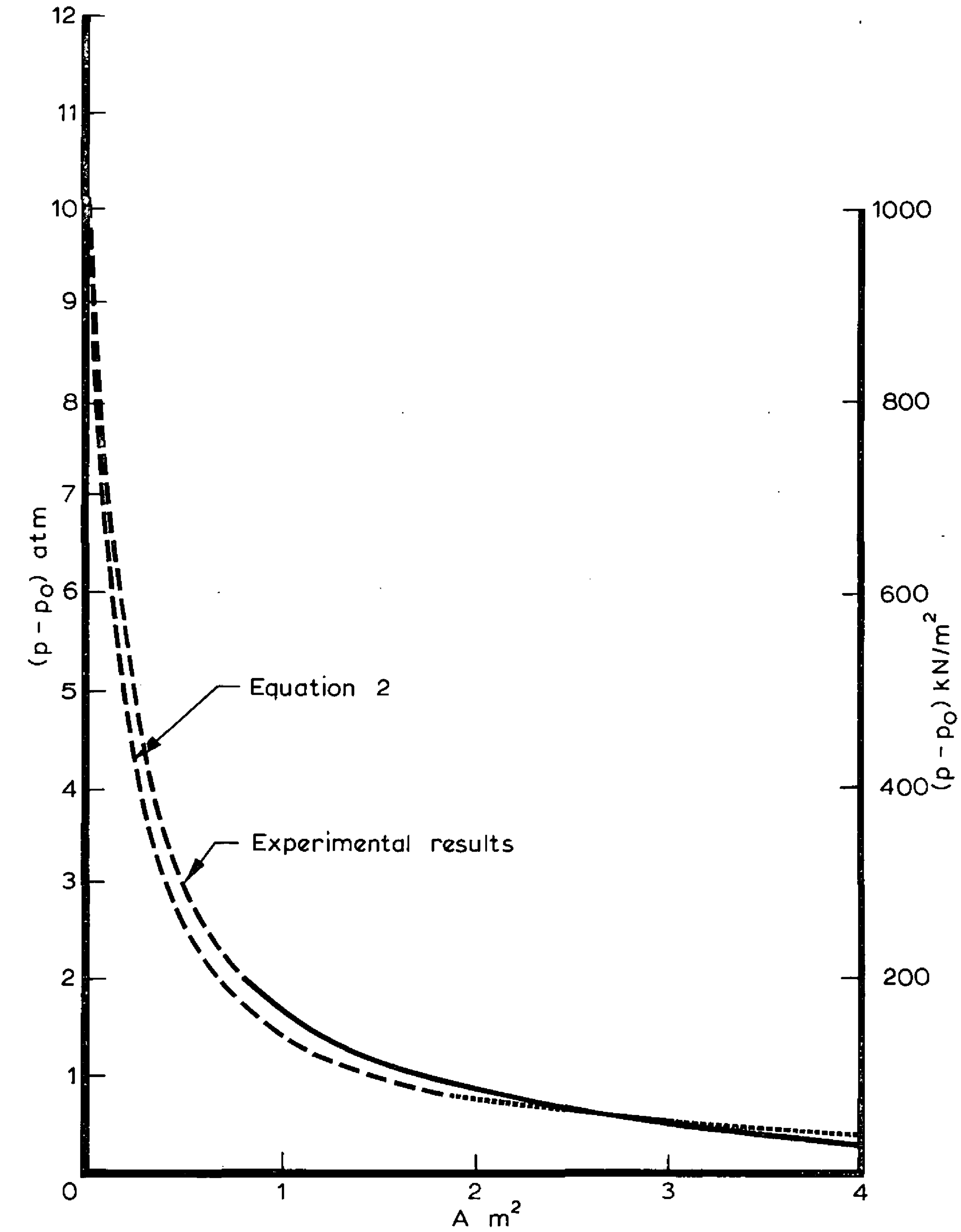

FIG. 12 ORGANIC PIGMENT EXPLOSION PRESSURES IN $30\,m^3$ VESSEL (Ref. 4)

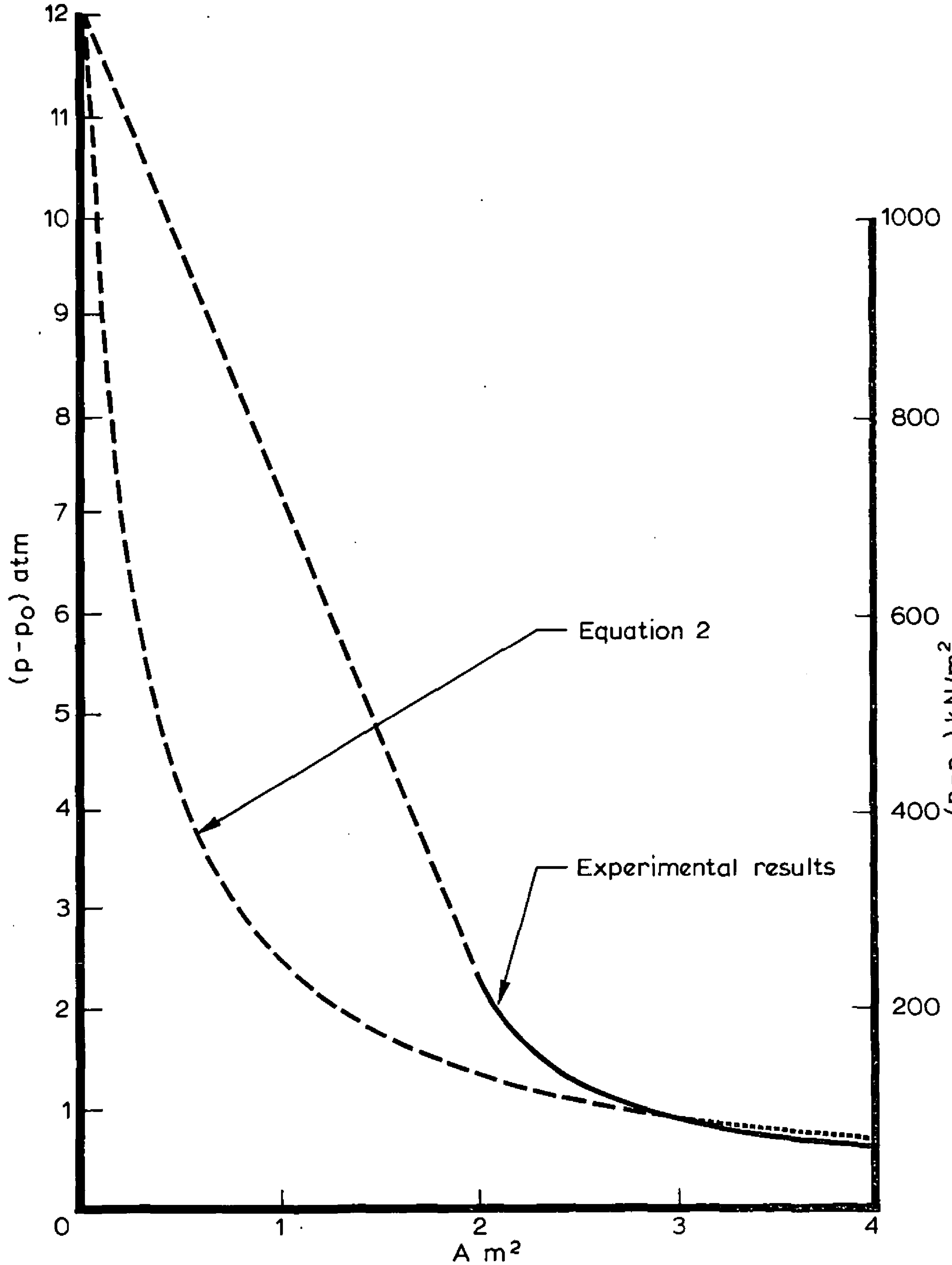

FIG. 13 ALUMINIUM DUST EXPLOSION PRESSURES IN $30m^3$ VESSEL (Ref. 4)

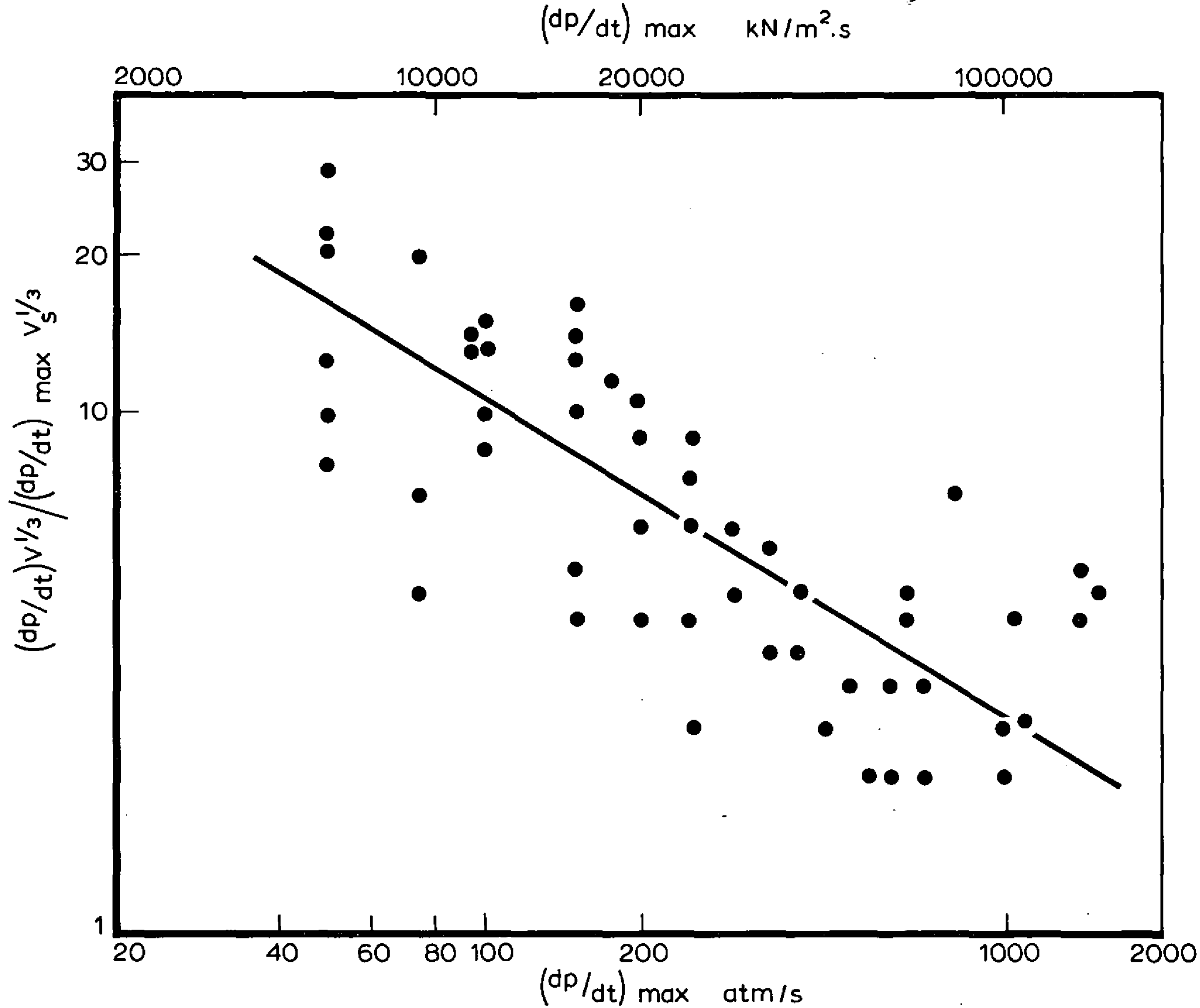

FIG. 14 APPLICATION OF EQUATION 4 TO EXPLOSION IN CLOSED VESSELS