SAFETY OF POWDER HANDLING SYSTEMS: REVIEW AND DETAILED DISCUSSION OF VENTING

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Many fine materials are explosible when dispersed in air. This paper briefly reviews the factors that influence the course of the explosion and methods that can be used either to prevent an explosion or protect plant, equipment and personnel against the destructive effects.
The major part of the paper concerns explosion venting, and describes and discusses published methods for estimating the vent requirements. The shortcomings of these methods are considered, along with the different types of vent closure and the special venting requirements for elongated vessels.

Keywords: Explosions, Venting, Powders, Safety.

INTRODUCTION

It is difficult in processes handling combustible dusts and powders to avoid the possibility of an explosion. Many fine materials e.g. coal, wood, flour, starch, sugar, rubber, plastics, some metals, pharmaceuticals etc are explosible if they are dispersed in air at a suitable concentration and in the presence of an effective ignition source. Pressures generated by explosions cannot be contained in most dust handling equipment and measures have to be taken either to prevent the explosion or to protect plant against the destructive effects.

The violence of the explosion depends on several factors concerning both the dust and the environment in which it is dispersed.

i) The dust itself: dusts vary in their explosibility, all other things being equal. Coal dust is of a relatively low explosibility, less explosible than aspirin and much less explosible than aluminium powder.

ii) The composition of the dust: some dusts - and coal is a prime example - are not homogeneous and can have very different compositions depending on the source. Coal dust is generally more explosible the higher the volatile content. Anthracite is sometimes considered to be non-explosible when its volatile content is low.

iii) The particle size and particle size distribution: the finer the particles the greater the surface area and thus the more explosible

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a given dust is likely to be. When the dust is made up of a series of particle sizes ranging from fine to coarse, the fines play the most prominent part in an ignition and in the propagation of an explosion; the effect of the coarse particles on the explosibility is not significant unless the fraction of coarse particles is high. Fine particles are more readily dispersible and stay in suspension longer, but can agglomerate in some circumstances, depending on the dust and the forces attempting to disperse it. The fineness of single particles - or the mean diameter of a particle size distribution - need not always be a reliable guide to the effective particle size in an actual explosion.

iv) The concentration of dispersed dust: when the concentration of dispersed dust is below a certain value, an explosion cannot be propagated. This concentration is the Lower Explosibility Limit (LEL). The explosibility of the cloud increases as the dust concentration increases until an optimum concentration is reached giving the highest explosibility; this concentration is usually well in excess of the amount of dust theoretically required to react with the available oxygen. At higher concentrations still the explosibility either decreases or stays roughly constant. The Upper Explosibility Limit (UEL) - the dust concentration above which an explosion cannot be propagated - is not as clearly defined as the lower limit. At high dust concentrations, the flame travels rapidly through a reactive volatiles/air mixture as soon as this mixture is formed and leaves the partly devolatilised particles in its wake (1). Only at very high dust concentrations is the inerting effect of these particles sufficient to quench the flame.

v) Moisture content: the explosibility of a dust falls as the moisture content increases. Eventually the dust is no longer explosible.

vi) Ambient temperature and pressure: although at a given dust concentration an increase in the ambient temperature decreases the maximum explosion pressure in an enclosed explosion, it has very little effect on the explosibility or rate of pressure rise. If the ambient pressure increases, both the maximum pressure and the explosibility increase.

vii) Turbulence of the dust cloud: dust clouds are usually turbulent to some degree because there must be some air movement if the dust is to remain dispersed. At low levels of turbulence the explosibility of a dust cloud may be relatively mild, but at high states of turbulence, when the flame front is broken up and its effective area much increased, the explosion will propagate much more rapidly and the effective explosibility will reach high values. This effect is very important in explosions moving through ducts and pipework because the confinement channels the air movement ahead of the explosion, generating high turbulence and driving the explosion to ever more rapid propagation. Constrictions and obstructions influence the development of turbulent explosions.

Over the years two methods have been preponderantly used to measure the explosibility of dusts : the Hartmann apparatus and the 20-l sphere.

The Hartmann apparatus was developed by the U.S. Bureau of Mines (2). The explosibility is defined as the rate of pressure rise measured in a confined explosion. Criticisms of the Hartmann technique centred around its small volume (1.3 l), its shape (cylindrical, giving ample opportunity for flame-quenching on the walls), its method of dispersion (a blast of air directed at a pile of dust) and difficulties associated with estimating the true dust concentration.

The 20-l sphere was developed at Ciba-Geigy and is now a widely accepted test for dust explosibility (3). A diagram of the apparatus is given in Figure 1. A weighed quantity of dust is kept under a pressure of 20 bar in the dust chamber and injected into the sphere through the perforated dispersion ring. The sphere is first evacuated so that as the injection of dust occurs the pressure at the moment of ignition equals 1 bar a. A delay of 60 ms between injection and actuation of a 10kJ chemical ignition source is specified in the standard test so that explosibility measurements are performed under similar states of turbulence.

The maximum measured rate of pressure rise in a series of tests at different dust concentrations is used to calculate a measure of the explosibility constant called the K_{St}-value. The maximum explosion pressure, P_{max}, is measured also in this test.

The K_{St}-value is given by:

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} V^{1/3} \qquad [1]$$

where $(dP/dt)_{max}$ is the maximum rate of pressure rise measured.

Equation [1] defines the so-called cube root law, and K_{St} is taken to be independent of volume, at comparable conditions of turbulence and dust concentration. Depending on the K_{St} value dusts are allocated to one of four groups:-

$K_{St} = 0$: Group St0 : Non-Explosible

$0 < K_{St} < 200$: Group St1
$200 < K_{St} < 300$: Group St2 (Increasing Explosibility)
$300 < K_{St}$: Group St3

Measurements of explosibility using the 20-l sphere cannot be correlated with measurement using the Hartmann apparatus.

Other important characteristics of explosible dusts measured in standard tests include:

i) The Minimum Ignition Energy - the electrical energy necessary to ignite a dust cloud. It ranges from a fraction of 1mJ to above 10^4 mJ (4).

ii) The Minimum Ignition Temperature - the minimum temperature of a standard furnace apparatus that will cause the ignition of a dust cloud. (5)

iii) The Glow Temperature - the temperature of a hot surface necessary to ignite a dust layer. In the standard test the layer is 5mm thick, but in practice the layer depth can strongly influence the glow temperature; the thicker the layer the lower the glow temperature. The glow temperature cannot be divorced from an induction time, defined as the time between initial heating and onset of glowing.

The standard test is limited to a period of 2 hours. (5)

iv) Limiting Oxygen Concentration - the concentration of oxygen in a mixture of oxygen and inert gas or gases which will just fail to support a dust explosion. In practice 2% is subtracted from the Limiting Oxygen Concentration to give the Permissible Oxygen Concentration. The Limiting Oxygen Concentration depends on the dust and the inert gas. Typical values range from 5-15% (4).

EXPLOSION PREVENTION AND PROTECTION : SHORT REVIEW

References (4), (6) and (7) give detailed guidance on dust explosion safety measures. A short discussion of prevention and protection techniques is given in this section of the paper; venting is discussed fully in subsequent Sections.

An explosion cannot take place if one of the following is true:

i) An explosible dust cloud is never allowed to form.
ii) There is insufficient oxygen to support an explosion at all times.
iii) All ignition sources capable of igniting a dust cloud are excluded.

It is difficult to prevent the formation of a hazardous dust cloud, although choice of plant can do much to minimise the problem. If the dust concentration normally exceeds the upper explosibility limit there will still be times - starting up, shutting down or in the event of a break down - when the concentration will be in the explosible range.

Like-wise, it is difficult to guarantee that the dust concentration will always remain below the lower explosibility limit. Dust particles readily settle out onto surface layers that can easily be dispersed by flow disturbances, producing a cloud with a concentration that will more than likely exceed the lower limit. Secondary explosions are a case in point: an explosion of a relatively small dust cloud can produce sufficient air movement to disperse dust which then fuels the flame and leads to extensive explosions causing much damage.

Limiting the oxygen concentration by feeding in inert gases - a technique known as inerting - is a highly effective method of preventing dust explosions if circumstances favour its application. Inerting is only suitable when the system is closed; it can be expensive both on initial outlay for equipment and monitoring devices and on running costs - depending on the leakage rate from the plant. Reliable monitoring of the oxygen concentration at various points in the plant is crucial, with trustworthy alarm and shut-down procedures.

The avoidance of all ignition sources capable of igniting dust clouds is generally not sufficient as a preventative measure because elimination is not reliable. This technique might be satisfactory when the dust has high values of minimum ignition energy and minimum ignition temperature and is handled in equipment that can be easily and thoroughly inspected, but when the dust has a low ignition energy or hybrid mixtures of dust and flammable gas are present, elimination of ignition sources is simply not feasible.

Important ignition sources that must be excluded as far as possible no matter what other precautions are taken include :- hot surfaces, electrical and mechanically generated sparks, static electricity, flames and spontaneous ignition of dust deposits.

Hot surfaces may be present by accident - welding and cutting operations - or by design - drying and heating plant. Precautions must be taken to exclude any dust while welding or cutting is undertaken. Indirect heating is preferable to direct heating. Electrical equipment should be kept away from dusty atmospheres if at all possible, and if it is not equipment should be designed to BS 6467. Dusts should not be allowed to accumulate on heated surfaces. The surface temperature should not be high enough to ignite settled dust layers. Burning material formed after surface heating or spontaneous combustion while in bulk storage can be conveyed into part of a plant where an explosible cloud exists and there act as an ignition source. Radiation detectors can be used to detect burning material in conveying systems and automatically actuate appropriate quenching methods - injection of water, carbon dioxide or other inerts - or isolation techniques - fast-acting valves. Carbon monoxide monitoring can be used to detect spontaneous combustion in storage plant. Tramp metal is often a cause of mechanically generated sparks and can be removed by magnetic separators or, alternatively, magnetic detectors can be used to automatically shut down the plant. Lubrication of moving parts such as bearings is an important measure against frictional heating; over-loading of equipment should be avoided. Static charges should be avoided by using conducting or anti-static material. Bulk dust itself can retain charges if the resistivity is high (greater than 10^8 - 10^9 ohm cm^{-3}).

If an explosion occurs there are several techniques used to curtail the destructive effects. The explosion can be completely enclosed. Explosion pressure resistant plant can withstand the explosion pressure of a confined explosion several times without permanent deformation. Explosion pressure shock resistant plant can withstand the explosion pressure of a confined explosion without rupture but with some permanent deformation (4). If plant is operated at pressures well below atmospheric either the explosion will not be supported because the pressure is too low, or the maximum explosion pressure will not reach 1 bar a e.g. if the operating pressure is 0.1 bar a then dusts with maximum explosion pressures less than 10 bar will remain confined in the plant (4).

Explosions must be isolated from other parts of dust-handling plant if the effects are to be limited. Rotary values, fast-acting valves, extinguishing barriers and relief pipes are some of the methods for doing this.

The most popular methods of keeping explosion pressures low are explosion suppression and explosion venting. Explosion suppression is a technique whereby suppressant is injected into an explosion as soon as possible after ignition. Explosion venting is a technique whereby low pressure panels open in the plant walls early in an explosion's life and the explosion is thus dissipated in the open air. However, it is not always a suitable method. Toxic, carcinogenic or radio-active material must never be vented.

STANDARD METHODS FOR ESTIMATING VENTING REQUIREMENTS

In this section, the basic methods of estimating venting requirements are described. A discussion of modifications and additions to these methods follows in later sections. Experiments show that the necessary vent area depends on several factors: the volume of the dust handling equipment, $V(m^3)$; the opening pressure of the vent cover, P_{stat} (bar a); the strength of the equipment, as indicated by the reduced explosion pressure, P_{red} (bar a) and the explosibility characteristics of the dust.

When the explosibility is characterised by the K_{St} value, a series of Nomographs, based on experiment and a model of explosion venting is available for estimating the venting requirements of compact enclosures.

A set of Nomographs is also available for the three St-Groups.

These Nomographs are published in VDI 3673 (8) and in reference (6), and allow the estimation of vent area when P_{stat}, P_{red}, V and the K_{St}-value are known; they apply to dusts with maximum explosion pressures up to 11 bar a for St1 and St2 dusts and 13 bar a for St3 dusts.

The original K_{St}-Nomographs do not apply when:

- i) vent bursting pressures, P_{stat}, are less than 1.1 bar a;
- ii) reduced explosion pressures, P_{red}, are less than 1.2 bar a;
- iii) K_{St}-values are less than 50 bar m s^{-1};
- iv) Vessel volumes are greater than 1000 m^3.

The first two limitations are especially important because they render the Nomograph approach unsuitable for low strength equipment, and in the UK and USA, low strength dust handling plant is widely used.

However, the Nomographs have recently been extended so that they can be used for dusts with K_{St}-values between 50 bar m s^{-1} and 10 bar m s^{-1}. These Nomographs are shown in Figures 2, 3 and 4 (9).

The Nomographs have been further extended so that guidance is available when the reduced explosion pressure is less than 1.2 bar a. A graph is shown in Figure 5 relating the reduced explosion pressure to the quantity $A_V/V^{2/3}$ for a series of K_{St}-values. Some proviso should be made about the value of P_{stat} in a practical situation, and it is recommended that in the range 1.2 bar a $< P_{red} >$ 1.05 bar a, the value of P_{stat} should not exceed $(1 + \frac{P_{red}-1}{2})$ bar a (9).

Another method that can be used to estimate vent areas for low-pressure equipment has been devised for the new NFPA 68 (10) and is described in a paper by Swift (11). Although derived for gas explosions the method can be used for dust explosions when an appropriate constant is substituted in the equation:

$$\text{Vent Area} = \frac{C\ A_S}{(P_{red}-Pa)^{1/2}} \qquad [2]$$

where A_S is the total internal surface area of the vessel, P_a is the atmospheric pressure and C is a constant with a value dependent on the dust explosibility and turbulence in the dust cloud. The values of C suggested in the Draft NFPA and its discussions are, in units of $(psi)^{1/2}$

	Set (a)	Set (b)
St1 dust	0.10	0.08
St2 dust	0.12	0.14
St3 dust	0.20	0.25

Swift suggests a value of 0.19 $(psi)^{1/2}$ for highly turbulent explosions of St1 and St2 dusts. Comparisons between calculations using Equation [2] and Figure 5 show that both methods give very similar results.

Comparisons can also be made between predictions from Figure 5 and estimates of vent area using a technique known as the vent ratio approach. The vent ratio approach is, however, based on Hartmann bomb results and rate of pressure rise measurements in the Hartmann bomb cannot be satisfactorily correlated with the K_{St}-value. Recommended vent ratios are given in Table 1; for $(dP/dt)_{max}$ <350 bar/s the vent ratio drops linearly from 1/6.1 m^{-1} to 1/25 m^{-1} when the volume increases from 30m^3 to 300m^3. Information given in reference (6) suggests that the vent ratio approach is applicable to low K_{St} dusts only, and an approximate comparison between Hartmann rates of pressure rise and K_{St}-value is given in reference (12).

The vent ratio approach is strictly applicable only when P_{red} equals 1.14 bar a; Table 2 gives some comparisons of predictions from Figure 5 and the vent ratio approach for this reduced explosion pressure.

When the vent ratio equals 1/6.1 m^{-1}, approximate agreement is obtained when the K_{St} is around 100-150 bar m s^{-1}, but in reference (6) it is suggested that the true comparison is with K_{St} = 50 bar m s^{-1}, and in that case, Figure 5 gives lower vent areas than the vent ratio approach at all volumes up to 1000m^3. Other comparisons in Table 2 show that, for approximately like conditions, Figure 5 gives lower vent areas than the vent ratio approach.

MODIFICATIONS OF THE NOMOGRAPH METHOD

Reducing Venting Requirements

The vent areas predicted by the Nomographs are generally conservative ie. they predict larger vent areas than may be necessary. This conservatism is a result of two factors - the high maximum explosion pressures at which the Nomographs apply, and the high state of turbulence generated in the standard method of measuring K_{St}-values. In practice, most dusts have maximum explosion pressures less than 11 bar a, and the turbulence of the dust cloud prior to an explosion may be much less than in the standard test, leading to lower rates of combustion, lower rates of pressure rise, lower reduced explosion pressures and lower vent area requirements. It has been argued that when conditions are relatively mild, venting requirements could be reduced with no real loss in safety.

By the same token, however, this conservatism introduces a factor of safety that can accommodate any unforeseen circumstances tending to make the explosion more violent than expected, and it is for this reason that relatively high turbulence is used in the 20-l sphere test.

Radandt has carried out some dust explosion tests on a number of compact vessels up to 250m^3; the results are reported in a paper by Bartknecht. The results showed that the reduced explosion pressure generated by a vented explosion in the larger volume is higher than suggested by extrapolation using the cube-root law (equal reduced explosion pressures when $A_{V1}/A_{V2} = V_1^{2/3}/V_2^{2/3}$) from measurements of reduced explosion pressures in smaller volumes. This effect has been attributed to the back pressure exerted by the explosion of vented dust external to the vent, and is greater at low reduced explosion pressures when the amount of dust burnt outside the vessel is necessarily large. When the volume exceeds 250m^3 vent area requirements are almost independent of K_{St}-values (in Groups St1 and St2) and in practice higher values of K_{St} may need to be specified than actually measured.

In addition to this departure from the cube root law the measured explosion pressures were less than predicted by the K_{St}-Nomographs because, whereas the

Nomographs apply to dusts with a maximum explosion pressure, P_{max}, of 11 bar a (for St1 and St2 dusts) the dusts used in Radandt's experiments had P_{max} values of less than 10 bar a. Radandt has published a set of Nomographs based on these results and they are reproduced in Figures 6 and 7; they refer only to the St1 and St2 groups and not to individual K_{St}-values. When the K_{St}-value is towards the lower end of the particular St group, the standard K_{St}-Nomographs predict lower vent area than the Radandt Nomographs.

The effect of turbulence on the reduced explosion pressure of dust explosions has been most effectively demonstrated by Eckhoff (14). In a series of experiments in a large silo and with a method of dust injection that produced relatively low turbulence, Eckhoff demonstrated that reduced explosion pressures were much less than predicted by the usual methods and measured in tests by other authors using higher levels of turbulence. In real dust handling systems the conditions are not necessarily as severe as the Nomographs allow for; reduced explosion pressures produced by explosions in dust handling equipment running as it would in normal use have been shown to be less than predicted values (15, 16). Eckhoff has gone on to describe a risk analysis approach to the assessment of vent area requirements (17). In real dust handling equipment explosions will not always be of the same severity because of variations in dust concentration, turbulence levels, energy and position of ignition source etc. So over the lifetime of a plant a distribution of reduced explosion pressures will be encountered. If the vent is oversized all likely explosions will generate low reduced explosion pressures which never even come close to exceeding the strength of the plant. If the vent is undersized an unacceptably large fraction of all likely explosions will produce reduced explosion pressures exceeding the strength of the vessel. Somewhere in between is a vent area at which there is an acceptable residual risk which needs to be determined by taking into account any precautions that have been taken to limit the risk of an explosion and an overall risk analysis. The Nomographs design for the worst possible case, and even if the Radandt versions are used, the level of turbulence and dispersion of the dust are such as to lead to more reactive conditions than are usually met with in practice.

Any comparison of the state of turbulence in a standard test and the likely state in a real situation is to some extent subjective, however. Eckhoff most probably would describe the turbulence generated by the dust injection procedure used in the 20-l sphere as high, whereas Pineau describes it as only moderately high (18) and suggests that in circumstances where an explosion results from an ignition by an extensive ignition source, such as a jet of flame entering a vessel from pipework, the K_{St}-Nomographs would under-estimate the necessary vent area. Pineau has devised some Nomographs that are applicable to highly turbulent explosions based on some tests in $1m^3$, $10m^3$ and $100m^3$ vessels with (L/D) ratios of 3.5, an end vent, and an ignition delay of 170 ms in the $1m^3$ vessel rather than the 600 ms in the standard VDI $1m^3$ vessel test. Dusts are characterised in this CERCHAR test by the rate of pressure rise (bar s^{-1}) and labelled $K_{MAX,T}$ but there is only a rough correlation between $K_{MAX,T}$ and the K_{St} value. The CERCHAR Nomographs are reproduced in Figures 8 and 9.

The problem that confronts the users of vent-sizing methods is how can a reliable safety margin be specified when the state of the dust cloud in many industrial processes is unknown. Although it is possible to divide industrial dust handling equipment into several broad ranges of likely turbulence the actual circumstances of a dust explosion may render such a classification invalid. A relatively low turbulence dust cloud may become highly turbulent during an explosion because of a large ignition source, rapid gas movement and presence of obstacles. A differentiated approach to vent sizing may be required in the future, but it will require a great deal of experimental work using dust-handling equipment operating in a real situation and with explosions generated in credible circumstances. Until the problem of accurate vent area specification is resolved with adequate consideration of acceptable risk and shortcomings in test methods - one of which is a probable lack of correlation beween different dusts when their explosion violence is measured by different methods and in different circumstances (19) - general Nomographs and simple equations remain the only reliable methods of vent sizing.

METHODS OF VENT CLOSURE

Several types of vent closure are available. All vent closures should open at as low a pressure as is possible in the prevailing circumstances and present a minimal amount of resistance to the venting process.

Diaphragms

A sheet or membrane of material firmly clamped around its edges can make an inexpensive vent closure (Figure 10). A wide mesh support is often fitted inside the vent when either the process is operating at pressures below atmospheric or as protection against gusts of wind. The vent area must be calculated with the blockage caused by this support taken into account. The membrane can be made out of a number of materials all with advantages and disadvantages (6). Ideally the material should tear and fragment rather than stretch; bursting pressures are best measured using the size of panel that will be used in practice because the static bursting pressure, P_{stat}, of most materials increases substantially as the area falls (< .15m diameter) (3). With some materials the dynamic bursting pressure may be markedly higher than the static bursting pressure, again especially at low areas (< .1m diameter). Some materials will soften at elevated temperatures and some will become brittle in cold weather.

Bursting Panels

Proprietary bursting panels are designed to open at pre-set values of P_{stat}. Usually they comprise scored steel sheets either backed by or sandwiching a PTFE membrane (Figure 11). When the panel opens the sectors petal apart leaving an unobstructed vent. When the explosion is particularly violent metal sectors can tear completely away and be projected for several metres. These panels usually operate within ± 10% of the quoted P_{stat}, although an elevated temperature will alter the opening pressure. Vibration or flutter of panels can cause a reduction in the working life of bursting panels (and diaphragms) especially if the area is large and P_{stat} low.

Rigid Panels

When the panel is held in place by a method that is less strong than the material of the panel, the panel will be ejected bodily from the vent opening when an explosion occurs; these vent closures are known as rigid panels or "pop-out" panels. The panels must have low weight (< 6kg/m²) and should be easily swept aside by the blast of the explosion so that there is minimal obstruction to the flow. Panels can operate at low overpressures (0.06 to 0.1 bar g) and generally have high stability, although very large panels should not be installed on vertical surfaces unless they have the necessary rigidity. One popular method of securing these metal panels is by shaped rubber clamps around the entire periphery (Figure 12). Rubber clamps need regular inspection so that corrosion or embrittlement does not go un-noticed. Light weight panels on horizontal surfaces (Figure 13) can be secured by magnets and sealed by a slightly compressed foam rubber strip (20). Spring-loaded latches and shear pins and washers can also be used but care must be taken to ensure the catches operate at the proper pressure - reliance should not be placed on manufacturer's values - and that corrosion, lack of lubrication and snow or ice have not rendered them ineffective. Panels should be restrained by chains or ropes to prevent them acting as missiles; if a vent duct is in place a cage can be fitted over the end to catch the panel without causing any subsequent impediment to the flow.

Explosion Doors

Explosion doors are hinged explosion panels, sufficiently strong that they are not destroyed and deformed. Their weight should be as low as possible, depending on the strength of the equipment being protected (typical values are $10kg/m^3$ or $25kg/m^3$). The doors are hinged at the top and flip open in the event of an explosion and then re-close, preventing the ingress of air and subsequent fires. The efficiency of explosion doors is only 60%-80% that of panels of the same area and this needs to be taken into account when vent areas are calculated. Doors can be sealed against foam rubber on horizontal or sloping surfaces.

All vent closures need to be well maintained. There should be no rise in the operating pressure either because of build-up of process material on the inside or because of snow or ice on the outside. Likewise their must be no fall in the operating pressure because of corrosion, fatigue or other deterioration of the closure.

VENTING METHODS FOR SPECIFIC DUST HANDLING EQUIPMENT

Information for venting particular types of dust handling equipment can be found in reference (6). In this section some information on silos and pipelines is given.

Silos

In any dust handling equipment the nearer the vent can be placed to the likely source of ignition then the lower the reduced explosion pressure will be, all other things being equal. Although silos have length/diameter (L/D) ratios greater than 5 and are thus outside the range of the K_{St}-Nomographs, Eckhoff (19) has compared predictions against measured reduced explosion pressures at different positions of the ignition source relative to a vent in the roof. When ignition is furthest from the vent, measured pressures exceed the predicted ones even for the low states of initial turbulence provided by Eckhoff's dust injection procedure. Radandt has published a set of Nomographs for silos and these are given in Figures 14 and 15. These Nomographs are based on experiments in a number of horizontal and vertical silos using the injection technique of the 20-l sphere (21). His measurements of reduced explosion pressure and its variation as the ignition position changes demonstrate the same trend as do Eckhoff's, and also show that the maximum rate of pressure rise occurs when ignition is at the centre point. Reduced explosion pressures decrease when the cloud occupies a fraction of the volume, but only when this fraction is less than 50%. Radandt's measurements exceed the predictions given for compact enclosures, as do Eckhoff's. The Radandt silo Nomographs are very conservative if compared to some of Eckhoff's results (14). Pneumatic conveying of dust into silos does produce lower reduced explosion pressures than the usual VDI method of injection, all other things being equal, although still in excess of predictions from the compact enclosure Nomographs (21).

Explosions in Ducts and Pipelines

In some circumstances, dust explosions in pipelines can reach very high velocities and generate very high pressures. When an explosion is initiated near the closed end of a duct, the volume expansion caused by the combustion has nowhere to escape except along the duct, and a flow away from the point of ignition begins, carrying the flame with it. The flow of gas ahead of the flame becomes turbulent, the flame front is broken up and its area increased. The rate of combustion is by this means accelerated, leading in turn to faster flow speeds along the duct, higher turbulence still and further increases in the rate of combustion. The explosion is thus carried along at an ever increasing rate, generating higher pressures as it goes, and eventually, if conditions are right, reaching a detonation or quasi-detonation state.

An idea of the flame speeds and explosion pressures that can be developed is given in work by Gardner and his colleagues at CERL (22). Using coal dust and 30m of 0.6m diameter straight duct, flame speeds of 300 m/s and pressures up to 2 bar a were recorded; but when a $20m^3$ explosion chamber was connected to 40m of duct, flame speeds of 2200 m/s and pressures as high as 33.3 bar were obtained. The highest pressure measured in Gardner's work was 81.5 bar, with a flame speed of 2850 m/s, using a coal containing 41.0% volatile matter. In this type of explosion there is a coincidence of the accelerating flame front with the peak of the pressure wave.

A model by Pickles (23) gives some approximate values for two critical conditions that are important for determining whether or not a dust explosion will propagate in a duct. Pickles' model suggests a critical initial velocity is necessary if a dust explosion is to develop; a value of 40 m/s or so is calculated for a coal dust explosion in a duct with a radius of 1.4m. This critical velocity increases as the duct radius falls, and the model suggests that below a certain radius the value of critical velocity increases so rapidly as the radius continues to fall that essentially it becomes impossible to propagate an explosion.

Pickles' model gives a critical radius of approximately 0.5m, a value which can be compared to data given by Cybulski (24), which indicates that a critical duct diameter for coal dust is about 0.5m.

Aspects of turbulent acceleration of dust flames in ducts have been considered in a model by Clark and Smoot (25). The calculations showed that the flame accelerates more rapidly and propagates at higher velocities in larger ducts because as the diameter increases so do the turbulent Reynolds Number and the turbulent flame velocity. This result is not borne out in measurements by Pineau and Ronchail (18), however, which show a decrease in both maximum measured flame speed and maximum explosion pressure as the duct diameter rises, although the experimental duct diameters (.25 - .7m) are below the diameters for which Clark and Smoot reported their calculations (1m - 2.5m). Pineau and Ronchail concluded that dust flames (wheat flour and wood flour in their experiments) were capable of propagating through ducts of diameter 0.5m and 1m (and length 40m) when an explosion vessel of $1m^3$ preceded the duct. There was only limited propagation through a 0.25m diameter duct, however. If the duct length exceeded 40m, flame speeds of 2000 m/s and pressures at least equal to 20 bar could develop. Vents of sufficient area placed either in the explosion vessel or the duct itself could prevent the development of these destructive explosions.

In later experiments with coal dust (26) Pineau and Ronchail showed that explosions in ducts on their own were improbable below a diameter of 0.25m, but could propagate towards an open end through ducts of 0.15m diameter if a $1m^3$ explosion vessel was attached to the duct. If the duct and vessel were totally unvented, high explosion pressures (10-20 bar) could develop even though the flame did not travel the whole length of the duct.

The new NFPA 68 code for dust explosion prevention and protection (10) provides guidance for safe venting of dust-carrying ducts, and the method for using it is discussed in reference (27).

THE EFFECT OF VENT DUCTS

The consequences of a vented dust explosion external to the vented vessel must always be considered. Reaction forces must be designed for; pressure effects, the magnitude of which will depend on the dust reactivity, size of the vented dust cloud and level of venting of the vessel, must be taken into account and their likely effect on surrounding structures assessed. The burning material cannot be allowed to vent into an area where lives and property could be put at risk.

If the dust-handling equipment cannot be placed in the open air, then it is best practice to guide the burning cloud to a safe place through a vent duct fitted to the vent opening. The duct's presence, however, alters the outflow characteristics of the vent, and whereas the venting requirements may have been appropriate for a vessel standing on its own, when the duct is fitted the reduced explosion pressure may be increased to a point at which it exceeds the strength of the vessel.

There has been little guidance on this topic, but recently a project has been completed, utilising an $18.5m^3$ explosion vessel at the Explosion and Flame Laboratory, Buxton and a 20-l apparatus at the Fire Research Station. The variables investigated in this project, which was carried out for the British Materials Handling Board, were: scale of the apparatus, K_{St}-value of the dusts, bursting pressure of the vent closure, P_{stat}, vent area, length of duct and the number and type (whether 90° or 45°) of bends in the duct.

From these results new guidance has been derived - which gives information on the effect of vent ducts on the reduced explosion pressures (9). This guidance has been designed to engage with the K_{St}-Nomographs in VDI 3673.

CONCLUSIONS

There are some well used procedures available for calculating the explosion venting requirements of dust handling equipment. Nevertheless, standard tests may not bear a close resemblence to conditions occurring in practice, as regards turbulence of the dust cloud, point of ignition, and volume of the cloud relative to volume of the equipment.

Methods for calculating vent areas with a differentiated approach still require a great deal of experimental work in realistic conditions. Until more information is forthcoming, general methods will still be necessary, but as this paper shows, modifications to the procedures have been attempted.

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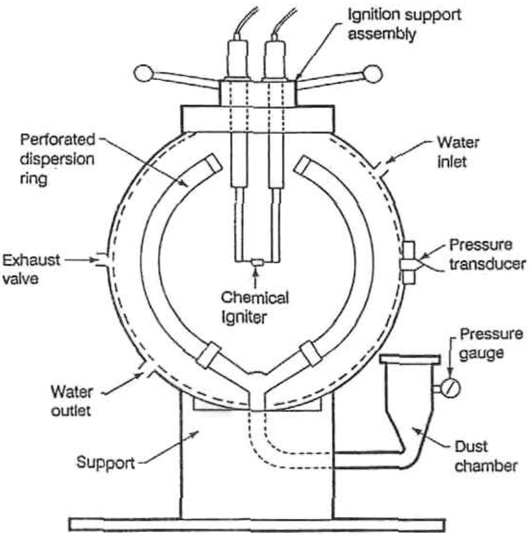


FIGURE 1. 20-L SPHERE TEST APPARATUS

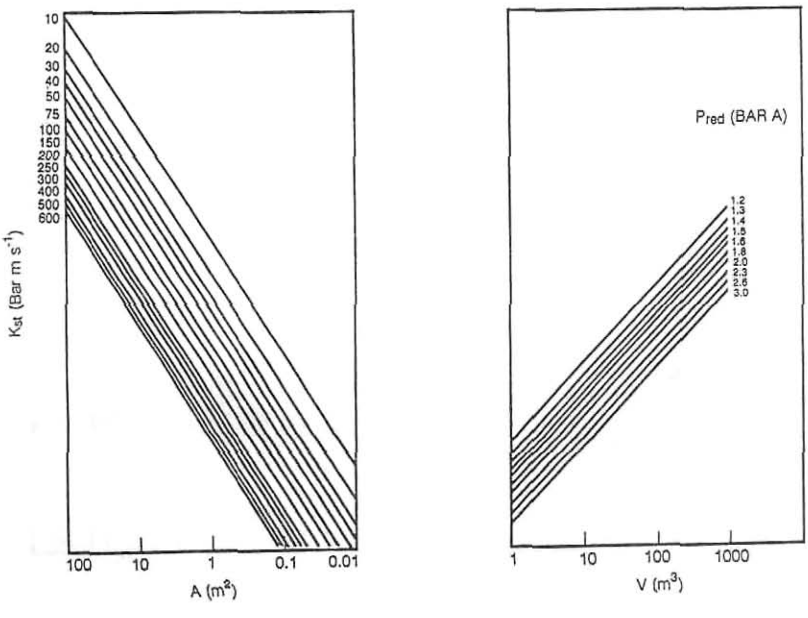


FIGURE 2. K_{ST}-NOMOGRAPH : P_{STAT} = 1.1 BAR A

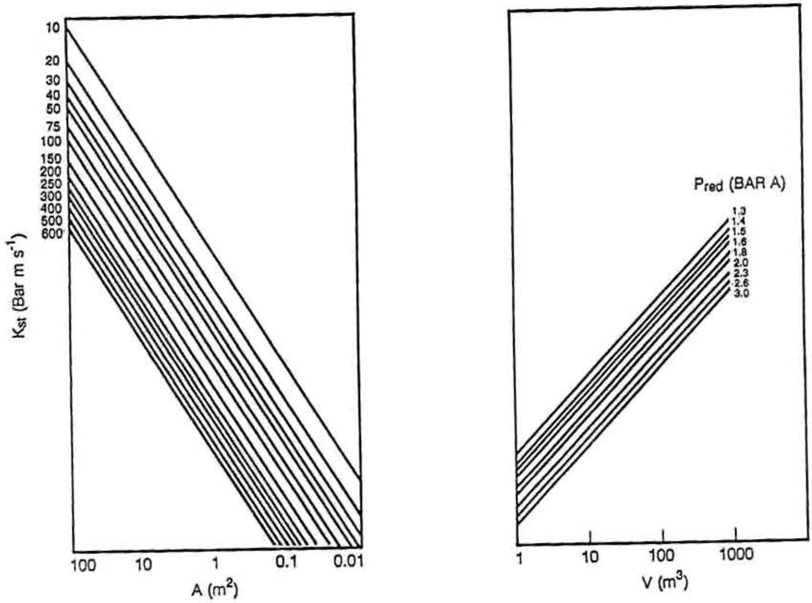


FIGURE 3. K_{ST} - NOMOGRAPH : P_{STAT} = 1.2 BAR A

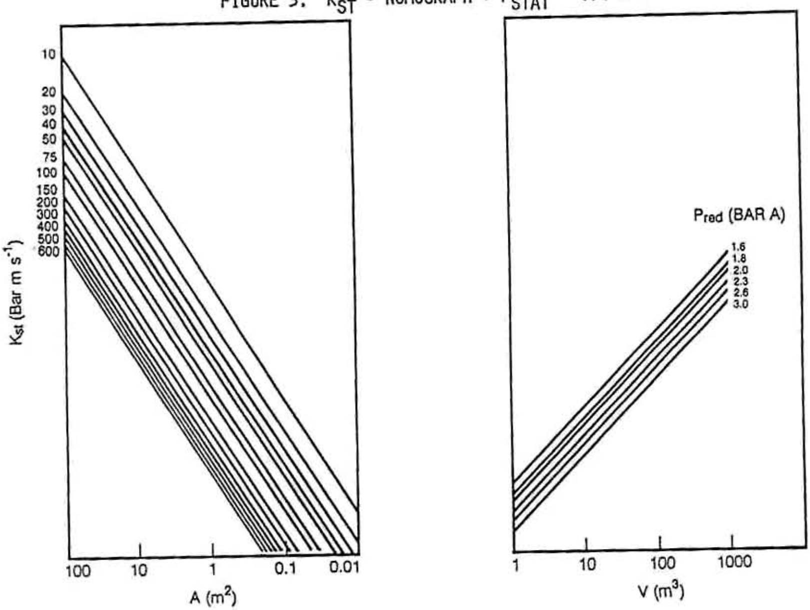


FIGURE 4. K_{ST}-NOMOGRAPH : P_{STAT} = 1.5 BAR A

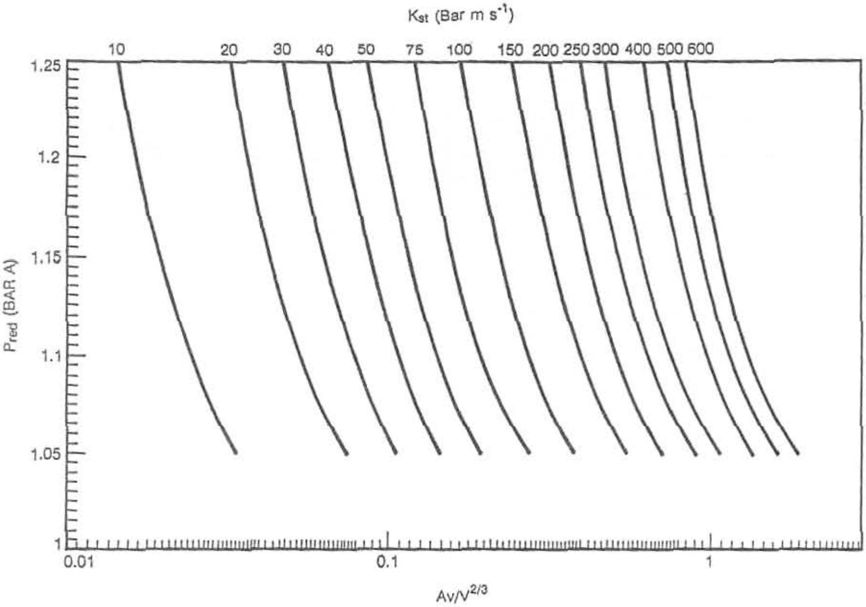


FIGURE 5. NOMOGRAPH : P_{RED} (BAR A) ≈ $A_V/V^{2/3}$ FOR $1.20 > P_{RED} > 1.05$ BAR A

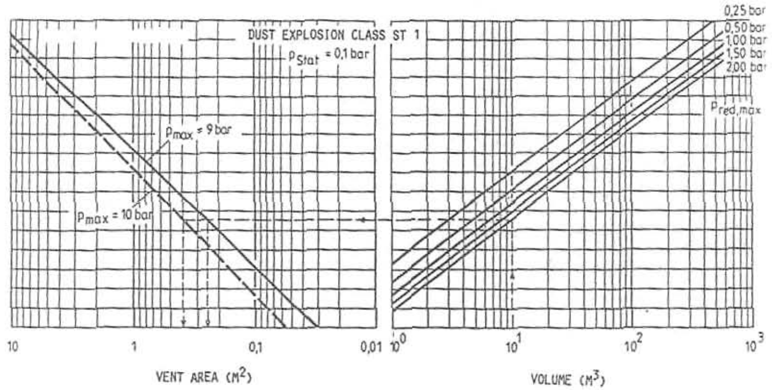


FIGURE 6. NOMOGRAPH FOR DUST EXPLOSION GROUP ST 1 (RADANDT)

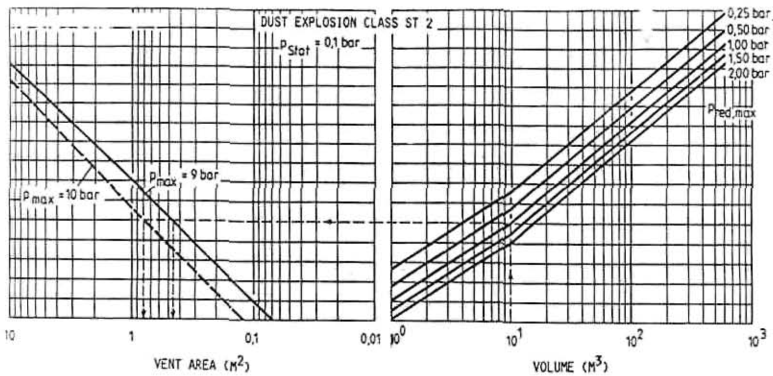


FIGURE 7. NOMOGRAPH FOR DUST EXPLOSION GROUP ST 2 (RADANDT)

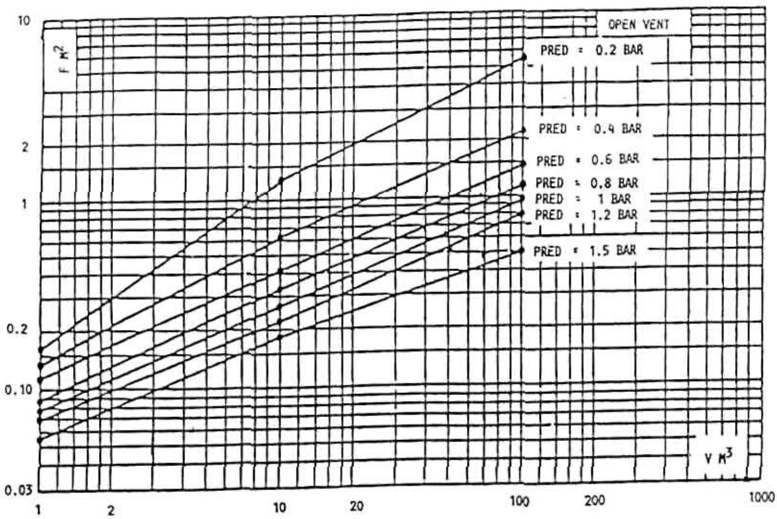


FIGURE 8. VENT AREA F AS A FUNCTION OF VOLUME V OF THE VESSEL TO BE PROTECTED FOR DIFFERENT REDUCED EXPLOSION PRESSURES P_{RED}, WITH $P_{STAT} \leq 1.2$ BAR, K_{MAXT} = 100 $BAR.S^{-1}$

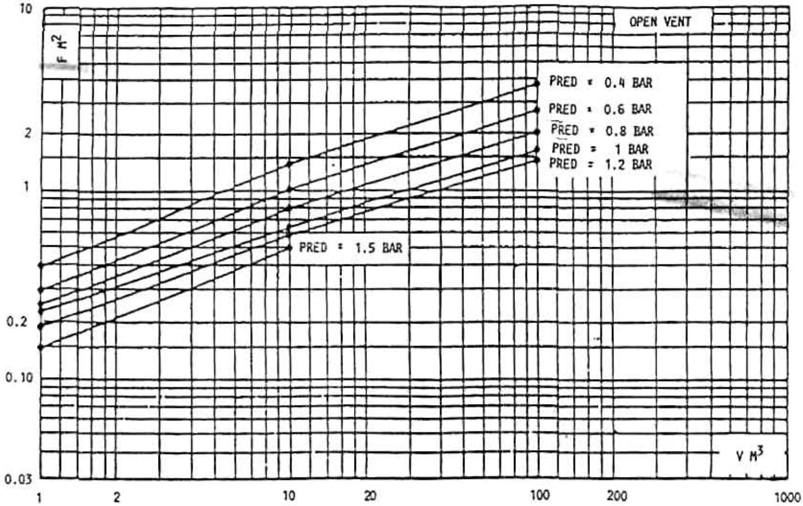


FIGURE 9. VENT AREA F AS A FUNCTION OF VOLUME V OF THE VESSEL TO BE PROTECTED FOR DIFFERENT REDUCED EXPLOSION PRESSURES P_{RED}, WITH $P_{STAT} \leq 1.2$ BAR, $K_{MAX,T} = 400$ BAR S^{-1}.

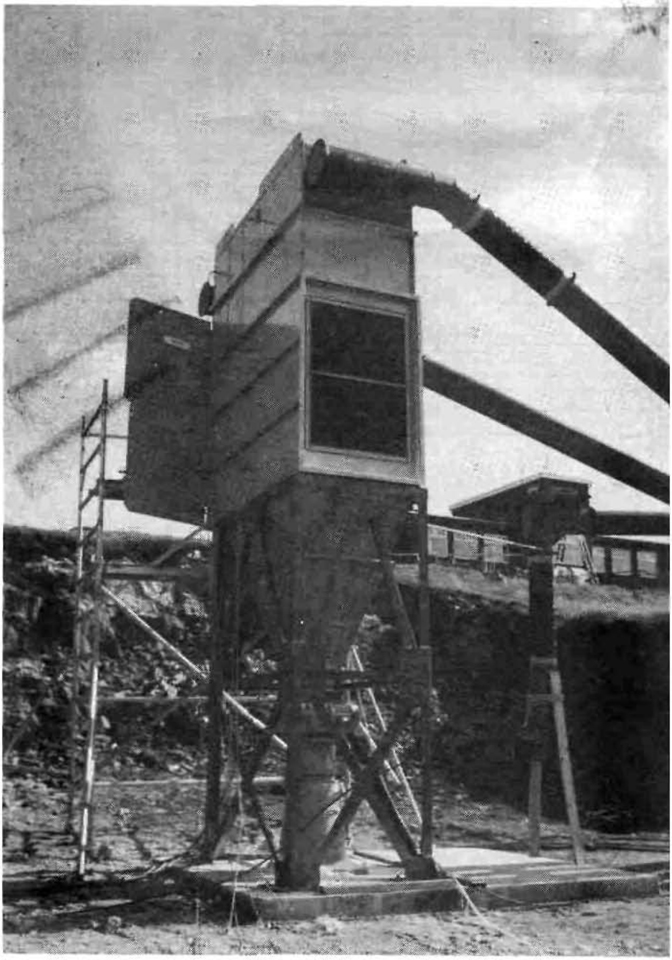


FIGURE 10. DIAPHRAGM VENT CLOSURE

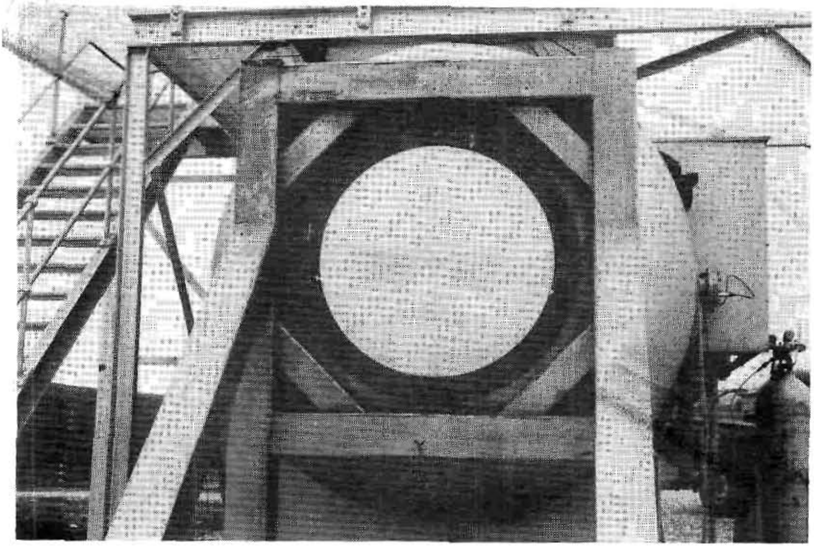


FIGURE 11. BURSTING PANEL

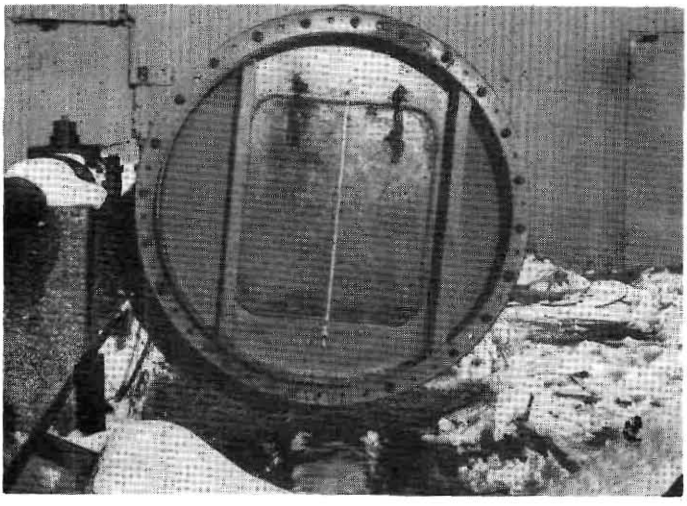
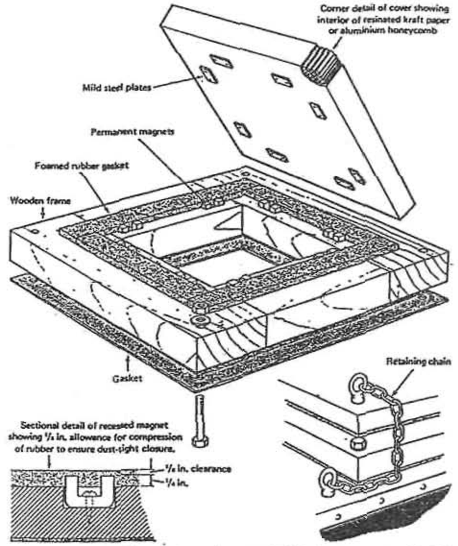


FIGURE 12. RIGID PANEL CLAMPED BY RUBBER SEAL



A duct fitted with an explosion vent cover held in place by magnets. The field strength of the magnets may be varied according to the strength of the plant and the pressure within it. (This is an experimental design and may be modified where necessary)

FIGURE 13. EXAMPLE OF LIGHT-WEIGHT PANEL

FIGURE 14. VENTING NOMOGRAPHS FOR SILOS (RANDANDT)
ST 1 DUSTS

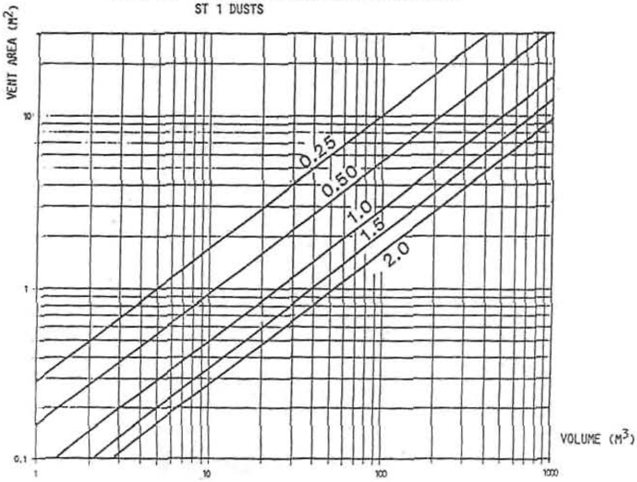


FIGURE 15. VENTING NOMOGRAPHS FOR SILOS (RANDANDT)
ST 2 DUSTS

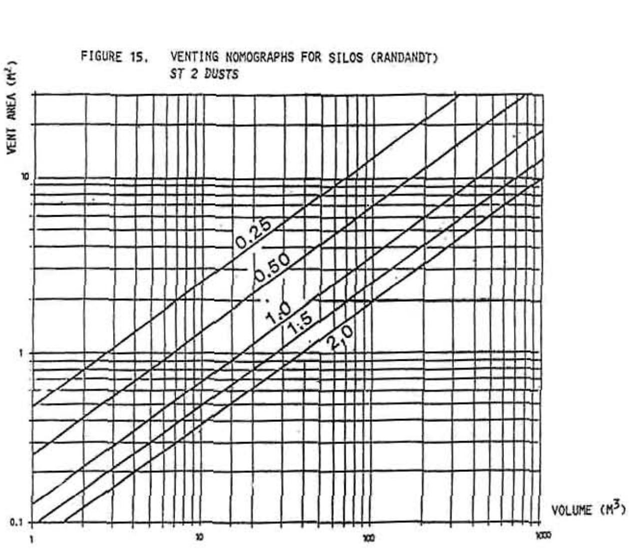


TABLE 1

<u>Ratios for the Vent Area Method for equipment volume up to 30^3</u>

Maximum rate of pressure rise $(dP/dt)_{max}$ bar/s	Vent Ratio $m^2/m^3 = m^{-1}$
<350	1/6.1
350-700	1/4.6
>700	1/3.1

TABLE 2

<u>Comparisons of Predictions from Figure 5 (Extended Nomograph) with Vent Ratio Approach</u>

(P_{RED} = 1.14 bar a)

Volume (m^3)	30	70	100	200	300	500	700	1000
Vent Area (m^2)								
(1) Vent Ratio $^1/_{6.1}m^{-1}$ at $30m^3$, decreasing linearly to $^1/_{25}$ m^{-1} at $300m^3$	4.9	6.3	7.3	10.0	12.0	20.0	28.0	40.0
(2) Figure 5:								
K_{st} = 50 bar m s^{-1}	1.16	2.04	2.58	4.1	5.4	7.55	9.46	12.0
K_{st} = 100 bar m s^{-1}	2.25	3.95	5.0	8.0	10.44	14.7	18.4	23.3
K_{st} = 150 bar m s^{-1}	3.28	5.77	7.32	11.6	15.23	21.4	26.8	34.0
K_{st} = 200 bar m s^{-1}	4.25	7.47	9.48	15.0	19.71	27.7	34.7	44.0
Vent Area (m^2)								
(1) Vent Ratio $^1/_{4.6}m^{-1}$	6.52							
(2) Figure 5 = K_{st} = 100 bar m s^{-1}	2.25							
(1) Vent Ratio $^1/_{3.1}m^{-1}$	9.68							
(2) Figure 5 = K_{st} = 200 bar m s^{-1}	4.25							