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DUST EXPLOSION HAZARDS IN PNEUMATIC TRANSPORT

by

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SUMMARY

A broad description is given of the general characteristics of dust explosions and their effects, the principal methods of protection, test methods and their application. The problems associated with low volume/ high pressure pneumatic conveying systems are described, together with means of protection. Two dust explosions involving such systems are discussed.

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WHAT IS A DUST EXPLOSION?

If many common combustible dusts are dispersed as a cloud in air and ignited a flame will propagate through the cloud. Such dusts included common foodstuffs like sugar, flour, cocoa; synthetic materials such as plastics, chemicals and pharmaceuticals; metals such as aluminium and magnesium; and traditional fuels such as coal and wood. A broad comparison can be drawn with gas or vapour explosions occurring under similar circumstances. For a cloud dispersed in the open air the result of ignition is a flash of flame, developing little hazardous pressure. If the dust cloud is confined as in a plant or a room, then pressure effects would be expected depending on the size of the cloud, the nature of the dust, and the ease of discharge to atmosphere.

In pneumatic conveying, dust is certainly dispersed as a cloud, usually in air, and consideration must therefore be given to the possibility of dust explosion, should a source of ignition be present. In this paper attention will be paid to the general characteristics of a dust explosion, followed by a description of the tests for dust explosibility, and concluding with a consideration of the specific problems and their solutions encountered in pneumatic transportation.

A comprehensive work on the principles of dust explosions, their effect on industrial plant and buildings, and protective measures has recently been published[1].

CHARACTERISTICS OF DUST EXPLOSIONS

Expansion effects

A dust explosion may be envisaged as combustion of a dust cloud which results either in a rapid build-up of pressure or in uncontrolled expansion effects. The gas in which the dust is suspended takes part in the combustion and hence in considering the properties of dust explosions both the nature of the dust and the gas are important. It is the expansion effect, or the pressure rise if expansion is restricted, which presents one of the main hazards in dust explosions. The expansion effects arise principally because of the heat developed in the combustion and, in some cases, to gases being evolved from the dust because of the high temperatures to which it has been exposed. The heat generated in a dust explosion is eventually lost to the surroundings and so the expansion and pressure effects are transient. In industrial plant the rate of heating is likely to greatly exceed the rate of cooling whilst the explosion is developing, and so expansion and pressure effects are able to become manifest.

Deflagration and detonation

In dust explosions the rate of propagation of flames through the dust cloud ranges from hundreds of metres per second to the slowest which are of order 1 m/s. The type of explosion occurring under industrial conditions is termed a deflagration, and an important property is that the flame speed is less than the velocity of sound. There is another mode of combustion termed detonation in which the flame speed is equal to the velocity of sound in the gaseous products and is accompanied by a shock wave. This velocity is of order 1000 m/s. Whether or not detonations can develop from relatively small ignition sources in industrial plant has not yet been proved, but in any case a detonation would initially start as a deflagration. It is general practice in considering protection against dust explosion hazards in industrial plant to assume that deflagrations rather than detonations occur. This procedure has proved to be satisfactory in practice, which is fortunate because deflagrations are simpler to deal with than are detonations.

Flame speeds

The flame speed in a dust explosion is not constant but depends on the number of factors. Two of these are the chemical composition of the dust and the oxidant, but with the present state of knowledge flame speed cannot be related simply to composition, including moisture content, or to heat of combustion. Furthermore the flame speed depends upon the particle size of the dust, the smaller the particles the higher the flame speed; it also depends on the turbulence of the gas in which the dust is dispersed, increased turbulence can lead to higher flame speeds. Both the characteristics of the dust and the design of the plant therefore affect the flame speed during an explosion.

Ignition

For an explosion to occur the dust cloud must be ignited. Apart from a few special instances where the act of dispersion of dust may ignite it, a separate source of ignition must be present and the concentration of dust in the cloud must be favourable. Two frequent sources met in industry are a hot surface and a spark. Consequently, the minimum ignition temperature and the minimum ignition energy are the ignition properties commonly measured in the routine testing of dusts. Ignition temperature is not a fundamental characteristic of the dust cloud and it depends upon the size and shape of the apparatus used to measure it, as well as on the rate of rise in temperature of the dust. Minimum ignition temperatures have therefore to be determined in a standardized form of apparatus for meaningful comparison between dusts, this point is considered further later. The minimum ignition energy in a dust cloud depends on the dust concentration, particle size, moisture content, etc, and there is some evidence that the design of the electrical circuit producing the spark can also affect the minimum value. Routine determinations of minimum ignition energies are made by a standardized procedure, which is again described below. There are a number of ways by which sparks can be produced, eg by electricity, friction, hot cutting. A characteristic of all these forms of spark as a small particle or a small volume of gas at high temperature is produced for a short time. It is much easier for experimental purposes to measure the energy delivered in an electric spark than that delivered by friction or other thermal processes and consequently the routine test uses an electric spark ignition source.

Explosibility limits

If flame is to propagate through a dust cloud the concentration of dust must lie within the lower and upper explosibility limits. The lower explosibility limit, or minimum explosible concentration, may be defined as the minimum concentration of dust in a cloud necessary for sustained flame propagation. It is a fairly well defined quantity, and can be determined reliably in small-scale tests. Values are usually in terms of weight of dust per unit volume of air or gas. When the concentration of dust is raised above the lower explosibility limit and past the stoichiometric value (ie when the dust concentration and the quantity of air present for its combustion are exactly in balance) the flame speeds and vigour of explosions increase. As the dust concentration is further increased the quenching effect of the surplus dust becomes more marked and eventually a concentration is reached at which flame propagation no longer occurs. This concentration is the upper explosion limit. This limit is not easy to measure, mainly because of the difficulty of ensuring that dust is uniformly dispersed in the cloud, and because of the difficulties relatively few values have been measured. The existence of the upper explosibility limit is of relevance to explosion hazards in pneumatic conveying. The explosibility limits depend not only on the composition of the dust but also on its particle size, moisture content as well as the ignition source used in the test.

Explosion pressures

When a dust explosion occurs in industrial plant spectacular destruction may result if an explosion is initially completely confined in a plant which is ultimately too weak to stand the full force of the explosion. Two of the factors influencing the violence of the explosion are the maximum explosion pressure and the maximum rate of pressure rise. The maximum values obtained with dusts in small closed vessels, which are sufficiently strong not to burst or leak during the explosion may be as high as 1000 kN/m^2 (150 lb/in^2) for maximum pressures, and 100 MN/m^2s (15000 lb/in^2s) for maximum rates of pressure rise. The values obtained under standard conditions depend on the explosion properties of the dusts including particle size, moisture content, as well as on basic composition. The values cannot be predicted from knowledge of the composition and thermal properties of the dust but must be obtained by measurement. Where it is intended to contain the explosion within the plant, the strength of the plant must be so designed that it is well capable of withstanding the maximum explosion pressure. The maximum rate of pressure rise is often used in connection with the design of explosion relief venting. Where rates of pressure rise are high products of combustion are being generated rapidly. If protection of plant is to be obtained by the relief of pressure through vents it is necessary that combustion products should escape whilst they are being formed. If the rate of formation of combustion products, ie the rate of pressure rise, is high the amount of venting will need to be greater than in explosions with lower rates of rise.

Primary and secondary explosions

Dust explosions have the characteristic that pressure waves transmitted through the atmosphere during the initial stages of the explosion can cause dust which is deposited to be thrown into suspension. Further dust clouds are formed which can be ignited by the explosion flame already present. The initial stage of the process during which disturbance of the dust occurs, is customarily termed the primary explosion and the subsequent stages when the newly disturbed dust becomes involved with the flame is termed the secondary explosion. The hazards arising from secondary explosions are now well established and their avoidance is one of the basic principles of dust explosion protection. The required precautions are obvious: to prevent emission of flame into the workroom from plant should an explosion occur inside the plant, and to avoid the presence of dust deposits in workrooms. This latter requirement means that clean working is necessary and that frequent and regular clearing of any dust spilled or accidentally discharged is vital.

Toxic gases

The flames and pressure effects arising from dust explosions are a principal source of casualties but there are also dangers arising from the combustion products of explosions. These are deficient in oxygen and also contain toxic gases, particularly carbon monoxide. The concentration of toxic gases can be sufficiently high for a few breaths to be fatal, so that momentary unconsciousnesss due to the blast can result in death. The toxic nature of the combustion products is particularly hazardous where the explosion has occurred in the working space with the operatives present, as occurs in secondary dust explosions. Toxic gases are also likely to be present inside the plant, after a dust explosion. Plants must not be entered by operatives or firefighters until either the atmosphere has by test been shown to be safe, or breathing apparatus is worn by all personnel entering.

EXPLOSIBLE DUSTS AND INDUSTRIES INVOLVED

Past experience in industry and in the laboratory testing of dusts has shown that a wide range of dusts can give rise to explosions. Not all materials that will burn in air can cause dust explosions, even if finely divided and dry; that is, not all combustible dusts are explosible. All explosible dusts must be combustible. The reason why some combustible dusts are not explosible has not been definitely established, but it is clear that it is not related directly to the heat of combustion or calorific value for the dust. Where combustible dusts are being handled it is necessary to either refer to previous records or to carry out laboratory tests to decide whether the dust is explosible.

The industries concerned in the manufacture or handling of explosion dusts are numerous, some of the principal ones are as follows:

Agricultural
Chemical including dyestuffs
Coal, mining and utilisation
Foodstuffs, human and animal
Metals
Pharmaceuticals
Plastics
Woodworking

This list gives only a few examples and consists of those where the principal products present dust explosion risks. There is in addition a wide range of industries which produce explosible materials in their processes, although dusts and powders may not be principal products as they are for instance in flour and sugar. Examples of industries where explosible dusts are present and have in fact caused explosions, are rubber dust in the footwear industry, esparto grass dust in the paper industry, and aluminium dust in the manufacture of refrigerators.

Although the principal product of the industry may not be a dust and presents no explosion hazard, consideration must also be given to intermediate materials used in the manufacture of the final product and to the processes involved in the manufacture. These processes may give rise to by-products or waste materials which are explosible and which in the factory may present as great a hazard as dusts in other industries where the principal product is explosible.

EFFECT OF DUST EXPLOSIONS ON PLANT AND BUILDINGS

Numerous dust explosions have occurred in plant which was inadequately protected and which as a result has become a part or total loss. Such dust handling plant, unless specially strengthened, is very weak compared with the stresses exerted by a dust explosion. Some of the most vulnerable parts of a dust handling system, eg the collection unit, may be capable of withstanding pressures of only 7–15 kN/m^2 (1–2 lb/in^2) and if exposed to higher internal pressures may burst or disintegrate. In dust explosions, under the most unfavourable conditions, pressures up to 1000 kN/m^2 have been reported and so an uncontrolled explosion in plant is liable to cause severe damage. Some plant units are inherently stronger, such as mills and grinders, and these in themselves may be able to withstand explosions. Usually, however, they are interconnected with ducting and collectors, of relatively light construction, which is structurally much weaker and it is these latter items which suffer the most severe damage, although the explosions have originated elsewhere in a stronger part of the system.

If plant is to withstand an explosion successfully all parts must be of adequate strength, not only those units in which an explosion might originate. Much dust handling plant is constructed to have mechanical strength sufficient only for normal working, and not for explosion conditions. A particularly dangerous situation can arise if the dust handled by the plant is changed from a non-explosible to an explosible material, or to one of greater explosibility; unprotected plant units may be unsuitable for the new situation; alternatively the amount of explosion protection initially provided may not be sufficient.

The provision of adequate explosion prevention and protection measures not only protects plant so that it may be put back into production with the minimum of delay after an incident, but also reduces the danger of missiles being generated during an explosion. The plant should be so constructed that missiles are not projected, and loose attachments to the plant are safely anchored. Because of the explosion, pressure waves may travel through the atmosphere and pick-up or dislodge loose articles nearby.

In the same way that much dust handling plant is incapable of withstanding the full effects of dust explosion, the strength of buildings in which the plant may be housed is also low, unless specially constructed. Factory buildings are therefore most unlikely to be able to withstand the full effects of dust explosions, and this underlines the need to prevent secondary dust explosions. Ordinary brick walls, not reinforced, are capable of withstanding internal explosions of pressures only 7–20 kN/m^2 (1–3 lb/in^2)without serious movement which can lead to collapse. In a multi-storey brick building an explosion on one floor caused the walls to move outwards, and as a result floors and the roof fell downwards leading to a total loss of building and contents. A further hazard with multi-storey buildings is that communication between floors in the building is often unprotected so that explosion effects may traverse the building by the openings. This hazard is particularly frequent when an old building is taken over from another process, or even another industry, and dust handling plant is installed within it.

If the opportunity arises, the best situation for dust handling plant is in the open air, with a minimum of enclosure, or in lightly constructed buildings with a minimum of weather protection. If permanent buildings do have to be used they should be preferably steel-framed and not unsupported brick. Where old buildings have to be employed particular care should be paid to protect them against explosions whether secondary or primary. All inter-communication between the floor levels should be controlled, and should be external rather than internal.

PRINCIPLES OF EXPLOSION PREVENTION AND PROTECTION

Although it is good practice to eliminate as far as possible the formation of a dust cloud, and of sources of ignition, these steps give only partial protection. Industrial operations demand the movement of explosible dusts, and the formation of suspensions in air is inevitable. The most severe precautions against the introduction or generation of sources of ignition may be taken, but because of unforeseen mechanical or human failures complete elimination of ignition sources cannot be relied upon, particularly where powered machinery is involved. To avoid disaster reliance must be placed on the adequate functioning for explosion protection providea in plants. The principles may be summarised as follows:

(a) Prevention of ignition
(b) Suppression or containment of the explosion flame
(c) Allowing the explosion to take its full course but to ensure that it does so safely.

The method of protection selected will depend upon a number of factors including the design of the industrial process, the running costs, the economics of alternative protection methods, the extent to which an explosion and its consequences can be foreseen, and the requirements of any authorities concerned. As a basic technical principle the explosion hazard in a given plant with given materials increases as the amount of energy released by the explosion increases. The damage caused by the explosion of a large volume of combustible dust suspension may be more than proportionately greater than the damage from a smaller volume because larger structures are often relatively weaker. The escalation does not always occur because in a large volume there is always the possibility that parts of it may be at unfavourable dust concentrations for an explosion to propagate and this introduces an uncontrolled safety factor. However, it is unwise to rely on this factor and in designing against an explosion hazard the accepted method is to assume the worst conditions.

In trying to minimise the energy delivered by an explosion the most attractive method of protection is to prevent ignition of the dust cloud. In addition to eliminating sources of ignition as far as possible, the oxygen concentration in the air can be reduced or eliminated. This may be done by introducing into the dust handling process an inert gas which either replaces the air originally present or at least dilutes it so that the level of oxygen is below that at which flames can be supported. This concentration level depends upon the dust concerned, and also on the inert gas used for diluting the air, and has to be determined in each case by an appropriate test. The disadvantages of the inerting technique are that it may only be applicable to closed or semi-closed plant, otherwise the loss of inerting gas is expensive. Monitoring devices for the gas concentrations have been installed and possible toxicity or suffocation risks to operatives have to be guarded against.

Once a dust explosion has begun to propagate its energy may be minimised by either suppressing it rapidly or else by restricting its spread through the plant. Explosion flame speeds are such that any suppression mechanism must be effected within about 10 ms of the detection of the explosion. Commercial equipment is available which is able to provide this rapid response. If spread of the explosion is to be restricted plant must be divided into small separate volumes, between which the explosion is unable to propagate, and that part of the plant within which the explosion occurs must be strong enough or sufficiently well protected to withstand explosion. The technique of suppression is widely used in industry and the suppression mechanism must always be available and ready to act. A process may continue for many years before a dust explosion develops, and after the flame has started to propagate suppression will be needed within a fraction of a second. Containment of explosions within industrial plant is frequently difficult because much modern plant is increasing in scale, and sub-division into small working volumes would be impracticable. Whilst sub-division should always be encouraged, as a safety measure, economic considerations may preclude the use of containment alone as the major precautionary measure.

Because of difficulties in preventing ignition, or the unsuitability of the process to suppression or containment of explosion, recourse is often made to sub-division of the plant as far as is economic, coupled with explosion relief venting to prevent dangerous pressures. In the venting of primary explosions to atmosphere strict attention must be given to the safe dissipation of the explosion products. It is a characteristic that the volume of flame discharged from vents can be very large, and must be directed to a safe place away from operatives and neighbouring plant. This is commonly done by attaching a length of ducting to the vent, or by installing deflector baffles. If the plant is inside a building, the vented flames should be ducted to the exterior; in all cases the duct attached to the vent should be short, free from bends and other restrictions to flow, and be kept clean from dust during all working.

The type and amount of explosion protection required will depend to a considerable extent on the explosibility of the dust. This must be determined by test, and in the United Kingdom official tests are carried out on a sponsored basis at the Fire Research Station. The apparatus used and the test procedures have been described in detail elsewhere[2].

TESTS FOR DUST EXPLOSIBILITY

All the tests are concerned with assessing the explosibility, or measuring explosion properties, of dusts in suspension, using methods agreed with HM Factory Inspectorate. The tests do not include measurement on layers or deposits of dust. With a dust which has not previously been tested the first step is to classify the dust for explosibility. The classification tests determine whether or not the dust is capable of propagating an explosion. If the dust is explosible, then subsequent tests may be carried out to measure particular explosion properties.

Dusts are classified for explosibility as follows:

Group (a) Dusts which ignited and propagated flame in the test apparatus.

Group (b) Dusts which did not propagate flame in the test apparatus.

Dusts are classified as Group (a) if they ignited and propagated flame in any of three tests with a small source of ignition, either 'as received' or after sieving and drying the sample. Group (a) dusts should be regarded as explosible, and liable to give rise to a dust explosion hazard, whereas Group (b) dusts are not explosible although they may present a fire risk.

The basic characteristics of the test apparatus used for the classification of dusts are summarised in Table 1.

Table 1

Classification test apparatus

Apparatus	Direction of dispersion of dust	Igniting source
Vertical tube	Vertically upwards	Electric spark or electrically heated wire coil
Horizontal tube	Horizontal	Electrically heated wire coil at 1300°C
Inflammator	Vertically downwards	Electrically heated wire coil or electric spark

Several types of test apparatus are required because dusts have a wide range of dispersability and different means to form the dust cloud are necessary, as well as scope for varying the quantity of dust and the pressure of the dispersing air.

A classified list of Group (a) and Group (b) dusts has been published[3].

MEASUREMENT OF EXPLOSION PARAMETERS OF DUSTS

If a dust is shown to be explosible further information on the extent of the explosion hazard may be required when considering suitable precautions for the safe handling of the dust. The following parameters can be determined:

(1) Minimum ignition temperature
(2) Maximum permissible oxygen concentration of the atmosphere to prevent ignition in the dust cloud
(3) Minimum explosible concentration
(4) Minimum ignition energy
(5) Maximum explosion pressure and rate of pressure rise.

The minimum ignition temperature and maximum permissible oxygen concentration are both measured in a furnace apparatus, whereas the minimum explosible concentration and minimum ignition energy are measured using a variation of the vertical tube (Table 1) with electric spark ignition. The maximum explosion pressure is measured in a similar tube, but which is closed and of high strength. Details of each of the test methods are available[2].

APPLICATION OF TESTS

A summary of the application of the various tests to practical conditions is given in Table 2; greater detail is given elsewhere[1,4].

Table 2

Tests for measurement of explosion parameters

Parameter	Hazard or method of protection concerned
Minimum ignition temperature	Hot surfaces
Maximum permissible oxygen concentration to prevent explosion	Use of inert gas
Minimum explosible concentration	Pneumatic conveying
Minimum ignition energy	Static electricity
Maximum explosion pressure and rate of pressure rise	Explosion relief venting

The minimum ignition temperature is clearly relevant to ignition by relatively hot surfaces, as opposed to sparks, and this is a topic on which considerable detail is available. However, it is outside the immediate scope of the present paper. The maximum permissible oxygen concentration is directly applicable where the use of inert gas to reduce oxygen concentrations is considered, including its use in conveying systems. The minimum explosible concentration is relevant to pneumatic conveying equipment, including dust extraction systems, but more particularly of the high volume/low pressure type which is the system commonly used for the conveying of dusts from grinding or polishing machines to collection units. The low volume/high pressure system used in pneumatic conveying as for road tankers to bulk storage is considered separately. The minimum ignition energy of a dust cloud is of particular interest in relation to static electricity hazards. In the movement of dust in plant generation of static electricity is to be expected and all metal components of the plant should be bonded to earth. If adequate precautions are taken the accumulation of the hazardous charge on the plant is prevented, although the dust itself may retain some charge. The charge on the dust may then become transferred to operatives. There is a possibility that a spark could pass in the presence of dust and the minimum ignition energy is relevant. A rule of thumb value of 25 millijoules is often taken, and dusts with ignition energies less than this value may be regarded as particularly prone to ignition by static electricity. Special precautions should be taken including anti-static clothing and footwear for operatives. Values of maximum explosion pressure are required if the plant is to be sufficiently strong to withstand the full explosion pressure, to which a safety factor must be added. In most applications this approach is not practicable, and weak plant is frequently protected by explosion relief venting. The maximum rate of pressure rise is then required, and can be related to the required area of explosion relief, which is usually expressed in terms of the vent ratio, ie the area of vent per unit volume of plant. The more vigorously explosible dusts require larger areas of venting (Table 3) the values in which are an empirical guide.

Table 3

Vent ratios for dusts of different rates of pressure rise

Maximum rate of pressure rise		Vent ratio	
kN/m^2s	lb/in^2s	m^{-1}	ft^{-1}
$<$ 35 000	$<$ 5000	1/7	1/20
35 000 - 70 000	5000 - 10 000	1/5	1/15
$>$ 70 000	$>$ 10 000	1/3	1/10

For very large volumes such as silos, the required amount of venting may be impracticable. For tall cylindrical vessels the area of vent may in fact exceed the area of cross-section, so that a reduced criterion is acceptable. For these large volumes the vent ratio can be reduced from 1/7 $metres^{-1}$ (ie 1 square metre per 7 cubic metres volume) to as little as 1/28 $metres^{-1}$. An alternative approach is to install a vent equal to half the cross-sectional area of a tall narrow collector, which often comes to much the same figure. The provision of explosion relief venting is a rule of thumb operation and until a more quantitative approach has been devised, the present methods are likely to continue.

APPLICATION TO PNEUMATIC CONVEYING

General considerations

Two types of pneumatic system are commonly used for transporting dusts in suspension, and may be summarily described as:

Low volume/high pressure air
High volume/low pressure air.

The latter system is really exhaust ventilation and although presenting numerous dust explosion problems is regarded as being outside the present scope. A useful guide in handling dusts in this type of system is available[5].

The low volume/high pressure systems are applied to the transport of dust within plant and also to the delivery of dust, eg from road vehicles to storage hoppers. The basis of the method is that a high concentration of dust is transported rapidly through a narrow pipe with a relatively high air pressure. A typical pipe diameter would be 10 cm (4 in) and an operating air pressure of 50 kN/m^2 (7 lb/in^2). Systems can also be designed to operate at negative pressures of about this magnitude. The weight ratio of dust/air will vary with the nature of the dust, but is commonly of order 40:1. This ratio is well above the upper explosible limit of all but the most exceptional dusts, such as those containing air and oxygen for combustion, and for most materials the mixture being transported in the pipe is not within the explosible concentration range. As explained previously the upper explosible limit is not well defined for dusts, but for most common materials is probably in the range 2–10 g/l. This represents dust/air weight ratios of 1.5–8.

Pneumatic conveying has the advantage that both horizontal and vertical travel is readily obtained and the system is self-cleaning and does not cause dust to accumulate in the pipe runs. Because of the high flow velocity and the density of the suspension there may be abrasion of the pipe walls, particularly at bends, and the design of installation should take this into account. A code of practice for the safe design of pneumatic conveying systems for agricultural dusts has been published in the United States[6]. The pipe construction in pneumatic conveying is relatively strong and by the use of suitable connections, could readily be made sufficiently strong to withstand a full explosion pressure should one develop. Because of the normal working pressure within the system, all hoppers and collectors incorporated must be sufficiently strong to withstand the air pressure, but they may not be sufficiently robust to withstand a dust explosion.

EXPLOSION PROTECTION OF PNEUMATIC SYSTEMS

The conveying system can conveniently be considered in the following parts:

Feed inlet, conveying pipes, dust separators and delivery units.

At the feed point the air, or other conveying gas, comes into contact with the dust. The air must be taken from a safe area, to be free of ignition sources. For systems working under positive pressure the blower, fan, pump, or compressor should be supplied with an air relief valve and an overload trip on the motor to ensure that in the event of blockage of the system air will not be delivered at excessive pressures or temperatures. A non-return valve can also be fitted to the air delivery line to prevent damage to the blower should a pressure surge arise from an explosion downstream in the system. It is important that burning dust should not be fed into a pneumatic system and also that the dust feed to the system is maintained at the optimum level. The dust should be supplied to the system at a controlled rate to ensure an adequate supply and to prevent choking. Where the dust is produced by grinding or similar processes, some form of choke, eg a rotary valve, must be installed to prevent explosion propagating from the grinding unit through the storage hopper into the pneumatic system. The choke valves may not prevent movement of smouldering dust through the system, and with dusts which do smoulder readily the use of an inert conveying gas instead of air should be considered.

The generation of static electricity is to be expected at all parts of the system because of the movement of the dust suspension. Appropriate precautions should be taken, and the bonding of all units to earth is essential. The use of electrically non-conducting flexible links in the pneumatic system is undesirable, even if these are bridged by bonding, and flexible metal parts are preferable.

At the feed point a dust explosion is unlikely because of the high concentration of dust in the suspension. However, if the dust is burning before introduction to the system then it is likely to continue to do so as it moves away from the feed point.

The pipe conveying the dust is customarily strong, and may be capable of withstanding the full explosion pressure, and providing it is non-combustible is then unlikely to be damaged by fire or explosion occurring in any part of the system. When running under optimum conditions the concentration of dust in suspension is high and explosion is not then expected, but burning dust may continue to burn during transit. The most hazardous periods are at start-up and shut-down, when the dust concentration may not be optimal, or at any other time when the supply of dust decreases due to bridging in the hopper, the hopper becoming empty, or failure of supply of dust to the whole system. The hazards should be minimised by reducing the period for which the dust suspension is not at optimum concentration. On start-up the air supply should be established, in a clean system, and the dust then fed at its optimum rate as rapidly as possible. On shut-down the dust supply should be stopped quickly and the air continue to run until all dust has been removed from the pipe system. A serious hazard could arise if the dust is not completely removed before shut-down of the air, and if it is burning. On subsequent start up, the ignited dust could then be thrown into suspension at less than optimum dust working concentration and an explosion could ensue.

On arrival in the delivery area the dust must be separated from the conveying air and the concentration of the dust in suspension inevitably varies, and will be within the explosible range at some points. It is at the separation stage that the dust explosion hazard is most serious. The separation may be made either by delivering the suspension into a large volume, eg a silo, and using it as a settlement chamber. The air escapes by a filter unit direct to atmosphere, and the dust accumulates at the bottom of the silo. Alternatively, the dust suspension may be fed into cyclone units, probably followed by bag filter units. Whichever method of separation is used the units must be protected against the effect of dust explosion, usually with relief venting (Table 3). The opening of an explosion relief vent may cause the flow of conveying air to be reduced, or may allow the discharge of dust suspension. Where cyclones or filter units are used the dust is delivered subsequently into storage bins or hoppers, whereas with a settlement chamber the dust accumulates in the separating unit. Apart from the explosion hazards, there is also a fire risk because of the residence of the dust over a period permitting the burning to spread throughout a mass and also because of the disturbance of the air associated with the pneumatic system. A small fire is thereby likely to be fanned into a large fire relatively quickly. It is advisable for the dust storage units to be of non-combustible construction, although plastics materials are beginning to be used.

If an explosion should occur in the separating units, the dust stored in the unit can be expected to ignite and the whole system should be subsequently emptied to remove all traces of the burning material.

Storage vessels for dusts, ranging from small bins to large silos, should if possible be situated outdoors. It is of course advantageous to minimise the volume of dust suspension generated in silos and other large volumes, eg by arranging that the dust does not discharge under gravity from roof level but can pass into the silo from a vertical duct within it having an aperture on its length enabling dust to move sideways into the silo. Explosion protection, usually relief venting, should also be provided, see Table 3 and modifications for larger volumes.

PRACTICAL PERFORMANCE

Relatively few dust explosions have been recorded in this type of pneumatic conveying system, there have been no catastrophic incidents, and the overall performance of the system in relation to dust explosions can be regarded as satisfactory. The method is superior, as regards safety, to various other mechanical means of transporting dusts and is certainly an acceptable alternative. As was observed earlier, such damage as has been caused to pneumatic conveying systems has been mainly in the dust collection part, and the pipeline itself has not suffered serious damage.

One incident in particular has been well documented and will be considered in more detail, because the events were in themselves instructive. The dust concerned was Bisphenol-A, a material used as an intermediate in the manufacture of plastics[7]. In fact two dust explosions occurred in a span of six days, and both explosions occurred inside 4,500 ft^3 silos which at the time were being filled with the dust from road vehicles by means of positive pressure transfer. No injury to personnel resulted from the explosions, as damage was confined to the silo top works and to their contents.

The first explosion occurred a few minutes after the unloading operation had begun. The explosion was relieved by the top cover of a silo and was followed by fire which lasted for approximately five minutes before extinguishing itself. Each silo was equipped with an explosion relief top cover, and three retaining chains connecting the cover to the silo, giving a vent ratio of 1 square to 40 cubic feet of volume. The vent functioned properly, limiting equipment damage to the top works of the silo. The cover was lifted from the top of the silo by the explosion but was held by retaining chains so that it remained on the silo after the explosion although not returning to its original position. No damage was incurred by the silo itself although the interior was blackened. The silo was later emptied of its contents, cleaned, the top cover removed and straightened, piping and wiring were repaired, and the unit was put back into service 15 days after the explosion.

The second explosion occurred about thirty minutes after unloading had commenced and again the explosion was relieved by the top cover being lifted up and remaining on the silo after the explosion. This explosion was not followed by fire. The damage was similar to that in the first explosion although more severe. The top cover was damaged to such an extent that it had to be replaced with a new one. The silo contents were removed and the silo again cleaned and put back into service after the new cover had been installed.

An investigation resulted in no positive conclusions as to the cause of either incident. However, the information that was obtained suggested that both explosions were due to static electricity.

The transfer lines used in pressure loading of the silos were installed so that they entered directly into the top of the silo without any prior separation of the powder from the conveying air. The silos were vented by means of the separate line through a filter unit on top of the silo to the atmosphere, with the dust collected in the filter unit being returned to the silo by a rotary air lock valve. With this type of loading system, a dust filled atmosphere would normally exist inside the silo during loading operations. At the time of each of the explosions the silos were less than 25 per cent full of powder creating a relatively larger volume of dust-filled air. From these facts it was concluded that both explosions were probably dust explosions.

By a process of elimination it was concluded that the source of ignition in both the explosions was probably a static electricity spark. At the time of the first explosion the road vehicle was not independently earthed and was connected to the transfer pipe by an unbonded rubber hose. In addition it was discovered that the bonding clips were missing at one of the couplings on the transfer line. Inspection of the interior of the transfer line showed no evidence that ignition had occurred inside the pipe. In the second explosion it was established that the road vehicle was properly earthed and that all other bond and ground connections were intact. However, the unbonded rubber hose had again been used to make the connection between the vehicle and the transfer pipe.

After the explosions the decision was made to cease unloading by positive pressure transfer, and to use the alternative vacuum transfer system. The lower rate of transfer of dust with the vacuum system could possibly contribute to the reduction of static electricity generation. The vacuum system also provided for separation of the powder from the airstream prior to entering the silo. The dust/airstream was pulled into the filter on top of the silo by means of a vacuum blower, the air was pulled through the filter bags and the dust was discharged to the silo.

Consideration was also given to providing inert gas to transfer the powder to the silos. Due to the large quantities of gas which would be required this idea was not considered feasible. Instead continuous low rate inert gas purges were installed in each silo in an effort to blanket the silos and at least prevent explosive atmospheres from developing within the silos themselves.

It will be seen that the general philosophy outlined earlier was used or considered in this particular case, and by the selection of suitable measures, bearing in mind the requirements of plant as a wide, a satisfactory solution was arrived at. The incident also illustrates the difficulty frequently encountered in trying to establish the origin of an explosion, particularly where it is a small transient spark, as seems likely in this case. Although the dust was relatively reactive, it was by no means untypical and the lessons learned from these two explosions can be applied with confidence to many other materials.

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