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If a dust layer of thickness h on the internal wall of a cylindrical duct of diameter D, is dispersed homogeneously over the whole tube cross-section, one has

$$c = \rho_{bulk} (4h/D) \tag{5.2}$$

In the case of a tube diameter of 0.2 m, typical of many dust extraction ducts in industry, a layer thickness of only 0.1 mm is sufficient for generating a dust concentration of 1000 g/m^3 with a dust of bulk density 500 kg/m^3. In general, dispersible dust layers in process plants represent a potential hazard of extensive secondary dust explosions, which must be reduced to the extent possible.

5.3 Ignition of Dust Clouds in Air

5.3.1 Introduction

A combustible dust cloud will not start to burn unless it becomes ignited by a source of heat of sufficient strength. The most common ignition sources are:

- smoldering or burning dust
- open flames (welding, cutting, matches, etc.)
- hot surfaces (hot bearings, dryers, heaters, etc.)
- heat from mechanical impacts
- electrical discharges and arcs

In addition, there are some more sophisticated potential ignition sources including:

- laser light
- adiabatic compression and shock waves
- ultrasonic waves

There is considerable variation in the ignition sensitivity of clouds in air of various types of dusts, not least due to variations chemical composition including moisture content, and particle size. In order to quantify the ignition sensitivity of dust clouds and dust deposits, when exposed to various kinds of ignition sources, a range of laboratory-scale test methods have been developed.

5.3.2 Smoldering or Burning "Nests"

As discussed in Chapter 4, experience has shown that combustible dusts, when deposited in heaps or layers, may under certain circumstances develop internal smoldering nests of high temperatures. This is due to the porous structure of dust deposits, which gives oxygen access to the particle surface throughout the deposit, and also makes the heat conductivity of the deposit low. The initial oxidation inside the deposit may sometimes be due to the deposited dust or powder having initially a higher temperature than intended or permissible. However, some natural vegetable materials may develop initial spontaneous combustion even at normal ambient temperatures due to biochemical activity, if the content of fat and/or moisture is high.

If a dust deposit containing such a hot reaction zone, often called a 'smoldering nest', is disturbed and dispersed by an air blast or some mechanical action, the burning dust may initiate a dust explosion if brought in contact with a combustible dust cloud. In other cases the dust deposit or layer rests on a heated surface, which supplies the heat needed to trigger self-ignition in the dust. Such surfaces can be overheated bearings, heaters in workrooms, light bulbs, walls in dryers, etc. Dust deposits on heated surfaces may prevent normal cooling by forming an insulating layer. This may cause a further temperature rise in the surface, which will, in turn, increase the likelihood of ignition of the dust further. In general the minimum temperature of a hot surface for a layer of a given dust to self-ignite decreases with increasing thickness of the dust layer.

Pinkwasser (1985, 1986) studied the possibility of dust explosions being initiated by smoldering lumps ('nests') of powdered material that was conveyed through a process system. The object of the first investigation (1985) was to disclose the conditions under which smoldering material that had entered a pneumatic conveying line would be extinguished, i.e. cooled to a temperature range in which the risk of ignition in the downstream equipment was no longer present. In the case of > 1 kg/m^3 pneumatic transport of screenings, low-grade flour and C3 patent flour, it was impossible to transmit a 10 g smoldering nest through the conveying line any significant distance. After only a few m, the temperature of the smoldering lump had dropped to a safe level. In the case of lower dust concentrations, between 0.1 and 0.9 kg/m^3, i.e. within the most explosive range, the smoldering nest could be conveyed for an appreciable distance, but no ignition was ever observed in the conveying line.

In the second investigation (1986) smoldering nests of 700°C were allowed to fall freely through a 1 m tall column containing dust clouds in air of 100–1000 g/m^3 of wheat flour or wheat starch. Ignition was never observed during free fall. However, in some tests with nests of at least 25 mm diameter and weight at least 15 g, ignition occurred immediately after the nest had come to rest at the bottom of the test column. This indicates that a smoldering nest falling freely through a dust cloud in a silo without disintegrating during the fall, has a higher probability of igniting the dust cloud at the bottom of the silo than during the fall. This result agrees with the findings of Alfert, Eckhoff and Fuhre (1989), who studied the ignition of dust clouds in a 22 m tall silo of diameter 3.7 m by falling smoldering nests. It was found that nests of low mechanical strength disintegrated during the fall and generated a large fire ball that ignited the dust cloud. With mechanically stable nests, ignition of the dust cloud occurred either some time after the nest had come to rest at the silo bottom, or when the best became disintegrated during the impact with the silo bottom. However, as soon as the nest had come to rest at the silo bottom, it could also become covered with dust before ignition of the dust cloud got under way.

5.3.3 Open Flames

The flames of welding and cutting burners are sufficiently powerful to initiate explosions in any dust cloud that is at all able to propagate a self-sustained flame. The cutting burner flame is particularly hazardous because it supplies excess oxygen to the working zone. All codes and regulations for preventing dust explosions contain strict requirements to the safety precautions that have to be taken when performing hot work in areas containing dust. Smoking should be prohibited in areas where combustible dusts exist. A burning wooden match develops about 100 J of thermal energy per second. This is more than sufficient for initiating explosions in most combustible dust clouds.

A pragmatic test method for assessing whether a dust cloud in air can be ignited by an open flame is illustrated in Figure 5–24. The test is based on the consideration that a welding burner flame is amongst the strongest ignition sources encountered in industrial practice. A vertical tube of length 40 cm and diameter 14 cm, open at both ends, was fitted with a U-shaped dust dispersion tube and an acetylene/oxygen welding burner. A quantity of the powder to be tested was placed at the bottom of the dispersion tube, and a controlled blast from a compressed air reservoir dispersed the dust into a cloud in the main tube where it was immediately exposed to the hot flame from the welding burner. The amount of powder and the dispersion air pressure was varied to produce optimal conditions for ignition. When a dust flame occurred, its maximum height, color and apparent violence were assessed by the observer.

5.3.4 Hot Surfaces

Besides igniting dust layers, hot surfaces can initiate dust explosions by direct contact between the dust cloud and the hot surface. However, the minimum hot surface temperatures needed for this are generally considerably higher (typically 400–500°C for organic dusts) than for ignition of dust layers.

In the U.S.A., the ignition temperature of dust clouds in contact with a hot surface was traditionally determined in the Godbert-Greenwald furnace, which is illustrated in Figure 5–25.

In this apparatus the internal surface of a vertical cylindrical ceramic tube, open at the lower end, is kept at a known, constant temperature, and a sample of the powder is dispersed as a dust cloud into the tube from above by means of a blast of air. The automatically controlled temperature of the internal wall of the tube is changed in steps and the experiment repeated until the minimum temperature for ignition has been identified. The International Electrotechnical Commission (IEC) investigated the performance of the Godbert-Greenwald furnace through several round-robin test series involving several central test laboratories in Europe and the U.S.A. The influences of a number of details of the apparatus itself and of the experimental procedure were studied and details of apparatus and procedure specified more closely. The resulting, improved Godbert-Greenwald furnace has now been adopted by IEC as a standard method for determining minimum ignition temperatures of dust clouds.

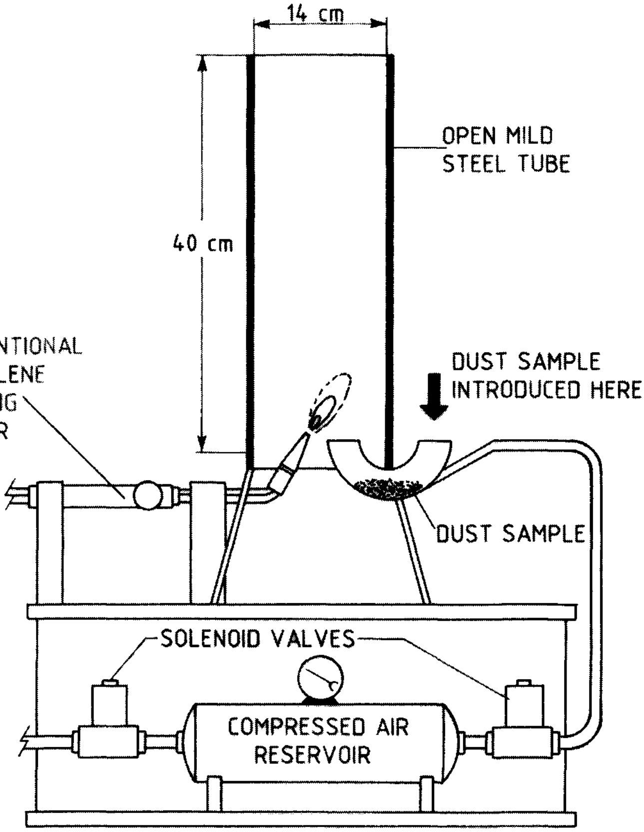

Figure 5–24 Welding torch ignition test apparatus used in Norway for assessing whether or not a dust cloud can be ignited by an open flame. From Eckhoff (2003).

5.3.5 Heat from Mechanical Impacts

The literature on dust explosions is sometimes confusing when discussing ignition of dust clouds by heat from mechanical impacts. This is reflected in the use of terms such as "friction" or "friction sparks" when categorizing ignition sources. In order to clarify the situation, it seems useful to distinguish between friction and impact.

Friction is a process of fairly long duration whereby objects are rubbed against each other and heat is gradually accumulated. This produces hot

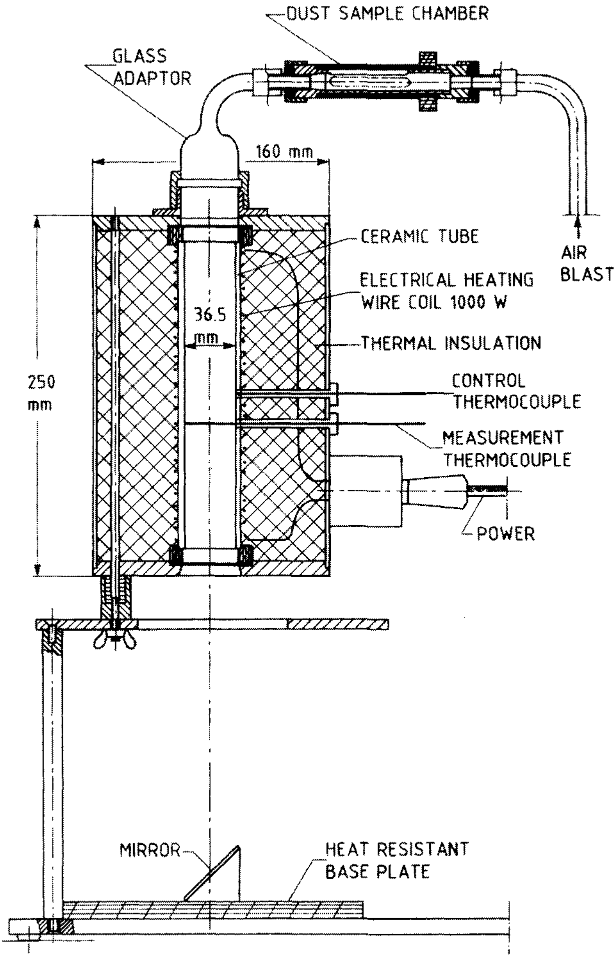

Figure 5–25 Godbert-Greenwald furnace for determination of the minimum ignition temperature of dust clouds. From Eckhoff (2003).

surfaces, and in some cases inflammation, for example when an elevator or conveyor belt is slipping.

Impact is a short-duration interaction between two solid bodies under conditions of large transient mechanical forces. Small fragments of solid material may be torn off, and if made of metal, they may start burning in air due to the initial heat absorbed in the impact process. In addition, local *hot-spots* may be generated at the points of impact. In some cases the impact may occur repeatedly at one specific point, for example when some misplaced stationary object inside a bucket elevator is repeatedly hit by the buckets. This may gradually generate a hot spot of sufficient size and temperature to ignite the dust cloud directly.

A practical mechanical impact situation may be as follows: A steel bolt is accidentally entering the top of a large concrete silo during filling of the silo with maize starch. The bolt falls down into the nearly empty silo and hits the concrete wall near the silo bottom at a velocity of 25–30 m/s. Visible sparks are generated. A dense, explosive cloud of maize starch occupies the region where the impact occurs. Is ignition of the cloud probable? A test method for investigating this problem is shown in Figure 5–26.

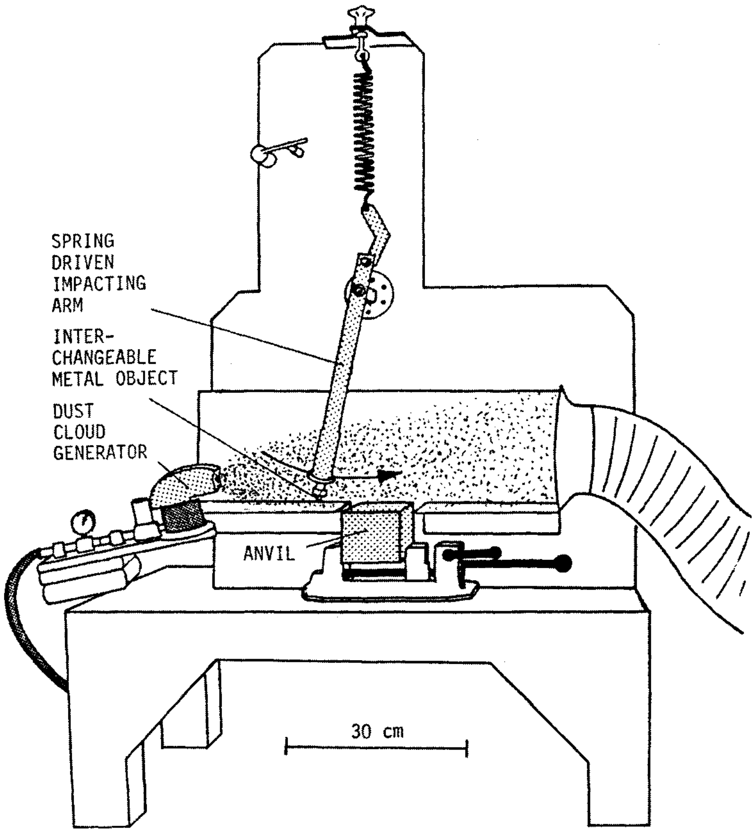

Figure 5–26 Apparatus for determining the sensitivity of dust clouds to ignition by single accidental mechanical impacts. From Pedersen and Eckhoff (1987).

Experiments using this apparatus indicated that ignition of clouds of natural organic materials by metal sparks from single impacts, where steel is the metal component, seems less likely than believed by many in the past. However, if the metal is titanium or zirconium, ignition can occur quite readily.

The thermite reaction ($2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe$ + heat) is often mentioned as a potential ignition source from impacts involving aluminum and rust. However, if a lump of normal soft aluminum collides with a rusty steel surface, a thermite reaction will not necessarily take place. In fact, due to the softness of the aluminum, the result is often just a thin smear of aluminum on top of the rust. However, if this sandwich of aluminum and rust is given a blow by a third hard object, a thermite flash capable of igniting dust clouds can easily be produced. The same applies to a rusty surface that has been painted with aluminum paint, if the pigment content of the paint is comparatively high.

5.3.6 Electric Sparks and Arcs; Electrostatic Discharges

5.3.6.1 Introduction

It has been known for more than 100 years that electric sparks and arcs can initiate dust explosions. The minimum spark energy required for ignition varies with the type of dust, the effective particle size distribution in the dust cloud, the dust concentration and turbulence, and the spatial and temporal distribution of the energy in the electric discharge or arc. For many decades it was thought that the electric spark energies needed for igniting dust clouds in air were generally much higher, by one or two orders of magnitude, than the minimum ignition energies for gases and vapors in air. However, it has now become generally accepted that many dusts can be ignited by spark energies in the range 1–10 mJ, and even below 1 mJ, i.e. in the range typical of gases and vapors.

5.3.6.2 Inductive and Capacitive Spark Discharges

5.3.6.2.1 General

One distinguishes between inductive sparks or arcs generated when live electric circuits are broken, either accidentally or intentionally (e.g. in switches), and discharges caused by release of accumulated electrostatic charge.

In the former case, if the points of rupture are separated at high speed, transient inductive sparks are formed across the gap as illustrated in Figure 5–27. If the current in the circuit prior to rupture is i and the circuit inductance L, the theoretical spark energy, neglecting external circuit losses, will be $1/2Li^2$. As an example, a current of 10 A and L equal to 10^{-5} H gives a theoretical spark energy of 0.5 mJ. This is too low for igniting most dust clouds in air. However, larger currents and/or inductances can easily give incendiary sparks. Sometimes rupture only results in a small gap of permanent distance. This may result in a hazardous stationary arc if the circuit stays live.

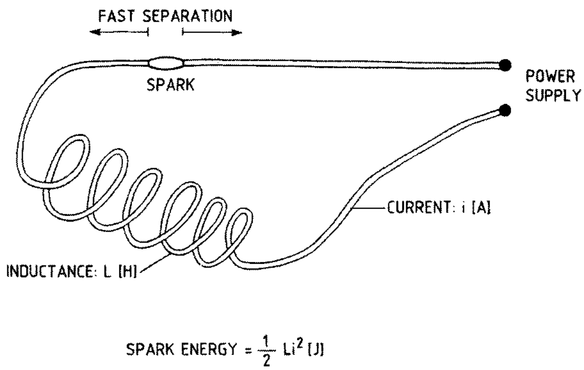

Figure 5–27 Inductive spark or "break flash" generated when a live electric circuit is suddenly broken and the points of rupture are separated at high speed. From Eckhoff (2003).

Capacitive spark discharges occur when charge that has accumulated on an electrically conducting, unearthed, object is discharged to earth across a small air gap. In the process industries producing and handling powders, electrostatic charging is generally tribo-electric, which implies transfer of electrons between objects of different electron affinity during contact and subsequent separation. In a process plant this occurs during handling and transport of powders and dusts whenever the powder/dust and the process equipment make contact and separates.

An electrostatic spark discharge results if the discharge of the accumulated charge occurs between two electrically conducting electrodes. The spark gap distance must then be sufficiently short to allow breakdown and spark channel formation at the actual voltage difference between the charged object and earth. On the other hand, in order for the spark to become incendiary, the gap distance must be sufficiently long to permit the required voltage difference to build up before break-down of the gap occurs. The theoretical spark energy, neglecting external circuit losses, equals $1/2CU^2$, where C is the capacitance of the un-earthed, charged process item with respect to earth, and V is the voltage difference. Figure 5–28 illustrates a practical situation that could lead to a dust explosion initiated by an electrostatic spark discharge.

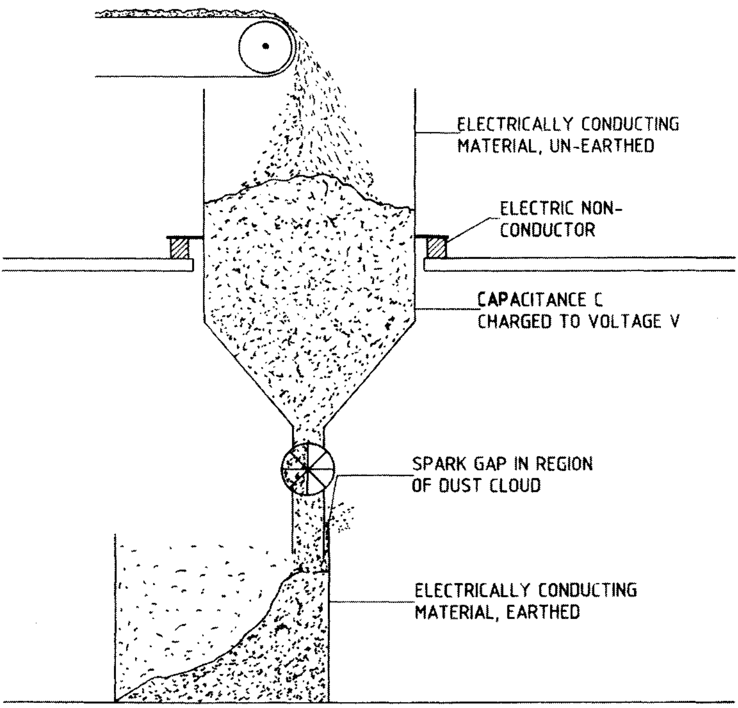

Figure 5–28 Illustration of a practical situation that could lead to a dust explosion initiated by an electrostatic spark discharge. From Eckhoff (2003).

Glor (1988) estimated typical approximate capacitance-to-earth values for objects encountered in the process industry. The values given in Table 2–11 in Section 2.2 (ignition of gases) are equally valid in the context of dust explosions. Such capacitance values are used for estimating the maximum theoretical spark energies $1/2CU^2$ when discharging a non-earthed metal object of capacitance C and at a voltage U, to earth.

5.3.6.2.2 The Minimum Ignition Energy (MIE) of a Dust Cloud

The MIE of a given dust in air is a commonly used measure of the ease with which the cloud is ignited by electric sparks and electrostatic discharges. A typical apparatus for laboratory determination of MIE of dust clouds is illustrated in Figure 5–29. An appropriate quantity of the dust is placed in the dispersion cup at the bottom of the 1.2 liter plastic or glass cylinder and dispersed by a blast of air deflected by a conical "hat" as indicated. A spark of the desired energy is discharged across the electrodes synchronously with the transient appearance of the dust cloud in the spark gap region, and it is recorded visually whether or not ignition takes place. MIE is often defined as the lowest spark energy that gives at least one ignition in ten trials at the same spark energy.

As discussed by Eckhoff (2003) there can be a strong influence of the spark discharge time on MIE for dust clouds, in particular for spark energies exceeding 1 J. In standard testing for MIE optimal discharge times for ignition is achieved by introducing a 1–2 mH inductance in the discharge circuit, and this feature is compulsory in the current international (IEC) and European standard methods for MIE determination for dust clouds. This inductance is to be removed, however, when the purpose of the test is to assess the sensitivity to ignition by electrostatic spark discharges. A major limitation of the standard test apparatuses commonly used, is that they cannot generate sparks of energies significantly lower than 2–3 mJ. However, recently Randeberg et al. (2005) developed a spark generator capable of producing synchronized capacitive sparks of energies down to less than 0.1 mJ, suitable for duct cloud ignition tests.

Figure 5–30 illustrates various circuits that have been used to generate the electric spark discharges in MIE tests. In the original circuit of U.S. Bureau of Mines, a substantial part of the capacitor energy was lost in the transformer. In the case of the direct high voltage discharge circuit the switch element needed for synchronization of dust dispersion and spark discharge requires special considerations. In the CMI circuit a trigger transformer feeding 2–3 mJ into the main discharge is used for triggering the discharge. Other synchronization principles are also in use, including a fast-moving earthed electrode.

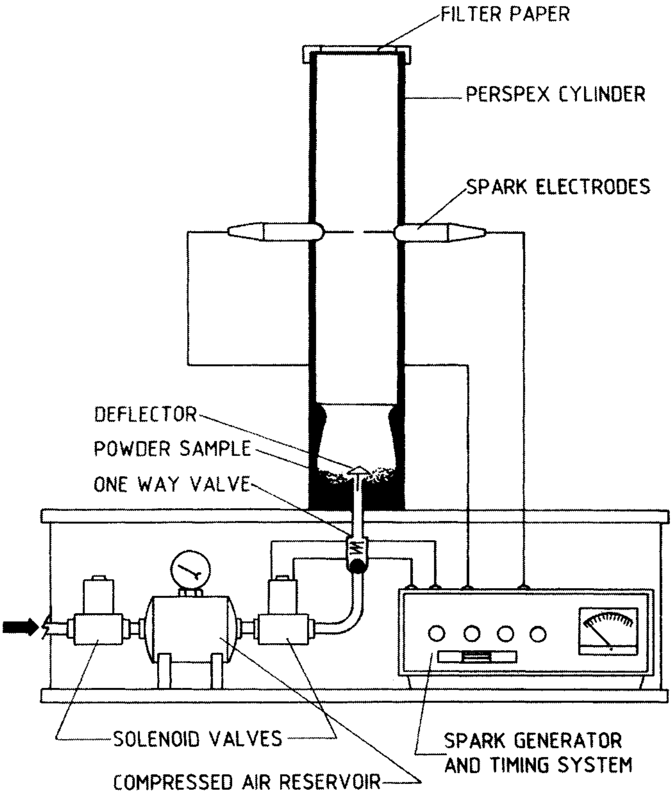

Figure 5–29 Illustration of an apparatus type commonly used for experimental determination of minimum electric spark ignition energies (MIE) of explosive dust clouds in air. From Eckhoff (2003).

5.3.6.2.3 Range of MIEs for Dust Clouds

Minimum electric spark energies (MIE) for ignition of dust clouds vary, as already mentioned, with dust type, particle size, and other factors. In the past it was thought that the absolute lower limit for MIEs of dust clouds in air was of the order of 10 mJ, i.e. nearly two orders of magnitude above typical MIEs of IIA gases (see Chapter 2). However, it is now accepted that MIEs of clouds of dusts in air span over at least 8 decades, from perhaps as low as 0.01 mJ in the lower end to beyond 1kJ in the upper.

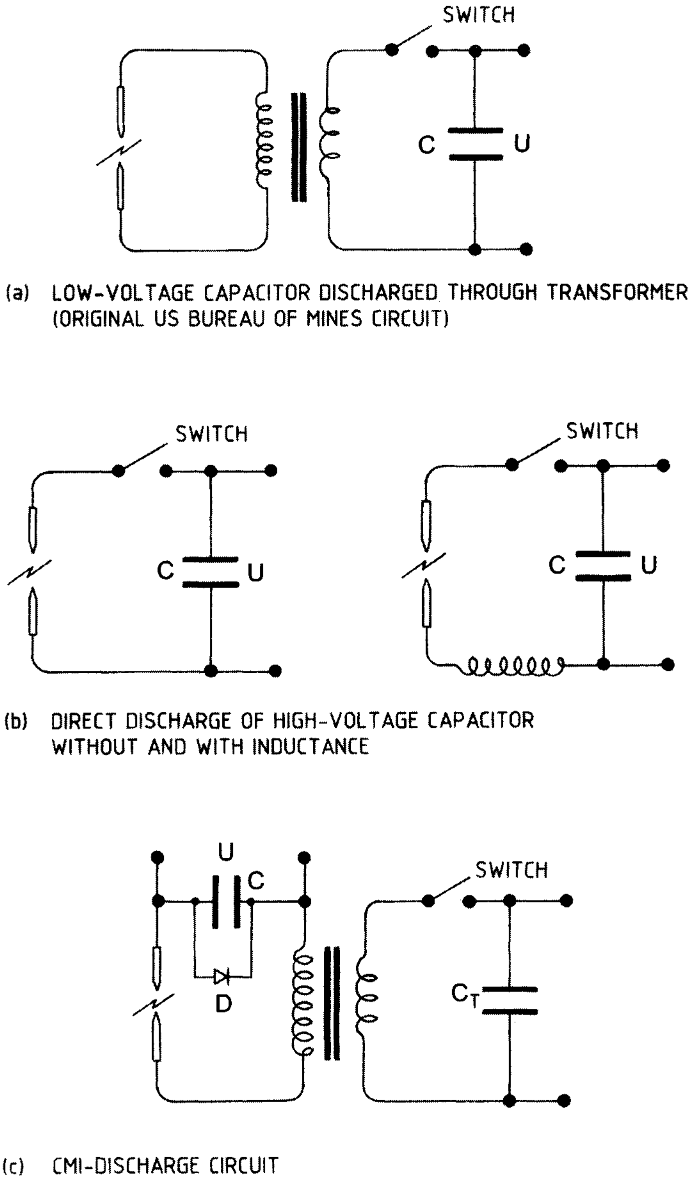

Figure 5–30 Three different electric circuits used in experimental determination of minimum electric spark ignition energies (MIE) of explosive dust clouds in air. From Eckhoff (2003).

5.3.6.2.4 Conservative Ignition Curves for Dusts Clouds Based on MIE

For capacitive circuits, conservative ignition curves are obtained directly from the equation $1/2CU^2$ = MIE. Charts showing this graphically, for a range of MIE values, are given in Figure 5–31. In the case of inductive circuits, conservative ignition curves are obtained directly from the equation $1/2Li^2$ = MIE for L > 1 mH. For smaller L, the ignition current will be independent of L, and the circuit will essentially be resistive. Charts showing conservative ignition curves for inductive circuits, for a range of MIE values, are given in Figure 5–32. For resistive ignition circuits Eckhoff (2002) has suggested that an equation of the form $I = A \cdot MIE^B/U^2$, where A and B are empirical constants, may provide a first order conservative estimate. Graphs representing this equation for preliminary values of A and B are given by Eckhoff (2003). More research is needed to establish more reliable resistive circuit ignition data in the range of higher MIEs.

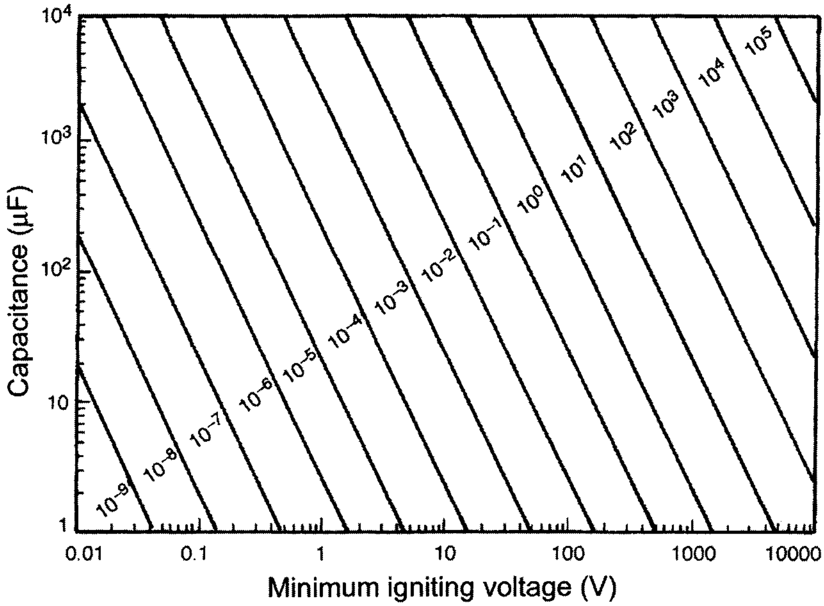

Figure 5–31 Theoretical conservative capacitive ignition curves for dust clouds based on the equation $1/2CU^2$ = MIE. The numbers attached to the straight lines are the respective MIE values in J. From Eckhoff (2003).

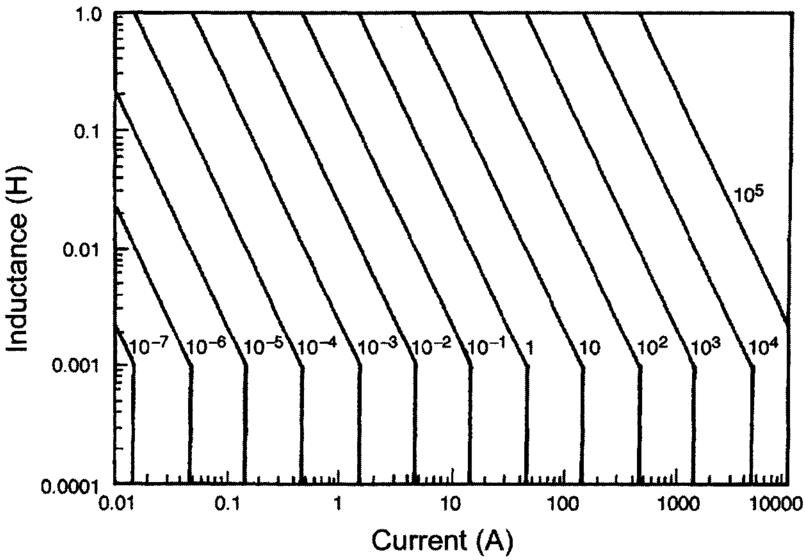

Figure 5–32 Theoretical conservative inductive ignition curves for dust clouds based on the equation $1/2Li^2$ = MIE, valid for L > 1 mH. The numbers attached to the straight lines are the respective MIE values in J. From Eckhoff (2003).

5.3.6.2.5 Parameters Influencing measured MIEs of Dust Clouds

Turbulence in the dust cloud raises the effective MIE and therefore provides a safety factor as far as ignition is concerned. This is illustrated by the work of Yong Fan Yu (1985), who was unable to ignite turbulent explosive clouds of wheat grain dust in a container at the exit of a pneumatic transport pipe, even with highly incendiary "soft" electric sparks of energies in excess of 1 J. In the type of test illustrated in Figure 5–29 the turbulence of the dust cloud at the moment of ignition can be varied by varying the delay between dust cloud generation and ignition. The larger the delay, the lower the turbulence. Figure 5–33 gives some results of MIE as a function of ignition delay.

Figure 5–34 shows how particle size influences the minimum ignition energy for three different dusts. The vertical scale is logarithmic, and it is seen that the effect is very strong. Kalkert and Schecker (1979) developed a theory indicating that MIE is proportional to the cube of the particle

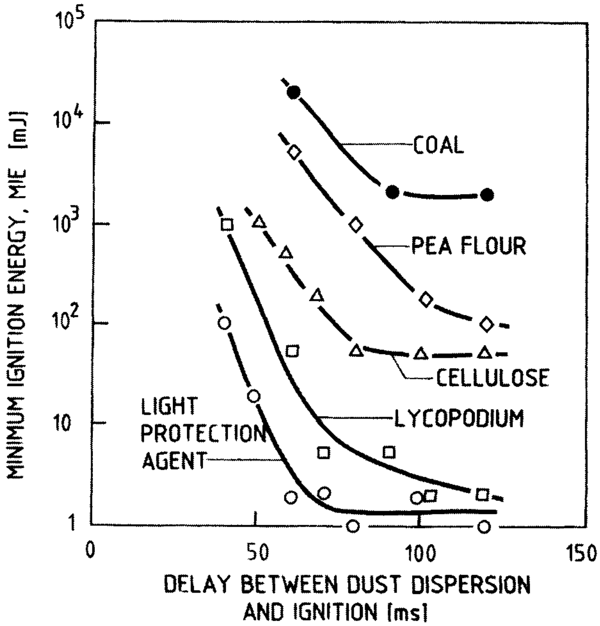

Figure 5–33 Illustration of the influence of initial turbulence of explosive dust clouds on the minimum electric spark energies required for ignition. Data from Glarner (1984).

diameter, as also illustrated in Figure 5–34 by their theoretical prediction of the relationship for polyethylene.

Moisture in the dust reduces both ignition sensitivity and explosion violence of dust clouds. Figure 5–35 illustrates the influence of dust moisture on MIE. The vertical axis is logarithmic, and it is seen that the effect is quite significant. If safety measures against electric spark ignition are based on MIE data for a given dust moisture content, it is essential that this content is not subsided in practice.

5.3.6.3 Electrostatic Discharges Other Than Sparks

5.3.6.3.1 Overview

Glor (1988) and Lüttgens and Glor (1989) distinguished between five different types of electrostatic discharges in addition to sparks, namely:

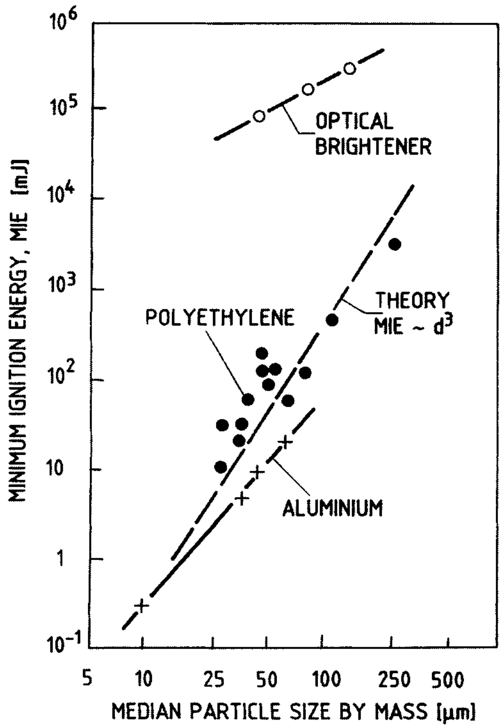

Figure 5–34 Minimum experimental electric spark ignition energies (MIE) of clouds in air of an optical brightener, polyethylene and aluminum, as functions of median particle size, from Bartknecht (1987), and theoretical line for polyethylene. From Kalkert and Schecker (1979).

- brush discharge
- corona discharge
- propagating brush discharge
- discharge along the surface of powder/dust in bulk
- lightning-like discharge

5.3.6.3.2 Corona Discharges

Corona discharges, illustrated in Figure 2–33 in Section 2.2, occur under the same conditions as brush discharges, but are associated with earthed electrodes of much smaller radii of curvature, such as sharp edges and needle tips. For this reason such discharges will occur at much lower field

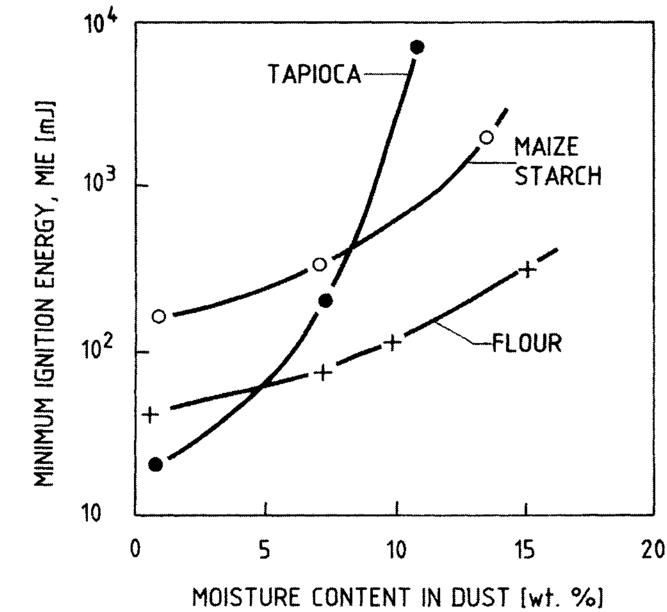

Figure 5–35 Influence of dust moisture content on minimum electric spark ignition energy (MIE) for three dusts. From van Laar and Zeeuwen (1985).

strengths than the brush discharges, and the discharge energies will therefore also be much lower. Consequently, the possibility of igniting dust clouds by corona discharges can be ruled out.

5.3.6.3.3 Brush Discharges

Brush discharges, illustrated in Figure 2–34 in Section 2.2, occur between a single curved, earthed metal electrode (radius of curvature 5–50 mm) and a charged non-conducting surface (plastic, rubber, dust). Brush discharges can ignite explosive gas mixtures. However, according to Glor (1988), no ignition of a dust cloud by a brush discharge had yet been demonstrated, not even in sophisticated laboratory tests using very ignition sensitive dusts. The conclusion that brush discharges cannot ignite dust clouds in air is strongly supported by the more recent experiments by Larsen et al. (2003). It must be emphasized, however, that this does not apply if the powder/dust contains significant quantities of combustible solvents, which can increase the ignition sensitivity of the cloud substantially, even when the vapor concentration in the air is well below the LEL of the vapor alone. Such clouds of a combustible dust suspended in a mixture of a combustible gas or vapor and air are called "hybrid" mixtures.

5.3.6.3.4 Propagating Brush Discharges

Propagating brush discharges, illustrated in Figure 2–35 and Figure 2–36 in Section 2.2, can, however, initiate dust explosions. Such discharges, which will normally have much higher energies than ordinary brush discharges, occur if a double layer of charges of opposite polarity is generated across a relatively thin sheet (< 8 mm thickness) of a non-conducting material (Glor, 1988). The reason for the high discharge energy is that the opposite charges allow the non-conductor surfaces to accumulate much higher charge densities than if the sheet had been charged on only one of the faces. Glor pointed out that in principle close contact of one of the faces of the sheet with earth is not necessary for obtaining a charged double layer. By adding electrons to one side of a plastic sheet and removing electrons from the other, the same result can be obtained. However, in practice earth on one side is the most common configuration. In the context of powders and dusts Figure 2–36 may illustrate pneumatic transport of a powder/dust in a steel pipe with an internal electrically insulating plastic coating. Due to the rubbing of the powder against the plastic, charge is accumulated on the internal face of the plastic coating. The high mobility of the electrons in the steel causes build-up of a corresponding charge of opposite polarity on the outer face of coating in contact with the steel. If a short passage between the two oppositely charged faces of the plastic coating is provided, either via a perforation of the coating or at the pipe exit, a propagating brush discharge can result. Lüttgens and Glor (1989) give an example of a dust explosion that was initiated by a propagating brush discharge. Acrylic powder was transported pneumatically in a 50 mm diameter plastic pipe outdoors, and rainwater and snow provided the earthed electrically conducting shield on the outer surface of the pipe.

Glor (1988) identified five typical situations which may lead to propagating brush discharges during transport and handling of powders:

- high-velocity pneumatic transport of powder through an electrically insulating pipe, or a conductive pipe with an insulating internal coating

- use of inspection windows of glass or Plexi glass in pneumatic transport pipes
- continuous impact of powder particles onto an insulating surface (e.g. a coated dust deflector plate in the cyclone of a dust separator)
- fast movement of conveyor or transmission belts made of an insulating material, or of a conductive material coated with an insulating layer of high dielectric strength
- filling of large containers or silos made of insulating material (e.g. flexible intermediate bulk containers) or of metallic containers or silos coated internally with an insulating layer of high dielectric strength

5.3.6.3.5 Electrostatic Discharge Along the Surface of Powder/Dust in Bulk

This type of discharge may occur if strongly non-conducting powders are blown or poured into a large container or silo. When the charged particles settle in a heap in the container, very high space charge densities may be generated and luminous discharges may propagate along the surface of the powder heap from its base to its top. However, under realistic industrial conditions only very large particles, of 1–10 mm diameter, are likely to generate spark discharges due to this process. It further seems that very high specific electrical resistivity of the powder is also a requirement ($>10^{10}$ ohm•m) which probably limits this type of discharge to coarse plastic powders and granulates. The maximum equivalent spark energy for this type of discharge has been estimated to the order of 10 mJ, but little is known about the exact nature and incendivity of these discharges. Because of the large particle size required to generate the charge, these particles are unlikely to give dust explosions, and therefore a possible explosion hazard must be associated with the simultaneous presence of an explosive cloud of an additional, fine dust fraction. Glor (1988) pointed out that the probability of occurrence of this discharge type increases with increasing charge-to-mass ratio in the powder, and increasing mass filling rate.

5.3.6.3.6 Lightning Type Discharge

Lightning type discharge, which may in principle occur within an electrically insulating container with no conductive connection from the interior to the earth is the last type of discharge mentioned by Glor (1988) and Lüttgens and Glor (1989). However, as Glor stated, there is no evidence that lightning discharges have occurred in dust clouds generated in industrial operations.

5.3.7 Jets of Hot Combustion Products

The basic process is the same as for explosive gas mixtures, as described in Section 2.2.7. In general terms, the maximum experimental safe gap (MESG) may be defined as the largest width of a slot that will just prevent transmission of a flame in a gas or dust cloud inside an enclosure to a similar gas or dust cloud on the outside. This definition is somewhat vague and raises several questions. It neither defines the length of the slot, nor the explosion pressure inside or the volume of the enclosure. Therefore, MESG is not a fixed constant for a given explosive cloud, but depends on the actual circumstances. MESG for dust clouds is of limited relevance in practice and has no relevance, in the context of electrical equipment enclosure design.

Schuber (1988, 1989) investigated the influence of various parameters on MESG for dust clouds. The situation addressed was possible transmission of a dust flame from one side of a rotary lock to the other, as illustrated in Figure 5–36.

The research apparatus used by Schuber is illustrated in Figure 5–37. Explosive dust clouds of desired concentrations were generated simultaneously from compressed dust reservoirs in both the large vessel (1 m^3) and the smaller vessel (40 liters) mounted inside the large one. The cloud in the smaller vessel was subsequently ignited, and it was observed whether the cloud in the large vessel was ignited by the flame jet being transmitted through the annular gap in the wall of the smaller vessel.

Schuber found that MESG increased with increasing initial turbulence in the dust clouds. This is in harmony with the increase of the minimum electric spark energy for ignition of both gases and dust clouds with increasing turbulence. In order to ensure conservative results, Schuber conducted his experiments with comparatively low initial turbulence in the dust clouds. He correlated his experimental MESG values with the product of minimum electric spark ignition energy and the dimensionless minimum ignition temperature, as shown in Figure 5–38. Because (TI + 273)/273 is in the range between two and three for most of the dusts tested, the double-logarithmic correlation in Figure 5–38 is essentially between MESG and MIE.

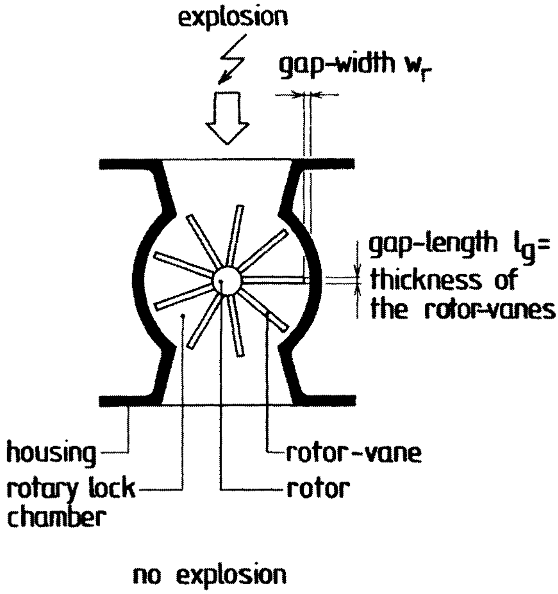

Figure 5–36 Illustration of a practical flame jet transmission situation for burning dust clouds: a rotary lock with a dust explosion occurring on one side. From Schuber (1988).

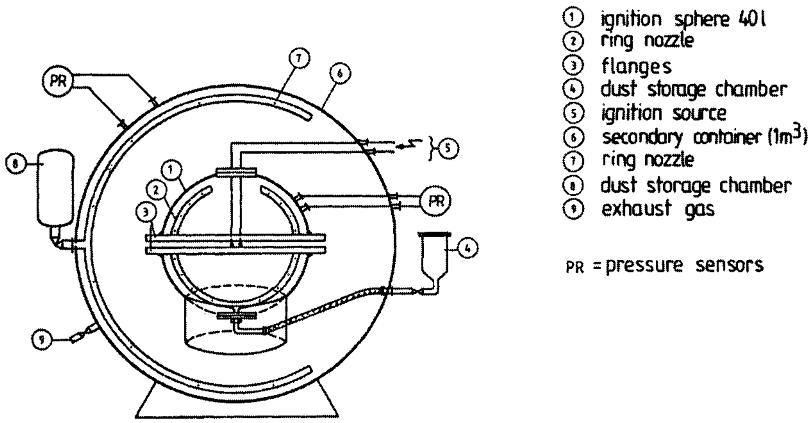

Figure 5–37 Illustration of the experimental set-up comprising a split and flanged 40 liter explosion vessel mounted inside a 1 m^3 explosion vessel. The annular gap for possible flame transmissions between the two flanges on the two halves of the 40 liter sphere. From Schuber (1989).

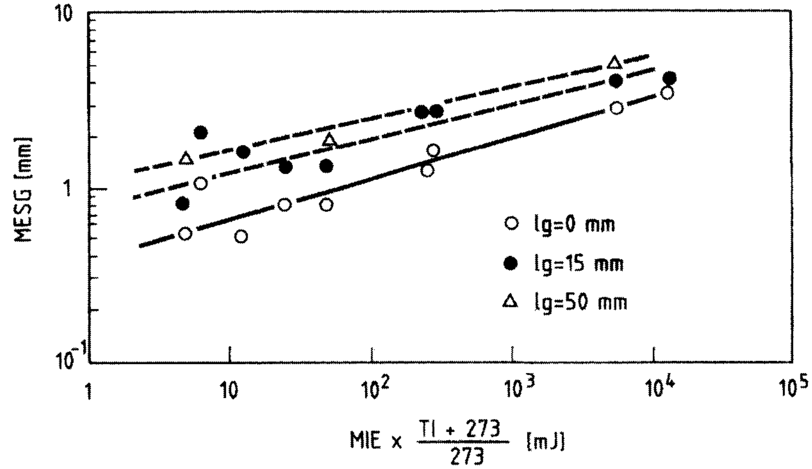

Figure 5–38 Correlations between MESG and ignition sensitivity of clouds in air of various dusts, for various gap lengths. From Schuber (1989).

As already pointed out the original motivation for Schuber's work was the uncertainty related to the ability of rotary locks to prevent transmission of dust explosions. He also carried out industrial scale experiments with a set-up as illustrated in Figure 5–36, with a rotary lock mounted between two vessels in which explosive dust clouds were generated simultaneously. The dust cloud on the one side was then ignited and it was observed if transmission of flame occurred to the extent that the dust cloud on the other side was also ignited. On the basis of numerous experiments, Schuber (1989) constructed a nomograph for predicting maximum permissible gaps between the edges of the rotary lock blades and the housing for preventing flame transmission. (See Eckhoff, 2003).

5.3.8 Shock Waves

Shock waves, i.e very steep and strong pressure wave fronts traveling at speeds larger than the speed of sound, can be generated by industrial accidents, e.g. by pressure vessel failure. An informative analysis of shock wave ignition of dust clouds was given by Wolanski (1990). His illustration of the particle interaction with the convective flow behind the incident shock wave is shown in Figure 5–39.

At the first moment of interaction, the stationary particle is subjected to the supersonic flow. A bow shock is formed near the particle; and since the tem-

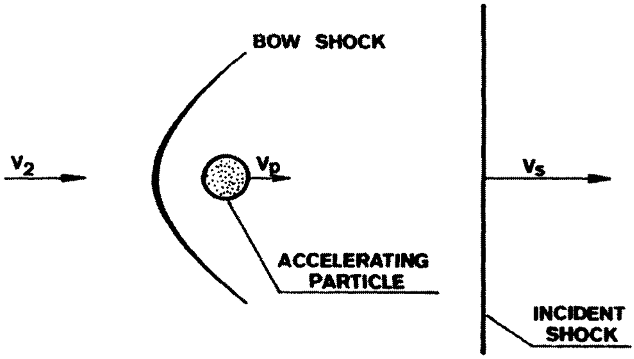

Figure 5–39 Schematic illustration of the interaction between a stationary dust particle and the convective supersonic gas flow behind the incident shock front. From Wolanski (1990).

perature of the gas between the particle and the bow shock is close to the stagnation temperature, the particle is heated rapidly. At the same time, the drag force causes the particle to accelerate and the temperature to decrease. The rate of particle acceleration depends on particle size and other properties. Because very small particles accelerate rapidly to supersonic speeds, the stagnation temperature at the particle front exists only for an extremely short time. Larger particles accelerate more slowly, thus remaining exposed to the higher stagnation temperature between the bow shock and the particle for a longer time. However, the larger particles require more heat for ignition. Wolanski suggested, therefore, that depending on the dust type, there is an optimal particle diameter range, which provides the most favorable conditions for ignition. In fact, in incident shock waves some dust particles can be more easily ignited than can even a hydrogen/oxygen mixture. According to Wolanski, experimental data do confirm that the ignition delay of dust particles behind the incident shock depends on particle diameter; and the optimum diameter for ignition varies with the nature of the particle. For organic particles the optimal diameter is of the order of 10 μm. Particles of diameters of only a few μm, or larger than 100 μm are usually more difficult to ignite in an incident shock than particles of intermediate sizes.

5.3.9 Light Radiation

Ignition experiments using laser light can provide basic information not only about dust cloud ignition processes, but also about flame propagation processes in dust clouds. Wel et al. (1994) used a simple, modified Semenov model for auto-ignition (no temperature gradients inside initially heated volume), for using experimental laser-light-pulse ignition data to predicted minimum ignition temperatures and energies of dust clouds. The predicted values were in approximate agreement with minimum ignition temperatures and energies measured directly. Zevenbergen (2002) reviewed various aspects of ignition of dust clouds by laser light.

Proust (1996), using a Nd-YAG CW laser, investigated experimentally the ability of a beam of laser light to ignite an explosive dust cloud. He was unable to find a generally valid correlation between the ease with which a dust cloud could be ignited directly by a laser beam, and the minimum electrical spark ignition energy of the same dust cloud. Proust also conducted experiments where ignition occurred indirectly, via a small solid target in the dust cloud that had first been heated by the laser beam. He found that the probability of a given laser beam igniting a given dust cloud was considerably higher with this set-up than with direct laser beam ignition. Proust (2002) extended these experiments by using both continuous and pulsed radiation, and both targets of layers of non-combustible material, e.g. iron oxide, and of layers of the same material as in the dust cloud to be ignited. He was able to quantify minimum laser beam powers impinging on a solid target required for igniting dust clouds by the heat absorbed by the target. The parameters included the laser beam diameter, the duration of the irradiation, the target material (combustible/non-combustible), and the type of dust (starch, lycopodium, lignite, sulphur, ABS, and aluminum). An inherent complicating element in this kind of experiment is that the laser light has to travel through some length of dust cloud before impinging on the target. The part of the beam power absorbed by the dust cloud is a function of both the length of the light path through the dust cloud, the dust concentration, and the material and geometry of the dust particles. Figure 5–40 shows a set of Proust's results for pulsed laser radiation.

The minimum ignition energies in Figure 5–40 were deduced from experimental graphs of the minimum radiated laser energy received by the target required for igniting the dust cloud, as a function of the time from onset of radiation to ignition. By extrapolating the almost linear relationships found to zero time, an estimate of the minimum ignition energy with very short laser pulses hitting an inert iron oxide target, could be deduced. The minimum ignition energies found in this way, ranging from 4–14 J

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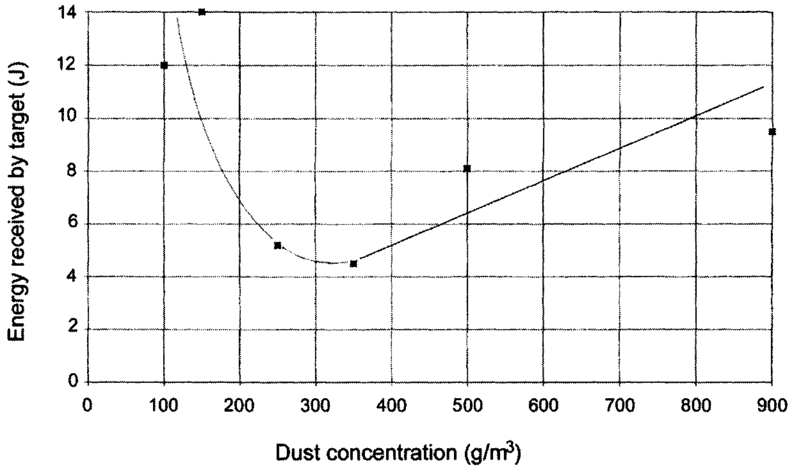

Figure 5–40 Deduced relationship for the minimum energy of a very short laser pulse, hitting a solid inert iron oxide target inside an explosive cloud of starch particles in air, required for igniting the cloud, as a function of the starch concentration in the cloud. From Proust (2002).

are substantially higher than the minimum electric spark ignition energy of 10 mJ found for the actual starch in a standard MIE test.

5.4 Case Histories of Dust Explosions

5.4.1 Motivation for Selection

Most of the case histories given in the following are taken from the book by Eckhoff (2003). Because of his close co-operation with Norwegian industry in investigating accidental dust explosions that have occured there. He has had access to detailed information on several such explosions. It was natural, therefore, to include some of this information even in the present book. However, the case history from China and the very recent one provided by CSB (2003) constitute most valuable additional examples illustrating that the dust explosion hazard continues to threaten a wide range or process industries in many countries.