FRICTIONAL IGNITION
OF
POWDERS:
A REVIEW

by

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1. INTRODUCTION

Surveys of industrial incidents in powder and dust handling plant show that in a substantial percentage, friction and mechanical failure and flames and flaming material are known ignition sources. Surveys for the UK[1,2] covering 1979-1988, and reviewing 303 events, showed friction and mechanical failure to be the reason for ignition in 18% of these incidents, and flames and flaming material to be responsible in another 15%. Overheating and spontaneous heating featured in a further 17%. Similarly, a survey by the Berufsgenossenschaftliches Institut für Arbeitssicherheit (BIA)[3] showed mechanical causes to be the most frequent source of ignition, with smouldering nests the second most frequent. The relevant percentages from the BIA survey were 26% for mechanical sparks, 11% for smouldering nests and 9% for mechanical heating.

A review by Billinge[4] of industrial friction ignition incidents divided potential frictional sources into three groups:

Low energy : approximately 10J, eg 500g falling 2m
Medium energy: approximately 1kJ, eg 25kg falling 4m
High energy : in excess of 1MJ, eg road tanker crash

The highest percentage by far of frictional ignitions is in the medium energy range, with some 50% of these due to impact.

When surfaces contact, impact and/or friction and grinding can produce sparks and hot spots; both are potential ignition sources for dust clouds or dust accumulations. If dust becomes trapped at the point of contact, some dusts may ignite at much lower friction-generated temperatures than those required to directly ignite a dust cloud. Clearly, plant operations such as grinding and screw-feeding have the potential to produce mechanical sparks and hot surfaces, as have accidental circumstances such as the presence of tramp-metal.

Impact is a short duration event in which local hot spots may occur and heated fragments of material are torn away to produce sparks. Friction and grinding occurs over a longer duration and may produce hot surfaces and showers of sparks.

The ATEX Directive[5] has introduced the hazard of mechanical ignition into legislation for the first time and there is currently underway an extensive programme of standards-making on techniques for prevention of ignitions due to mechanical effects. Although there is some published work on ignition by mechanical sparks[6] and hot surfaces[7], there is little in the way of practical guidance except in limited areas. Gibson has recently reviewed the likely scenarios for mechanical ignitions and the availability of published data, and has discussed the information required to complete an overall picture of the risks in real plant[8].

This paper is a review of the literature on the effects that frictional heating and sparking can have on combustible dusts, on the ways in which frictionally ignited dusts can burn, and on the methods by which combustion in burning dusts can ignite an explosive dust cloud or propagate into a more extensive dust accumulation.

2. REVIEW

The energy dissipated when two surfaces slide over each other produces heat and thus hot surfaces. Generally, temperatures not exceeding the lower of the melting points of the materials concerned develop, but, if wear and transfer of materials takes place, temperatures can approach the higher of the two melting points[9]. Mechanical sparks are hot particles of surface material torn off by impact, friction and grinding. If the spark material can oxidize in air, the spark temperature increases during flight.

2.1 Mechanically Generated Sparks

The ignitability of a spark depends on its temperature, its size and probably its velocity. Powell[9] has reviewed published data on the temperature of sparks and their ability to ignite gas-air and vapour-air mixtures. Particles of 100 micron diameter need to be greater than 2000°C if they are to ignite methane-air; but carbon steel sparks in air were measured at 1850°C only, 1750°C in methane-air and 1500°C in fuel-air mixtures where towns gas, hydrogen and acetylene were the fuels. The addition of fuel to air decreases the oxygen concentration and so slows the reaction between the steel and the air. Light metals burn at well in excess of 2000°C.

The surface materials are of crucial importance in determining whether an ignition of a specific explosive atmosphere will occur. Powell[9], in his review of gas and vapour ignitions, has produced tables that give a ranking of the incendivity of ignition sources produced by a range of impact and rubbing situations. These tables are reproduced as Tables 1 and 2. Available evidence in the literature suggests a similar ranking for ignition of dust clouds.

Mechanically generated sparks take three forms:

Grinding sparks -	a quick contact (20-50 milliseconds) of two surfaces in relative motion
Friction sparks -	rubbing together over an extended time (0.5 - 2.0 seconds) of two surfaces in relative motion
Impact sparks -	single contact of two surfaces in relative motion

Impact sparks are the result of the application of high forces - sufficient to cause permanent deformation - for the order of a millisecond[9], and they account for the largest proportion of frictional ignitions in non-mining industry - 65% of dust and powder ignitions is the figure from a published review of incidents due to mechanical ignition[4]. During impact, energy dissipation occurs at a high rate eg. a hammer blow of 1 J for 1 ms gives a power of 1 kJ if all the available energy is dissipated[9], although only about a third goes into heating the impact surfaces. Measurements by Pedersen and Eckhoff[10] show that ignition of dust clouds by sparks from single impacts is very difficult. They concluded that up to a net impact energy of 20J, single, tangential impacts between steels, steel and rusty steel or concrete were unable to ignite clouds of grain and feed dust, or flour even when dry. Titanium impacting on rusty steel was able to ignite dust clouds, the probability of ignition increasing as the MIE of the dust decreased.

Similarly, in experiments by Reimer on the ignition of methane-air mixtures by steel-on-steel impact sparks[11], ignition by a flying spark was never observed. Mixtures were either ignited either at the point of impact of the drop weight on the test plate or by a glowing spark lying on the floor of the explosion vessel.

Reimer's experiments identified the important factors influencing the incendivity of the impact sparks. The hardest material pairs gave the most intensive sparks; the more the available kinetic energy is converted into shearing energy and frictional heat, the larger the number of sparks produced. As the available energy increased, so did the incendivity of the sparks. The roughness of the test plate, however, had an effect on the type of sparks produced. If the potential energy was not sufficient to break through the grooves making up the roughness, small, individual, highly incandescent pieces of steel were produced from the grooves. At higher potential energies a larger, cohesive splinter was removed from the plate material below the grooves, resulting in lower incendivity. If, however, the roughness can be broken off, rather than sheared, (eg. lateral grooves rather than longitudinal ones) the incendivity of the sparks is likely to be similar to those from a smooth plate. The effect of surface roughness on spark incendivity depends on the hardness of the steel; generally the harder the steel the higher the increase in spark incendivity.

Between 35° and 65°, the angle of impact of the drop weight on the test plate had little effect on spark incendivity. Rust had an inhibitory effect on the formation of incendive sparks, especially on rough plates, and the addition of a 1 mm thick coal dust layer to the test plate decreased the incendivity due to its lubricating effect.

A very incendive type of spark is produced if the impacting materials can produce the thermite reaction. Gibson et al[12] used a stainless steel hammer striking a rusty mild steel target with an aluminium smear to test for ignition of dusts. Of the 95 powders used 46 produced flame following a thermite flash, of which 27 produced flames that propagated beyond the ignition zone. Impacts of standard quality aluminium on rusty steel produced no sparks in some experiments by Pedersen and Eckhoff[10], only a smear of aluminium. Similarly, when Gibson et al used several metals and alloys to test for the production of the thermite reaction during impact, soft metals such as zinc and aluminium rarely produced the reaction in the first strike against rusty steel smeared with aluminium. Only if the soft metal became impregnated with rust and aluminium after repeated impacts did the reaction occur. Hard metals such as steels and brass readily produced the thermite reaction.

Friction and grinding are examples of continuous or intermittent contact giving a rubbing action - intermittent contact between rotating components, for example, is more likely to be a rubbing action than impact[9] - and they can produce sparks that are capable of igniting dust clouds[13]. The likelihood of ignition depends on the dust and the materials of contact. Dahn and Reyes[14] showed that contact between a rotating grinding wheel and stainless steel rods produced ignition, but when the rods were aluminium, ignition did not occur. The peripheral speed of the wheel was 20 m/s. Dahn and Reyes’ data also show that the relative speed between components required for ignition depended on the dust[13]. The shower of sparks from a high-carbon steel in contact with a grinding wheel can contain many large burning particles (> 100 microns)[15]; ignitions of 10% moisture grain elevator dust were consistently obtained; ignitions were obtained with as few as five sparks.

The first real attempt at quantifying the probability of igniting explosive dust atmospheres by specific types of spark was made by Ritter[6] and Muller[16], who introduced the idea of the equivalent electric spark energy. This equivalent ignition energy is defined[17] as the amount of energy in the spark from the discharge of a capacitor that has the same incendivity as the ignition source under characterisation. The electrical circuit contains an inductance to ensure the discharge is over an extended time period.

The equivalent ignition energy is measured by comparing the range of ignitable concentrations for a given mechanically generated ignition source to the spark discharge Minimum Ignition Energy (MIE) over the same range. Figure 1 demonstrates the procedure for a flintstone friction spark and lycopodium dust[18]. The ignitable concentration for the friction sparks ends at concentrations for which the MIE is 100 mJ. This, then, is the value of the equivalent ignition energy for this particular type of friction spark.

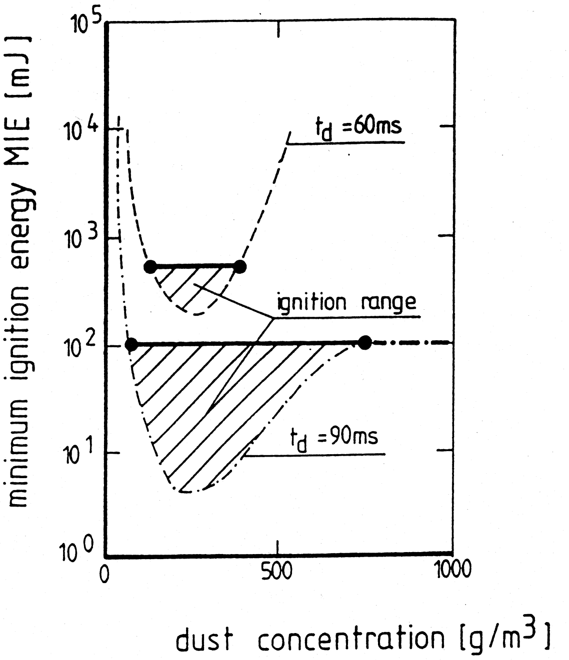
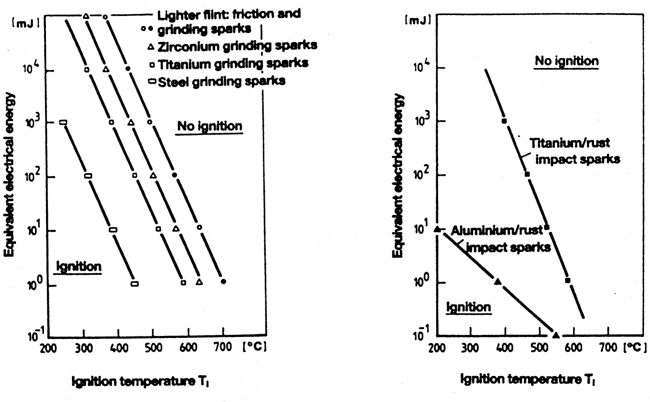


Figure 1. Determination of the Equivalent Ignition Energy

(from Reference 18)

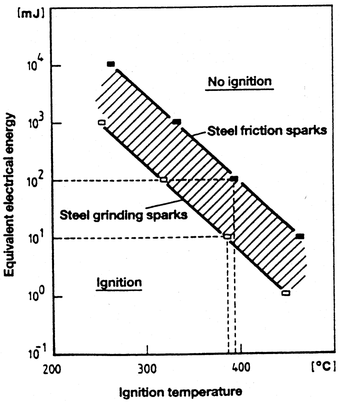
Figure 1 shows that it is easier to ignite a dust cloud when the turbulence is low.

The characteristics of the sparks depend on the nature of the contacting surfaces. Guidance has been published on the igniting ability of different types of mechanical spark[19], with dusts classified either as ignitable or non-ignitable based on the measured values of Minimum Ignition Energy (MIE) and Minimum Ignition Temperature (MIT). These data are reproduced in Figure 2, and show that the type of spark, whether impact, friction or grinding, influences the likelihood of ignition. The higher effect of steel friction sparks as compared to steel grinding sparks can be explained as due to a high temperature of the torn away material because of longer exposure to frictional heating.



Grinding sparks: relationship between equivalent electrical energy E_{Ae} and ignition temperature T_I
– $F_A = 60$ N, $v_U = 30\ \mathrm{m \cdot s^{-1}}$ –

Impact sparks: relationship between equivalent electrical energy E_{Ae} and ignition temperature T_I
– $F_A = 60 - 100$ N, $v_U = 25\ \mathrm{m \cdot s^{-1}}$ –



Steel grinding and friction sparks: relationship between equivalent electrical energy E_{Ae} and ignition temperature T_I
–$F_A = 60–90$ N, $v_U = 25\ \mathrm{m \cdot s^{-1}}$–

Figure 2. Conditions for Ignition of Dusts by some Mechanically Generated Sparks

(Reference 19)

The guidance given in Figure 2 is applicable only to mechanically generated sparks, and should not be applied when the ignition source is the hot surface produced by friction. Neither should it be used indiscriminately even for sparks; the characteristics of mechanical sparks can alter when the frictional behaviour creating them changes, for example, if the load between the surfaces varies[11]. Furthermore, there is no evidence in the literature for the implication in Figure 2 that dust clouds react to different ignition sources with the same relative sensitivities. In fact, the very opposite appears to be true. Gibson et al[12] demonstrate a lack of correlation between ignition of dusts by the thermite reaction and measurements of Minimum Ignition Temperature from the Godbert-Greenwald furnace. They state that MIT measurements cannot be used to assess sensitivity of a powder to ignition by the thermite reaction. If measurements of dust MIEs and MITs are displayed on a graph, as in Figure 3 [20], the lack of correlation between these ignitability characteristics is immediately obvious.

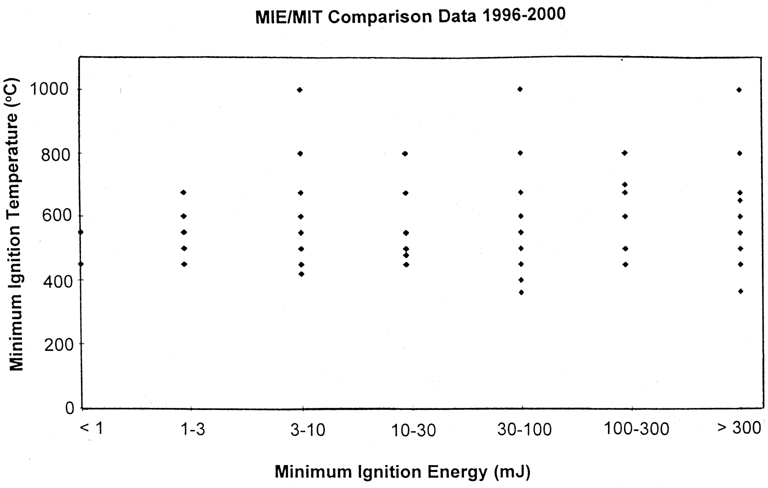


Figure 3. Measurements of Minimum Ignition Energy and Minimum Ignition Temperature of dusts. (Reference 20)

It is also well known that the minimum energy required for ignition of a dust cloud by an electric spark varies with the characteristics of the spark. The spatial and temporal distributions of energy in electric sparks are important factors. Boyle and Llewellyn[21] showed that the minimum capacitor energy capable of igniting a given powder decreased substantially when a series resistance was included in the circuit. Because the series resistance absorbs a large fraction of the capacitor energy during discharge, the energy going into the spark gap is only a small part of the theoretical stored energy, generally about 5 to 10%[13]. Thus, in Boyle and Llewellyn's experiments, at a series resistance of 10^4 - 10^5 ohms, for some dusts the ignition energy was reduced to approximately 1% of the energy necessary without the resistance. Similar changes were measured by Line et al[22]. Smielkow and Rutkowski[23] increased the spark duration either by adding a large inductance or by adding a large resistance to the circuit, and again the theoretical ignition energy from the capacitor decreased by a factor of ten, approximately.

The optimum spark discharge duration measured by Matsuda and Naito[24] and estimated in reference 13 from the data in references 21 and 22 were 0.1 - 1.0 milliseconds, decreasing with the net spark ignition energy.

Measurements by Parker[25] showed that for some dusts there was a fairly distinct region where the discharge duration produced the lowest ignition energies. With other dusts, however, no such region occurred. Parker used four dusts, and those with the higher ignition energies showed the optimum spark duration effect.

The physical length of the spark gap also has an effect on the ignition energy. Tests by Ballal[26], using metal dusts and carbon, demonstrated that there was an optimum spark gap length for each dust, and that it increased as the ignition energy at the optimum gap length increased, although the result for carbon did not fit in with the results for the metal dust. The optimum spark gaps fell in the range 2 - 7 mm. Measurements by Norberg et al[27] showed the optimum spark gap length to be in the range 6 - 8 mm, for short duration capacitative sparks.

Likewise, complex characteristics of mechanical sparks and showers of sparks will affect the ignition process. It is difficult to see the justification for suggesting that the graphs in Figure 2 linking MITs and the equivalent ignition energy give guidance that is universally applicable to dusts. Dusts can have very different mechanisms of ignition and combustion depending on the means of ignition and the characteristics of the ignition source, and there is no universal ranking of dust ignitability. An important practical requirement is that these graphs should be checked for their true meaning, and, if possible, extended to different ignition sources.

The likelihood of frictional ignition at rubbing surfaces depends on the relative velocity and the pressure at the contact point. A relation between the igniting ability of rotating parts and their relative speed, V, has been published[19].

$V < 1$ m/s	no additional hazard from friction contact
$V = 1 - 10$ m/s	each case must be considered on its own merits taking into account data for the specific product and material
$V > 10$ m/s	an ignition hazard exists

The test results from which these velocities are derived apply to grinding and friction sparks and hot surfaces. The tests were done with a 4 mm diameter steel pin contacting a grinding wheel. The contact pressure required for ignition at a given relative velocity rises rapidly as the relative velocity drops to 2-3 m/s, as is shown in Figure 4.

Sparks falling onto dust deposits could produce smouldering combustion and eventually produce a sufficiently energetic burning volume that could act as an ignition source for a dust cloud. The amount of energy necessary to produce such an event from a small, high temperature source such as a single spark is not known, but Eckhoff describes a test for measuring the energy of an electric spark necessary to ignite a 2mm thick dust layer[13].

With the specific example that Eckhoff gives - a pyrotechnic powder - the minimum net spark energy is approximately 1-2 mJ with an optimum spark discharge time of 2-3x10^{-4} seconds. The ignition energy rises to 8-10 mJ when the spark duration is 10 milliseconds.

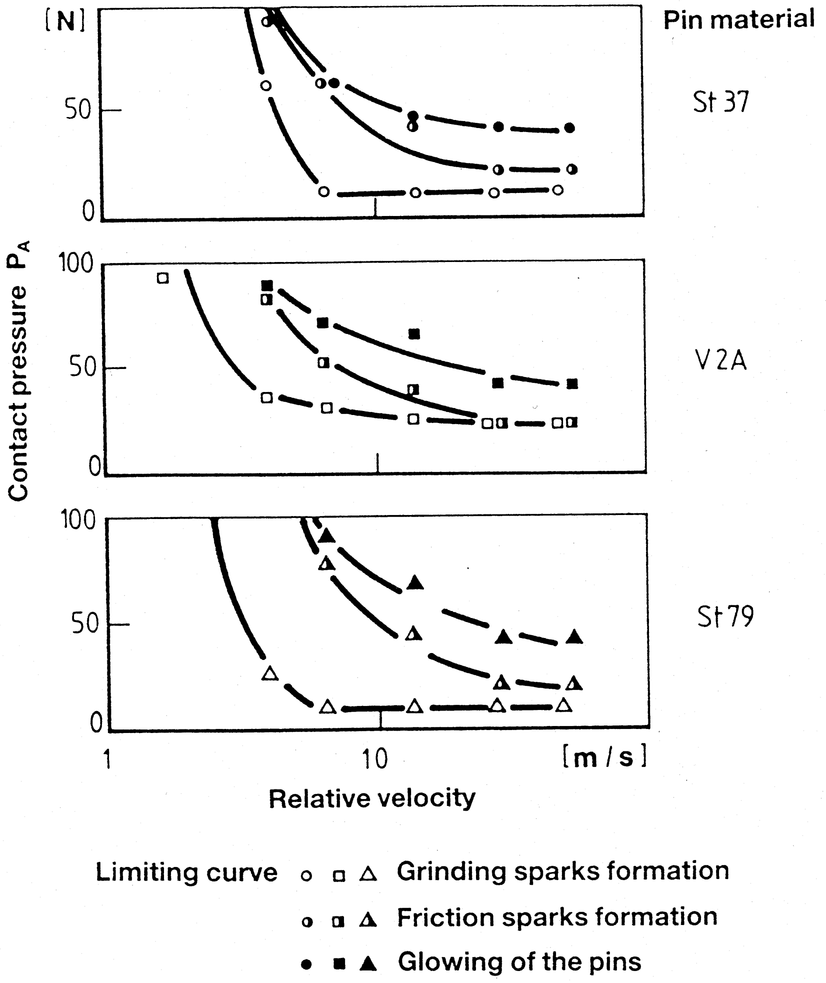


Figure 4.
Limit curves for the formation of grinding and friction sparks as well as hot surfaces (Reference 19)

Disc materials:
St 37, V2A, St 79 -
Pin diameter:
4 mm

2.2 Hot Surfaces produced by mechanical means

Although friction-generated sparks ignite dust clouds, this is, experimentally, a rare event compared to the frequency of ignition by the hot surface simultaneously produced. The likelihood of ignition depends on the dust characteristics and the area and temperature of the hot surface. Temperatures in the range 500-1000^{o}C can be developed in local areas by friction between metal surfaces[28]. Bartknecht reports data on dust cloud ignitions produced by steel pins rubbing against steel discs[18]. Temperatures of at least 1200^{o}C are required when the pins are 4 mm and 6 mm in diameter. This temperature was reached in a rubbing time of 1.5-3.5 seconds. A graph relating the measured Minimum Ignition Temperature of the dust to a parameter involving the optimum surface temperature of the pin, the diameter of the rubbed spot, the length of the temperature-discoloured zone and the temperature difference at the rubbed spot is shown in Figure 5. It is difficult from Bartknecht's text to fully understand what these definitions precisely mean, but the parameter has the unit of area modified by a temperature ratio, and as this parameter increases the more likely are dusts of decreasing ignitability to ignite. Measurements reported by Pinkwasser[29], also show that dusts with Minimum Ignition Temperatures of approximately 400^{o}C require temperatures of 1000^{o}C-1200^{o}C to ignite if the area of the hot surface is in the range 12-20 mm^2 (Figure 6).

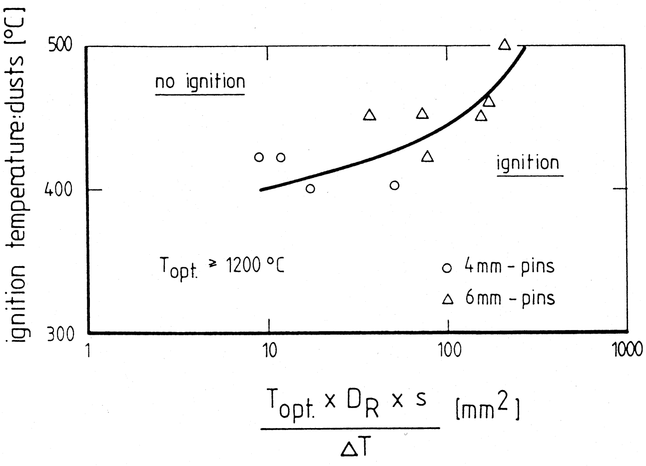


Figure 5. Ignition of Dusts by Hot Pins (from Bartknecht, reference 18)
(Minimum Ignition Temperature vs Properties of the Hot Surface)

T_{opt} - Optimum Temperature ^{o}C
<T - Temperature Difference ^{o}C
D_R - Diameter of hot surface mm
S - Length of temperature – discoloured zone

The configuration of the hot-surface is also a factor. The MIT measurements from the BAM oven are lower than expected from an extrapolation of Pinkwasser's results because the hot surface is a relatively large one and surrounds the dust cloud as a cylinder - Pinkwasser's areas were made up of hot wires and coils.

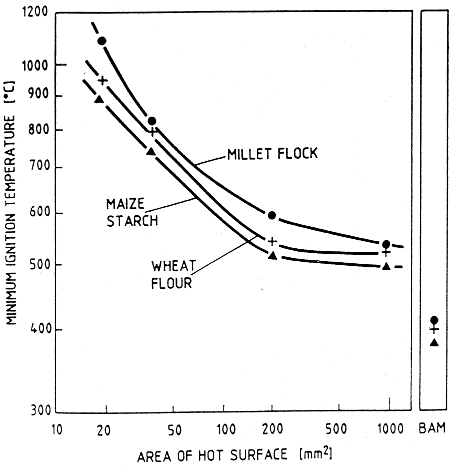


Figure 6. Effect of Surface Area on Minimum Ignition Temperature of Dust Clouds (Reference 29)

The most important hazard as regards a hot surface is the potential ignition of a dust layer that has settled on it. The layer ignition temperature is measured in a standard test for a depth of 5 mm[30], but because of the insulating effect of dusts, thicker layers can ignite at lower temperatures. The practical dangers are that a smouldering or burning layer can act either directly as an ignition source for a dust cloud or nests of burning material can break away from deposits and ignite a dust cloud in another part of the plant.

Harper, Plain and Gibson[31] have discussed the burning behaviour of powder accumulations on hot surfaces. The stages of ignition and the form of the combustion zone can be complex. Some powders burn directly in the solid phase either with a flame or by smouldering, others melt and burn as a liquid, whilst some burn with a large amount of flame. Some dusts can evolve large amounts of flammable gas when subjected to heat. A change from solid to liquid or agglomeration/expansion of dust particles to give an extended mass of material can block burning if diffusion of oxygen to the seat of burning is prevented.

A measure of the ignitability of a dust layer and intensity of burning of a dust layer is the Combustion Class (CC)[30]. This classification is based on the behaviour of a defined dust heap when subjected to a gas flame or hot platinum wire:

CC1	No ignition; no self-sustained combustion
CC2	Short ignition and quick extinguishing; local combustion of short duration
CC3	Local burning or glowing without spreading; local sustained combustion but no propagation
CC4	Spreading of a glowing fire; propagation of smouldering combustion
CC5	Spreading of an open fire; propagating open flame
CC6	Explosible burning; explosive combustion

The train firing test assesses flammability with reference to different ignition sources, and allots the Combustion Class. This test is shown in Figure 7.

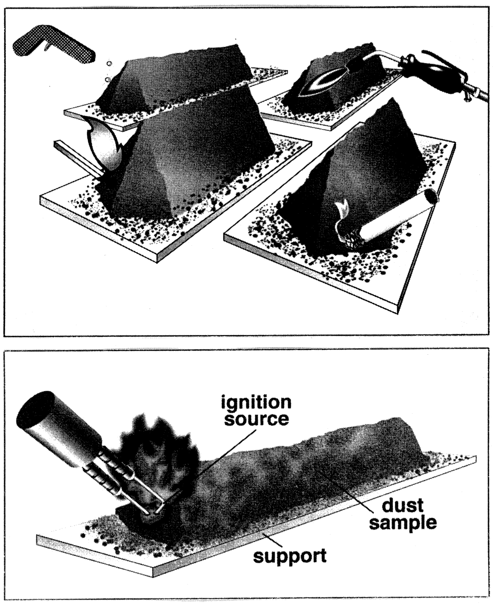


Figure 7. Testing the flammability and burning behaviour of dust deposits with different ignition sources (Reference 30)

At temperature above ambient, the Combustion Class of a particular dust will increase. Dextrin, for instance, has a CC of 2 at 22^{o}C, but a CC of 5 at 100^{o}C.

The train firing test does not, however, at first sight, give an indication of the likelihood that a burning nest will form. The powder or dust needs to coagulate and any accumulations that detach need to travel for some distance as a unit. Furthermore, combustion behaviour in plant with flowing air will be different to when the air is stationary, as Zockoll[32] has shown.

The ignition hazard of deposits close to or at points of friction has been studied, for powders capable of fast decomposition, by Gibson and Harper[33]. With three different methods for producing mechanical friction, Gibson and Harper found that small differences in test method produced very different behaviour with regard to both initiation and progress of combustion. The mass of metal at the site of frictional heating is an important factor in determining the likelihood of ignition. They concluded that laboratory attempts to simulate industrial mechanical friction to characterise powders, and make the tests relevant to industrial situations would be generally unsuccessful. For unconfined powders Gibson and Harper decided that the Train Firing Test was appropriate, using a small flame as ignition source, and with a (2:1 w/w) mixture of silicon/lead dioxide mixture intermixed with the first 1-2 cms of the train. A temperature of 1000^{o}C was considered to represent the likely temperature in a situation of high mechanical friction.

Once a smouldering or burning deposit has developed, nests, ranging in size from several millimetres to several centimetres, may break off and, carried along by an air stream until they reach an extensive dust cloud, then act as an ignition source.

Work at Syngenta[34] on the ignition of dust clouds has shown that clouds can be ignited by various burning or smouldering ignition sources. Three ignition sources - paraformaldehyde, which burns with a flame, $Fe^{3+}(H_2)$, which smoulders and incandescent particles of saw dust - were used. Sulphur and lycopodium dust clouds of various concentrations were blown over the first two of the ignition sources, and both dusts ignited. The incandescent particles were introduced into the dust clouds soon after the clouds had been produced. The sulphur clouds ignited, but the lycopodium did not.

These tests were repeated with dusts of various MIT values, from 270^{o}C to above 1000^{o}C as measured in the Godbert Greenwald furnace. With the burning layer, dusts with MITs above 600^o to 800^{o}C did not ignite; with the smouldering layer, dusts with MITs above 340^{o}C, approximately, did not ignite; with the incandescent particles, dusts with MITs above about 330^{o}C did not ignite.
Some tests using layer ignition sources of various areas and temperatures showed that as the area decreased, for a given temperature, the dust MIT above which a dust cloud did not ignite increased.

At present, however, it is unclear what properties of a dust nest make it an effective ignition source in practice. Despite all the reports of ignition incidents in industrial plant, experimental studies have in the main indicated that ignition of dust clouds by hot nests is not easy. Pinkwasser[29] showed that smouldering material entering a pneumatic conveying line was soon extinguished - the distance to extinguishment depending on the dust concentration. Pinkwasser used an 80m length of 100/110 mm i.d. pipe, with six 90° elbows, which ended in a cyclone tested to 10 bar. Nests of smouldering material were introduced through an air-lock at the end of the pipe remote from the cyclone. The powder conveying rate was measured from the weight of powder introduced into a known volume of conveying air over a given time, and the mean powder concentration calculated. The temperature of the smouldering material was measured by thermocouples, and the distance of travel of the smouldering material by spark detectors and flame detectors. The powders examined were three grades of flour, with K_{st} - values below 100 bar m s^{-1}, and CC ratings of 5.

Only one of the powders was capable of producing smoulder nests. The powder properties were: moisture content 8.9%, bulk density 290 kg/m^3, median particle size 120 microns and Minimum Ignition Energy approximately 1000 mJ. A much coarser-grained flour with a bulk density of 510 kg/m^3 failed to produce nests, as did a finer grained flour with the properties: moisture content 13.1%, bulk density 440 kg/m^3, median particle size 55 microns and Minimum Ignition Energy approximately 500 mJ.

Glowing clumps up to 1.5 cm diameter, with temperatures of 500°C to 550°C, were fed into the line. In dust-free air, glowing particles were transported, in conveying velocities of 10 and 20 m/s, as far as 68m. But as the powder loading in the airstream increased the distance to extinction of nests of approximately 10g decreased substantially, as shown in Figure 8. Extinction was promoted by breaking up of a smouldering nest into individual glowing particles. No dust explosions were detected when powder-loading was within the explosive range.

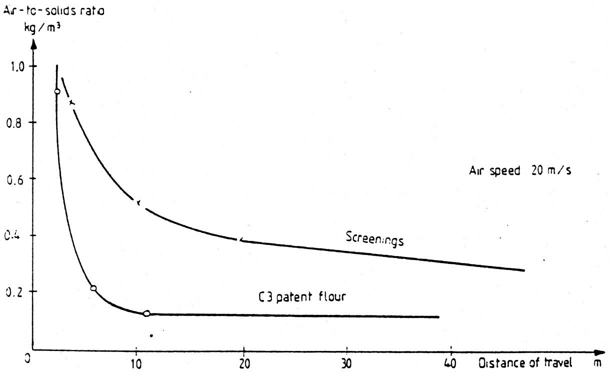


Figure 8. Hazard range for pneumatic transport of patent flour and screenings: from Pinkwasser's experiments. (Reference 29)

Pinkwasser concluded that it was impossible, with the dusts tested, for smouldering nests of approximately 10g weight to be conveyed in a powder loading of greater than 1 kg/m^3 of air, but that in conditions where powder loading is low - exhaust systems and under startup - smouldering material could be conveyed over relatively long distances.

Alfert et al[35] used a pneumatic transport system ending in a 5.8 m^3 filter unit. At an air speed of 35 m/s, only very strong nests were transported. Charcoal nests of 50 cm^3 volume entered the filter only as small agglomerations (<1 cm^3) even after a relatively short distance (11 m), and with maize starch as the explosive atmosphere in the filter even large nests (0.5 litre) produced no ignitions in the system. When fine wood dust was used to give the explosive atmosphere, ignition occurred in the filter, but not in the pipeline.

Pinkwasser[36] showed those smouldering nests with a temperature of 700°C, free-falling into dust clouds, did not produce an ignition in explosive atmospheres of wheat flour or wheat starch. Only when nests of at least 25 mm diameter and weight of at least 15g landed on the bottom of the 1m tall test column did some ignitions occur. Jaeger[37] found that smouldering nests could be produced only with dusts having a Combustion Class greater than 3. A minimum nest area of 75 cm^2 and surface temperature of 900°C were required for igniting clouds of dust with Minimum Igniting Temperatures less than 600°C. Alfert et al[35] noted that nests of low mechanical strength disintegrated during a fall and generated a large fire ball that acted as an ignition source. Mechanically stable nests were capable of igniting the cloud only when they reached the silo floor, but could be covered with dust before an explosion had time to start. In these tests, nests of known size were dropped through dust free air in a silo with a height of 22m. The nests were made of charcoal, cork dust and wood dust. Charcoal has a strong nesting structure; no burning of the charcoal particles occurred, and when the nest reached the floor of the silo, a shower of glowing particles was produced. Cork dust forms stable nests; flaring up of the nests was noted at approximately half the height of the silo, and on the silo floor. Wood dust produces unstable nests; these could break up in the very top part of the silo creating a fireball, remain intact and flare up in the upper half of the silo or reach the floor and flare up on impact or not at all.

When nests were dropped into an explosive atmosphere of maize starch, nests of wood dust with a size of 0.5 to 1 litre produced no ignition in 40% of the tests. Nests with volumes of 1 to 1.5 litres ignited equally in the upper part of the silo or on the floor. Nests of cork dust produced no ignitions, but could start fires in settled maize starch powder. Charcoal nests could produce ignitions if they were mechanically broken up, and also a short time after reaching the floor.

Zokoll[32] has reported some tests using milk powders as both the nest material and the explosive dust cloud. Initial tests in which both dust and smouldering nest were dropped into the test chamber simultaneously showed that fist-sized nests at temperatures approximately 100°C or more above bulk powder Minimum Ignition Temperature as measured in the BAM furnace test did not ignite ground corn and milk powder clouds. Even when the nests were broken up by blades while falling ignitions did not occur. Ignition of dust clouds could not be achieved with nests which did not burn but had internal temperatures of 700-800°C. Nests of 1200°C did ignite the dust clouds but only after impact on the floor of the explosion vessel. When dust was dropped over smouldering nests on the vessel floor, cloud explosions could occur at temperatures of about 860°C. A flaming nest could, however, be practically extinguished by the dispersal of milk powder around it in the explosion vessel. Tests on the development of smouldering in nests under the influence of a 0.5 m sec air stream showed that smouldering developed differently depending on the type of milk powder. At higher air speeds open fires occurred in relatively large quantities of skimmed milk powder. At air speeds of about 10 m/s compact smouldering nests reached temperatures of 1200°C in the hottest spots. The transition from smouldering into open fire occured around 800 - 850°C, depending on the type of milk.

In summary, the likelihood of ignition of a dust cloud by a hot nest depends on the temperature of the nest, its residence time in the dust cloud and the availability of oxygen to the burning area. Greische and Brandt[38] have shown that the Minimum Ignition Temperature of a dust-cloud decreases substantially when the residence-time of a dust in a Godbert-Greenwald furnace increases as Figure 9 shows. The longer a local part of a dust cloud remains in contact with a smouldering nest, the more likely it is that an ignition will occur. It appears, also, that burning nests can be extinguished by dust clouds and an ignition prevented, if conditions are right.

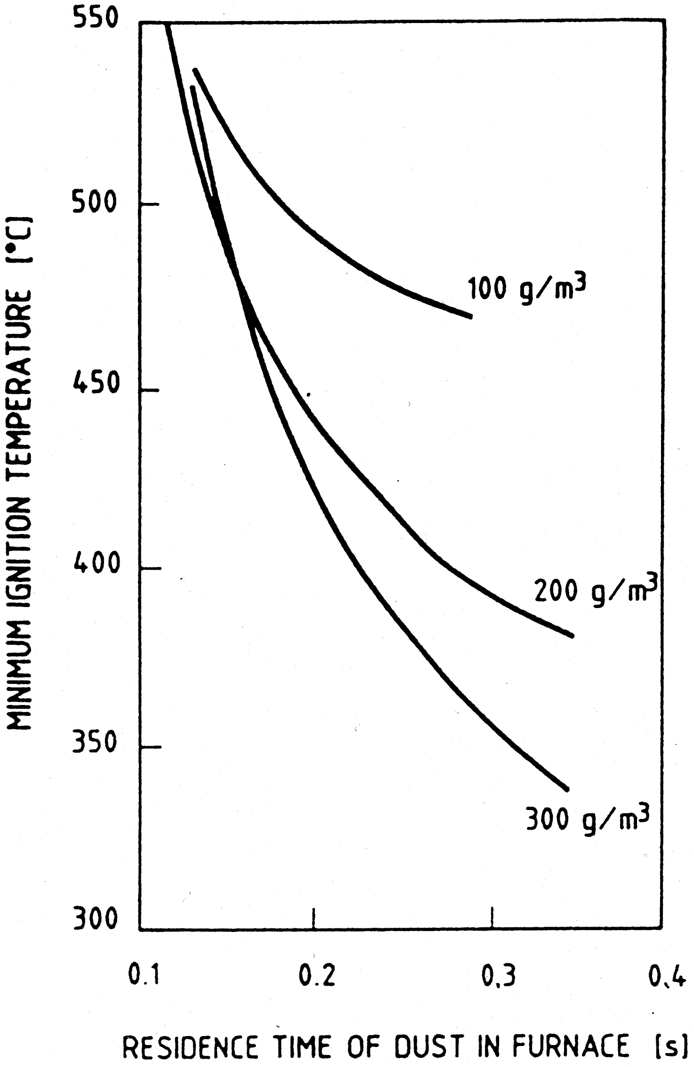


Figure 9. Variation of Minimum Ignition Temperature of Brown Coals with residence time in the Godbert – Greenwald Furnace. (Reference 38)

The size and temperature that are necessary if a solid hot body is to ignite a dust cloud have been studied by Alfert et al[35]. Steel cylinders with a diameter of 20 mm and lengths of 20 - 30 mm were heated and introduced into an explosive cloud of maize starch in a silo. Cylinders of 75 g weight and a temperature of 950°C ignited the cloud, but 75 g cylinders at 900°C, and 50 g cylinders at 950°C did not.

Eisfeld[39] has conducted experiments on the heating of coal dust deposits by an electrically heated wire, and has made recommendations for the prevention of a fire hazard from high power intrinsically safe circuits. On the basis of his experiments, Eisfeld calculated the maximum permissible power dissipation at an intermittent contact of a single stranded copper cable with a cross-section of 0.5 mm^2, as well as the associated maximum current. The values were 0.72W and 4.3A. Safety in respect of a fire hazard in coal dust is assured if the circuit has been tested with the break flash apparatus with a maximum rms short circuit current of 2.6A or less. If this current is greater than 2.6A, and the intrinsic safety with regard to firedamp has been demonstrated, the fire hazard with regard to coal will be avoided provided the cables are single stranded and the copper cross-section is 0.2 mm^2 or greater.

Another potential hazard from smouldering nests is propagation into a larger accumulation of burning from a hot nest fallen on to a dust deposit. Work has been done on the effect of deposits of embedded hot nests and hot bodies, by Krause and Schmidt[40], and by Nelson[7]. Alfert et al[35] have done some work on the effect of surface hot spots. A smouldering nest or other hot object may fail to ignite a cloud, but could cause extensive smouldering in a deposit which could then act as a much more effective ignition source. In the work by Krause and Schmidt[40], combustion on the surface did propagate back into the bulk sample. In Alfert et al's work, hot steel cylinders were dropped onto a 20 cm thick layer of maize starch or wood dust[34]. If any effect occurred, it was either on instant flaring up of the contact surface or initiation of a slow burning fire. With a 75 g cylinder, flaring up of wood dust occurred at 650°C, maize starch at 700°C. A slow burning fire occurred in wood dust at 450°C, but not up to 700°C in maize starch. The glow temperature of the wood dust was 280°C and the Minimum Ignition Temperature (MIT) 430°C; the MIT of the maize starch was 470°C.

Krause and Schmidt[40] have investigated the behaviour of hot nests and hot bodies embedded in powder accumulations. The materials used were fine and coarse cork, beech wood and cocoa. The hot bodies were porcelain spheres with diameters of 25, 30, 35 and 40 mm, and the hot nests were held in cylindrical mesh baskets 11, 15, 25, 34, 40 and 45 mm in diameter and a height to diameter ratio of unity. The accumulations of dusts were held in cylindrical mesh baskets with volumes of 6, 12, 50 and 200 litres with height to diameter ratios of unity. The hot bodies and nests were heated in a furnace, positioned at the centre of the cylinder and the bulk dust then introduced. A smouldering front propagated from hot nests, if ignition occurred, moving through the dust accumulation at an approximately constant smouldering temperature. The larger the size of the glowing nest, the more likely the dust accumulation was to ignite. The minimum size of hot nest required for ignition depended on the dust. The smouldering temperature produced by hot bodies was independent of the size of the hot body, but decreased as the size of the dust accumulation increased. The temperature of the hot body necessary to produce ignition of a given size of an accumulation of a given dust fell as the size of the hot body increased. The onset of smouldering was caused by temperatures above 400°C.

The rate of smouldering propagation was connected with the availability of oxygen. Fine cork dust with a bulk density of 59 g/m^3 smouldered more quickly than coarse cork with a bulk density of 171 g/m^3. The propagation velocity was 0.33 mm/min.

Leisch, Kauffman and Sichel[41] have studied the smouldering behaviour of grain dust. A layer of 10.2 cm was used in all tests, with the dust held in a box 56.2 cm by 61.0 cm. The upper surface of the layer was level with the floor in grain dust varied from 0.21 mm/s to 0.48 mm/s depending on the depth in the layer and the ignition source depth. With an airflow of 4 m/s over the layer, the smouldering velocity increased by a factor of 2 to 2.5. In some tests with the airflow, a transition from smouldering to flaming combustion occurred after a substantial cavity had formed due to propagation of the combustion wave. The temperature of the combustion zone increased by about 180^{o}C once flaming combustion occurred. The availability of oxygen influenced the velocity of propagation.

Clearly, hot surface ignition is not only related to surface temperature. Geometry, contact time, air flow, contamination and the chemistry and history of the material can have an effect. If the air above the dust deposit is at a temperature higher than normal room temperature, the requirements for ignition of a deposit by embedded hot objects may fall. Layer ignition temperatures typically decrease by 40^{o}C-60^{o}C at an air temperature of 100^{o}C. Various tests have been developed to measure the ignition behaviour of dust deposits in streams of hot air.

The IChemE Guide, *Prevention of fires and explosions in dryers* described tests developed to simulate various conditions and obtain measurements of the temperature at which exothermic reaction begins[42].

The aerated powder test simulates conditions where a hot air stream passes through material. The powder is held in an 80 mm long, 50 mm diameter glass cylinder closed at each end by sintered glass. Air is passed downwards through the powder at the same temperature as the surroundings inside the fan-assisted oven in which the test is performed. A screening test may be performed, but a more thorough study is made with isothermal tests at different temperature and periods. The number of isothermal tests will depend on the precision required in the result.

Impurities, slight changes in composition and autocatalytic reactions can have a marked effect on the temperature at which exothermic activity begins. Performing the test with a temperature cycle akin to that likely to occur in practice is a useful addition to the isothermal tests. In order to minimise the hazard, a material temperature 30-50^{o}C below the measured temperature is generally recommended, but this safety factor should not be the only basis for safety. A layer test where hot air passes over deposits or layers uses a layer 75 mm by 40 mm and 15 mm deep. A screening test can be used, but isothermal tests, each lasting perhaps for several hours, are the main tests by which an ignition temperature is obtained. If the layer depth properly simulates practical conditions, the temperature at which an exotherm can progress to red heat can be used as a basis for safe procedures rather than the somewhat lower temperature at which exothermic activity begins. An adequate safety margin is usually 20^{o}C.

A bulk powder test utilises the same apparatus as for the aerated powder test but the hot air flows around the sample and not through it. Screening tests, isothermal tests, low heat loss tests and simulation of process cycles can be performed. If the operating temperature is 50^{o}C less than the measured exotherm onset temperature from the screening tests, dangerous decomposition is unlikely to occur at least up to 1 tonne capacity. However, if this temperature difference is less than 50^{o}C, or the operating cycle is longer than the test duration, or the measured temperature is less than 200^{o}C, isothermal tests should be performed at 50^{o}C above the process temperature and with a duration longer than the operational time, followed by a low heat loss test using a Dewar flask.

Nelson[7] has reviewed the literature on smouldering combustion, and concluded that the rate of smouldering is controlled by the diffusion of oxygen to the combustion front. Thus, the more porous the sample the higher the rate of smouldering. Thermal conductivity is also important - the higher the thermal conductivity, the more heat required to initiate smouldering, all other things being equal.

In an extensive series of tests Nelson used small electric heaters to simulate a hot spot formed by frictional heating. The hot spots were controlled at a constant power. Nelson found that localised combustion took place around the hot spot at sub-critical power, and self-sustaining combustion above. The temperature at which wheat flour began to combust fully was 500^{o}C. Nelson’s results showed that the size of the bed had negligible influence on the critical power if the bed was large relative to the size of the hot spot, and that for iron oxide there was little change in the critical power with size of hot spot. As the ambient temperature of the deposit increased the critical power fell, but as the ambient temperature approached the isothermal ignition temperature, the critical power did not fall as rapidly as expected, because of a decreased power output from the deposit material due to some oxidation at these elevated temperatures. The critical power increased with thermal conductivity, all other things been equal, decreased as the heat of reaction increased and increased as the activation energy increased.

2.3 Industrial Plant

Prevention of ignitions is an unavoidable part of the basis of safety in the design and operation of powder handling plant, and taking heed of published data leads to some simple precautions. In Scholl's opinion[43], screw feeders, rotary valves and elevators should have external bearings and be operated with a relative speed of < 1 m/s, middle bearings in screw feeders should be temperature-monitored, and off-track running, slip and temperature should be monitored at the bottom bearing of some elevators. Overload protection may also be appropriate. It is impossible to identify all the places in specific items of equipment where mechanical impact and friction difficulties may arise. Dust handling plant comes in a variety of shapes and sizes and design features may alleviate the risk from mechanical ignition. For instance, if large masses of metal surround the contact surfaces, the temperature will not rise as rapidly or as high as in locations which are more insulated against heat loss. The size of the contact area may vary depending on the scale of the equipment.

A new concept of 'constructional safety' has been introduced for non-electrical equipment for use in explosive atmospheres; a draft standard has been prepared by Working Group 2 of CEN Technical Committee 305[44]. Types of equipment that contain no ignition source in either normal operation or cases of expected malfunction have good design and engineering principles applied to them so that the probability of mechanical failures leading to incendive impact or friction sparks and hot surfaces is reduced to a very low level. Requirements for bearings, power transmission systems, clutches and couplings, brakes and braking systems and springs are included in the draft document.

In this section of the paper some items of industrial plant prone to mechanical ignition problems are discussed.

Publications which contain descriptions of powder handling plant include a booklet published by the 'Machine Safety' section of the International Social Security Agency (ISSA), Working Group 6: Dust Explosions: Collection of Examples[45] and 'Bulk Solids Handling' by Woodcock and Mason[46].

2.3.1 Grinders and Pulverizing Machines

Blockage, high-speed internal fitments and tramp metal are all capable of producing mechanical ignition sources in grinders and pulverizing machines. There have been occasional incidents in the US where explosions in coal pulverizers have been ignited by hot surfaces or sparking due to tramp metal, but most ignitions have been due to spontaneous combustion of coal deposits[47].

a) *High-speed mills*

Pinned disk mills, beater mills and hammer mills are invariably sources of ignition. Hammer mills[46] employ swing hammers mounted on rotating shafts to impact raw material and pulverize it against an adjustable block. They have relatively high power requirements. Avoidance of ignition sources is only applicable as an explosion prevention method in exceptional circumstances, when the powder or dust has a very high Minimum Ignition Energy and Minimum Ignition Temperature[45].

b) *Tumbling mills*

Ball Mills, tube mills and rod mills pose an ignition hazard due to a substantial heating effect. Ball mills comprise a rotating horizontal cylinder with steel or alloy balls inside. As the cylinder rotates the material is crushed by the impact and grinding action of the balls. The particles are carried to classifiers by hot air. Reference 47 gives an example that in mills of 2-3 m diameter, the temperature can rise from 20^{o}C to 100^{o}C within the space of 2 hours. Lumps of smouldering material are a hazard from some powders, if the deposits are thick enough, and the residence time in the mill is long enough. These lumps can act as ignition sources for dust explosions.

A document published by the Expert Commission for Safety in the Swiss Chemical Industry[48] allots products, with regard to milling, into safety classes on the bases of Minimum Ignition Energy (MIE), Minimum Ignition Temperature (MIT), Burning Class, Thermal Stability, presence of flammable liquids and the result of the Impact test (see Figure 10). Products presenting the least hazard (class SCM 0) have MIEs above 1 J, and MITs above 500^{o}C, which, judging by the data in Figure 2, means they are difficult to ignite by mechanical sparks. Reference 48 recommends, however, that effective ignition sources must be avoided by separation of tramp metal, regular inspection of bearings for hot running and other rotating parts for friction and caking and other precautions.

c) *Roll mills*

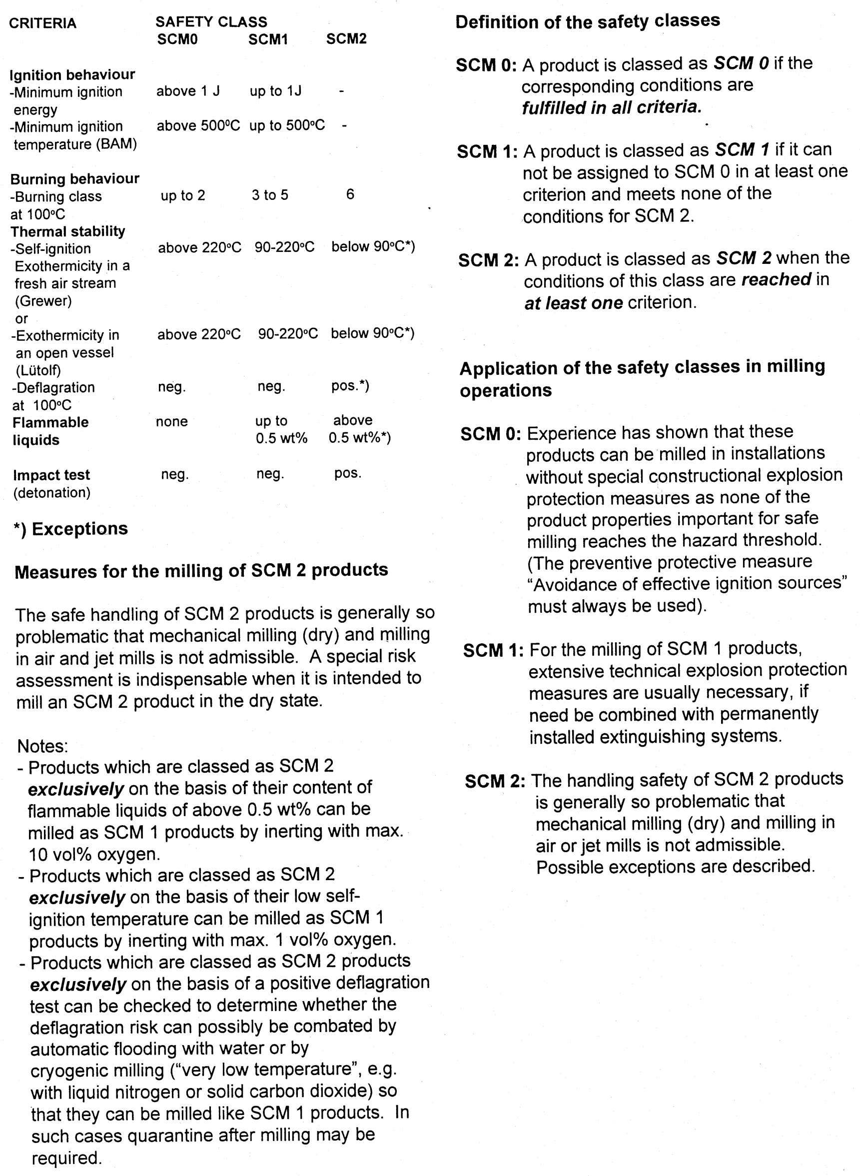
Roll mills are vertical cylinders containing a rotating bowl in contact with two or more spring-loaded rollers[47]. Raw material is crushed between the rollers and a grinding ring on the bowl. Roll mills are usually not an ignition hazard if frictional heating and tramp metal can be avoided[45].

d) *Cutting mills*

If large quantities of fine dust are produced in cutting mills, then the mills pose the same threat as high-speed mills[45].

2.3.2 Crushers

The hazard from high-speed crushers is the same as from high-speed mills. Low speed crushers, with a circumferential speed of around 1 m s^{-1}, have been shown by experience not to be ignition sources[45].



CRITERIA	SAFETY CLASS SCM0	SCM1	SCM2
Ignition behaviour			
-Minimum ignition energy	above 1 J	up to 1J	-
-Minimum ignition temperature (BAM)	above 500°C	up to 500°C	-
Burning behaviour			
-Burning class at 100°C	up to 2	3 to 5	6
Thermal stability			
-Self-ignition Exothermicity in a fresh air stream (Grewer) or	above 220°C	90-220°C	below 90°C*)
-Exothermicity in an open vessel (Lütolf)	above 220°C	90-220°C	below 90°C*)
-Deflagration at 100°C	neg.	neg.	pos.*)
Flammable liquids	none	up to 0.5 wt%	above 0.5 wt%*)
Impact test (detonation)	neg.	neg.	pos.

***) Exceptions**

Measures for the milling of SCM 2 products

The safe handling of SCM 2 products is generally so problematic that mechanical milling (dry) and milling in air and jet mills is not admissible. A special risk assessment is indispensable when it is intended to mill an SCM 2 product in the dry state.

Notes:

- Products which are classed as SCM 2 ***exclusively*** on the basis of their content of flammable liquids of above 0.5 wt% can be milled as SCM 1 products by inerting with max. 10 vol% oxygen.
- Products which are classed as SCM 2 ***exclusively*** on the basis of their low self-ignition temperature can be milled as SCM 1 products by inerting with max. 1 vol% oxygen.
- Products which are classed as SCM 2 products ***exclusively*** on the basis of a positive deflagration test can be checked to determine whether the deflagration risk can possibly be combated by automatic flooding with water or by cryogenic milling ("very low temperature", e.g. with liquid nitrogen or solid carbon dioxide) so that they can be milled like SCM 1 products. In such cases quarantine after milling may be required.

Definition of the safety classes

SCM 0: A product is classed as ***SCM 0*** if the corresponding conditions are ***fulfilled in all criteria.***

SCM 1: A product is classed as ***SCM 1*** if it can not be assigned to SCM 0 in at least one criterion and meets none of the conditions for SCM 2.

SCM 2: A product is classed as ***SCM 2*** when the conditions of this class are ***reached*** in ***at least one*** criterion.

Application of the safety classes in milling operations

SCM 0: Experience has shown that these products can be milled in installations without special constructional explosion protection measures as none of the product properties important for safe milling reaches the hazard threshold. (The preventive protective measure "Avoidance of effective ignition sources" must always be used).

SCM 1: For the milling of SCM 1 products, extensive technical explosion protection measures are usually necessary, if need be combined with permanently installed extinguishing systems.

SCM 2: The handling safety of SCM 2 products is generally so problematic that mechanical milling (dry) and milling in air or jet mills is not admissible. Possible exceptions are described.

Figure 10. Safety Classes for Milling Operations (Switzerland. Reference 48)

2.3.3 Mixers

When mixers have moving internal components frictional ignition hazards are present[45]. If the internal components are slow moving (a circumferential speed of less than 1 m s^{-1}) and the mixer has low power requirements (no higher than 4 kW) then experience suggests that no additional ignition hazards are introduced. When components move more rapidly and the power requirements are moderately high, then the ignition hazard can be avoided, if:

- there is a high degree of filling (ƒ 70%) to limit occurrence of explosive dust atmospheres
- the mixer is operated at reduced speeds (1 m s^{-1}) during charging and re-charging
- sufficient clearance is present between moving parts to avoid contact
- tramp material is avoided
- products with a tendency to spontaneously ignite under the operating conditions are not used

These rules for limiting speeds and limiting power requirements generally apply to other dust handling plant with moving internal components such as screens, dust collectors and classifiers[45].

The conditions inside plant, and the dusts ignition properties, are also important. In jet mills with classifiers, frictional ignition sources may occur, but because of the high turbulence ignitions of dusts with a Minimum Ignition Energy > 10 mJ and a Minimum Ignition Temperature >300^0C is not expected[45]. When the ignitability of the dust is greater, ignitions must be expected.

2.3.4 Feeders

a) Rotary Table Feeders

This device is a horizontal circular table below and concentric with the hopper opening. A fixed blade acts as a plough to remove the material. Most of the shearing resistance to the rotation of the table comes from the mass of material in the centre. The table rotates at, typically, 2-10 revs/min. There is, probably, little likelihood of frictional ignition.

b) Screw Feeders

The enclosed screw or auger conveyor is designed to run at relatively high speeds (200 revs/min to 2000 rev/min). There is always the risk that dust can be trapped or heated at contact points between the flight and the casing, and some dusts may ignite and begin to smoulder.

2.3.5 Conveyors

Conveyors are items of equipment that transport powders from one place to another. They have moving parts, power transmission systems and bearings.

An example of an Ignition Hazard Assessment for a belt conveyor is given in the documentation for a one-day seminar on the ATEX Directive given under the TREX European Network programme[49]. The effects of temperature rises in moving parts, loss of lubricant, misalignment of components, excessive vibration in worn parts, slippage in the belt, friction between the belt and moving parts and filling by dust of gaps between moving parts which are close together are some of the situations which should be considered.

2.3.6 Elevators

Centrifugal discharge elevators generally have speeds of travel of the buckets in the range 1.3 to 2 m/s, but with free flowing granular material the speed can be greater than 3.5 m/s without difficulty. Positive discharge elevators, generally used for sticky materials or those that tend to pack, have a speed of 0.7 m/s. Continuous bucket elevators are typically operated at around 1 to 1.3 m/s.

There is always the danger that moving buckets may strike the elevator casing and produce hot spots and frictional sparks among other mechanical friction effects. The same ignition hazards as arise with conveyors should be considered.

3. CONCLUSIONS

Although there is much experimental data in the published literature it is not sufficient to produce a unified and wide-ranging set of guidance. There are too many gaps in the information that is necessary for both linking the general behaviour and characteristics of mechanical ignition sources to the ignitability and combustibility properties of dust clouds and dust layers and relating the ignition sources produced and studied in the laboratory to those likely to be created in full-scale powder handling plant.

3.1 Ignition by mechanical sparks

There is the possibility that some potentially explosive dust atmospheres can be ignited by single impact sparks, though the evidence suggests that this is true only for very easily ignitable dusts and with impacting materials producing high temperature sparks. Single sparks have failed to ignite methane-air mixtures during flight[11], and ignition of maize dust clouds by a single spark was never witnessed in other tests[10]. A more likely danger is that a spark falling on a dust deposit may initiate smouldering combustion leading eventually to a sufficiently energetic volume of burning that could act as an ignition source for an explosive dust atmosphere. Sparks falling onto a surface may smoulder for a time - the same single sparks that failed to ignite a methane-air mixture when in flight did produce ignitions if they landed on the floor of the test chamber and continued to glow there[11]. An example of the level of energy required to ignite a dust layer comes from tests with an electrical spark ignition apparatus, in which, admittedly for a powdered pyrotechnic, energy of 1-2 mJ was sufficient[13].

Dusty environments are more likely to be ignited by showers of sparks, even when the mechanical event is an impact; although showers consisting of only five particles have been shown to be capable of igniting dust clouds[15]. The thermite reaction readily ignites some dust clouds[12].

Some guidance has been produced linking the igniting ability of certain types of sparks to the ignitability characteristics of dusts[19], but any temptation to apply it to the hot surfaces that are simultaneously produced should be resisted. Furthermore, the sparks produced from two materials vary depending on the way the two surfaces rub together[11]. At low loads, sparks may be at a relatively low temperature and do not oxidise rapidly while in flight. At high loads, hotter sparks are produced and combustion during flight will be faster, leading to higher temperatures. In addition, the relative sensitivity of dust clouds to ignition is not the same for all ignition sources[12, 20]. Care must be taken in applying to practical situations information that relates ignition sensitivity to correlations between ignition measurements from widely different ignition sources. Real mechanical sources may be different to laboratory created ones and the different modes of combustion that dusts can have may render simple classifications void.

The ignition risk from mechanically produced sparks requires systematic investigation.

3.2 Ignition by hot surfaces

Conditions inside dust handling plant are so varied that any attempt to describe a typical mechanically produced hot surface is practically impossible. There is an infinite number of permutations of temperature, area and configurations. The power inputs necessary to produce a given temperature and the temperature necessary to ignite a deposit of a given dust can vary widely. For instance, a power input of less than five watts can produce temperatures in a hot spot of 10mm diameter sufficient to ignite deposits of wheat flour (500°C)[7]; tens of watts are required to ignite conical dust deposits over a heated box with dimensions 100mmx50mmx25mm (280°C for saw dust)[50]; hundreds of watts are required for two steel wheels rotating against each other (270°C for wood flour)[51]. Experiments show that the ignition temperature of dust clouds depends on the size and configuration of the hot surface. Clearly, potential ignitions in practice have to be anticipated by determining the type of frictional event likely to occur and applying data and information from a test that is close as practicable to the expected event.

In practice, only a limited set of tests to determine the risk of ignition will be available and they will be expected to cover all likely situations; they will be chosen not only on technical grounds but on cost and time considerations also. What is first required is an accepted test for measuring the ignition temperatures of dust deposits by hot surfaces, followed by accepted tests for generating the hot surfaces produced by rubbing surfaces. There are opportunities in current research work to go some distance towards this goal. The European funded project SMT4-CT98-2273: Electrical Ignitions in Dusty Environments with a Potential Risk of Explosion is part concerned with ignitions of thick layers and large accumulations. The outcomes from these parts of the project may lead to tests not only applicable to electrical apparatus but also to the hazards from mechanically generated hot surfaces. Ignitions of dust accumulations by rotating surfaces submerged in the dust is being studied at the Health and Safety Laboratory. Comparisons between the results from these experiments and other methods of igniting dusts at hot surfaces are being made to see whether ignition temperatures from relatively easy tests can be used to quantify the risks from mechanically produced hot surfaces. The risks of an explosion produced by hot nests encountering a dust cloud are also being studied in this project.

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TABLE 1 : SUMMARY OF IMPACT TESTS

(Reference 9)

Group	I or N	Impact < 200 J	Impact > 200 J
Group 1 methane	I	Ce, Zr, Hf, Ti on hard materials Hand hammer blows on light metal smears on rust Mg, Ti, Al and Alloys on rusty steel Chrome-steel on sandstone and carborundum Al bronze, CuBe, glass on sandstone Tool steel, bronze, nickel chrome steel on sandstone Brass on corroded magnesium anode	Very hard steel on very hard steel Carbon steel on carbon steel Rotary impact high carbon steel on high carbon steel Tungsten carbide, steel on sandstone Hobnail on sandstone
	N	Mild steel on sandstone Tungsten carbide on sandstone	Zu, Cd, Al bronzes on rusty steel C Steel, CuBe. Brass on rusty steel Mild Steel on sandstone
Group 11A Propane etc	I	Carbon Steel on Carbon Steel Hobnail, tungsten carbide, Al bronze, CuBe Tool steel, Lamp glass on sandstone	Rotary impact carbon steel on carbon steel Rotary impact carbon steel on mild steel Mild Steel on Mild Steel (600J)
	N	Mild Steel on rusty mild steel (180J) Hard steel on hard steel (180J) Al bronze on rusty steel (180J)	Rotary Impact of steel on steel
Group 11B Ethylene etc	I	Bottle glass on sandstone Tool steel on rusty mild steel Mild Steel on rusty mild steel Al bronze on clean mild steel	
	N	Tool steel, Mild Steel on clean mild steel Brass, CuBe, Al bronze on rusty steel	
Group 11C Hydrogen etc	I	CuBe on clean and rusty mild steel Al bronze on clean and rusty mild steel Silver steel on rusty mild steel CuAl Alloy on rusty steel	Mild steel on rusty mild steel Rotary impact bronzes on steel CuNi Alloy on rusty steel CuAlNi Alloys on rusty steel and hard steel CuZnAl Alloy on rusty steel
	N	Brass on rusty mild steel Silver Steel on clean mild steel	Zinc Alloys on steel

TABLE 2 : SUMMARY OF RUBBING TESTS
(Reference 9)

Group	I or N	Rubbing < 10 m/s	Rubbing > 10 m/s
Group 1 Methane	I	Sandstone on Sandstone (500-750W) Rusty steel and light metals and alloys. Tungsten carbide tipped machine picks on sandstone. Mild Steel on mild steel (>3700W) – 1%P Cast irons on mild steel	Steel of buffing disk (460W) Mild steel on mild steel Thermosetting plastics on materials mpt $>723^{o}$C (>22 m/s) Sandstone, Al bronze 197, Mild Steel on Al bronze 197 disk AB197. AB2 on mild steel disk CMA2. mild steel on CMA2 disk Brass on light alloy S19 (90 m/s) - 1% P Cast irons on mild steel
	N	0.5% Cr Cast iron on mild steel 3%P Cast iron on mild steel Brass on sandstone	Mild steel on buffing disk (460W) Drill steel on grindstone (1000W) CMA2 on mild steel disk (46 m/s) 70/30 Brass on mild steel (90 m/s)
Group 11A Propane etc	I		Grinding of steels – from hot surface, not sparks Ti, Mg, Steels on runway materials Ti alloy, St steel on anodised Al alloy disk
		0.5% Cr Cast iron on mild steel	Al alloy on runway materials (18 m/s)
Group 11B Ethylene etc	I	Steel on steel (400W)	Steels on grindstone Rusty steel on copper disk (75 m/s) AB197, AB2, CMA2 on mild steel disk (46 m/s) 70/30 Brasses, Copper on mild steel disk (90 m/s) 0.5% Cr Cast iron on mild steel
	N		60/40 Brasses on mild steel disk (90 m/s) Light alloy on light alloy (140 m/s) Non-metallic composite brake material on mild steel
Group 11C Hydrogen etc	I		Stainless steel on Al alloy and GRP disks Al on GRP disk CuBe, Ni alloy, phosphor bronze on steel wheel Copper on rusty steel wheel (70 m/s) Steel on copper wheel Bronzes, CuBe, Copper alloys on grindstone if long enough
	N		Sparks from high alloy and chromium steel on grindstone CuBe and Cu alloy sparks from grindstone Carborundum on Al alloy and GRP disks Al on Al disk 90 m/s Al Zn and their alloys on grindstone