



Chapter III

Fundamentals of Dust Explosion

3.1 Historical Review

Although dust explosions have been recorded for over a century, appreciation of their true character was relatively slow in developing. In particular great difficulty was experienced in accepting that an explosion could be caused by the dust alone, and that the presence of a flammable gas to support the explosion was not necessary. For instance, an account of a flour dust explosion in Turin in 1785 was published shortly afterwards (Morozzo,1795) in which it was postulated that ignition first occurred in flammable gas given off by the disturbed dust, although it was recognized that the dust itself contributed to the subsequent explosion. Over 100 years elapsed before it was generally accepted that dust explosions in coal mines could be initiated and sustained by coal dust alone, without needing support from flammable mine gas. When the position was finally clarified early in the present century, explosions in numerous other industrial dusts had occurred, and the way was open for a more rational assessment of the explosion hazard and the need for adequate precautions.

A review of the position gave details of numerous explosions in various industrial dusts, and estimates of life and economic losses (Price,1922). A record of important dust explosions in the United States and Canada since 1860 (NFPA,1957), excluding those in coal mining, gave details of the causes of explosions, the extent of damage and casualties, and numerous photographs of damages to plants and buildings. Comparable statistics have not been published for the number of explosions and loss of life and property in the United Kingdom. The number of incidents notifiable by law in the U.K., involving dusts, in recent years has averaged about two or three per month. A technical review, covering data up to 1959, gave general references (Brown,1962) particularly to dust explosion in factories. A review of mining explosions in India (Deshmukh,1966) covered both dust and gas, and explosions involving both.

The causes and effects of the explosions were similar to those reported earlier in the West.

3.1.1 Definitions of Dusts and Dust Explosions

What is dust?

Dust consists of solid particles which, because of their small size, will reach a uniform settling velocity in still air after a short distance of acceleration. The velocity is about 0.03 to 11 cm/s (0.012 to 4.3 in/sec). Bartknecht (1989) defines dust as "a dispersed solid of any form, structure, and density". It is common to use the term "dust" if the particle size is 100 to 300 μm . Mixtures with particle size of 100 to 300 μm are designated as fine dust and ones with particle size of 30 to 100 μm as "finest dust." The portion of particles less than 30 μm are called "dust in dust." (Bartknecht, 1989)

(Note: NFPA 68 (1988) defines dust as any finely divided solid, 420 microns (μm) or smaller (less than 40 mesh)).

What is a dust explosion ?

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

In pneumatic conveying, dust is certainly dispersed as cloud, usually in air, and consideration must therefore be given to the possibility of dust explosion, should a source of ignition be present (Palmer, 1973).

3.1.2 Occurrence of Dust Explosions

Dust explosions have been known for approximately 200 years, ever since the wind mill was introduced in 1752-1756 for the purpose of grinding cereal grains.

The first explosion which was recognized as a dust explosion occurred in Italy on December 14, 1785. It was reported by the Turin Academy of Science as a flour dust explosion in a warehouse in Turin.

Five additional explosions creating considerable excitement occurred over the next 100 years.

Table 3.1 Dust explosions (Bartknecht,1989)

Year	Location	Installation	Dust type	Damage
1785	Turin (Italy)	Warehouse	Flour	Warehouse destroyed
1858	Stettin (Poland)	Roller mill	Grain	Mill building destroyed
1860	Milwaukee (USA)	Mill	Flour	Mill building destroyed
1864	Mascoutah (USA)	Mill	Flour	Mill building destroyed
1869	Unknown (Germany)	Mill	Pea flour	Local damage to mill
1887	Hameln (Germany)	Silo	Grain	Silo and building destroyed

In 1887, a grain dust explosion destroyed a silo of the "new Wesermuhle" in Hameln, Germany (Table 3.1). The journal of the "Verein Deutscher Ingenieure" of November 1887 described the explosion as follows: "This accident is unique on the continent". Until then, people had no idea of the enormous destructive effects of such forces.

With increasing industrialization and the change from smaller facilities to large industrial complexes, the frequency of dust explosions has increased since 1887.

Most early dust explosions occurred in places where production and dust generation were high due to size and productivity. Up to 1992, the USA and Canada experienced 217 dust explosions. These involved organic dusts from mills, grain elevators and silos, starch plants and refineries, as

well as plants processing aluminum, chocolate, paper, rubber, seasoning, etc. The multitude of installations affected by dust explosions is striking.

A more recent USA statistic for the time period 1900-1952 lists the dust types involved in 769 explosions (Table 3.2). The total damage amounted to 88 million dollars and involved 464 casualties and 1229 injured.

Statistical information on dust explosions in Germany is scarce for that time period. Nevertheless, 66 sugar dust explosions were reported for the time period 1890-1922, with moderate to catastrophic results. One of the worst explosions occurred on March 16, 1917 in Frankenthal, killing 6 operators and causing considerable damage.

Table 3.2 Type of Dusts involved in dust explosions in the USA (1900-1952) (Bartknecht,1989)

%	Number of explosions	Type of dust
24.8	191	Grain
16.8	129	Wood
14.7	113	Feedstuff
13.1	101	Flour
5.6	43	Starch
4.8	37	Cork
3.4	26	Sugar
3.3	25	Plastics
3.1	24	Sulfur
3.1	24	Malt
1.8	14	Bark
5.5	42	Miscellaneous
100	769	

Nowadays, dust explosions are - in the true sense of the word - commonplace in the former Federal Republic of Germany, although only a fraction are recorded, as mentioned earlier (BIA,1982). But not all the mishaps have such a terrible outcome as the 1979 flour dust explosion in the

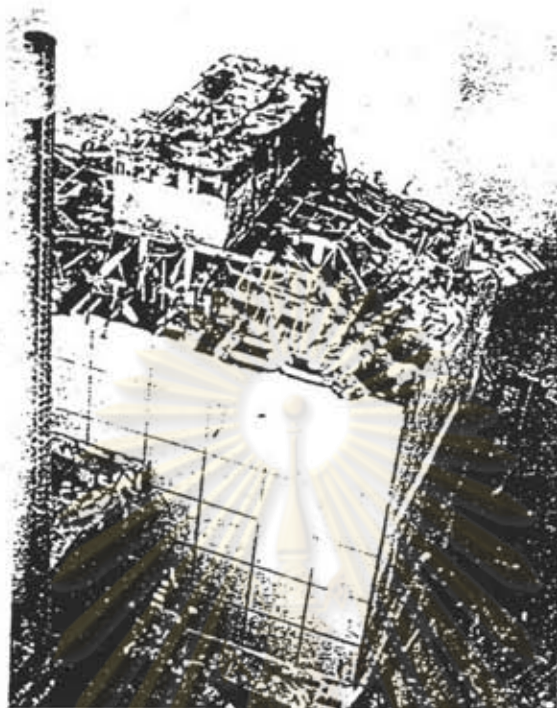


Figure 3.1: "Bremer Roland Mill" after a flour dust explosion, 1979

"Bremer Roland Mill" (Fig. 3.1) which left 14 dead, 17 injured, and property damage of 100 million DM.

Statistics on dust explosions in Japan are difficult to obtain since only major incidents are covered by the Labor Standards Inspection Offices (Bartknecht, 1989). However, there were 241 major dust explosions reported with 93 worker deaths and 500 injured during the past 38 years between 1952 and 1989. Twenty percent of the dust explosions between 1952 and 1967 were caused by organic chemicals such as phthalic anhydrides, but about 27 percent of these explosions between 1968 and 1986 arose from metals. Naturally, industrial processes have been varied with the times. In concert with that, the dust involved in the accidents also have changed in Japan. In other countries, the grain elevators and coal mines are the two most often cited locations where dust explosions have occurred.

357 dust explosions have been analyzed and the frequency of involvement of the various dust categories tabulated (Fig. 3.2).

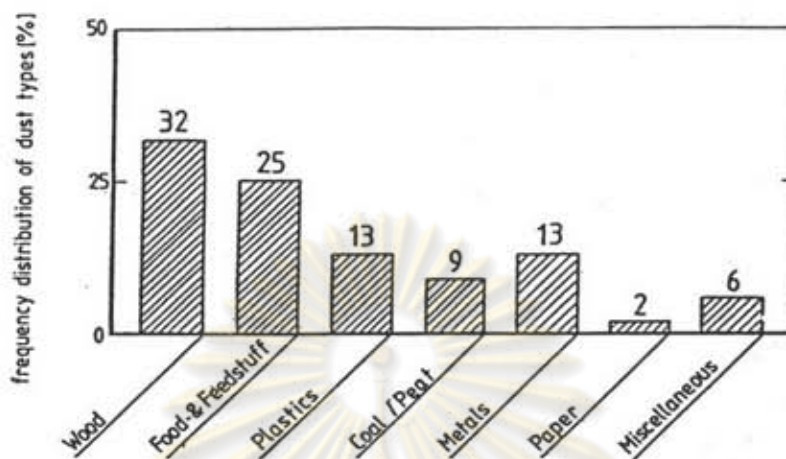


Figure 3.2 Frequency distribution of dust types involved in 357 dust explosions (BIA,1982) (1965-1980)

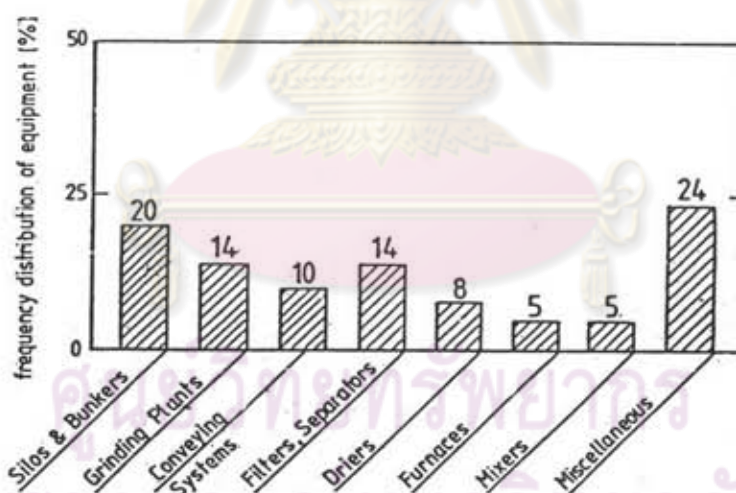


Figure 3.3 Frequency distribution of types of equipment involved in 357 dust explosions (BIA,1982) (1965-1980)

In Germany, as well as in the USA, most of the dust explosions occurred in the industries cited above. The percentages given in Fig. 3.2 are therefore representative of both countries.

Figure 3.3 shows the percentage of each equipment category involved in the dust explosions. Every fifth of these happened in a silo or bunker.



Figure 3.4 Effect of a grain dust explosion in a group of silos

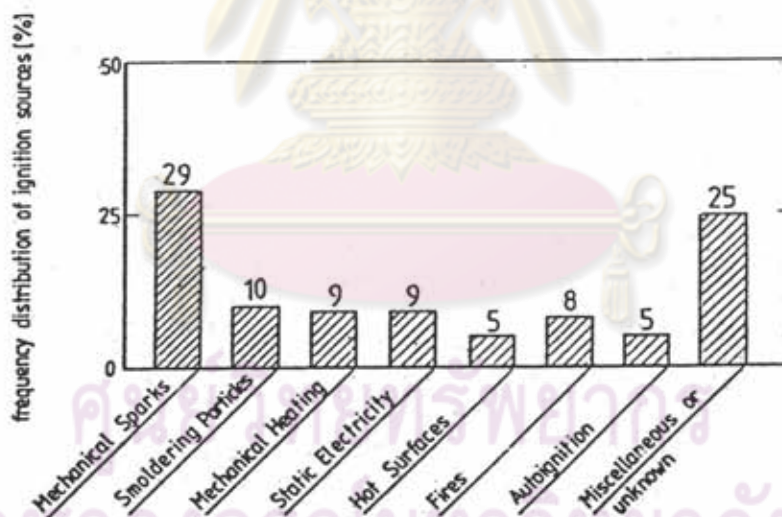


Figure 3.5 Frequency distribution of ignition sources responsible for 357 dust explosions (BIA, 1982) (1965-1980)

Such silo explosions are often spectacular, especially if an entire cluster of silos is involved (Fig. 3.4). Grinding and conveying systems, as well as dust collectors, participate at almost the same ratio.

In conclusion, Fig. 3.5 represents the frequency distribution of the various ignition sources responsible for the above dust explosions. Although it is sometimes very difficult to determine the actual ignition source, it is

apparent that mechanically produced sparks present the most frequent source in industrial practice, with 29 %. This includes sparks generated through friction, grinding, and impact. Therefore, it is not surprising that present research is concentrated on the effectiveness of such sources in the case of dust/air mixtures. All the other sources combined participate practically with the same probability as mechanical sparks.

The outlined case histories, which are certainly not complete, may serve as an overview of the dangers which have been known to exist for the past 200 years in processing or handling combustible dusts. The often-voiced opinion that a plant which is processing dusts is safe because it has not experienced an explosion in the past years or decades has been frequently disproven in practice.

3.1.3 Apparatus for the Testing of Airborne Dusts

The attempt to simulate dust explosions in available laboratory equipment and to record the course of the explosion in a reproducible fashion was met with substantial difficulties. The prerequisite for such tests was the existence of a uniform and reproducible dust/air mixture. Such a requirement seemed easiest achieved in small equipment for the determination of the most important explosion characteristics and the assessment of the dangers of an explosion. The equipment was mostly made of glass, which allowed a visual check of the homogeneity of the dust mixture.

Vital (1875) was one of the first to conduct comparative tests to determine the hazards of various dust types. He blew a dust cloud through a gas flame into a long pipe which had a ball made of elder wood at the end. From the shape and length of the explosion flame as well as the throw of the wooden ball, Vital estimated the "relative hazard" of the tested dust.

Approximately at the same time, R. Weber (1875) ran flour tests using the equipment shown in Fig. 3.6. The dust was deposited on top of a sieve. Through shaking action, the product fell into a vessel containing an ignition source (not shown in Fig. 3.6).

By changing the speed of revolution of the cogwheel, by adjusting the stroke of the sieve and by combining sieves with varying mesh sizes, dust streams of differing densities could be produced. The stream was gradually reduced to just that volume that barely gave ignition. In such fashion, Weber determined the lower explosible limit of flour at 25 g/m^3 .

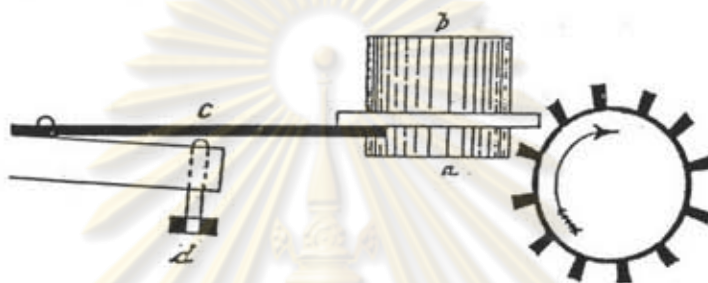


Figure 3.6 Apparatus for the determination of the lower explosion limit, as per Weber

In 1911, Tifanel and Durr (Bartknecht, 1989) used a photographic method to determine the relative danger of a few dust types. A pre-weighed amount of dust was conveyed by a stream of oxygen into a well-defined gasoline flame and a picture taken of the length and size of the flame. Mainly flour, sugar, and Lycopodium were tested.

Figure 3.7 shows the apparatus R. Bauer developed in 1917 (Bartknecht, 1989) for the determination of the lower explosible concentration of aluminium dust. The apparatus consisted of a vertical tube with an impeller with electric drive in the lower portion, plus an ignition source and a loose cover. After the addition of a known amount of dust, the motor was started and the ignition activated. With this arrangement, the lower explosible limit of aluminium dust was determined at approximately 400 g/m^3 .

The apparatus which was developed by Steinbrecher (1968) for the determination of the lower explosible limit of industrial dusts (Fig. 3.8) differed from the previously described unit in its singly activated dust dispersion system through a blast of air. The combustion chamber consisted of a vertical glass pipe with a hemispherical end and a volume of 0.135 L. The pipe also housed an ignition source and a thermocouple.

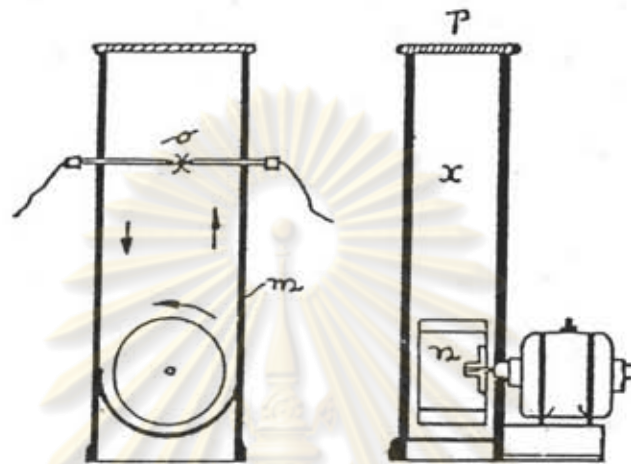


Figure 3.7 Apparatus for the determination of the lower explosion limit, as per R. Bauer

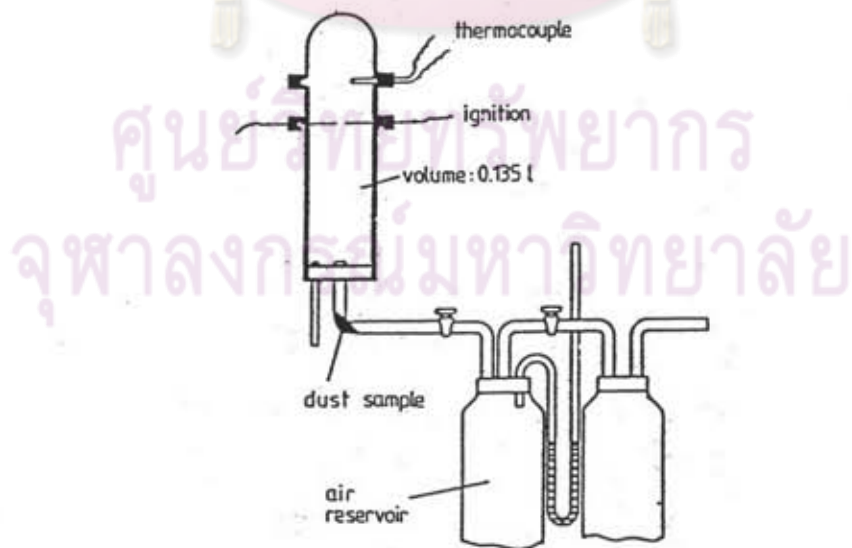


Figure 3.8 Apparatus for the determination of the lower explosion limit, as per Steinbrecher

The dust sample was stored just ahead of the explosion chamber and then dispersed in the cylinder by a jet of air. These ignition tests often destroyed the glass tube.

The Chemisch-Technische Reichsanstalt (1933-1935) (German Chemical Technical Institute) used the apparatus shown in Fig. 3.9 for the determination of the explosibility of dust/air mixtures.

The dust was first deposited at the bottom of the apparatus and then swirled up by a jet of compressed air discharged through a nozzle. A glowing wire was used as an ignition source. The test results indicated that Zirconium was especially explosible over a markedly wide range of concentrations.

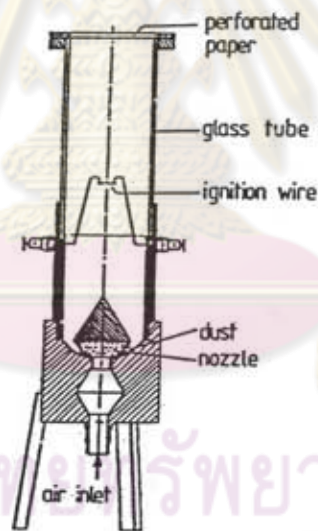


Figure 3.9 Apparatus used by the Chemisch-Technische Reichsanstalt to investigate the explosibility of dust/air mixtures

Until recently, Eckhoff (1981) used an oxyacetylene torch for ignition in testing the explosibility of dust in order to eliminate the risk of a misjudgement.

The hazard of a combustible dust is not only defined by its explosibility and explosible range but also by the pressure and violence of its combustion. In such a context, the maximum explosion pressure and the pertinent pressure are of special interest. Closed equipment is needed to

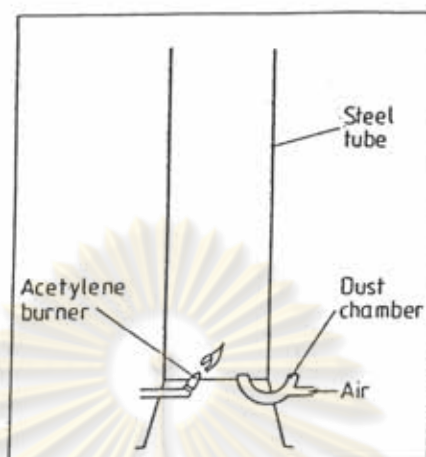


Figure 3.10 Apparatus for the determination of the explosibility of dust/air mixtures, as per Eckhoff ($D = 14 \text{ cm}$, $H = 40 \text{ cm}$)

test for these parameters. Obviously, the test equipment shown in Fig. 3.6-3.10 is unsuited for this purpose.

Mason and Taylor (1937) used a 0.75-L cylindrical glass vessel as the explosion chamber (Fig. 3.11). For the dust dispersion, they employed Steinbrecher's principle (Fig. 3.8). A mechanical indicator for the time-pressure recording of the dust explosion was flanged to the top of the vessel.

Trostal and Frevert (Bartknecht, 1989) developed a method which directed an air jet from the top down into a cup containing the dust layer (Fig. 3.12). Thus, the dispersion of the dust/air mixture occurred in a spherical explosion vessel of 1.4-L volume. Again a mechanical indicator recorded the time-pressure behavior of the dust explosion.

In following Trostel's and Frevert's concept, the "Bundesanstalt für Material-prüfung" (H. Selle, 1957) (German Federal Institute for Materials Testing) used a very similar apparatus for their dust testing (Fig. 3.13). Initially, lead strain gages were used for the determination of the maximum explosion pressure. Once it became obvious that the flame temperature influenced the results, it was decided to use a mechanical indicator for pressure recording. As the dust dispersion method generated a slight pressure in the explosion

vessel, a negative pressure was set at start in order to arrive at 1 bar (abs) at the initiation of the dust explosion.

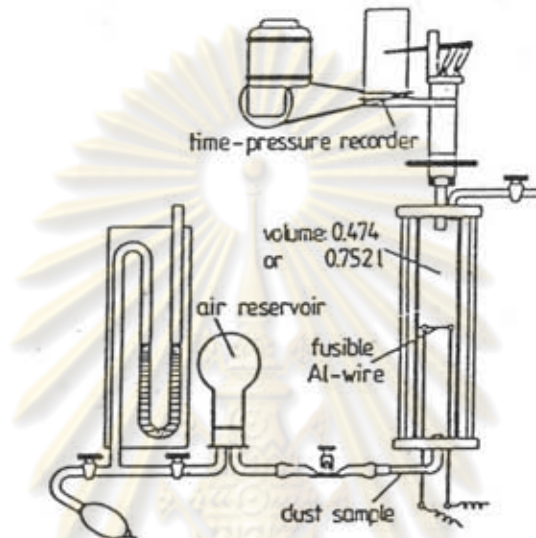


Figure 3.11 Apparatus for the determination of the pressure rise of dust explosions, as per Mason and Taylor

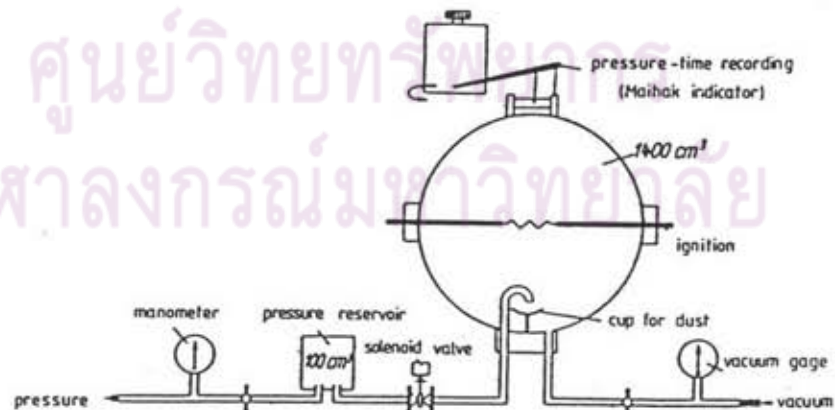


Figure 3.12 Apparatus for the determination of the pressure/time behavior of dust explosions, as per Trostel and Frevert (Volume of the explosion chamber : 1.4-L)

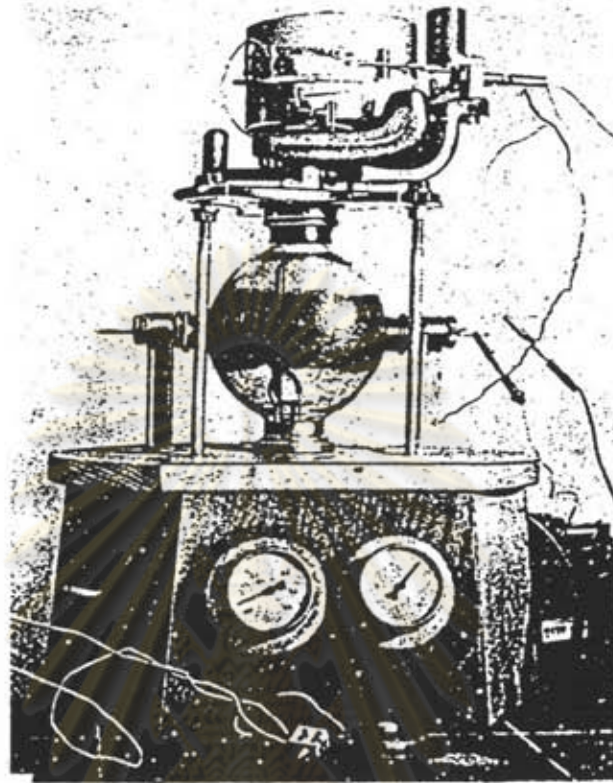


Figure 3.13 Apparatus for the determination of the pressure/time behavior of dust explosions, as per BAM (Volume of the explosion chamber : 1.4-L)

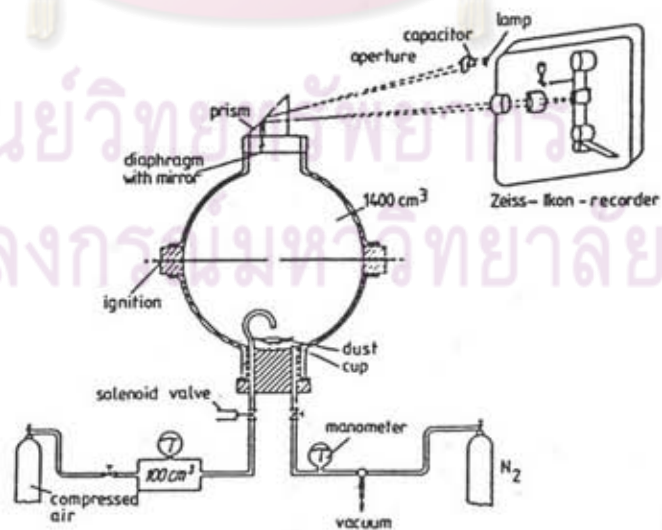


Figure 3.14 Improved BAM apparatus with a metallic sphere and optical recording unit for dust investigations (Volume of explosion chamber : 1.7-L)

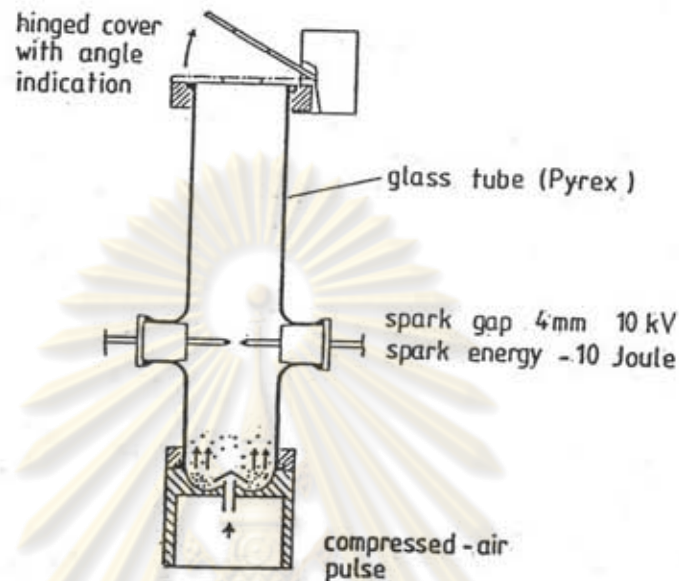


Figure 3.15 "Modified Hartmann apparatus" for dust investigations, as per Lutolf (Volume of the explosion chamber: 1.2-L)

Subsequently, the apparatus was modified again. Figure 3.14 shows the arrangement developed in 1957. The sphere was made out of metal and had a volume of 1.7-L. The pressure rise of the dust explosion was transmitted through a membrane which had a mirror attached. The deflected light beam was photographically recorded.

Homemade "capignitors" served as the ignition source; with a composition similar to thermite, these ignitors required no atmospheric oxygen. This type of ignition was considered extremely powerful since it also made hard-to-ignite dusts explode. This method of ignition became the standard for all dust tests in order to maintain equal starting conditions for dust explosions to be studied.

At approximately the same time, the US Bureau of Mines developed the so-called "Hartmann apparatus". The closed explosion chamber was cylindrical and had a volume of 1.2-L. The dust to be tested was dispersed into the chamber onto a continuous electrical spark (arc) or a glowing wire

coil. The values of the pressure and rate of pressure rise were recorded with either a mechanical indicator or a piezoelectrical pressure transducer (Anonym,1982).

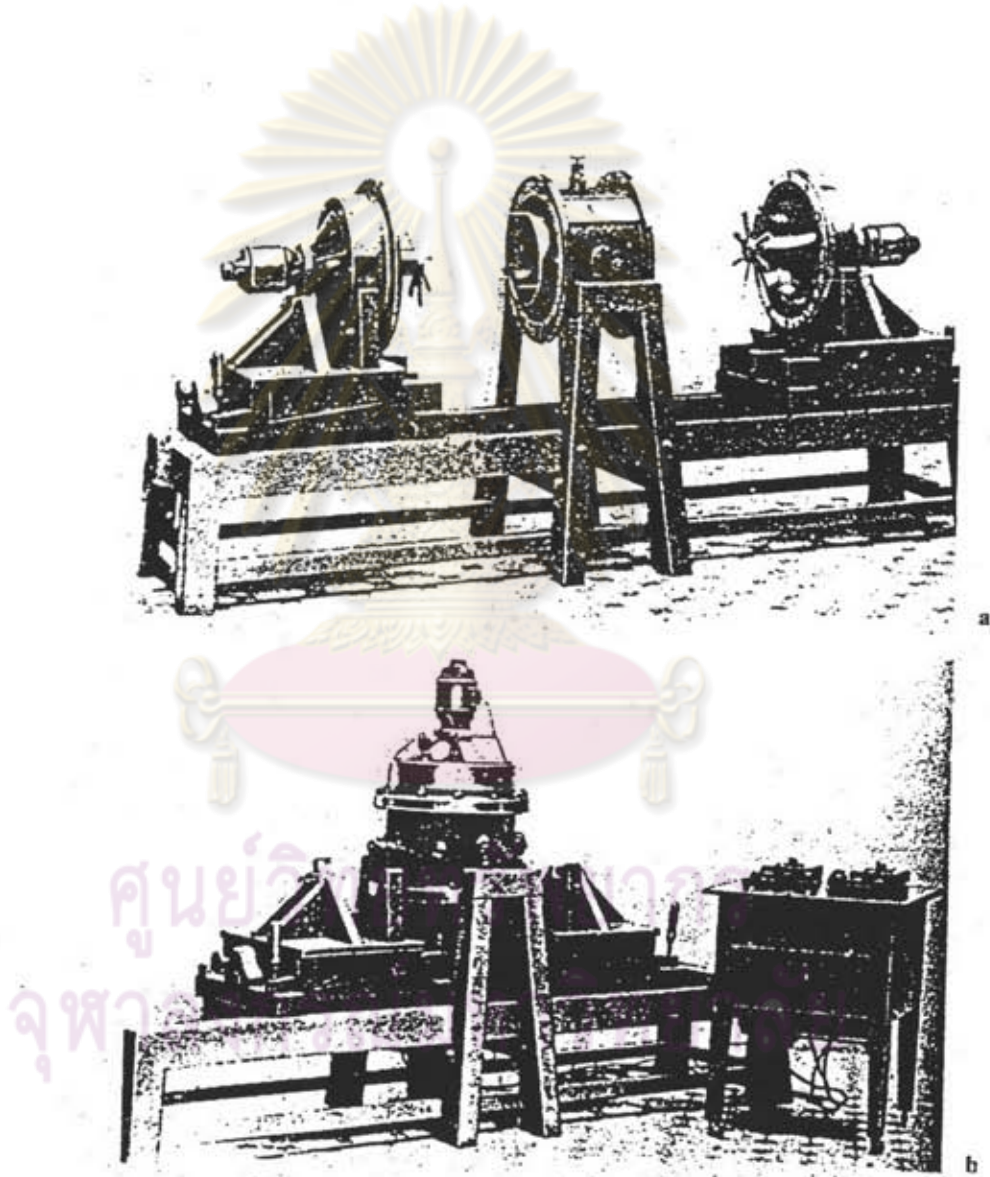


Figure 3.16 a/b. Apparatus for the determination of the explosion limits and the rate of pressure rise of dust explosions, as per Gliwitzky; a : equipment / b : ready for testing (Volume of the explosion chamber : 43-L)

Subsequently, J. Lutolf (1971) simplified the Hartmann apparatus, a modification which became known as the "modified Hartmann apparatus" (Fig. 3.15). It was made out of pyrex glass and the violence of the explosion was expressed at two levels, depending upon the opening angle of the hinged cover. The test apparatus resembled closely the one shown in Fig. 3.9, which is used by the "Chemisch Technische Reichsanstalt".

However, some unavoidable shortcomings were inherent in the testing in small equipment; the safety data obtained -e.g., lower explosible limit, explosion pressure, and rate of pressure rise - did not explain the effect dust explosions had in industrial practice. Therefore, a theoretical method was developed which allowed the calculation of the maximum explosion pressure of a dust on a thermochemical basis from the combustion temperature (H.Selle, 1957). According to this, the maximum explosion pressure range of most dust had to be expected to be in the range of 8-12 bar gage. However, the values obtained from the small-scale tests barely reached 50 % of the theoretical value.

A better correlation of the values seemed to require increasing the size of the explosion vessel and improving the dust dispersion.

In 1938 Gliwitzky took the first step towards a larger test vessel (1933-1935, 1938) by using a 43-L explosion vessel for his tests (Fig. 3.16). Impellers dispersed the dust. He was also one of the first to recognize that the activation of the ignition source had to be synchronized with the dust dispersion in order to arrive at reproducible results. The ignition source was a wire bridging two electrical terminals.

Such an apparatus was used to determine the explosion limits and the rate of pressure rise of dust explosions. The values gained from this equipment for the maximum explosion pressure for combustible dusts, e.g., aluminum, approached very closely the theoretical ones.

3.1.4 Explosible Dusts and Industries involved (Palmer, 1973)

Past experience in the industry and in the laboratory testing of dusts has shown that a wide range of dusts can give rise to explosions. Not all materials that will burn in air can cause dust explosions, even if finely divided and dry; that is, not all combustible dusts are explosible. All

explosible dusts must be combustible. The reason why some combustible dusts are not explosible has not been definitely established, but it is clear that it is not related directly to the heat of combustion or calorific value for the dust. Some dust of relatively high heat of combustion, such as graphite and some anthracites, are not explosible whereas other materials of lower heats of combustion, such as wood saw dust, are readily explosible. Dusts which are not explosible in air at atmospheric temperatures may be able to cause explosions in a heated chamber, such as a furnace or oven. When combustible dusts are being handled it is necessary to either refer to previous records or to carry out laboratory tests to decide whether the dust is explosible.

Over the years a considerable amount of information on the explosibility of dusts has been accumulated both from practical experience and from laboratory tests, and this information is of great assistance in assessing dust explosion hazards. Clearly where new materials are involved, or mixtures of old materials, or old materials made by new processes where their characteristics may be different, recourse must be made to further laboratory testing.

The industries concerned in the manufacture or handling of explosible dusts are numerous, and further details will be considered later. However, some of the principal industries are as follows :

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

This list gives only a few examples and consists of those where the principal products present dust explosion risks. There is in addition a wide range of industries which produce explosible materials in their processes, although dusts and powders may not be principal products as they are, for

instance, in flour and sugar. Examples of industries where explosible dusts are present, and have in fact caused explosions, are rubber dust in the footwear industry, esparto grass dust in the paper industry, and aluminium dust in the manufacture of refrigerators.

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

3.2 Outline of Practical Problem

3.2.1 Conditions for Occurrence of Dust Explosions

The term 'dust' with respect to explosion and fire, should be regarded as combustible particulate matter which can be airborne and generally has a particle size less than 500 μm . Fine fibrous materials or flock from chemical and natural fibres with deniers 0.5 - 6.0 and lengths of 0.5 - 1.5 mm, should also be recognized as being dust explosion risks. It was reported that in 1987 a tragic linen dust explosion occurred in Harbin, P.R. of China, with 58 people dead and 177 injured.

In general, a combustion reaction requires the three components of fuel, oxygen (or air) and ignition source, which constitute a hazard triangle (Fig. 3.17). If one of the components is missing from the triangle there can be neither combustion nor explosion. Dust fires may be initiated when the fuel is in a dust layer, heap, or deposit on supporting surfaces. Even though there are obvious differences in dust fires and explosions, explanation will not be given to the dust fires in this chapter.

For an explosion to occur, the fuel must be dispersed in the air as a cloud in certain proportions and must be ignited. Although there are many similarities between dust and gaseous explosions, the following three conditions must be fulfilled together to cause dust explosions;

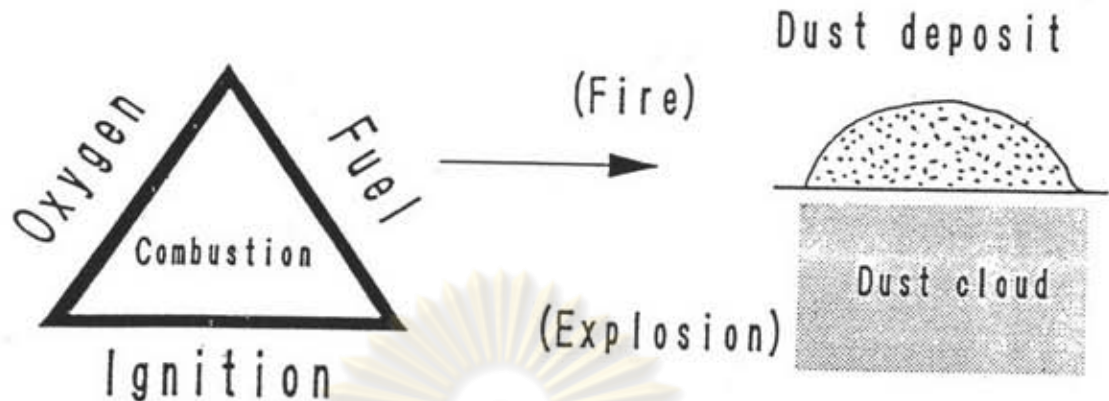


Figure 3.17 Hazard triangle and the dust forms

- (A) The dust must be dispersed and mixed with the air.
- (B) The concentration of dispersed dust must be above the minimum explosible concentration.
- (C) An ignition source of sufficient energy capable of initiating flame propagation must be in contact with the dust suspension.

The condition (A) is related to dispersability and suspension properties of the dust. The ease of the dispersion depends on many factors of the dust characteristics such as the density of the particles, their diameters, their shape and their cohesive and agglomerative properties with respect to each other. In industries the dust suspension will be formed by independent mechanical action, such as handling or transportation of the dust. A jet flow of air is usually required to form the dust-air mixture against gravity, but it's not easy to maintain the dust suspension in a uniform dispersed state and for a long time due to the settling of the dust particles. Coupled with this mode of dust dispersion, the presence of combustible dust deposits in industrial situations will show potential hazards of dust explosions as a prerequisite leading to the condition (A).

Flame propagation is possible through a dust cloud, when the concentration of dust is higher than the minimum concentration necessary to sustain the dust flame, which may be defined as the lean limit of explosibility. Generally, the dust concentration varies in space and time, and then the condition (B) largely depends on industrial processes. If the

condition (A) is met, it will be necessary to take some precautions by estimating that condition (B) will be fulfilled in some cases. In the industry, steady dust flows will be obtained in a pneumatic transport system, but it is inevitable to have dust clouds within explosible concentrations in the top of the horizontal tube, or at the start-up and shut-down of the system. Many powder handling processes raise unsteady dust suspensions and the concentration of dust suspensions can rarely be controlled outside the explosible range at all times. A typical example is the shaking of the filter pads in a bag filter unit. The housing of the filter assembly will contain suspensions of dust of uncontrolled concentration almost certainly within the explosible range. The dust accumulated on the filter is mostly fine, which means the smaller the particle size, the greater are the explosion hazards in accordance with expectations.

The condition (C) refers to the ignition source and there is a variety of ignitions having various temperatures, energies, durations, etc. These include flames, hot surfaces, glowing combustion and smoldering, spontaneous heating, welding and cutting, friction and impact, electric sparks, and electrostatic discharge sparks. Although attempts must be made to exclude the possible ignition sources from all powder handling processes, it still seems difficult to eliminate totally the sources of ignition as they may arise from a breakdown or may even be introduced erroneously. However, they are readily related to specific processes and in many cases, several kinds of precautions could prevent their occurrence.

3.2.2 Flame Propagation in Dust-Air Mixtures

The mechanism of a dust explosion has not fully been explained on theoretical base since a number of variables are included in the phenomena. Complexity may arise from a very wide range of materials, scales in dust flames and aerodynamic effects. Even though a simple statement of chemical composition would not be a sufficient guide to the behavior of materials in a dust explosion, we consider combustible dusts of common organic materials at first.

When the dusts are ignited, there will be the production of volatile matters from the particles by thermal decomposition rather than vaporization.

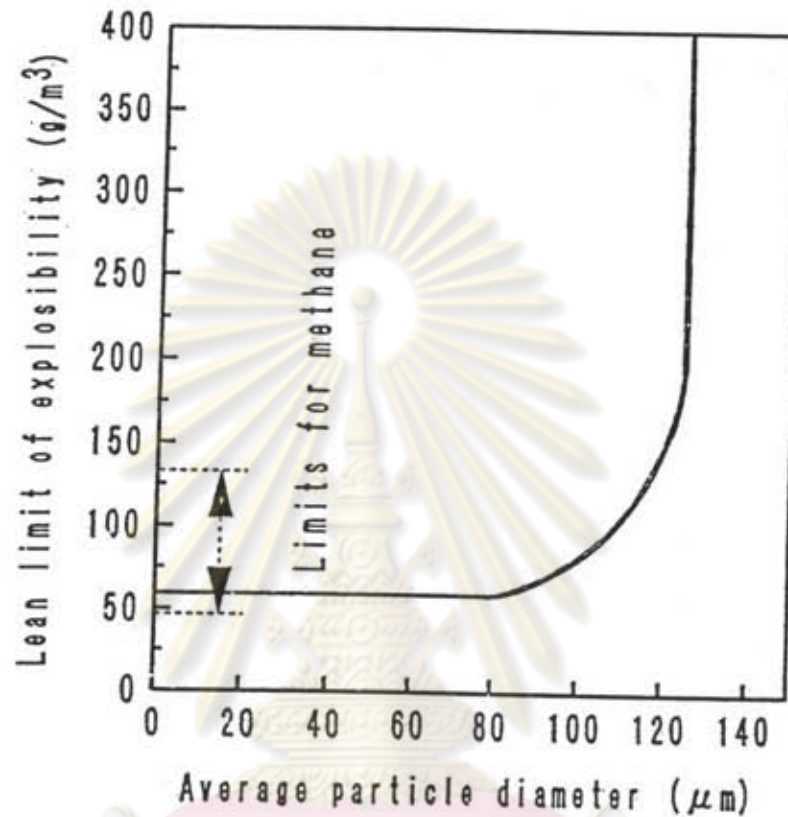


Figure 3.18 Variation of lean limit of explosibility for polyethylene with average particle size

The volatile matters will be mixed with air, leading to ignition of the mixture, if the rate of supply and the effective concentration of the volatiles would be attained. The heat produced with the combustion of the mixture will promote further pyrolysis of the neighboring particles. The process of the mass and heat transfer between one another particle is referred as flame propagation mechanism in a dusty system, in which suspended dust particles would suffer pyrolysis by interaction with its propagating flame. Although the gas dynamic flow structure generated by the flame plays a dominant role for propagating dust flames, it is difficult to describe the flame structure in general, which is strongly dependent on a system apparatus. Likewise, it may be hard to distinguish which the dominant role is, conductive or

convective heat transfer, although radiation is important in dust flame propagation. The effect of surrounding particles in the context of radiative heat transfer between particles has been recognized as a cooperative mechanism.

Clearly, the pyrolysis behavior is different with different dusts and influenced by the heating rate of the particles. Furthermore, pyrolysis may depend on a particle diameter as it may be partial or complete. Thus, the more coarser particles will not present a dust explosion hazard unless they can liberate enough volatile materials to react in gas-phase during passage of the flame. On the contrary, the more finer particles of carbonaceous dusts would fully volatilize at a flame temperature, causing its gas-phase combustion. The dependence of pyrolysis on the particle size is reflected on the experimental measurements of the lean limit of explosibility with variation of particle diameter, as shown in Fig. 3.18 for polyethylene. It would be expected that the lean limit for the totally volatile particles is almost identical to that for explosible gaseous mixtures such as methane-air mixture, although an extra process of pyrolysis is included in the dust combustion.

3.2.3 Hazards in Industries

The dust explosion hazards strongly depend on the industrial situations, and individual industrial installation has its specific hazard of the dust explosion and fire. An incident illustrated in Fig. 3.19 shows instructive features of the dust explosion hazards. A wood dust explosion occurred in 1986 causing an estimated total damage of 300 million yens and involving eight workers. An ignition by some unknown cause started in a cyclone, which was used to collect wood dusts from a pulverizer. The cyclone was malfunctioned with its bottom hopper full of dusts. Deflagration in the cyclone blew up the accumulated dusts and the explosion flame was accelerated in the duct toward an exhaust fan, in which the flame was extremely stirred up and the rate of burning was promoted with increase in the flame area. A violent dust explosion was created outside the fan and the blast wave blew up layered wood dust on the belt conveyer in the

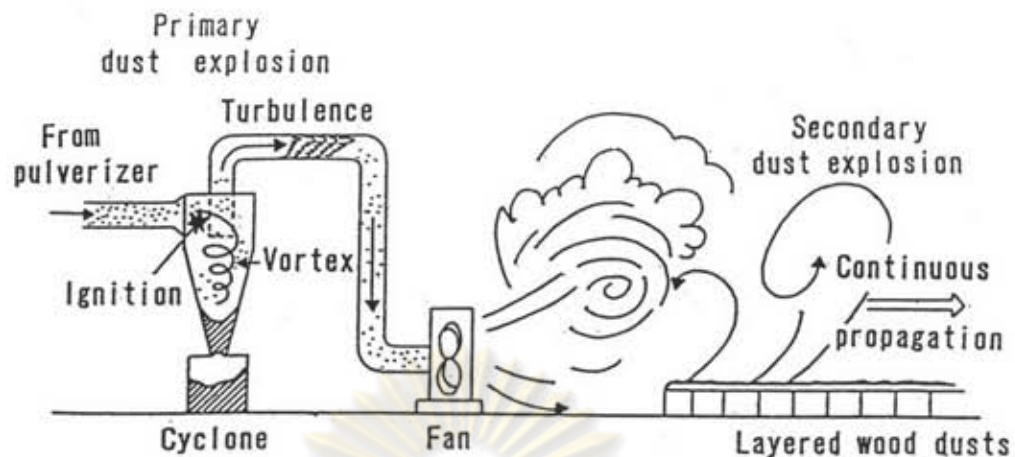


Figure 3.19 Characteristics of dust explosion

vicinity, resulting in a secondary dust explosion. The wood dust layers were prepared for manufacturing hard boards. Fire caused by the explosion continued overnight and the factory was entirely destroyed. The accident clearly indicates the risk of secondary dust explosion and reveals that turbulence is an important factor in dust explosion development.

Industrial dust explosions typically occur in series. The convective flow induced by the primary explosion disperses the surrounding layered dust and ignites the newly formed dust cloud, which in turn disturbs further dust layer and generates a still more serious explosion. Continual repetition of this process results in a secondary explosion. The primary explosion is often small and no major structural and material destructions normally occur, but the consequences of a dust explosion may be disastrous, as cited above.

3.2.4 Evaluation of Explosion Parameters

3.2.4.1 Needs of Evaluation

On the production and handling of combustible dusts in the industry, it is necessary to know whether these dusts are explosible, since not all combustible dusts are explosible. Explosion tests show the the existence of the dust explosibility hazard of the materials and degree of such hazards. The tests are carried out in various countries with certain points in common.

When a dust has been tested and found to be explosible, further measurement of its explosion parameters should be made to assess the possible risk associated with it. The explosion parameters can be divided into two factors, the first denoting susceptibility to ignition and the second denoting severity of explosion. The first factor is called as ignition sensitivity, consisting of the minimum values of explosible concentration, ignition temperature, ignition energy and permissible oxygen concentration, respectively. Maximum explosion pressure and maximum rate of pressure rise belong to the second factor, that is explosion severity. They relate to the methods of prevention and protection and the results of the tests may be used to decide the explosion countermeasure that shall be applicable or whether a new material shall be used in an industrial process.

With regard to the explosion hazard in a process, it will be necessary to assess the explosion risks in the process since each installation used in the process have their own specific hazards. Then, the overall hazard in an industrial process is denoted by a combination of the two evaluations; the explosion parameters of a dust, and the explosion hazard of the installations in which the relevant dust is treated.

3.2.4.2 Minimum Explosible Concentration

The lean limit of explosibility is the dust concentration below which dust will not ignite. According to the test method on dust explosibility of APPIE (The Association of Powder Process Industry and Engineering in Japan) (APPIE,1991), the value is determined in a dust blow-up apparatus (a modified Hartmann tube) or in a sieve-tapping apparatus, both with an electric spark as the source of ignition. Fig. 3.20 shows the vigorous explosion flame of a fine metal silicon powder in the blow-up apparatus. The sieve-tapping apparatus has been adopted because it produces a rather quiescent or non-turbulent dust cloud.

The criterion for an explosion is to observe propagation flames, 10 cm upwards away from the ignition source at least. The value measured for lycopodium, a standard dust for the testing, is reported to be 40 g/m^3 . Although the testing is simple but unlikely to give highly accurate figures because of the non-uniform and turbulent dust clouds in the blow-up

apparatus, the values obtained in the test are recognized to give realistic and safe indications of dust explosion. However, if a dust does not ignite in this test, care should be taken to apply a more powerful source of ignition to the dust-air mixture. The testing is usually carried out under ambient temperature and pressure. The direct effect of these factors is small up to 100 °C, but at higher values of these factors additional precaution must be taken.



Figure 3.20 A silicone dust flame

The 'true' value of the lean limit of explosibility, measured using a large-scale vertical tube of 22.5 cm diameter and about 2 m in length is 70 g/m³ for lycopodium and some common organic dusts.

3.2.4.3 Minimum Ignition Temperature

Minimum ignition temperature is measured in an apparatus in which the dust is dispersed by a small quantity of compressed air. As long as flame propagation is observed, the furnace temperature is reduced until the dust cannot ignite into flame in any dust concentrations. The value measured is the minimum temperature at dust cloud in flames, and it will represent the ease of ignition of different dusts, and a maximum which should not be exceeded in the plant.

3.2.4.4 Minimum Ignition Energy

Minimum ignition energy of a dust cloud is determined with capacitance sparks between electrodes, which are generated by discharging condensers. The value (E) is given from the capacity of the condensers (C) and the charging voltage (V); $E = 0.5 \cdot CV^2$. An advanced method to give the minimum energy of ignition is to make the integration of current times voltage across a spark gap over the spark duration. However, it will still be questionable whether the total amount of electrical energy is a direct measure for the energy finally available for ignition. Some dusts have minimum ignition energies as low as those of gases (hydrogen 0.02 mJ, methane 0.3 mJ; lycopodium (31 μm) 5-15 mJ, anthraquinone (18 μm) 2-6 mJ, polyacrylonitrile (27 μm) 2-6 mJ) (Bartknecht, 1989).

The main application of values of the minimum ignition energy of dust clouds is in relation to the problems created by electrostatic discharges. During the movement of dust in plant the generation of static electricity is to be expected and all metal components of the plant must be bonded to the ground. When the minimum value of the ignition energy of the relevant dust is extremely low, special precautions should be taken, such as requiring special clothing and footwear for operators.

3.2.4.5 Maximum Permissible Oxygen Concentration to Prevent Ignition

As oxygen concentration in the air is reduced by the addition of inert gas a value will be reached at which ignition of a dust cloud is no longer possible. This value is the limiting oxygen concentration to prevent

the dust explosion for a given dust. The oxygen is normally replaced by nitrogen, carbon dioxide or argon, while flue gas and steam will be useful unless they react with the relevant dusts.

Inerting is one of the most useful methods of preventing industrial dust explosions even with the appearance of ignition source in the plant, although it entails some costs and requires good maintenance of controlling the oxygen concentration in a closed or recirculating system. In practice, a maximum permissible oxygen concentration to prevent ignition should be applied, that is 2 percent lower than the limiting oxygen concentration as a safety margin (Grumer,1975).

3.2.4.6 Explosion Pressure and Maximum Rate of Pressure Rise

The maximum explosion pressure is the highest explosion pressure reached in a test vessel during the course of an explosion at the optimum concentration of the dust tested, whereas the maximum rate of pressure rise is the highest value for the rate of pressure increase per unit time reached at the optimum dust concentration. The maximum explosion pressure is related to the energetics of the dust-air mixture and the maximum rate of pressure rise will be proportional to the turbulent burning rate. They are determined from the pressure-time curve obtained in the constant - volume dust explosion by a series of tests over a large range of dust concentrations. These parameters are required to design a plant to withstand the full explosion pressures of a dust explosion without damage.

In Europe, the 1-m³ cylindrical vessel has become standardized for realistic explosibility determination, as described in ISO 6184/1-1985 (International Standard Organization, ISO-1985). Turbulence level created in the vessel seems to be quite high from an industrial point of view and the dust-air mixture is fairly uniform inside the vessel. However, the testings using the 1-m³ vessel are really hard work involving a high cost. Consequently, the smallest-size spherical vessel of 20 liters, that gives comparable data to those of the 1-m³ vessel, has become adopted as an alternative standard in place, as described in ASTM Standard E 1226 (ASTM,1988). The 20-liter explosion apparatus is now commercially available and used for dust explosion tests in many countries. A 30-liter spherical

explosion bomb with a pyrotechnic igniter has been used at the RIIS for hazard assessment of combustible dusts upon industrial usages, together with the ISO 1-m³ standard vessel (ISO,1985).

The maximum explosion pressure usually remains constant as the volume of the explosion vessel, V , is varied, but the maximum rate of pressure rise, $(dP/dt)_{max}$ changes according to the following :

$$K_{st} = (dP/dt)_{max} * V^{1/3}$$

K_{st} factor has been developed to classify combustible dusts for explosion venting purposes and the different classes according to the K_{st} values are shown in the Table 3.3 below : (St comes from Staub in German; dust)

Table 3.3 Classification of level of hazards

Dust Explosion Class	K_{st} (bar.m/s)	Explosion Characteristics
St 0	0	No Explosion
St1	1-200	Weak
St2	201-300	Strong
St3	>301	Severe

By classifying a given dust into an explosion class, safe relief area of the explosion venting can be determined with aid of VDI guideline 3673 (VDI,1983) or APPIE Standard-1983 (APPIE,1983).

Even though the factor appears to be quite meaningful in its applications, the K_{st} value largely depends on the turbulence level of the dust-air mixtures and is not necessarily constant. So, when the K_{st} value is used to evaluate dust explosion hazards in a plant, care should be taken to consider the turbulence level and the influence of scale. The explosibility data for some dusts are given in the Table 3.4, referred from the work at three German laboratories (BIA, BA and IES) using an ISO 1-m³ vessel (ISO,1985) to determine the lean limit of explosibility, the maximum explosion pressure, and the K_{st} value. When data on the explosion parameters are referred to, precaution must be paid that process conditions can largely affect

most of the parameters. Different test methods also can give different evaluation of explosibility.

The published data refer only to the sample materials tested and will vary even for the same material if the particle size, agglomeration or moisture content changes. Therefore, the use of literature data requires careful interpretation and individual tests for the relevant dust will be necessary.

Table 3.4 Summary of the information obtained from the tests

Dust	Mean particle size	Maximum explosion pressure	Lean limit of explosibility K_{st}	Minimum ignition temperature	Minimum ignition energy	Limiting oxygen conc.	
	(μm)	(bar)	(bar·m/s)	($^{\circ}\text{C}$)	(mJ)	(vol.%)	
Starch	<10	10.2	128	-	520	295	-
Sugar	10	8.3	75	60	440	14	-
Cellulose	51	9.3	66	60	500	250	11
Naphthalene	95	8.5	178	15	660	<1	-
Anthracene	235	8.7	231	15	600	-	-
Polyvinyl alcohol	64	8.5	152	60	400	-	-
Polyacrylate	62	6.9	38	125	460	>1800	-
Polyethylene	26	8.7	104	-	490	-	10
Aluminium	23	12.4	620	60	560	29	-
Aluminium	22	12.5	400	-	650	-	6
Magnesium alloy	21	9.9	267	-	560	35	3
Toner	<10	8.9	196	60	520	~4	-
Coal, Braun	42	9.6	112	60	440	159	12

Note : Published data reference and explosions properties of dusts are shown in Appendix 1.

3.2.5 Influence of Factors on Dust Explosions

3.2.5.1 Effect of particle size and nature of material.

As an example, of the effect of particle size of material on the LEL, a plot of the lower limit of MMA beads against particle diameter is shown in Fig. 3.21 (Enomoto,1985). This shows that above a certain fineness, the limit becomes approximately independent of fineness, and when the MMA beads are coarse, a higher concentration is required for ignition but above a certain coarseness the cloud will not ignite. From Fig. 3.21 the LEL of MMA beads is approximately independent of fineness for particles finer than 80 μm .

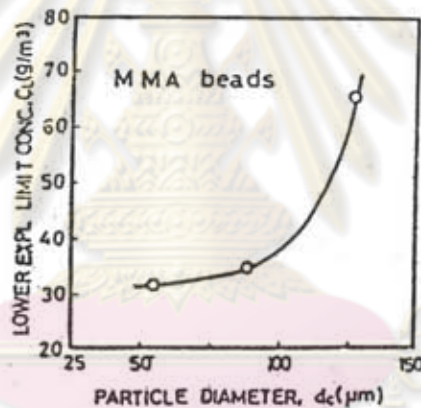


Figure 3.21 Lower Explosion Limit of MMA beads as a function of particle size

Usually, carbonaceous dusts contain volatile matter, Ishihama plotted the LEL against the volatile content, as shown in Figure 3.22.

In the case of the explosion shown in Figure 3.22, at the same % volatile, coarse particles are more difficult to emit the volatile substances in the dust than finer particles. Therefore a decrease in the particle size will reduce the value of LEL. Furthermore, at the same particle size ($D : 200-270$ mesh) in range of % volatile 25 % to 45 %, an increase in % volatile will decrease the LEL, and the LEL may be thought to be independent of % volatile if % volatile is more than 45 %.

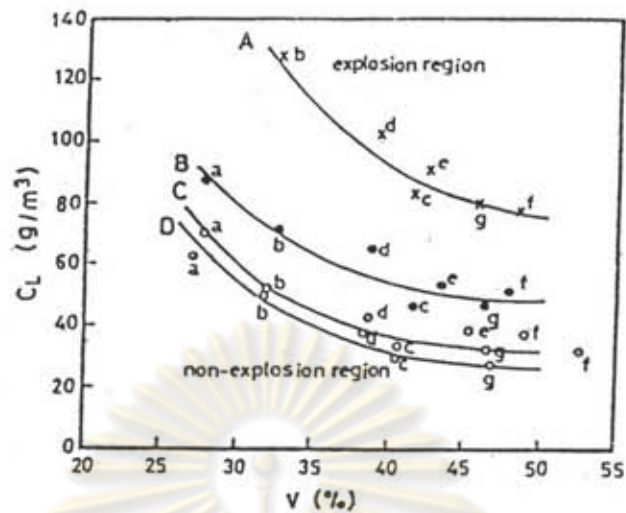


Figure 3.22 Influence of volatile content on the LEL of coal dusts (Ishihama, 1961) :

A : 80-100 mesh, B : 100-150 mesh, C : 150-200 mesh, D : 200-270 mesh;
 a : Kayanuma No. 5, b : Kayanuma Nos. 1&2, c : Kayanuma Nos. 3&4,
 d : Ohyubari, e : Nisso-Teshio, f : Taiheiyo, g : Chikubetsu

3.2.5.2 Effect of moisture content.

In 1985, Van Laar and Zeeuwen (1985) reported that flour of 14 % moisture had a minimum ignition temperature of 470 °C, whereas dry flour had 440°C. For starch the values were 400 °C for the dry powder and 460 °C with 13 % moisture.

Influence of the water content of dusts upon the MIE is shown in Figure 3.23. They found that an increase water content of dusts the value of MIE will rise and the effect of water is much more effective in the ignition. Therefore, the ignition behavior of dusts has to be tested in the dry state.

Figure 3.24 illustrates how the explosion violence is systematically reduced with increasing dust moisture content. The ignition delay characterizes the state of the turbulence of the dust cloud at the moment of ignition in the sense that turbulence intensity decreases as the ignition delay increases.

The specific role of moisture in reducing both the ignition sensitivity and explosion violence of clouds of organic dusts is complex. First, evaporation and heating of water represents an inert heat sink. Secondly,

the water vapour mixes with the pyrolysis gases in the preheating zone of the combustion wave and makes the gas mixture less reactive. A third factor is that moisture increases the inter-particle cohesion of the dust and prevents dispersion into primary particles.

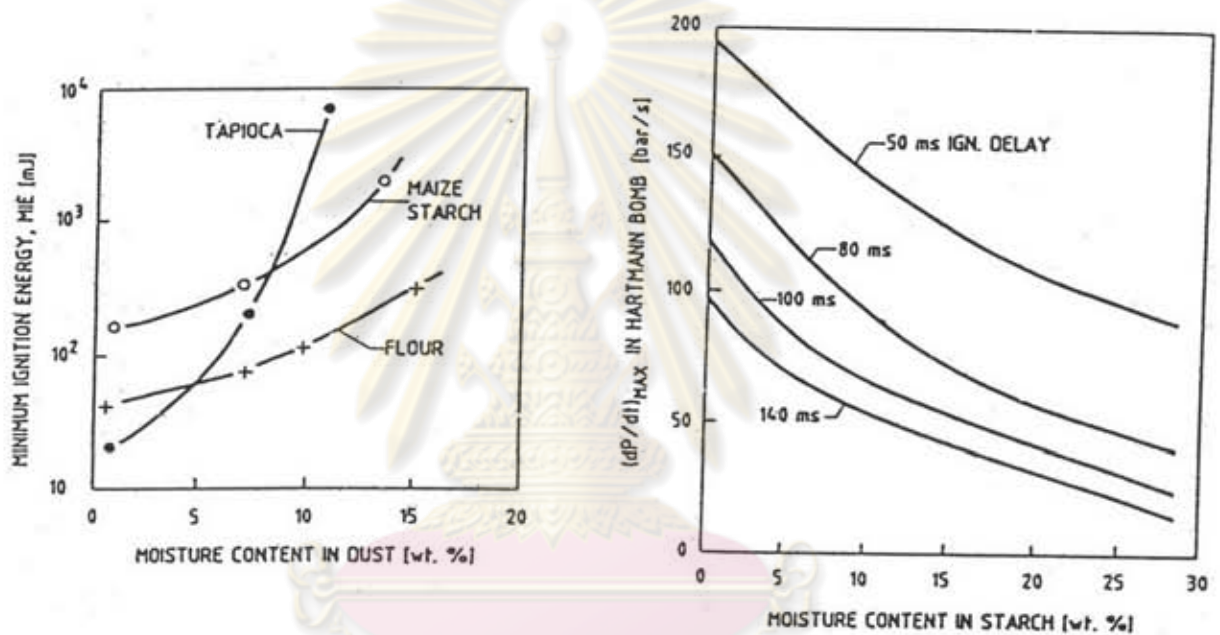


Figure 3.23 Influence of dust moisture content on minimum electrical spark ignition energy (MIE) for three dusts (From van Laar and Zeeuwen, 1985)

Figure 3.24 Influence of moisture content in maize starch on maximum rate of pressure rise in Hartmann bomb for various ignition delays (time from dust dispersion to ignition) (From Eckhoff and Mathisen, 1977/1978)

3.2.5.3 Effect of hybrid mixtures

The behavior of the LEL of hybrid mixtures is very important for practical safety audits in manufacturing plants. Figure 3.25 shows the correlation of the LEL of three combustible dusts with the content of propane

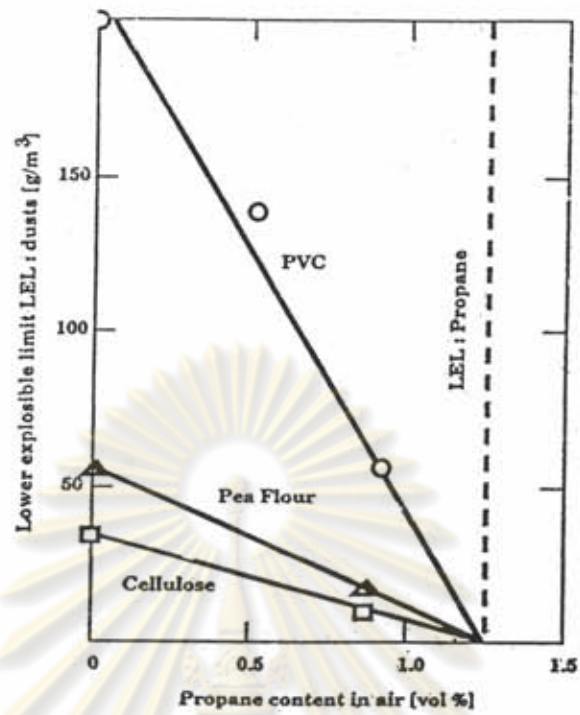


Figure 3.25 LEL of hybrid mixtures consisting of combustible dust and propane

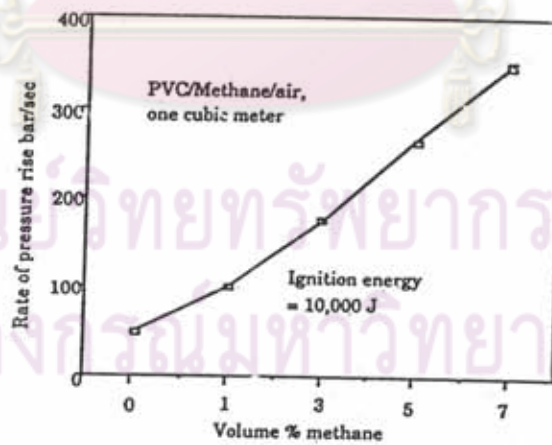


Figure 3.26 Rate of pressure rise data for hybrid mixtures, PVC/CH₄/air (Bartknecht, 1989)

in air. A linear decrease of the LEL of the solids can be noticed with increasing gas content.

The rate of pressure rise may be considerably higher for a hybrid mixture compared to the dust by itself. Figure 3.26 shows the rate of pressure rise of polyvinylchloride (PVC) dust as a function of the amount of flammable gas (methane) in the mixture.

3.2.6 Type of Countermeasure for Prevention

- Prevent Occurrence of Dust Explosion

Avoid the hazardous dust cloud formation

Remove any ignition source

- Vent explosion pressure safely

Lead the explosion pressure to safe atmosphere in order to protect persons and facilities

- Explosion suppression

Suppression system : Detect the ignition of dust cloud immediately, prevent propagation of flame by high discharge rate extinguishers

- Explosion confinement

Building a plant to withstand the maximum explosion pressure

- Isolation

- Prevent escalation of explosion

3.3 Test for Dust Explosibility

3.3.1 Reasons for Tests

Where combustible dusts are being handled or produced in an industry, it is necessary to know whether these dusts are explosible. At present there is no reliable method of predicting the explosibility from the composition or heat of combustion of a dust. Until further information becomes available to enable this to be done, direct tests of explosibility have to be carried out.

Laboratory tests have been set up in various countries to enable investigations of dust explosion properties and these tests have become

formalized. The test procedures accepted at present differ between countries because they have been developed independently, to some extent, and international standardization has not yet been made.

The tests in the various countries have certain points in common. Those concerned particularly with explosibility properties provide for a small sample of dust to be dispersed in the presence of a source of ignition. In some countries tests of ignition in dust deposits are also undertaken. Although some large scale tests are made to study factors affecting propagation and control of explosion, evaluations of dust explosibility are generally made in the laboratory, which enable small samples of dust to be investigated. This is important industrially, because some dusts are expensive or are produced only in small quantities. In other cases at the time of testing, only the output from a pilot plant or test rig may be available. By working on the laboratory scale the time required for testing is minimized, and precautions are simplified if the dust is toxic or has other obnoxious properties.

The dust explosibility tests allow a rapid assessment to be made of the hazards to be expected with new materials, mixtures of materials previously tested, or existing materials manufactured by new processes. The results of the tests may either be implemented directly, or may be used in comparison with results already available for other materials whose explosion characteristics have been established in previous industrial experience. The tests may also be used to decide whether a new material should be used in an industrial process, bearing in mind that if explosion precautions be necessary, the use of that material could be uneconomic.

The explosibility tests are of laboratory scale, and the results obtained from them have therefore to be extrapolated to the full scale for use in the industry. The extrapolation introduces a measure of uncertainty, because the theoretical background for such scaling up is not yet available. Past experience in the interpretation of the tests results has given confidence that they are realistic, and that scaling is permissible; there have also been laboratory investigations leading to the same conclusion. The present practice is to regard dusts which respond vigorously to tests as presenting

definite explosion hazard in industrial scale plant, and dusts which do not respond to the small scale tests as non-explosible on the large scale.

Because the test methods used in various countries differ, it is convenient to consider practice in these countries separately, although some of the tests are common. In the United Kingdom, the United States, and the Federal German Republic there are comprehensive ranges of tests which have become standard in their respective countries. Some other countries use tests from these ranges, so separate consideration has not been given here. Some miscellaneous tests for specific explosion properties from countries other than those specified above, are of technical interest and have been included. A summary of the information obtained from the tests is given in Appendix 1. This is intended as a guide for those concerned with the design and operation of industrial plant; for detailed consideration of a particular dust, reference back to the original publication is recommended.

3.3.2 Selection of Dust Sample

To ensure the usefulness of tests it is important that the sample of dust should be representative of the material concerned. The explosion properties of particular fractions can be measured under controlled conditions. The chemical composition of the dust is usually obtained from the supplier. The sample taken for testing may be only a very small part of the total dust present, and the difficulty in obtaining a representative sample under these conditions is well known. The difficulty is increased if the dust is known to be a mixture of materials. Techniques have been developed for the withdrawal of representative samples from larger amounts by mechanical means e.g. by using a spinning riffler. The method of quartering may be resorted to if other facilities are not available, but it is very dependent on the operator. Where a dust sample is to be taken from an industrial process in operation, a further composition can arise because a fine dust is likely to be more explosible than a coarse material. In general the dust from which the sample is taken should be representative of the process or condition in which it is present and also most likely to be explosible. Examples would be fine materials rather than the standard product, freshly

prepared materials if the explosibility is likely to be reduced by ageing (due to oxidation of particle surfaces), the product after milling rather than before, the product after drying rather than before. Where coarse materials are handled in bulk, considerable amounts of fines may be produced by attrition and these fines may be present in sufficient quantities to enable a sample of them rather than the coarse material to be taken. Usually a few kilograms (about 5 lbs) of dust is required for the testing, although the quantity may be less if the dust is finely divided and well mixed. Considerable care should be taken in the collection of the dust sample because the results of the tests depend on the composition of the dust, and the collection of the sample is usually not done by personnel engaged on the testing but by others, often less familiar with the tests.

If there is doubt concerning the place from which the dust is likely to be most hazardous, it is safer to take samples from several alternative positions, and then have each of the samples tested. A similar situation may arise if the composition of the dust is changed during processing through the plant, where again samples taken at various stages of manufacture should be tested. Because of the importance of ensuring that dusts submitted for testing are representative, expert advice should be taken in cases of doubt. Such advice can often be obtained from the laboratory where the testing is to take place.

3.3.3 Test Methods in Various Countries

THE UNITED KINGDOM

Dust explosibility testing is now carried out at the Fire Research Station, Boreham Wood, Herts. A detailed account of the test apparatus and methods has been published, together with a summary of the explosion properties of a considerable number of dusts (Raftery, 1968). The tests use methods agreed with H.M. Factory Inspectorate. All the tests are concerned with assessing the explosibility, or measuring explosion properties, of dusts in suspension; the tests do not include measurements on layers or deposits of dust.

The basic scheme of the tests is outlined in Fig. 3.27. With a dust which has not previously been tested, the first step is to classify the dust for explosibility. The classification tests determine whether or not the dust is capable of propagating a dust explosion. If the dust is explosible, then subsequent tests may be carried out to measure particular explosion properties. If the dust is already known to be explosible, then measurements of its explosion properties may be undertaken without prior classification.

THE UNITED STATES

Tests for evaluating the explosibility of dusts were devised at the laboratories of the Federal Bureau of Mines, US Department of the Interior, Pittsburgh, Pennsylvania. The test methods are extensive and include investigation of dust suspensions and dust layers, with a wide range of ignition sources under a variety of conditions of dispersion. A full account of the equipment and test procedures has been published (Dorsett,1960) and a short summary of available test results has appeared (Marks,1958). Detailed results have appeared for the explosibility of agricultural (Jacobson,1961), carbonaceous (Nagy,1965), metal (Jacobson,1964), plastics (Jacobson,1962), chemical (Dorsett,1968) and miscellaneous dusts (Nagy,1968). Explosion pressure measurements (Nagy,1964) and prevention of dust explosions by inerting (Nagy,1964), have been the subjects of further reports. The basic scheme of the tests is outlined in Fig. 3.28.

The first step in the preliminary examination of a dust sample is to screen it through a No. 20 U.S. mesh sieve; the fraction not passing the sieve is weighed and discarded. The fraction which passes the sieve, referred to as the "as received" dust, is further screened through 100 and 200 U.S. mesh sieves to evaluate the particle size distribution. For a pure substance a through 200 mesh fraction is obtained by sieving, whereas for a mixture a representative sample is ground until it passes the 200 mesh. The complete range of tests is then carried out on the through 200 mesh fraction, with a few tests on the through 20 mesh fraction. The moisture content of the "as received" dust is determined by heating in a drying oven;

if the moisture content exceeds 5 per cent the dust is dried before it is tested for explosibility. The dust is also dried if the moisture content is below 5 per cent but the dispersability is affected by the moisture. The sample is examined under a microscope before testing, and other physical properties are measured when relevant.

FEDERAL GERMAN REPUBLIC

The principal establishment for the laboratory testing of dusts for explosion and fire properties is the Federal Institute for the Testing of Materials, Dahlem, Berlin. The explosions and fire hazards section does not include investigations of explosives or of toxic hazards which are undertaken in other sections of the Institute. In addition the hazards associated with coal dust are investigated elsewhere, e.g., at Dortmund.

A detailed account of the test methods used in assessing the explosion and fire hazards of dusts at the Federal Institute (BAM) has been published (Leuschke, 1966). The tests are wide ranging, and include observations and measurements on dust suspensions, dust layers, and the combustible volatiles produced by the heating of dust layers.

The basic scheme of the tests is shown in Fig. 3.29. It is recommended that the sample should consist of fine dust that is as fresh and dry as possible, for material in this condition has been found to be the most dangerous. In the preliminary tests the particle size of the dust sample is examined, and when the sample as received contains particles greater than 200 microns the dust is either sieved or ground to yield particles below this maximum size. The dust is then dried for 24 hours at 75° C before any further tests are carried out.

OTHER COUNTRIES

In the USSR a test is used in which the minimum ignition energy of dust suspensions is defined in terms of the discharge energy of electrical condensers capable of igniting the optimum concentration of dust, with the optimum characteristic of the discharge circuit. The gap between the spark electrodes is such as to exclude any flame quenching effects (Smelkov, 1968).

The apparatus consists of a steel box containing a dust hopper with a perforated base; on vibrating the hopper a column of dust falls through the box to a dust collector in its base. The electrodes, which are pointed, are carried in insulators on opposite sides of the box; the number of spark discharges is counted automatically. A control unit synchronizes the operation of the hopper, the sparking circuit, and the counter. The voltage of the condenser is measured before and after the discharge.

The test procedure is to measure firstly the optimum mixture concentration, then the optimum inductance and resistance of the circuit, and finally the minimum gap between the electrodes to prevent quenching. In each case the probability of ignition is defined as the number of ignitions divided by the total number of discharges, the number of ignitions must be not less than 10. With each of the variables the maximum ignition probability is measured and the corresponding experimental conditions used in the test.

The minimum ignition energy is measured by plotting the ignition probability as a function of ignition energy, and the minimum is taken as that at which the probability is 10^{-2} . In this test the particle diameters must be less than 75 microns.

The minimum explosible concentration, or lower limit of explosibility, of magnesium powder in air has been measured using a 2-L closed steel sphere (Propov, 1968). The dust is placed in a small bowl at the centre and dispersed by air from a jet blowing down upon the powder, and spark electrodes are nearby. The presence of flame is detected by observation through points in the wall of the sphere. The minimum explosible concentration is that below which explosion does not occur when the experiment is repeated five times. Dust / air mixtures with a minimum explosible concentration of 0.065 g / l or less are considered explosible, and those with a higher minimum concentration are flammable.

3.3.4 Special Methods

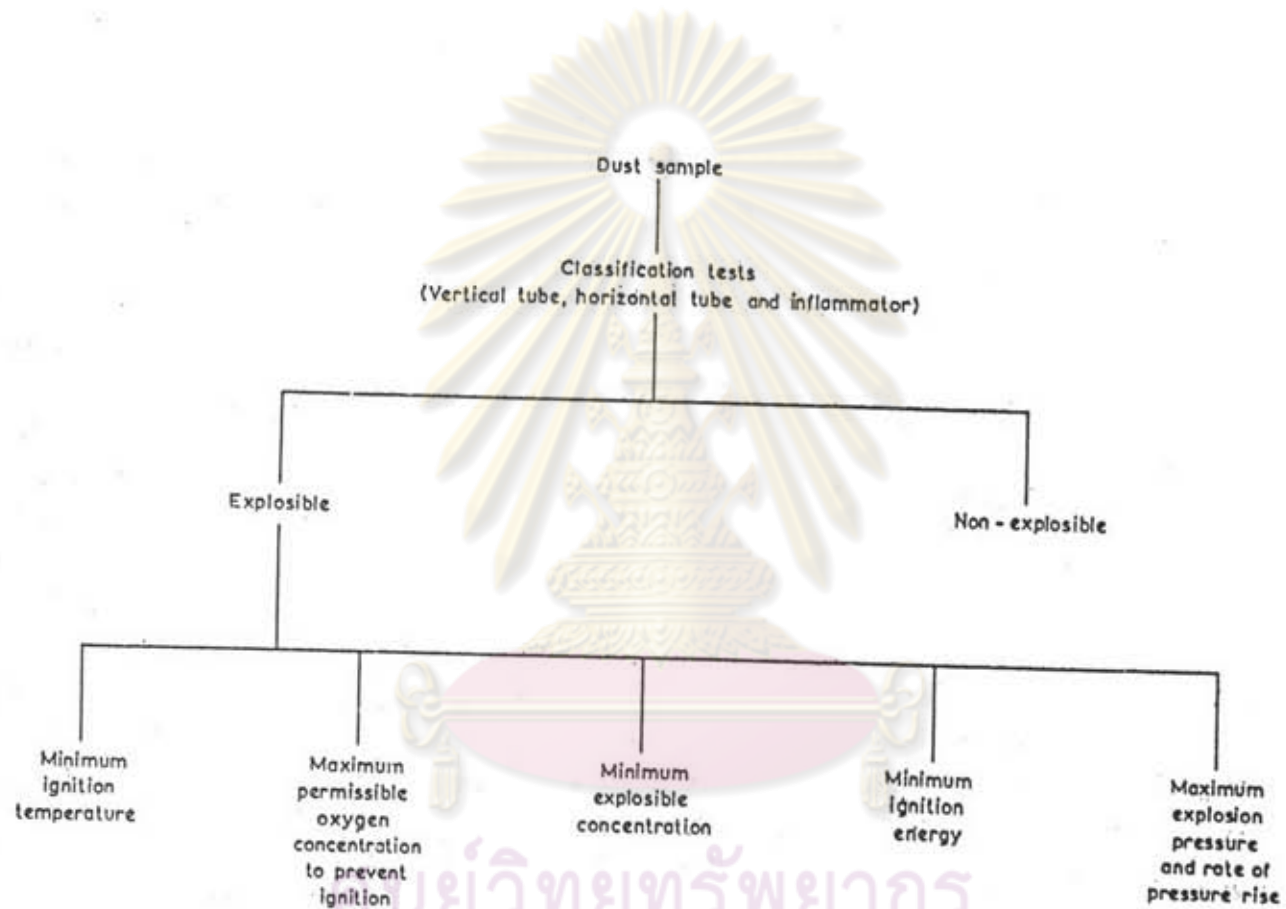
In addition to the test methods recognized nationally within different countries, special methods have been developed by industries, authorities etc in various countries. The purpose of the special methods has usually been

to provide *ad hoc* information for specific industries, processes, or materials, which enables comparisons to be made between materials more rapidly than by the national tests. They are particularly useful for rapid comparisons within a series of similar materials, e.g. a range of dyestuffs, where the *ad hoc* approach is often helpful.

An outstanding example of special test methods is the series adopted by a group of chemical manufacturers in the Federal German Republic (Lutolf, 1971). The tests were aimed at ascertaining those dusts which were particularly hazardous during drying or grinding operations, and since coming into use have led to a substantial decrease in the incidence of decompositions and fires. There are five tests in the series, as follow :

1. A flammability test in which a platinum wire at 900°C is applied to a small heap of the dust.
2. An ignition test in which about 100 mg of dust is deposited on an aluminium block, thermostatically controlled, at various temperatures.
3. A decomposition test in which the dust, contained in a tube, is inserted in an aluminium block, the temperature of which is raised in stages, and signs of exothermic reaction are sought.
4. A drop-hammer test in which a 5 kg weight is dropped about 75 cm onto a steel punch, of area 1 cm^2 , resting on the dust which is deposited on a steel anvil. Observation is made for flames, sparks or explosion.
5. A dust explosion test in which the Vertical Tube Apparatus is fitted with a hinged aluminium lid, and the opening angle of the lid is taken as a measure of explosibility.

จุฬาลงกรณ์มหาวิทยาลัย



ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

Figure 3.27 Basic scheme of tests in the United Kingdom (Palmer, 1973)

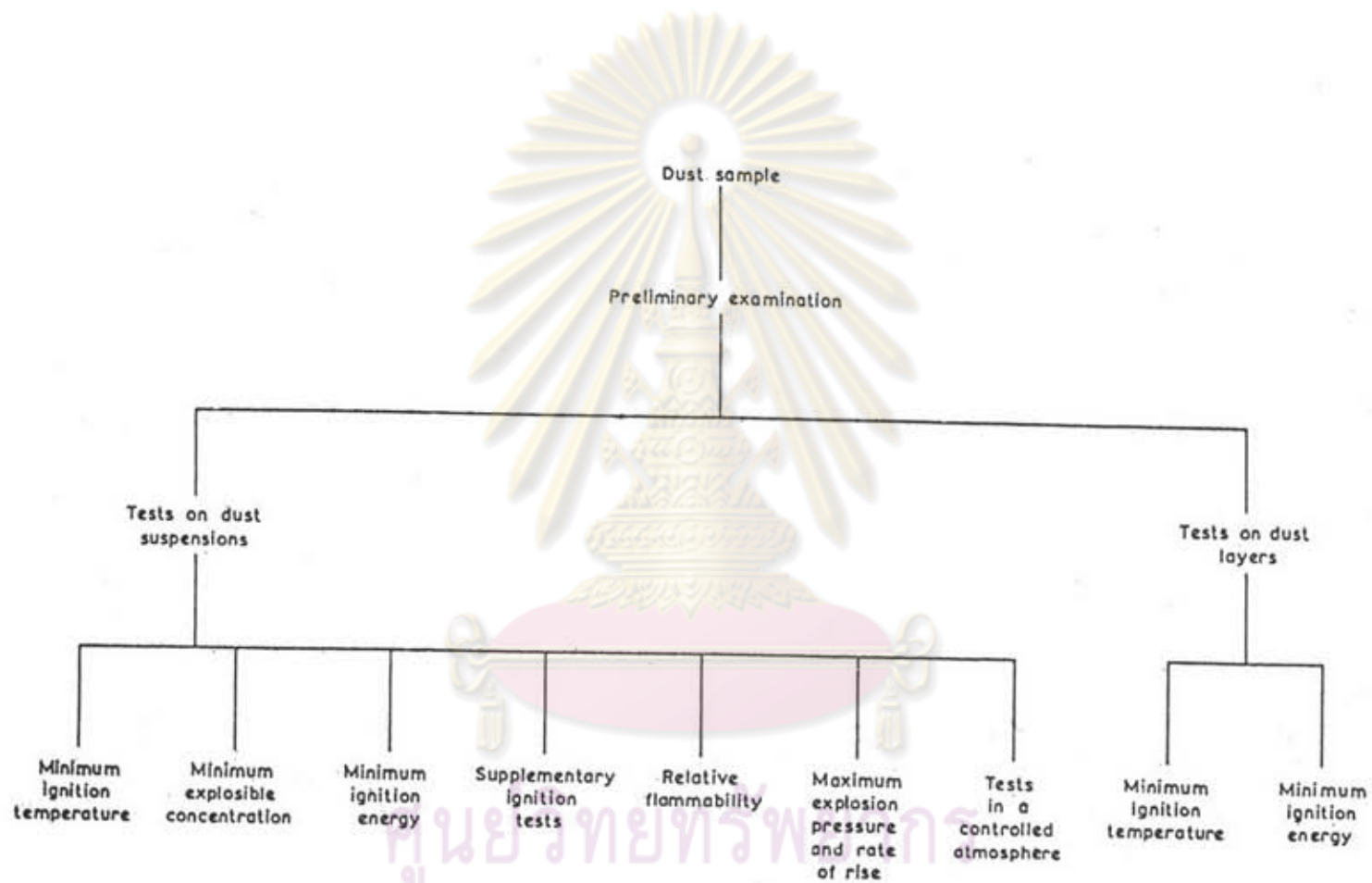


Figure 3.28 Basic scheme of tests in the United State (Palmer, 1973)

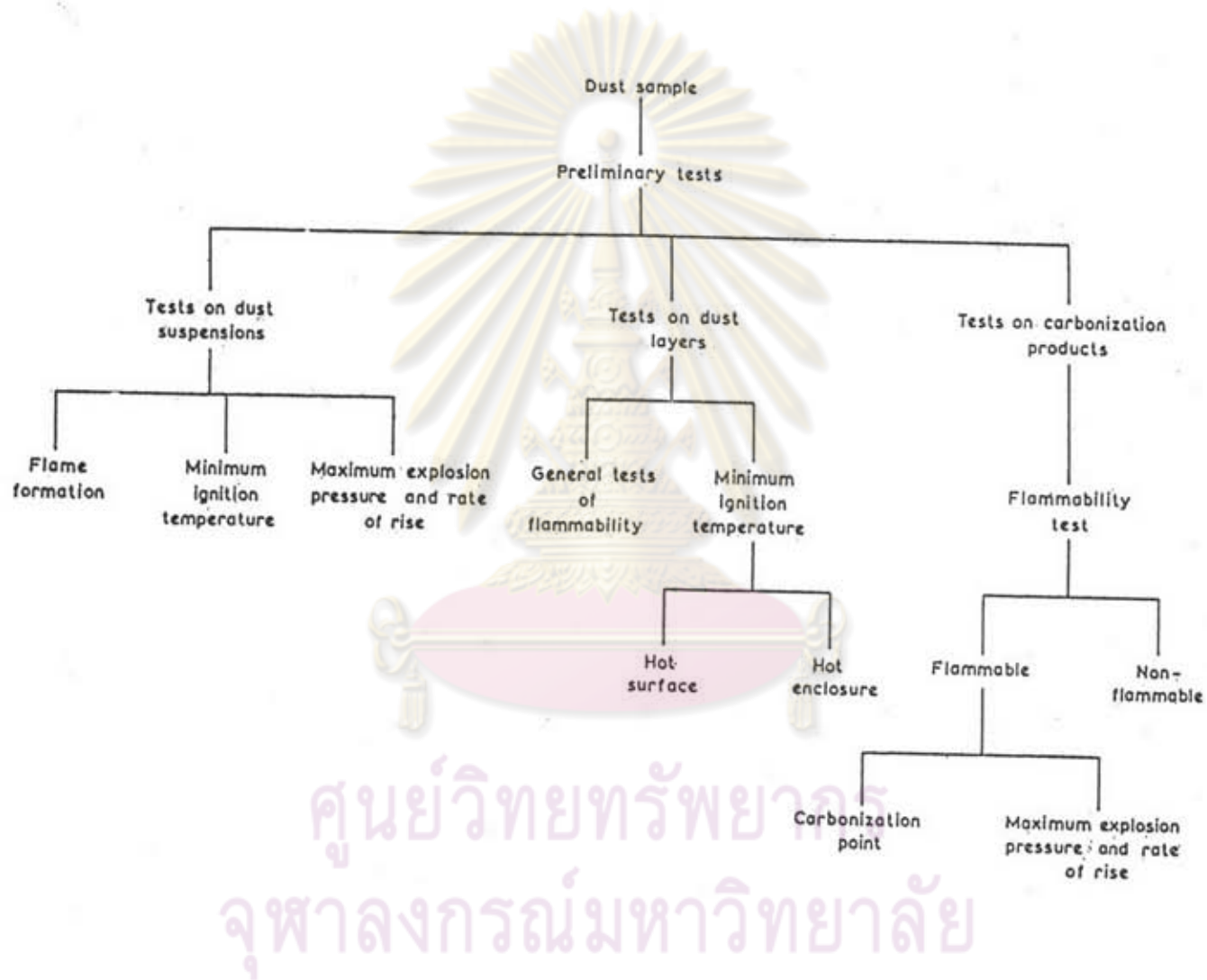


Figure 3.29 Basic scheme of tests in the Federal German Republic (Palmer, 1973)