DUST EXPLOSIONS

in the Process Industries

THIRD EDITION

ROLF K. ECKHOFF

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With deep gratitude for their love and support, I dedicate this book to my wife Astrid and our children Kristian, Ragnar, Solveig, and Jorunn, and their families, and to my mother and the memory of my father. The words in Isaiah 42.16 also gave me hope and courage.

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Foreword

Experience has shown all too clearly that ignition and explosion can occur wherever combustible dusts are handled or permitted to accumulate as a by-product of related activities. Despite reasonable precautions, accidents can and do happen; recognition of this universal hazard and the potential means for its control is widespread, as evidenced by the many individuals and groups worldwide performing research and developing codes and regulations.

The primary means of controlling and minimizing this recognized hazard are study, regulation, and education; to accomplish this, specific knowledge must be generated and disseminated for the benefit of all interested people. Rolf Eckhoff has, in my estimation, prepared an outstanding book. It presents a detailed and comprehensive critique of all the significant phases relating to the hazard and control of a dust explosion and offers an up-to-date evaluation of prevalent activities, testing methods, design measures, and safe operating techniques.

The author is in an outstanding position to write this text, having spent a lifetime in research on dust and gas explosions. He assimilates information from worldwide contacts while retaining his independence of thought and the ability to see clearly through problems. His clear and concise language and thorough approach will benefit his fellow workers and all who read his book. His presentation of the mathematics, tables, and figures is clear and striking. The inclusion of a comprehensive bibliography indicates not only his own thoroughness but also the widespread nature of research into dust explosions throughout the world.

To my knowledge this book is the most complete compilation to date of the state of the art on industrial dust explosions.

John Nagy, Finleyville, PA
(Formerly of the U.S. Bureau of Mines)

Prefaces

PREFACE TO THIRD EDITION

As with the second edition, I have not revised the entire book, which, although desirable, would have been an impossible task for me to undertake. However, the entire original body of the book (Chapters 1–7) had, for various reasons, to be reproduced for this new edition. This has given me the opportunity, when reading through the new production, to make minor adjustments in the original text, where this was considered necessary in the light of more recent evidence.

The major revision has been limited to the final review chapter of the second edition, which has been expanded and rewritten to cover the whole span 1990–2002. Nearly 400 new literature references have been added. I am indebted to all the colleagues, over the whole world, who have kindly provided reprints and reports of their valuable work.

An entirely new chapter on electrical equipment for areas containing explosible dusts has been added to the book. I became acquainted with this special field over the last 12 years and gradually realized that a chapter devoted to this topic would be useful. I am greatly indebted to Thore Andersen, secretary of the Norwegian national Ex committee, NK 31, for many valuable discussions, help with retrieving printed information, proofreading the new chapter, and arranging for me to take part in some of the meetings of the IEC working group 31H WG3. Sincere thanks are due also to Dr. Gerold Klotz-Engmann, Endress + Hauser, Germany, for valuable advice and help during the preparation of the section on intrinsic safety.

My special thanks goes to my outstanding research student Trygve Skjold, for numerous stimulating discussions and bringing to my attention many important papers. He also kindly proofread both Chapters 8 and 9.

In the original part of the book, the adjective *explosible* is used both in connection with *dust* and *dust cloud*, hence *explosible dust* and *explosible dust cloud*. In the new Chapters 8 and 9, I distinguish between *explosible dust* and *explosive dust clouds*. The reasoning is that a combustible dust as such is only potentially explosive, whereas a dust cloud that can propagate a flame is *explosive* in the same sense as a premixed gas cloud.

PREFACE TO SECOND EDITION

The present book was first published in August 1991 as a hardcover version, which was out of print by spring 1994. The publisher then decided to produce a new paperback version, which was essentially the original book with some minor adjustments. This second version was out of print by mid-1996.

In 1992 I was asked to give a review lecture on the state of the art of research on dust explosion prevention and mitigation, at an international summer school. This provided an opportunity to pick up from where I had to stop reviewing the most recent literature for inclusion in the original book manuscript. The summer school was repeated both in 1993 and 1994, which encouraged me to update the review accordingly. It gradually came clear to me that the review would only need to be modified slightly to form a useful new Chapter 8 of my book. The publisher agreed to this idea and decided that such a chapter, covering material published after 1990, be included in the second addition of the book to appear in 1996/1997. I therefore continued to incorporate new material right up to the submission of the final manuscript.

After having worked for more than 30 years at CMR (CMI up to 1992), performing contract research and consultancy work for industry, I started, from 1996, a new challenging career as a full-time professor in process safety technology at the University of Bergen. It is my hope that my students will find the present book, with the new Chapter 8, a helpful guide into one of the important facets of process safety.

PREFACE TO FIRST EDITION

The ambitious objective of this book is to provide an overview of the present state of the art. However, the amount of published information on dust explosions worldwide is vast, and a substantial amount of additional work was never printed in retrievable literature. While I feel that I may have been able to cover some of the English/American and German open literature fairly well, most of the valuable research published in other languages had to be left out simply because of the language barrier.

Although I have tried to give a reasonably balanced account, the book also reflects my personal research background. To me the important role of powder mechanics in understanding dust explosions is evident. I have, therefore, included a separate chapter on the mechanics of dust particles and dust deposits. The book also reflects that most of my dust explosion research has been related to ignition, venting, and testing.

The confrontation with the early research carried out by the pioneers in the United Kingdom, Germany, United States, and other countries creates deep humility and admiration for the outstanding work performed by these people. Lack of sophisticated diagnostics did not prevent them from penetrating the logical structures of the problems and to draw long-lasting conclusions from their observations. It is a pity that much of this work seems to be forgotten in more recent research. Too often humankind "reinvents the wheel." This also applies to dust explosion research.

I am indebted to professor emeritus H. E. Rose for bringing the existence of the phenomenon of dust explosions to my attention for the first time and for giving me the opportunity to become acquainted with the subject, during my two years of post-graduate studies at King's College, London, 1966–1968.

I am also indebted to Mr. Alv Astad and Mr. Helge Aas for their encouragement and active participation when dust explosion research, sponsored by Norwegian industry, was initiated at Chr. Michelsen Institute, Bergen, Norway, about 1970.

The Royal Norwegian Council for Scientific and Industrial Research (NTNF) has given valuable financial support to CMI's dust (and gas) explosion research from 1972 until today, and also allocated a generous special grant for the writing of their book. An additional valuable grant for the work with the book was given by the Swedish Fire Research Board (Brandforsk).

I am also most grateful to all the industrial companies, research institutions, and colleagues in many countries, who made available to me and allowed me to make use of their photographs and other illustrations. A special thanks to Berufsgenossenschaftliches Institut für Arbeitssicherheit (BIA), in Germany, for permission to translate and publish the tables in the Appendix.

I also wish to express my gratitude to those who have kindly read through sections of the draft manuscript and/or given constructive criticism and advice: John Nagy, Derek Bradley, Geoffrey Lunn, Bjørn Hjertager, Gisle Enstad, Dag Bjerketvedt, Ivar Ø. Sand and Claus Donat should be mentioned specifically.

Also my indebtedness goes to Chr. Michelsen Institute, Department of Science and Technology, with its director Dr. Jan A. Andersen, which in its spirit of intellectual freedom coupled with responsibility, offered me the opportunity to establish dust explosion research as an explicit activity of CMI. The institute also gave high priority to and allocated additional resources for the writing of this book, for which I am also most grateful.

This short Preface does not allow me to mention all the good people with whom I had the privilege to work during my 20 years of dust explosion research at CMI and who deserve my sincere thanks. The exception is Kjell Fuhre, who worked with me from 1970 to 1988. I wish to thank him specially for having devoted his exceptional engineering talent to our experimental dust and gas explosion research, in laboratory scale as well as in full-size industrial equipment.

Finally, I wish to express a special thanks to Mrs. Aaslaug Mikalsen, who, aided by more than 20 years' experience in interpreting my handwriting, was able to transform the untidy handwritten manuscript to a most presentable format on CMI's word-processing system. Many thanks also go to Mr. Per-Gunnar Lunde, CMI, for having traced the majority of the drawings in the book.

Rolf K. Eckhoff

Dust Explosions in the Process Industries

Chapter 1

Dust Explosions—Origin, Propagation, Prevention, and Mitigation: An Overview

1.1
THE NATURE OF DUST EXPLOSIONS

1.1.1
THE PHENOMENON

1.1.1.1
What Is an Explosion?

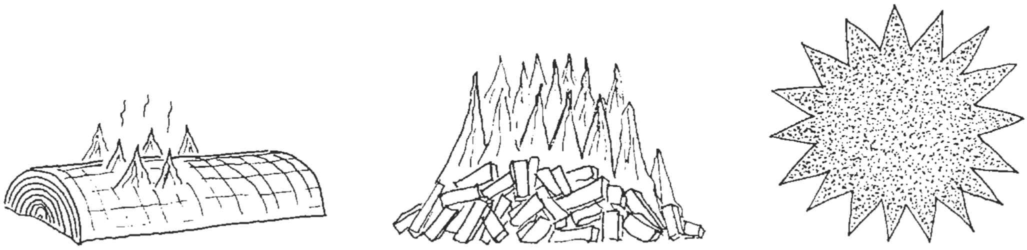
The concept of explosion is not unambiguous. Encyclopedias give varying definitions that mainly fall in two categories. The first focuses on the noise or "bang" due to the sudden release of a strong pressure wave, or blast wave. The origin of this pressure wave, whether a chemical or mechanical energy release, is of secondary concern. This definition of an explosion is in accordance with the basic meaning of the word ("sudden outburst").

The second category of definitions is confined to explosions caused by the sudden release of chemical energy. This includes explosions of gases and dusts and solid explosives. The emphasis is then often put on the chemical energy release itself, and *explosion* is defined accordingly. One possible definition could then be "An explosion is an exothermal chemical process that, when occurring at constant volume, gives rise to a sudden and significant pressure rise."

In this text, the definition of an explosion shifts pragmatically between the two alternatives, focusing on either cause or effect, depending on the context.

1.1.1.2
What Is a Dust Explosion?

The phenomenon named *dust explosions* is in fact quite simple and easy to envisage in terms of daily life experience. Any solid material that can burn in air will do so with a violence and speed that increases with increasing degree of subdivision of the material. Figure 1.1(a) illustrates how a piece of wood, once ignited, burns slowly, releasing its heat over a long period of time. When cut in small pieces, as illustrated in Figure 1.1(b), the combustion rate increases, because the total contact surface area between wood and air has increased. Also, ignition of the wood has become easier. If the subdivision is continued right down to the level of small particles of sizes on the order of 0.1 mm or less and the particles are suspended in a sufficiently large volume of air to give each particle



(a) SLOW COMBUSTION (b) FAST COMBUSTION (c) EXPLOSION

Figure 1.1 *Illustration of how the combustion rate of a given mass of combustible solid increases with increasing subdivision.*

enough space for its unrestricted burning, the combustion rate is very fast and the energy required for ignition very small. Such a burning dust cloud is a dust explosion. In general, the dust cloud is easier to ignite and burn more violently the smaller the dust particles are, down to some limiting particle size that depends on the type of dust material. If such an explosive combustion of a dust cloud takes place inside process equipment or work rooms, the pressure in the fully or partly enclosed explosion space may rise rapidly; the process equipment or building may burst; and life, limb, and property can be lost.

1.1.1.3

Specific Surface Area—A Convenient Measure of Dust Fineness

The degree of subdivision of the solid can be expressed in terms of either a characteristic particle size or the total surface area per unit volume or unit mass of the solid. The latter characteristic is called the *specific surface area* of the subdivided solid.

Figure 1.2 illustrates the relationship between the particle size and the specific surface area. After subdivision of the original cube to the left into eight cubes of half the linear dimension of the original cube, the total surface area has increased by a factor of 2, which indicates that the specific surface area is simply proportional to the reciprocal of the linear dimension of the cube. This can be confirmed by simply expressing the specific surface area S as the ratio between surface area and volume of one single cube of edge length x. One then finds

$$S = \frac{6x^2}{x^3} = \frac{6}{x} \tag{1.1}$$

This is also the specific surface area of a powder or dust consisting of monosized cubes of edge length x.

The same result applies to spheres of diameter x, because

$$S = \frac{\pi x^2}{(\pi / 6)x^3} = \frac{6}{x} \tag{1.2}$$

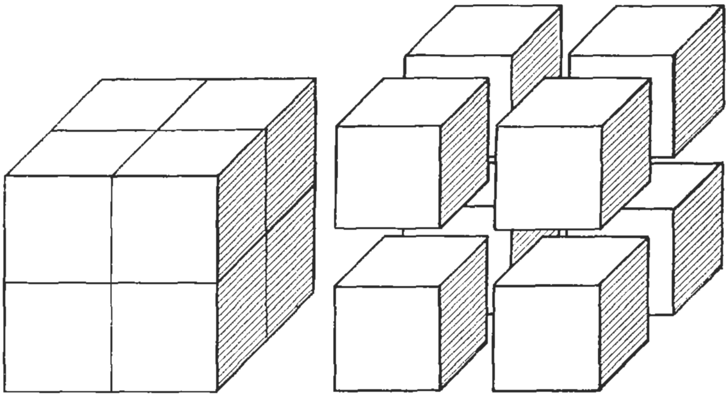


Figure 1.2 *Illustration of the increase of the specific area of a solid with increasing subdivision (From Hammond and Kaye, 1963).*

For flake-shaped particles, for which the thickness x is much smaller than the characteristic flake diameter, one has

$$S = \frac{2}{x} \tag{1.3}$$

If a spherical particle of diameter 5 μm, for example, is compressed and deformed plastically to a thin flake of thickness, for example, 0.2 μm (flake diameter about 20 μm), equations (1.2) and (1.3) show that the specific surface area increases by a factor of 8.3. This effect is utilized when producing highly reactive aluminum flakes from atomized (spherical) aluminum particles (see Section 1.3.2).

If the "particles" are fibers of large length-to-diameter ratio and the diameter is x, one gets

$$S = \frac{4}{x} \tag{1.4}$$

Fibrous dusts may either be natural (for example, cellulose) or synthetic (such as flock materials). Ignitability and explosibility of synthetic flock materials were discussed by Schenk (1984).

In the case of polysized cubes or spheres, the specific surface area equals

$$S = 6\Sigma x_i^2 n_i / \Sigma x_i^3 n_i \tag{1.5}$$

where n_i is the number of particles in the size category x_i in the sample considered.

As the particles get smaller, the interparticle forces play an increasingly important role compared with gravity forces; and in a given practical situation, the dust in a dust cloud may not necessarily be dispersed into the small individual primary particles but rather into larger agglomerates, or lumps. The effective particle size therefore is larger and the effective specific surface area smaller than if the primary particles had been completely dispersed. This important aspect is discussed in Section 1.3.3 and in depth in Chapter 3, see also Section 7.4.2.

1.1.1.4
Factors Influencing Ignition Sensitivity and Explosion Violence of Dust Clouds

Particle size/specific surface area of the dust is a central factor. However, there are other important factors too, and the comprehensive list may look as follows:

1. Chemical composition of the dust, including its moisture content.
2. Chemical composition and initial pressure and temperature of the gas phase.
3. Distributions of particle sizes and shapes in the dust, determining the specific surface area of the dust in the fully dispersed state.
4. Degree of dispersion, or agglomeration, of dust particles, determining the effective specific surface area available to the combustion process in the dust cloud in an actual industrial situation.
5. Distribution of dust concentration in an actual cloud.
6. Distribution of initial turbulence in an actual cloud.
7. Possibility of generation of explosion-induced turbulence in the still unburned part of the cloud. (Location of ignition source important parameter.)
8. Possibility of flame front distortion by mechanisms other than turbulence.
9. Possibility of significant radiative heat transfer (highly dependent on flame temperature, which in turn depends on particle chemistry).

Factors 3 and 4 have already been mentioned. These and other factors are discussed in more detail in the subsequent sections. Factors 1, 2, 3, and 9 can be regarded as basic parameters of the explosible dust cloud. Factors 4 to 8 are, however, influenced by the actual industrial dust cloud generation process and explosion development. These, in turn, depend on the nature of the industrial process (flow rates, etc.) and geometry of the system in which the dust cloud burns. The location of the ignition point is another parameter that can play an important role in deciding the course of the explosion.

In view of the wide spectrum of dust cloud concentrations, degrees of dust dispersion and turbulence, and locations of potential ignition sources in industry, a correspondingly wide spectrum of possible dust cloud ignition sensitivities and combustion rates must be expected.

This complex reality of the process industry is also shared by laboratory experimentation and represents a constant challenge in the design of adequate experiments and interpretation of experimental results.

1.1.1.5
Previous Books on the Dust Explosion Problem

Over the years, several textbooks on the dust explosion hazard have been produced. One of the first ones, by Beyersdorfer (1925), was published in Germany; he mentioned that his motivation for writing the book arose from three questions. The first, asked by most people, was, "Are dust explosions really existing?" The second question, asked by the plant engineer, was, "Why are we having so many dust explosions?" The final question was asked by the researcher, "Why are we not having many more dust explosions?" Although out of date on some points, Beyersdorfer's pioneering book is still fascinating reading.

Almost half a century elapsed from the publication of Beyersdorfer's text until the next comprehensive book on dust explosions appeared. It should be mentioned though, that in the meantime some valuable summaries were published as parts of other books or as reports. Examples are the reports by Verein deutscher Ingenieure (1957) and Brown and James (1962) and the sections on dust explosions in the handbook on room explosions in general, edited by Freytag (1965). In his book on hazards due to static electricity, Haase (1972) paid attention to the dust explosion problem as well. However, Palmer (1973a) produced the long-desired updated, comprehensive account of work in the Western world up to about 1970. In Eastern Europe, a book on the prevention of accidental dust explosions, edited by Nedin (1971), was issued in the USSR two years earlier. Cybulski's comprehensive account of coal dust explosions appeared in Polish in 1973, that is, simultaneously with the publication of Palmer's book, and the English translation came two years later (Cybulski, 1975). In the Federal Republic of Germany, Bartknecht had conducted extensive research and testing related to dust explosions in coal mines as well as in the chemical process industries. This work was summarized in a book (Bartknecht, 1978), which was subsequently translated to English. The book by Bodurtha (1980) on industrial explosion prevention and protection also contains a chapter on dust explosions.

Two years later, two further books were published, one by Field (1982a) and one by Cross and Farrer (1982), each quite comprehensive but emphasizing different aspects of the dust explosion problem. In the next year, a book by Nagy and Verakis (1983) was published, in which they summarized and analyzed some of the extensive experimental and theoretical work conducted by the U.S. Bureau of Mines up to 1980 on the initiation, propagation, and venting of dust explosions. Three years later, a book by Korol'chenko (1986) was issued in the USSR, reviewing work on dust explosions published in both the West and Eastern Europe. The next year, Bartknecht's (1987) second book was published, describing his extensive, more recent research and testing, at Ciba-Geigy AG, related to dust explosion problems. The Institution of Chemical Engineers in the United Kingdom published a useful series of booklets reviewing the status of various aspects of the dust explosion problem (Lunn, 1984, 1988; Schofield, 1984; and Schofield and Abbott, 1988). The comprehensive book by Glor (1988) on electrostatic hazards in powder handling should also be specifically mentioned at this point. Valuable information on the same subject is also included in the book by Lüttgens and Glor (1989).

The proceedings of the international symposium on dust explosions, in Shenyang, Peoples Republic of China, published by North East University of Technology (1987), contains survey papers and special contributions from researchers from both Asia, America, and Europe. EuropEx (1990) produced a collection of references to publications related to accidental explosions in general, including dust explosions. The collection is updated at intervals and contains references to standards, guidelines, and directives as well as to books and papers. Finally, attention is drawn to the proceedings of three conferences on dust explosions, in Nürnberg, published by the Verein deutscher Ingenieure (VDI) in 1978, 1984, and 1989 (listed under the publisher's name in the References). Section 9.1.2 in Chapter 9 reviews books and conference proceedings published after 1990.

1.1.2
MATERIALS THAT CAN CAUSE DUST EXPLOSIONS

Dust explosions generally arise from rapid release of heat due to the chemical reaction

$$\text{Fuel} + \text{oxygen} \rightarrow \text{oxides} + \text{heat} \qquad (1.6)$$

In some special cases, metal dusts can also react exothermally with nitrogen or carbon dioxide, but most often oxidation by oxygen is the heat-generating process in a dust explosion. This means that only materials not already stable oxides can give rise to dust explosions. This excludes substances such as silicates, sulphates, nitrates, carbonates, and phosphates and therefore dust clouds of Portland cement, sand, limestone, and the like cannot produce dust explosions.

The materials that can cause dust explosions include

- Natural organic materials (grain, linen, sugar, etc.).
- Synthetic organic materials (plastics, organic pigments, pesticides, etc.).
- Coal and peat.
- Metals (aluminum, magnesium, zinc, iron, etc.).

The heat of combustion of the material is an important parameter, because it determines the amount of heat that can be liberated in the explosion. However, when comparing the various materials in terms of their potential hazard, it is useful to relate the heat of combustion to the amount of oxygen consumed. This is because the gas in a given volume of dust cloud contains a limited amount of oxygen, which determines how much heat can be released in an explosion per unit volume of dust cloud. Table 1.1 lists the heat of combustion of various substances, per mole of oxygen consumed. Ca and Mg top the list, with Al closely behind. Si is also fairly high up on the list, with a heat of combustion per mole of oxygen about twice the value of typical natural and synthetic organic substances and coals. Table 1.1 is in accordance with the experience that the temperatures of flames of dust of metals like Al and Si are very high compared with those of flames of organic dust and coal.

Table 1.1 Heats of combustion (oxidation) of various substances per mole O_2 consumed

Substance	Oxidation product (s)	KJ/mole O_2
Ca	CaO	1270
Mg	MgO	1240
Al	Al_2O_3	1100
Si	SiO_2	830
Cr	Cr_2O_3	750
Zn	ZnO	700
Fe	Fe_2O_3	530
Cu	CuO	300
Sucrose	CO_2 and H_2O	470
Starch	CO_2 and H_2O	470
Polyethylene	CO_2 and H_2O	390
Carbon	CO_2	400
Coal	CO_2 and H_2O	400
Sulphur	SO_2	300

The equation of state for ideal gases describes the mutual interdependence of the various parameters influencing the explosion pressure:

$$P = \frac{TnR}{V} \tag{1.7}$$

Here P is the pressure of the gas, T its temperature, V the volume in question, n the number of gas molecules in this volume, and R the universal gas constant. For constant volume, P is proportional to T and n. Normally, the increase of T due to the heat developed in the burning dust cloud has the deciding influence on P, whereas the change in n plays only a minor role.

Combustion of metal dust can cause the maximum possible relative reduction of n, by consuming all the oxygen in the formation of condensed metal oxides. If the gas is air and all the oxygen is consumed and all the nitrogen is left, n is reduced by about 20%.

In the case of organic dust and coal, assuming that CO_2 (gas) and H_2O (gas) are the reaction products, the number of gas molecules per unit mass of dust cloud increases somewhat during combustion. This is because two H_2O molecules are generated per O_2 molecule consumed. Furthermore, in organic substances containing oxygen, some H_2O and CO_2 are generated by decomposition of the solid material itself, without a supply of oxygen from the air.

Consider as an example a starch of composition $(C_6H_{10}O_5)_x$ suspended in air at the dust concentration that just consumes all the oxygen in the air to be completely transformed to CO_2 and H_2O (= stoichiometric concentration); 1 m^3 of air at normal ambient conditions contains about 8.7 moles of O_2 and 32.9 moles of N_2. When the starch is oxidized, all the O_2 is spent on transforming the carbon to CO_2, whereas the hydrogen and the oxygen in the starch are in just the right proportions to form H_2O by themselves. The 8.7 moles of O_2 is then capable of oxidizing $8.7/6 = 1.45$ moles of $(C_6H_{10}O_5)$, that is, about 235 g, which is the stoichiometric dust mass per m^3 of air at normal conditions. The reaction products then are 8.7 moles of CO_2 and 7.3 moles of H_2O. The total number of 41.6 moles of gas in the original 1 m^3 of dust cloud has therefore been transformed to 48.9 moles, that is, an increase by 17.5%. In an explosion, this contributes to increasing the adiabatic constant-volume explosion pressure correspondingly.

It must be emphasized, however, that this formal consideration is not fully valid if the combustion of the organic particles also results in the formation of CO and char particles. This is discussed in greater detail in Chapter 4.

1.1.3

EXPLOSIBLE RANGE OF DUST CONCENTRATIONS—PRIMARY AND SECONDARY EXPLOSIONS

The explosive combustion of dust clouds, illustrated in Figure 1.1(c), cannot take place unless the dust concentration (i.e., the mass of dust per unit volume of dust clouds) is within certain limits. This is analogous to combustion of homogeneous mixtures of gaseous fuels and air, for which the upper and lower flammability limits are well established. Figure 1.3 shows the explosible range for a typical natural organic material, such as corn starch, in air at normal temperature and atmospheric pressure.

The explosible range is quite narrow, extending over less than two orders of magnitude, from 50–100 g/m^3 on the lean side to 2–3 kg/m^3 on the rich one. As discussed in greater detail in Chapter 4, the explosibility limits differ somewhat for the various dust materials. For example, zinc powder has a minimum explosible concentration in air of about 500 g/m^3. Explosible dust clouds have a high optical density, even at the lower

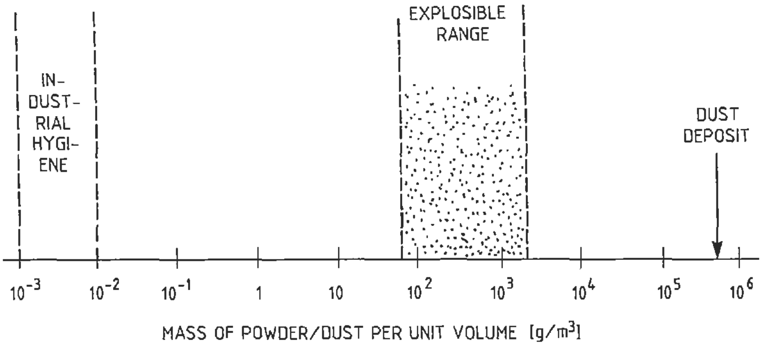


Figure 1.3 *The range of explosible dust concentrations in air at normal temperature and atmospheric pressure for a typical natural organic dust (corn starch), compared with typical range of maximum permissible dust concentrations in the context of industrial hygiene, and a typical density of deposits of natural organic dusts. (Note that self-sustained flame propagation may also occur in such deposits.)*

explosible limit. This is illustrated by the fact that the range of maximum permissible dust concentrations specified in the context of industrial hygiene in working atmospheres are three to four orders of magnitude lower than minimum explosible dust concentrations. This means that the unpleasant dust concentration levels that can sometimes occur in the general working atmosphere of a factory, and calls on the attention of industrial hygiene authorities, are far below the concentration levels that can propagate dust flames. Therefore, the minimum explosible concentration corresponds to dust clouds of high optical densities, which are unlikely to occur regularly in work rooms of factories.

A visual impression of the density of explosible dust clouds is provided in Figure 1.4, which illustrates a cubical arrangement of cubical particles.

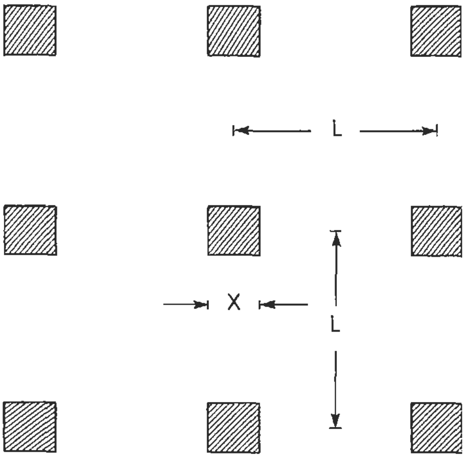


Figure 1.4 *Cubical dust particles of edge x arranged in a cubical pattern, with interparticle center-to-center distances of L.*

On average, there is one cubical particle of volume x^3 per cube of dust cloud of volume L^3. If the particle density is ρ_p, the dust concentration equals

$$c = \rho_p(x/L)^3 \tag{1.8}$$

or, in a rearranged form,

$$L/x = (\rho_p/c)^{1/3} \tag{1.9}$$

For particles of density 1 g/cm^3, that is, 10^6 g/m^3, a dust concentration of 50 g/m^3 corresponds to $L/x = 27$. For 500 g/m^3, which is a typical worst-case explosible concentration, $L/x = 13$. The actual density shown in Figure 1.4, of $L/x = 4$, corresponds to a very high dust concentration, 16 kg/m^3, which is well above the maximum explosible concentration for organic dust (2–3 kg/m^3).

It is important to note that the absolute interparticle distance corresponding to a given dust concentration decreases proportionally with the particle size. For example, at a dust concentration of 500 g/m^3 and a particle density of 1 g/cm^3, L equals 1.3 mm for 100 μm particles, whereas it is only 13 μm for 1 μm particles.

Zehr (1965) quoted a rule of thumb by Intelmann, saying that, if a glowing 25-W lightbulb is observed through 2 m of dust cloud, the bulb cannot be seen at dust concentrations exceeding 40 g/m^3. This is illustrated in Figure 1.5. It follows from this that the dust clouds in which dust explosions are primarily initiated are normally found inside process equipment, such as mills, mixers, screens, dryers, cyclones, filters, bucket elevators, hoppers, silos, aspiration ducts, and pipes for pneumatic transport of powders. Such explosions, initiated by some ignition source (see Section 1.1.4) are called *primary explosions*.

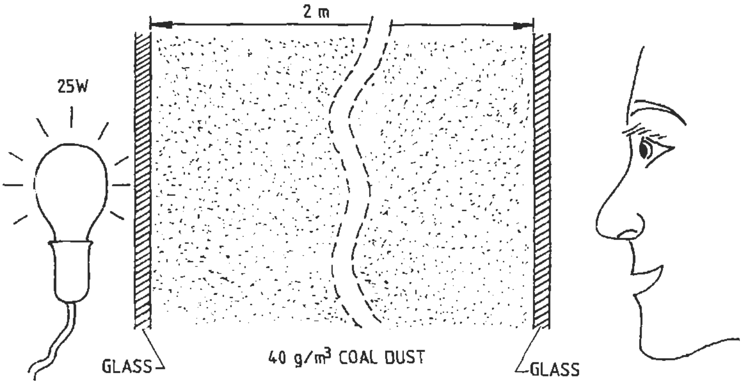


Figure 1.5 *A cloud of 40 g/m^3 of coal dust in air is so dense that a glowing 25-W lightbulb can hardly be seen through a dust of cloud 2 m thick.*

This reveals an important difference between primary dust and gas explosions. In the case of gases, the process equipment normally contains fuel only, with no air, and under such circumstances, gas explosions inside process equipment are impossible. Therefore, most primary gas explosions occur outside process equipment, where gas from accidental leaks is mixed with air and explosible atmospheres generated.

An important objective of dust explosion control (see Section 1.4) is to limit primary explosions in process equipment to the process units in which they initiate. A central concern is then to avoid *secondary explosions* due to entrainment of dust layers by the blast wave from the primary explosion. Figure 1.3 shows that there is a gap of two orders of magnitude between the maximum explosible dust concentration and the bulk density of dust layers and heaps. The consequence of this is illustrated in Figure 1.6. This figure

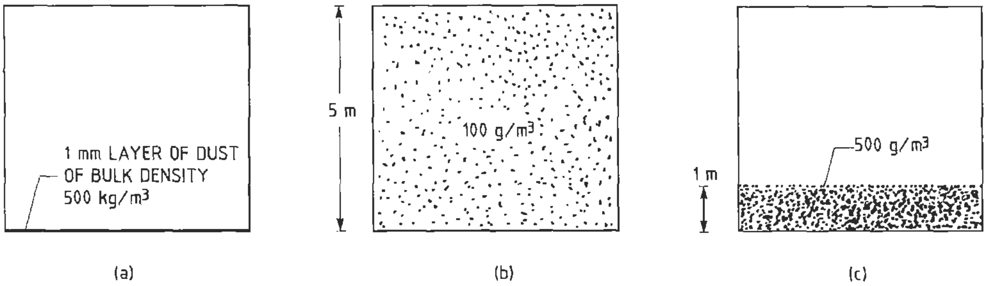


Figure 1.6 *The potential hazard of even thin dust layers. A 1-mm layer of a dust of bulk density 500 kg/m³ (a) generates a cloud of average concentration 100 g/m³ if dispersed in a room of 5 m height (b). Partial dispersion up to only 1 m gives 500 g/m³ (c).*

shows that the simple relationship between the bulk density of the dust layer, ρ_{bulk}; the layer thickness, h; the height, H, of the dust cloud produced from the layer; and the dust concentration, c, is

$$c = \rho_{\text{bulk}} \frac{h}{H} \tag{1.10}$$

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

$$c = \rho_{\text{bulk}} \frac{4h}{D} \tag{1.11}$$

In the case of a tube diameter of 0.2 m, typical of many dust extraction ducts in industry, a layer thickness of only 0.1 mm is sufficient for generating a dust concentration of 1000 g/m³ with a dust of bulk density 500 kg/m³.

In general, dispersible dust layers in process plants represent a potential hazard of extensive secondary dust explosions, which must be reduced to the extent possible. Figure 1.7 illustrates how secondary explosions in workrooms can be generated if preventive precautions are inadequate.

1.1.4
IGNITION SOURCES

1.1.4.1
Background

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

- Smoldering or burning dust.
- Open flames (welding, cutting, matches, etc.).
- Hot surfaces (hot bearings, dryers, heaters, etc.).
- Heat from mechanical impact.
- Electrical discharges and arcs.

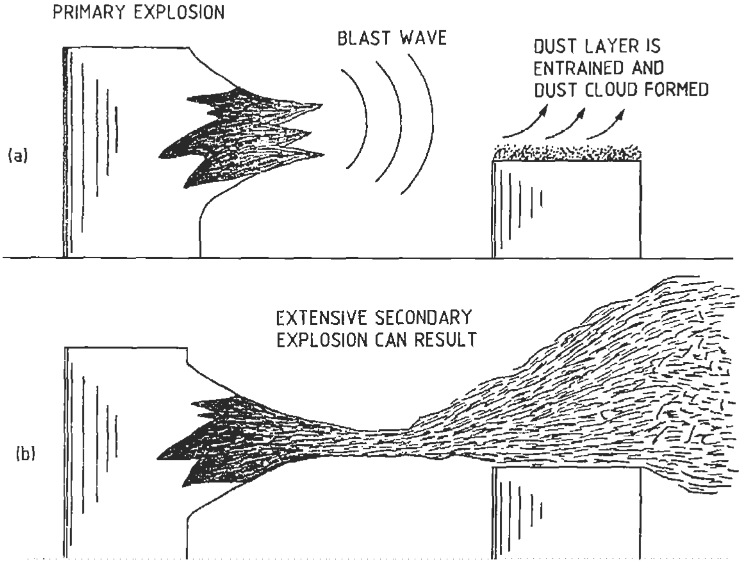


Figure 1.7 *How the blast wave from a primary explosion (a) entrains and disperses a dust layer, which (b) is subsequently ignited by the primary dust flame.*

Some of these sources are discussed more extensively in Chapter 5, and only a brief outline is given here.

There is considerable variation in the ignition sensitivity of various types of dusts. This is discussed in Section 1.3. To quantify the ignition sensitivity of dust clouds and dust deposits when exposed to various kinds of ignition sources, a range of laboratory-scale test methods have been developed, which are described in Chapter 7.

1.1.4.2
Smoldering or Burning Dust

Experience has shown that combustible dust, when deposited in heaps or layers, may under certain circumstances develop internal combustion and high temperatures. This is due to the porous structure of dust deposits, which gives oxygen access to the particle surface throughout the deposit and makes the heat conductivity of the deposit low. Consequently, heat developed due to comparatively slow initial oxidation at moderate temperatures inside the dust deposit may not be conducted into the surroundings sufficiently fast to prevent rising temperature in the reaction zone. As long as oxygen is available, the increased temperature increases the rate of oxidation, and the temperature inside the dust deposit increases even further. Depending on the permeability of the dust deposit and geometrical boundary conditions, the density difference between the hot combustion gases and the air of ambient temperature may create a draft that supplies fresh oxygen to the reaction zone and enhances the combustion process.

If a dust deposit containing such a hot reaction zone, often called a *smoldering nest*, is disturbed and dispersed by an air blast or a mechanical action, the burning dust can easily initiate a dust explosion if brought in contact with a combustible dust cloud. Sometimes, the dust in the deposit that has not yet burned, forms the explosible dust cloud.

The initial oxidation inside the deposit may sometimes be due to the dust or powder being deposited having a higher temperature than planned. However, some natural vegetable materials may develop initial spontaneous combustion even at normal ambient temperatures due to biochemical activity, if the content of fat or moisture is high.

In other cases, the dust deposit or layer rests on a heated surface, which supplies the heat needed to trigger self-ignition in the dust. Such surfaces can be overheated bearings, heaters in workrooms, lightbulbs, walls in dryers, and the like. If the surface is not intended to be covered with dust, the dust deposit may prevent normal cooling by forming an insulating layer. This may give rise to an undesirable temperature rise in the surface, which further increases the probability of ignition of the dust. In general, the minimum temperature of the hot surface for the dust layer to self-ignite decreases with increasing thickness of the dust layer.

Figures 1.8, 1.9, and 1.10 illustrate various ways in which smoldering combustion in dust deposits can initiate dust explosions. The critical conditions for the generation of smoldering nests are discussed in Chapter 5, and test methods assessing the self-heating tendency of various dusts are described in Chapter 7.

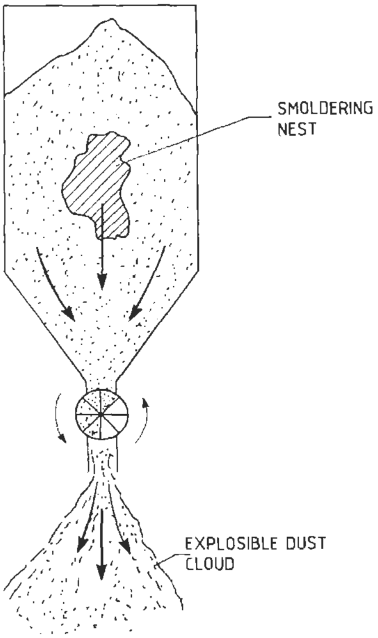


Figure 1.8 *A smoldering nest in a dust or powder deposit in a silo can initiate a dust explosion if the nest is discharged into an explosible dust cloud.*

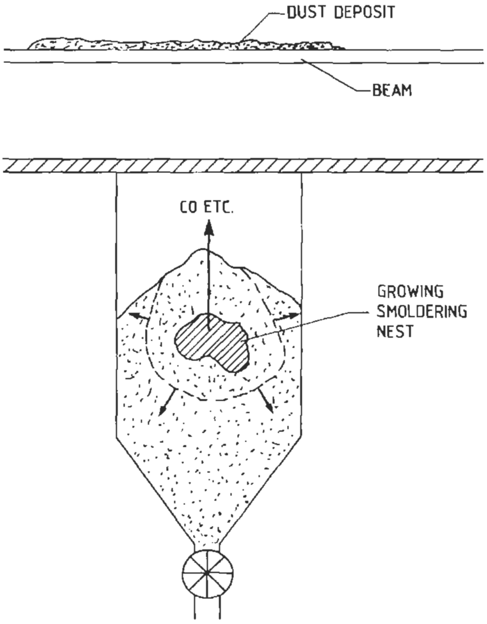


Figure 1.9 *Complex ignition sequence via gas explosion: Due to limited supply of oxygen, the smoldering nest develops CO and other combustible gases and creates an explosible mixture above the dust deposit. When the edge of the smoldering nest penetrates the top surface of the dust deposit, the gas ignites and the gas explosion blows up the silo roof. Dust deposits in the room above the silo are dispersed and a major secondary dust explosion results.*

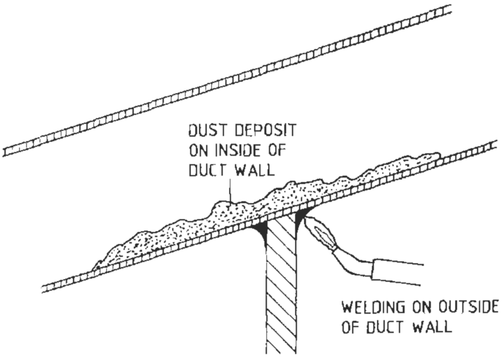


Figure 1.10 *A hidden dust deposit inside a duct can be brought to ignition by heat supplied to the duct wall from the outside.*

It should be mentioned that van Laar (1981) found that burning cigarettes and cigars may give rise to smoldering fires in tapioca and soybean meal. Further information is given in Sections 1.4.2.5, and 9.2.3.3 and 9.3.5.2 in Chapter 9.

1.1.4.3
Open Flames

The flames of welding and cutting burners are sufficiently powerful to initiate explosions in any dust cloud able to propagate a self-sustained flame. The cutting burner flame is particularly hazardous, because it supplies excess oxygen to the working zone. If combustible dusts are dispersed in atmospheres containing more oxygen than in air, both ignition sensitivity and explosion violence increases compared with clouds in air (see Section 1.3.6). All codes and regulations for preventing dust explosions contain strict requirements to the safety precautions that have to be taken when performing hot work in areas containing dust.

Smoking should be prohibited in areas where combustible dusts exist. A burning wooden match develops about 100 J of thermal energy per second. This is more than sufficient for initiating explosions in most combustible dust clouds. Further information is given in Section 1.4.2.3.

1.1.4.4
Hot Surfaces

In addition to igniting dust layers, hot surfaces can initiate dust explosions by direct contact between the dust cloud and the hot surface. However, the minimum hot surface temperatures needed for this are generally considerably higher (typically 400–500°C for organic dusts) than for ignition of dust layers. Further details are given in Section 1.4.2.4, and in Chapters 5, 7, and 9.

1.1.4.5
Heat from Mechanical Impact

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

Friction is a process of fairly long duration whereby objects are rubbed against each other and heat is gradually accumulated. This produces hot surfaces, and in some cases inflammation; for example, when an elevator or conveyor belt is slipping.

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

A practical mechanical impact situation is illustrated in Figure 1.11. A steel bolt accidentally enters the top of a large concrete silo during filling of the silo with corn starch. The bolt falls into the nearly empty silo and hits the concrete wall near the silo bottom at a velocity of 25–30 m/s. Visible sparks are generated. A dense, explosible cloud of corn starch occupies the region where the impact occurs. Is ignition of the cloud probable? This problem is discussed in detail in Chapter 5, but it should be indicated at this point that ignition by simple impact, where steel is the metal component, seems less likely than believed by many in the past. However, if the metal had been titanium or zirconium, ignition could have occurred in this situation.

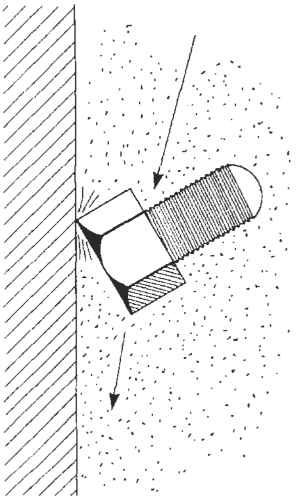


Figure 1.11 *A steel bolt falls into a tall silo for corn and collides with the concrete silo wall at high velocity. Can the steel sparks generated initiate an explosion in the corn starch cloud in the silo?*

The thermite reaction ($2Al + Fe_2O_3 \rightarrow Al_2O_3 + 2Fe + \text{heat}$) is often mentioned as a potential ignition source from impact involving aluminum and rust. However, if a lump of normal soft aluminum collides with a rusty steel surface, a thermite reaction will not necessarily take place. In fact, due to the softness of the aluminum, the result is often just a thin smear of aluminum on top of the rust. However, if this sandwich of aluminum and rust is given a hard blow by a third object, a thermite flash capable of igniting dust clouds can easily be produced. The same applies to a rusty surface that has been painted with aluminum paint, if the pigment content of the paint is comparatively high. (Further information is given in Section 1.4.2.6 and Chapters 5, 7, and 9).

1.1.4.6
Electric Sparks and Arcs: Electrostatic Discharges

It has been known since the beginning of this century that electric sparks and arcs can initiate dust explosions. The minimum spark energy required for ignition varies with the type of dust, the effective particle size distribution in the dust cloud, the dust concentration and turbulence, and the spatial and temporal distribution of the energy in the electric discharge or arc.

It was long thought that the electric spark energies needed for igniting dust clouds in air were generally much higher, by one or two orders of magnitude, than the minimum ignition energies for gases and vapors in air. However, it is now generally accepted that many dusts can be ignited by spark energies in the range 1–10 mJ, that is, close to the range of gases and vapors. Some dusts may ignite at even lower energies.

It may be useful to distinguish between discharges caused by release of accumulated electrostatic charge and sparks or arcs generated when live electric circuits are broken, either accidentally or intentionally (switches). In the latter case, if the points of rupture are separated at high speed, transient inductive sparks are formed across the gap, as illustrated in Figure 1.12. If the current in the circuit prior to rupture is i and the circuit inductance L, the theoretical spark energy, neglecting external circuit losses, will be $^{1}/_{2}\, Li^2$. As an example, a current of 10 A and L equal to $10^{-5}\ H$ gives a theoretical spark energy of 0.5 mJ. This is too low for igniting most dust clouds in air. However, larger currents or inductances can easily produce incendiary sparks. Sometimes, rupture results in only a small gap of permanent distance. This may result in a hazardous stationary arc if the circuit is still live.

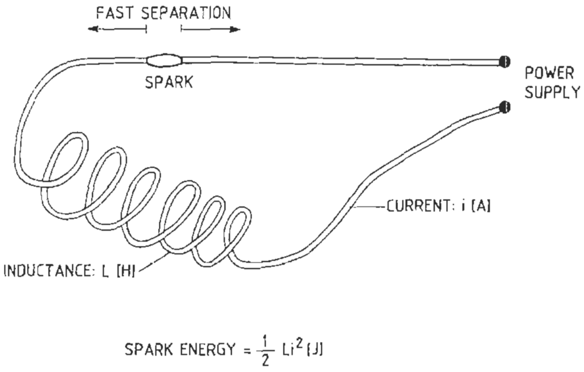


Figure 1.12 *Inductive spark or "break flash" generated when a live electric circuit is suddenly broken and the points of rupture are separated at high speed.*

Over the years, the question of whether electrostatic discharges can initiate dust explosions has been discussed repeatedly. The basic mechanism causing accumulation of electrostatic charges in industrial plants is the transfer of charge between objects during rubbing. This occurs easily during the handling and transport of powders and dusts, where charge is exchanged between the powder or dust and the process equipment. The charge accumulated on process equipment or bulk powder can be released in various ways, depending on the circumstances. Glor (1988) and Lüttgens and Glor (1989) distinguished among six different types of electrostatic discharges:

- Spark discharge.
- Brush discharge.
- Corona discharge.
- Propagating brush discharge.
- Discharge along the surface of the powder or dust in bulk.
- Lightninglike discharge.

The differentiation among the various discharge types is not always straightforward, but Glor's classification has turned out to be very useful when evaluating electrostatic hazards in practice in industry.

Spark discharges and propagating brush discharges are by far the most hazardous types of the six with regard to initiating dust explosions in industry. Spark discharges occur when the charge is accumulated on an electrically conducting, nongrounded, object and discharged to ground across a small air gap. The gap distance must be sufficiently short to allow breakdown and spark channel formation at the actual voltage difference between the charged object and ground. On the other hand, for the spark to become incendiary, the gap distance must be sufficiently long to permit the required voltage difference to build up before breakdown of the gap. The theoretical spark energy, neglecting external circuit losses, equals $\frac{1}{2}CV^2$, where C is the capacitance of the nongrounded, charged process item with respect to ground, and V is the voltage difference. Figure 1.13 illustrates a practical situation that could lead to a dust explosion initiated by an electrostatic spark discharge.

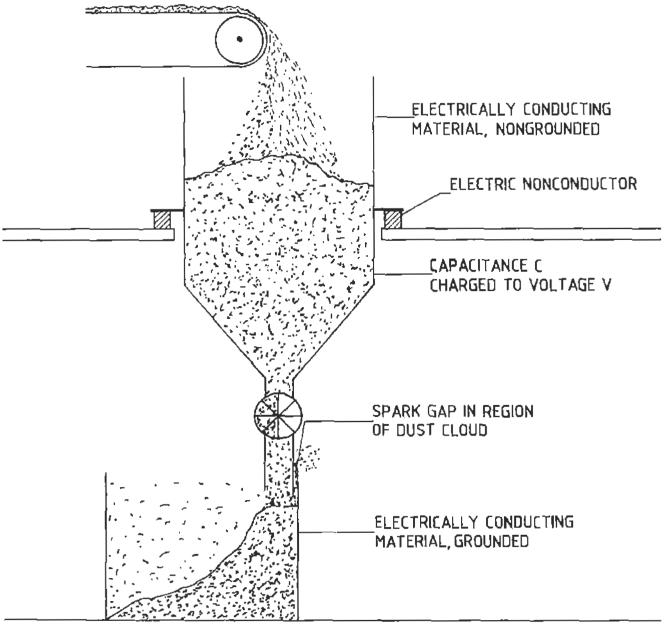


Figure 1.13 *A practical situation that could lead to a dust explosion initiated by an electrostatic spark discharge.*

Table 1.2 Maximum theoretical spark energies $\frac{1}{2}CV^2$ from discharge of various types of electrically conducting objects (typical approximate capacitance values)

Object	Capacitance (pF)	$\frac{1}{2}CV^2$ (mJ) at various voltages		
		10 kV	**20 kv**	**30 kV**
Single screw	1	0.05	0.2	0.45
Flange (100 mm nominal size)	10	0.5	2	4.5
Shovel	20	1	4	9
Small container (bucket, 50 liters drum)	10–100	0.5–5	2–20	4.5–45
Funnel	10–100	0.5–5	2–20	4.5–45
Drum (~200 liters)	100–300	5–15	20–60	45–135
Person	100–300	5–15	20–60	45–135
Major plant items (large containers, reaction vessels)	100–1000	5–50	20–200	45–450
Road tanker	1000	50	200	450

Source: Glor, 1988.

Glor (1988) has given some typical approximate capacitance-to-ground values for objects encountered in the process industry. These have been incorporated in Table 1.2 and used for estimating the maximum theoretical spark energy $\frac{1}{2}CV^2$ when discharging an object of capacitance C at a voltage V to ground.

Minimum electric spark energies (MIE) for ignition of dust clouds vary, as already mentioned, with dust type, particle size, and so forth, but many dusts have MIE values well below the higher $\frac{1}{2}CV^2$ values in Table 1.2. However, it may not be appropriate to apply MIE values from standard tests directly to the electrostatic spark problem (see Chapter 5).

Turbulence in the dust cloud raises the effective MIE and therefore provides a safety factor. For example, Yong Fan Yu (1985) was unable to ignite turbulent clouds of wheat grain dust in a container at the exit of a pneumatic transport pipe, even with soft electric sparks of energies on the order of 1 J.

Glor (1988) emphasized that, due to increasing use of nonconducting construction parts in modern industrial plants, the chance of overlooking nongrounded conducting items is high. Therefore, the effort to ensure proper grounding of all conducting parts must be maintained, in particular in plants handling dusts of low MIE. According to Glor (1988) adequate grounding is maintained as long as the leak resistance to ground does not exceed 10^6 Ω for process equipment and 10^8 Ω for personnel. However, in practice, one aims for considerably lower resistances to ground.

Brush discharges occur between a single curved, grounded metal electrode (radius of curvature 5–50 mm) and a charged nonconducting surface (plastic, rubber, dust). Brush discharges can ignite explosible gas mixtures. However, according to Glor (1988), no ignition of a dust cloud in air by a brush discharge has yet been demonstrated, not even in sophisticated laboratory tests using very ignition sensitive dusts. Section 9.2.3.4 in Chapter 9 gives further information. It must be emphasized, however, that this does not apply if the powder or dust contains significant quantities of combustible solvents (see Section 1.3.9).

Corona discharges occur under the same conditions as brush discharges but are associated with grounded electrodes of much smaller radii of curvature, such as sharp edges and needle tips. For this reason, such discharges occur at much lower field strengths than the brush discharges, and the discharge energies therefore are much lower. Consequently, the possibility of igniting dust clouds by corona discharges can be ruled out.

Propagating brush discharges can, however, initiate dust explosions. Such discharges, which normally have much higher energies than ordinary brush discharges, occur if a double layer of charges of opposite polarity is generated across a thin sheet (<8 mm thickness) of a nonconducting material (Glor, 1988). The reason for the high discharge energy is that the opposite charges allow the nonconductor surfaces to accumulate much higher charge densities than if the sheet had been charged on only one of the faces. Glor pointed out that, in principle, close contact of one face of the sheet with ground is not necessary for obtaining a charged double layer. However, in practice, ground on one side is the most common configuration. An example is illustrated in Figure 1.14. Powder is transported pneumatically in a steel pipe with an internal electrically insulating plastic coating. Due to the rubbing of the powder against the plastic, a charge accumulates on the internal face of the plastic coating. The high mobility of the electrons in the steel causes buildup of a corresponding charge of opposite polarity on the outer face of coating in contact with the steel. If a short passage between the two oppositely charged faces of plastic coating is provided, either via a perforation of the coating, due to electrical breakdown, or at the pipe exit, a propagating brush discharge can result.

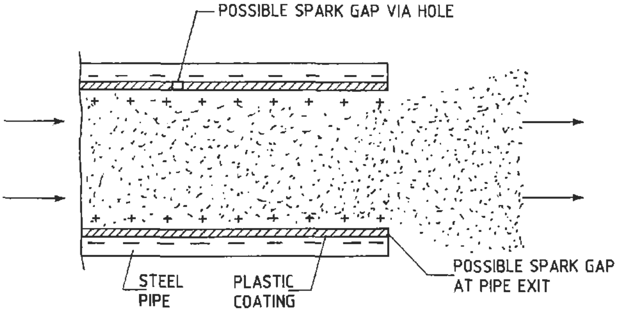


Figure 1.14 *Illustration of practical configuration of pneumatic powder transport that can lead to dust explosions initiated by propagating brush discharges.*

Lüttgens (1985) and Lüttgens and Glor (1989) discussed a dust explosion in the Federal Republic of Germany that was initiated by a propagating brush discharge. Acrylic powder was transported pneumatically in a 50-mm diameter plastic pipe outdoors, and the grounded electrically conducting shield on the outer surface of the pipe was provided by rainwater and snow.

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

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

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

Discharge along the surface of powder or dust in bulk may occur if nonconducting powders are blown or poured into a large container or silo. This is a fifth type of electrostatic discharge. When the charged particles settle in a heap in the container, very high space charge densities may be generated and luminous discharges may propagate along the surface of the powder heap, from its base to its top. However, theoretical calculations by Glor (1985) revealed that, under realistic industrial conditions, only very large particles, of 1–10 mm diameter, are likely to generate spark discharges due to this process. It further seems that very high specific electrical resistivity of the powder is also a requirement ($>10^{10}\ \Omega \cdot \text{m}$), which probably limits this type of discharge to coarse plastic powders and granulates. Because of this large size, the particles generating the discharge are unlikely to cause dust explosions, and therefore a possible explosion hazard must be associated with the simultaneous presence of an explosible cloud of an additional, fine dust fraction. The maximum equivalent spark energy for this type of discharge has been estimated on the order of 10 mJ, but still little is known about the exact nature and incendivity of these discharges. Glor (1988) pointed out that the probability of occurrence of such discharges increases with increasing charge-to-mass ratio in the powder and increasing mass filling rate.

Lightning-type discharge, which may in principle occur within an electrically insulating container with no conductive connection from the interior to the ground, was the last type of discharge mentioned by Glor (1988) and Lüttgens and Glor (1989). However, as Glor stated, there is no evidence that lightning discharges have occurred in dust clouds generated in industrial operations. Thorpe et al. (1985) investigated the hazard of electrostatic ignition of dust clouds inside storage silos in a full-scale pneumatic conveying and storing facility. Sugar was used as test dust. They were able to draw some spark discharges from the charged dust cloud, but these were of low energy and incapable of causing ignition. In fact, these spark discharges were not able to ignite even a propane/air mixture of minimum ignition energy less than 1 mJ.

Figure 1.15 provides an overall comparison of the equivalent energy ranges of the various electrostatic discharges just discussed and typical MIE ranges for gases/vapors and dusts in air. *Equivalent energy*, introduced by Gibson and Lloyd (1965), is defined as the energy of a spark discharge that has the same igniting power as the actual electrostatic discharge.

Further details on the generation and nature of the various types of electrostatic discharges are given by Glor (1988) and Lüttgens and Glor (1989). Some further details concerning electric sparks and their ability to ignite dust clouds are given in Chapter 5.

Appendix 2 gives some MIE values, determined by a standardized method, for various dusts. Further information on ignition of dust clouds by electric sparks and electrostatic discharges is given in Sections 1.4.2.7, and 9.2.3.4 and 9.3.5.4 in Chapter 9.

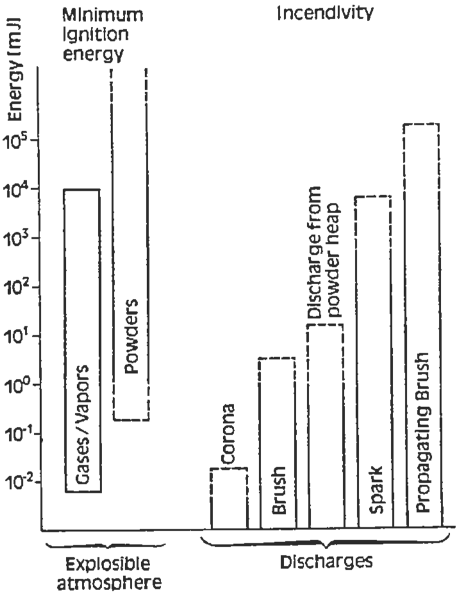


Figure 1.15 *Comparison of ranges of minimum ignition energies of dusts and gases in air, with the equivalent energies of various types of electrostatic discharges. The dotted parts of the columns represent approximate maximum and minimum limit ranges (From Glor, 1988).*

1.2
SIGNIFICANCE OF THE DUST EXPLOSION HAZARD: STATISTICAL RECORDS

1.2.1
RECORDING DUST EXPLOSIONS, AN ACTIVITY OF LONG TRADITIONS

Dust explosions have been a recognized threat to humans and property for a long time. One of the earliest comprehensive reports known is Count Morozzo's (1795) detailed analysis of an explosion in the flour warehouse of Mr. Giacomelli in Turin in 1785 (see full report in Chapter 2). It is interesting to observe that Morozzo also mentions even earlier incidents of violent combustion of clouds of flour in air.

However, at the time of Morozzo, the coal mining industry was not fully aware of the important part played by coal dust in the serious coal mine explosions, which had become quite common. Faraday and Lyell (1845) were probably some of the first scientists to realize the central role of coal dust in these explosions. In their report to Sir James Graham, they discussed the fatal explosion in the Haswell coal mine near Durham, United Kingdom, on September 28, 1844. It was concluded that the primary event was a methane/air ("fire-damp") explosion initiated by a defective Davy lamp. However, the central role of the coal dust in developing the devastating main explosion was emphasized, based on a systematic analysis that is exemplary even today. In their report Faraday and Lyell stated:

> In considering the extent of the fire for the moment of explosion, it is not to be supposed that fire-damp is its only fuel; the coal dust swept by the rush of wind and flame from the floor, roof, and walls of the works would instantly take fire and burn, if there were oxygen enough in the air present

> to support its combustion; and we found the dust adhering to the face of the pillars, props, and walls in the direction of, and on the side towards the explosion, increasing gradually to a certain distance, as we neared the place of ignition. This deposit was in some parts half an inch, and in others almost an inch thick; it adhered together in a friable coked state; when examined with the glass it presented the fused round form of burnt coal dust, and when examined chemically, and compared with the coal itself reduced to powder, was found deprived of the greater portion of the bitumen, and in some instances entirely destitute of it. There is every reason to believe that much coal-gas was made from this dust in the very air itself of the mine by the flame of the fire-damp, which raised and swept it along; and much of the carbon of this dust remained unburned only for want of air.

During the 150–200 years that have passed since the days of Morozzo and Faraday, the phenomenon of dust explosions has become fully accepted as a serious industrial hazard. Furthermore, since that time, the expanding chemical and metallurgical industries have given birth to a steadily increasing number of new, finely divided combustible solid materials that have caused dust explosions to remain a significant hazard in many industries. As an important element in the constant efforts to fight the dust explosion hazard, actual accidents are carefully investigated. In some countries, valuable statistical records are available, some of which are discussed in the following sections.

1.2.2
DUST EXPLOSIONS IN THE UNITED STATES, 1900–1956

The National Fire Protection Association published a report of important dust explosions in the United States from 1900 to 1956 (NFPA, 1957). The report gives informative details of a selection of 75 of the most serious and recent of the 1123 explosions recorded. The selection covers a wide range of dusts from all the categories—wood, food and feed, metals, plastics, coal, paper, and chemicals. In addition, each of the 1123 explosions is mentioned briefly individually by specifying the date, location, dust involved, probable ignition source, number of fatalities and injuries, and material losses.

Table 1.3 gives an overall summary of the consequences of explosions involving various dust categories. The table illustrates some interesting differences. For example, the metal dust explosions, representing 7.1% of the total number of explosions, were responsible

Table 1.3 Dust explosions in the United States, 1900–1956: fatalities, injuries, and material losses in a sample of 1123 accidental explosions

	Explosions		Fatalities			Injuries			Material losses	
Type of dust	**Number**	**(%)**	**Number**	**(%)**	**Per explosion**	**Number**	**(%)**	**Per explosion**	**Million $***	**Per explosion**
Wood and bark	162	14.5	38	5.6	0.23	160	9.0	0.99	11.4	0.070
Food and feed	577	51.4	409	60.5	0.71	1061	60.0	1.84	75.8	0.131
Metals	80	7.1	108	16.0	1.35	198	11.2	2.48	3.2	0.040
Plastics	61	5.4	44	6.5	0.72	121	6.8	1.98	3.7	0.061
Coal (not mines)	63	5.6	30	4.4	0.48	37	2.1	0.59	1.6	0.025
Paper	9	0.8	0	0.0	0.0	0	0.0	0.0	0.5	0.056
Others	171	15.2	47	7.0	0.27	193	10.9	1.13	4.3	0.025
All	1123	100.0	676	100.0		1770	100.0		100.5	

*Numerical value in U.S. dollars at year of explosion, not inflated.
Source: Data from NFPA, 1957.

for 16% of all the fatalities and 11.2% of all the injuries but only 3.2% of the material losses. The food and feed dust explosions also were responsible for higher percentages of fatalities and injuries than the 51.4% share of the number of explosions. Furthermore, food and feed caused by far the highest material loss per explosion. The pulverized coal dust explosions (not mining), on the contrary, caused lower percentages of fatalities, injuries, and material losses than their share of the total number of explosions.

1.2.3
DUST EXPLOSIONS IN THE FEDERAL REPUBLIC OF GERMANY, 1965–1985

Berufsgenossenschaftliches Institut für Arbeitssicherheit (Institute of Safety at Work of the Trade Unions) in the Federal Republic of Germany conducted a program of recording dust explosion accidents in the Federal Republic of Germany since the beginning of the 1960s. The first comprehensive report, covering 1965–1980, was by Beck and Jeske (1982). A condensed version of the findings was written by Beck (1982). The comprehensive report contains a brief description of each explosion accident, specifying the type of plant, the precise plant item, the type of dust, the likely ignition source, the numbers of fatalities and injuries, and the material losses. A further comprehensive report covering explosions recorded from 1981 to 1985 was written by Jeske and Beck (1987), the corresponding short version by Beck and Jeske (1988). Finally, Jeske and Beck (1989) produced an informative overview covering the whole span 1965–1985.

The total numbers of explosions recorded were 357 for 1965–1980 and 69 for 1981–1985. Beck and Jeske (1982) estimated the recorded explosions from 1965 to 1980 to be about 15% of the total number of explosions that actually occurred. The estimated number of actual dust explosions in the Federal Republic of Germany from 1965 to 1980 was therefore about 2400, that is, about 160 per year. The number of explosions recorded per year for 1981–1985 was somewhat lower than for 1965–1980. However, because of the low percentage of recorded explosions, it may not be justified to conclude that the annual number of accidental explosions dropped significantly after 1980.

Table 1.4 provides some data from the Federal Republic of Germany that can be compared directly with the older data from the United States in Table 1.3. There are interesting

Table 1.4 Dust explosions in the Federal Republic of Germany 1965–1980: fatalities and injuries in a sample of 357 explosions

	Explosions		Fatalities			Injuries		
Type of dust	Number	%	Number	%	Per explosion	Number	%	Per explosion
Wood	113	31.6	12	11.7	0.11	124	25	1.10
Food and feed	88	24.7	38	36.8	0.43	127	26	1.44
Metals	47	13.2	18	17.5	0.38	91	18.5	1.94
Plastics	46	12.9	18	17.5	0.39	98	20	2.13
Coal and peat	33	9.2	7	6.8	0.21	39	8	1.18
Paper	7	2.0	0	0.0	0.0	0	0	0.0
Others	23	6.4	10	9.7	0.43	13	2.5	0.56
All	357	100.0	103	100.0		492	100.0	

Source: Beck, 1982.

differences in the distribution of the number of explosion accidents on the various dust categories. This may reflect both a change with time, from the first to the second part of this century, and differences between the structure of the industry in the United States and the Federal Republic of Germany. One example is food and feed, which only represented 25% of all the explosions in the Federal Republic of Germany, whereas in the United States the percentage was more than 50. However, the percentages of both fatalities and injuries for this dust group both in the Federal Republic of Germany and the United States was higher than the percentage of explosions. On the other hand, the percentage of the explosions involving metal dusts was about twice as high in the Federal Republic of Germany as in the United States. The higher percentage of both fatalities and injuries for metal dust explosions than the percentage of the number of explosions is, however, in agreement with the older data from the United States. This probably reflects the extreme violence and temperatures of flames of metals like magnesium, aluminum, and silicon.

Table 1.5 shows how the involvement of various categories of plant items in the explosions varies with dust type. This reflects differences between typical processes for producing, storing, and handling the various categories of powders and dusts.

Table 1.5 Dust explosions in the Federal Republic of Germany 1965–1985: frequencies in percent of primary involvement of various plant items in a total of 426 dust explosions and in the explosions of various categories of dusts

Type of plant item	Total of 426 explosions			Wood and wood products	Coal and peat	Food and feed	Plastics	Metals
	Number	% of Total	% Change 80/85					
Silos and bunkers	86	20.2	0	35.9	23.1	22.9	2	2
Dust collecting systems	73	17.2	+2.9	18.0	5.1	9.5	13.5	45.6
Milling and crushing plants	56	13.0	−0.7	7.0	12.8	18.1	15.4	5.3
Conveying systems	43	10.1	0	4.7	5.1	26.7	17.3	2.0
Dryers	34	8.0	+0.4	10.2	2.0	7.6	9.6	2.0
Furnaces	23	5.4	+0.1	10.9	18.0	2.0	0	0
Mixing plants	20	4.7	+0.2	0	5.1	2.0	17.3	3.5
Grinding and polishing plants	19	4.5	0	3.9	0	0	2	22.8
Sieves and classifiers	12	2.8	−0.3	4.7	0	2.8	0	3.5
Unknown and others	60	14.1	−2.6	4.7	28.8	8.4	22.9	13.3
All	426	100.0	0	100.0	100.0	100.0	100.0	100.0

Source: Jeske and Beck, 1989.

Table 1.6 shows the frequencies of the various ignition sources initiating explosions in the same dust categories as used in Table 1.5. The category Mechanical sparks may not be entirely unambiguous, which causes some problems with interpreting the data.

Table 1.7 provides an interesting correlation between the various plant items involved in the explosions and the probable ignition sources. Mechanical sparks are frequent ignition sources in dust collectors, mills, and grinding plants, whereas smoldering nests are typical when the explosion is initiated in silos, bunkers, and dryers. Apart from in dryers,

Table 1.6 Dust explosions in the Federal Republic of Germany: frequencies in percent of initiation by various types of ignition sources in a total of 426 explosions and in the explosions of various categories of dusts

Type of ignition source	Total of 426 explosions			Wood and wood products	Coal and peat	Food and feed	Plastics	Metals
	Number	% of Total	% Change 80/85					
Mechanical sparks	112	26.2	−2.8	26.6	5.1	22.8	21.2	56.1
Smoldering nests	48	11.3	+1.5	19.5	20.5	5.7	9.6	0
Mechanical heating and friction	38	9.0	0	9.4	5.1	12.4	9.6	3.5
Electrostatic discharges	37	8.7	0	2.3	0	6.7	34.6	5.3
Fire	33	7.8	−0.6	14.8	12.8	4.8	2	2
Spontaneous ignition (self-ignition)	21	4.9	+0.4	3.1	15.4	6.7	2	3.5
Hot surfaces	21	4.9	−0.4	5.5	10.3	2.8	3.9	3.5
Welding and cutting	21	4.9	+0.4	2.3	2.6	12.4	2	2
Electrical machinery	12	2.8	−0.3	0	2.6	5.7	2	0
Unknown or not reported	68	16.0	+1.7	16.5*	25.6*	20.0*	13.1*	24.1*
Others	15	3.5	+0.1					
All	426	100.0	0	100.0	100.0	100.0	100.0	100.0

*This figure also includes "others."

Table 1.7 Dust explosions in the Federal Republic of Germany 1965–1985: frequencies in percent of various types of ignition sources of explosions initiated in various plant items

Type of ignition source	All 426 explosions	Silos and bunkers	Dust collectors and separators	Mills and crushing plants	Conveying systems	Dryers	Mixing plants	Ginding plants	Sieves and classifiers
Mechanical sparks	26.2	16.3	41.1	60.0	25.6	0	15.0	89.5	16.7
Smoldering nests	11.3	27.9	11.0	0	2.3	29.4	0	0	8.3
Mechanical heating and friction	9.0	3.5	6.8	12.7	25.6	2.9	25.0	5.3	0
Electrostatic discharges	8.7	2.3	9.6	5.5	18.6	5.9	45.0	0	16.7
Fire	7.8	4.7	4.1	2	0	0	5.0	0	16.7
Spontaneous ignition (self-ignition)	4.9	2.3	2.7	0	4.7	14.7	0	0	8.3
Hot surfaces	4.9	11.6	0	3.6	2.3	23.5	0	0	0
Welding and cutting	4.9	5.8	2	0	4.7	2.9	5.9	0	0
Electrical machinery	2.8	2.3	2	0	0	0	0	0	0
Unknown and others	19.5	23.3	20.7	16.2	16.2	20.7	4.1	5.2	33.3
All	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Source: Jeske and Beck, 1989.

spontaneous ignition was not very frequent. The distinction between smoldering nests and spontaneous heating may not always be obvious.

Electrostatic discharges were the dominating ignition source in mixing plants, but as Table 1.6 shows, electrostatic discharge ignition occurred almost solely with plastic dusts. Presumably, mixers are quite frequent in plants producing and handling plastic dusts, and the combination of mixers and plastic dusts is favorable for generating electrostatic discharges. Section 9.5 in Chapter 9 provides references to more recent German statistics.

Proust and Pineau (1989) showed that there is reasonably good agreement between the findings of Beck and Jeske for the Federal Republic of Germany and statistics of industrial dust explosions in the United Kingdom from 1979 to 1984, as reported by Abbot (1988).

1.2.4
RECENT STATISTICS OF GRAIN DUST EXPLOSIONS IN THE UNITED STATES

Schoeff (1989) presented some statistical data that are shown in a slightly rearranged form in Table 1.8. The data for 1900–1956 are from the same source as the data in Table 1.3. The alarming trend is that the annual number of explosions seems to increase rather than decrease. The annual number of fatalities is also higher for the last period, 1979–1988, than for the previous one, 1957–1975. The annual number of injuries for the last period is higher than for both previous periods. From 1957–1975 to 1979–1988, the annual estimated damage to facilities seems to have increased more than what can be accounted for by inflation. Section 9.5 in Chapter 9 provides references to more recent U.S. statistics.

Table 1.8 Grain dust explosions in the United States: recent development

	1900–1956		1957–1975		1979–1988	
Loss category	**Total**	**Per year**	**Total**	**Per year**	**Total**	**Per year**
Number of explosions	490	8.6	192	10.1	202	20.2
Fatalities	381	6.8	68	3.6	54	5.4
Injuries	991	17.4	346	18.2	267	26.7
Estimated damage to facility (U.S. $ millions), not inflated	70	1.3	55	2.9	169	16.9

Source: Data from Schoeff, 1989.

It can be misleading to take the figures in Table 1.8 too far. However, the data do indicate that dust explosions remain a persistent threat to human life and limb and to property. Therefore, the efforts to fight the dust explosion hazard have to continue.

1.3
DUST AND DUST CLOUD PROPERTIES THAT INFLUENCE IGNITABILITY AND EXPLOSION VIOLENCE

1.3.1
DUST CHEMISTRY, INCLUDING MOISTURE

There are two aspects to consider, the thermodynamics of the explosion and the kinetics. Thermodynamics is concerned with the amount of heat liberated during combustion; kinetics with the rate at which the heat is liberated.

Dust chemistry influences both thermodynamics and kinetics, which are also to some extent coupled. Table 1.1 shows a considerable difference between the amounts of heat developed per mole of oxygen consumed for various groups of materials. Calcium, magnesium, and aluminum top the list with 1100–1300 kJ/mole O_2. The lowest value is 300 kJ/mole O_2 for copper and sulfur. It would be expected that this difference is to some extent reflected in the maximum pressure of explosions, when performed adiabatically at constant volume. Zehr (1957) made some calculations of the maximum pressures to be expected under such conditions. In Figure 1.16 his results have been plotted against data from experiments in either 1 m^3 or 20 liter closed bombs, taken from Table A1 in Appendix 1. For aluminum and magnesium, Zehr indicated only that the theoretical values would be larger than 10 and 13.5 bar (g), respectively. Figure 1.16 suggests a fair correlation between the theoretical and experimental data, with the theoretical results somewhat higher than the experimental ones. This would be expected because of the idealized assumptions of stoichiometry and complete oxidation of all fuel, on which the calculations were based.

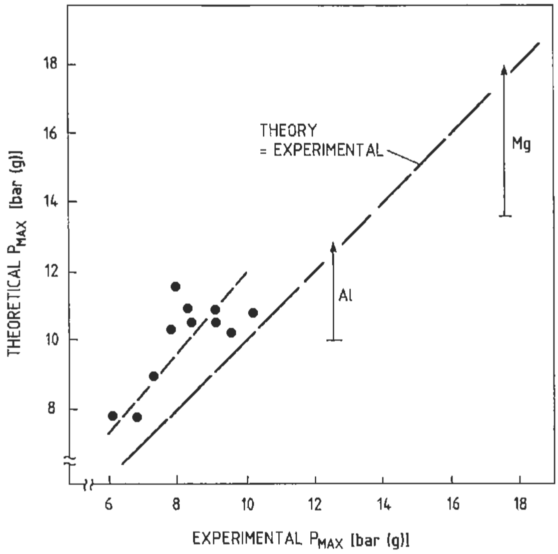


Figure 1.16 *Correlation between experimental P_{max} at constant volume from experiments in 1 m^3 or 20 liter closed vessels (Table A.1, Appendix 1) and theoretical P_{max} calculated by Zehr (1957).*

As discussed in detail in Chapter 7, the maximum rate with which the explosion pressure rises in closed-bomb experiments is a frequently used relative measure of the violence to be expected from explosions of a given dust.

Figure 1.17 shows how the maximum rates of pressure rise of starch (potato and corn starch) are systematically higher than for protein (two fish powders with fat removed) for the same specific surface area. The nitrogen compounds in the protein probably in some way slow the combustion process.

Eckhoff (1977/1978) used the data in Figure 1.17 to produce an empirical equation, based on simple linear interpolation, for predicting maximum rates of pressure rise for

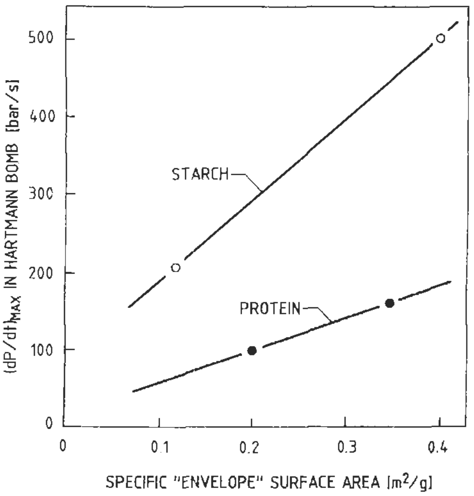


Figure 1.17 *Influence of chemistry (starch or protein) and specific surface area of natural organic materials on maximum rate of pressure rise in a closed 1.2 liter Hartmann bomb (From Eckhoff, 1977/1978).*

natural organic dusts. Reasonable agreement with experiments was found for a range of food and feedstuffs dust, fish meals, and cellulose.

Another example of the influence of dust chemistry on the explosion kinetics is shown in Figure 1.18. The heats of combustion of PVC and polyethylene are not very different. Closed-bomb experiments also find about the same maximum pressure for very small particle sizes. However, the chlorine in the PVC causes quite a dramatic drop in

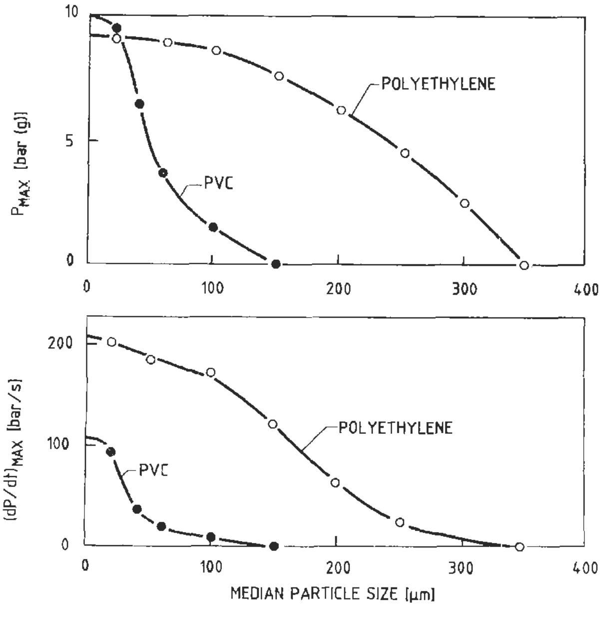


Figure 1.18 *The influence of chlorine in molecule of dust material on maximum explosion pressure and maximum rate of pressure rise in 1 m^3 standard ISO vessels, for various particle sizes (From Bartknecht, 1978).*

the rate of heat release as the median particle size increases beyond about 20 μm. Due to the very slow combustion, the P_{max} for PVC also drops much faster as the particle size increases than for polyethylene. The retarding influence of chlorine on the combustion process most probably is of the same nature as that of the halogens in the halons, which were extensively used for explosion and fire suppression before the negative influence of such materials on the global environment was fully realized.

Moisture in the dust reduces both the ignition sensitivity and explosion violence of dust clouds. Figure 1.19 illustrates the influence of dust moisture on the minimum electric spark ignition energy. The vertical axis is logarithmic, and it is seen that the effect is quite significant. If safety measures against electric spark ignition are based on MIE data for a finite dust moisture content, it is essential that this moisture content is not subsided in practice. The influence of dust moisture on the minimum ignition temperature of dust clouds is less marked. For example, 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.

Figure 1.20 illustrates how the explosion violence is systematically reduced with increasing dust moisture content. The ignition delay characterizes the state of turbulence of the dust cloud at the moment of ignition in the sense that the turbulence intensity decreases as the ignition delay increases (see Chapter 4).

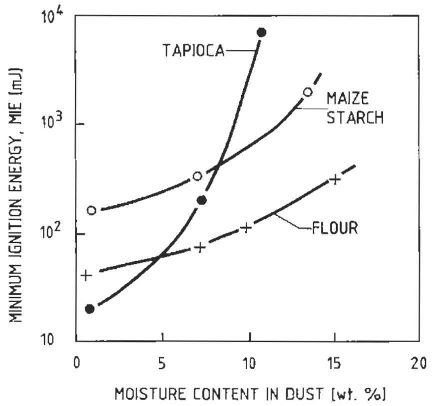


Figure 1.19 *Influence of dust moisture content on minimum electric spark ignition energy for three dusts (From van Laar and Zeeuwen, 1985).*

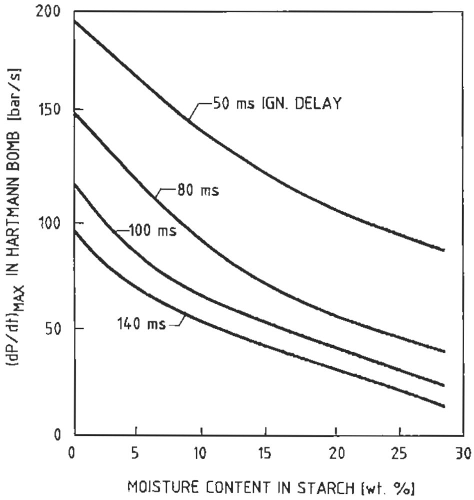


Figure 1.20 *Influence of moisture content in maize starch on maximum rate of pressure rise in Hartmann bomb for various ignition delays (time from dust dispersion to ignition) (From Eckhoff and Mathisen, 1977/1978).*

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. Second, the water vapor mixes with the pyrolysis gases in the preheating zone of the combustion wave and makes the gas mixture less reactive. Third, moisture increases the interparticle cohesion of the dust and prevents dispersion into primary particles (see Chapter 3).

More detailed analyses of flame propagation in dust clouds of various materials are given in Chapter 4.

1.3.2
PARTICLE SIZE OR SPECIFIC SURFACE AREA

Figure 1.17, in addition to illustrating the influence of dust chemistry on the dust cloud combustion rate, shows a clear dependence on particle size or specific surface area for both materials. This is a general trend for most dusts. However, as discussed in detail in Chapter 4 for coal, this trend does not continue indefinitely as the particles get smaller. In the case of coal and organic materials, pyrolysis or devolatilization always precedes combustion, which primarily occurs in the homogeneous gas phase. The limiting particle size, below which the combustion rate of the dust cloud ceases to increase, depends on the ratios between the time constants of the three consecutive processes: devolatilization, gas-phase mixing, and gas-phase combustion. Particle size primarily influences the devolatilization rate. Therefore, if the gas-phase combustion is the slowest of the three steps, increasing the devolatilization rate by decreasing the particle size does not increase the overall combustion rate. For coals, it was found that the limiting particle diameter is on the order of 50 μm. However, for materials yielding gaseous pyrolysis products that are more reactive than volatiles from coal, e.g., due to unsaturated gaseous compounds, one would expect the limiting particle size to be smaller than for coal. For natural organic compounds, such as starch and protein, the limiting particle diameter is probably not much smaller than about 10 μm; whereas for reactive dusts, such as some organic dyes, it may well be considerably smaller.

Figures 1.21 and 1.22 show scanning electron microscope pictures of two typical natural organic dusts, a wood dust containing very irregular particle shapes and maize starch having well-defined, nearly monosized, spherical particles.

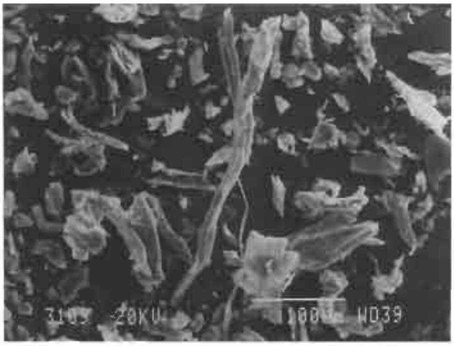


Figure 1.21 *Scanning electron microscope picture of wood dust (Courtesy of W. C. Wedberg).*

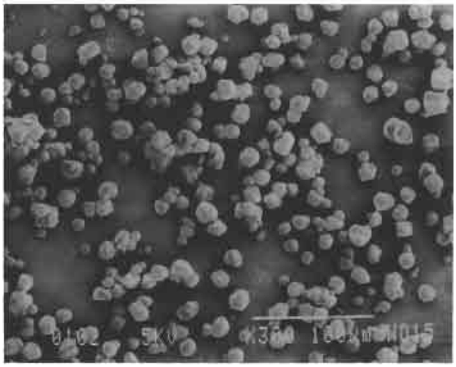


Figure 1.22 *Scanning electron microscope picture of native maize starch; typical particle size 10–15 μm (Courtesy of W. C. Wedberg).*

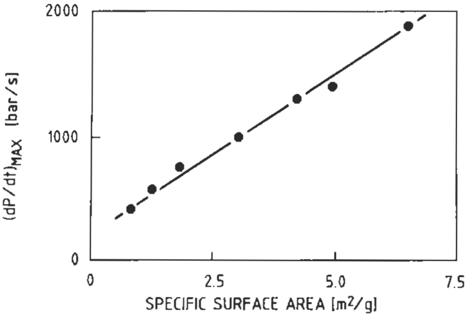


Figure 1.23 *Influence of specific surface area of aluminum dust on the maximum rate of pressure rise in standard 1 m^3 ISO vessel (From Bartknecht, 1978).*

For metals, in particular those at the top of Table 1.1, the limiting particle size, below which the ignition sensitivity and explosion violence no longer increase, is considerably smaller than for most organic materials. This is because these metals do not devolatilize or pyrolyze, but melt, evaporate, and burn as discrete entities (see Chapter 4). Figure 1.23 shows how the combustion rate of clouds of aluminum dust in air increases systematically with the specific surface area of the dust, in agreement with the trend in Figure 1.17. However, the range of specific surface areas in Figure 1.23 is more than 10 times that of Figure 1.17. For aluminum, a specific surface area of 6.5 m^2/g corresponds to monosized spheres of diameter 0.34 μm, or flakes of thickness 0.11 μm, which is a more-likely particle shape for the most violently exploding powders in Figure 1.23.

Figure 1.24 shows a comparatively coarse atomized aluminum powder of specific surface area only 0.045 m^2/g, and Figure 1.25 shows a fine aluminum flake powder. Note that the maximum rate of pressure rise of 2600 bar/s found for this powder in the 1.2 liter Hartmann bomb is not comparable to the values in Figure 1.23. This is due to different degrees of turbulence, degrees of dispersion into primary particles, and vessel volumes.

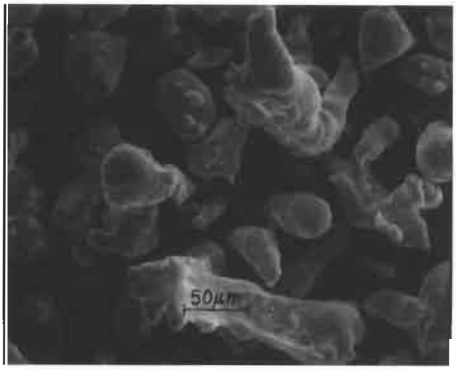


Figure 1.24 *Scanning electron microscope picture of atomized aluminum: typical particle size 50 μm, minimum ignition energy 3000 mJ (Courtesy of W. C. Wedberg).*

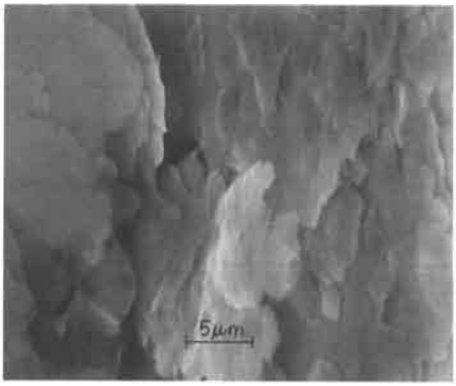


Figure 1.25 *Scanning electron microscope picture of aluminum flakes of thickness <1 μm. Minimum ignition energy <1–2 mJ: $(dP/dt)_{max}$ in Hartmann bomb 2600 bar/s (Courtesy of W. C. Wedberg).*

Figures 1.26 and 1.27 shows typical particle shapes in ground silicon in the comparatively coarse and fine particle size regions. The shapes are not very different for the two fractions. Note that the size fraction, 37–53 μm, is unable to propagate a dust flame. It is necessary to add a tail of much finer particles. The influence of the detailed shape of the particle size distribution on the ignitability and explosibility of metal dust clouds needs further investigation.

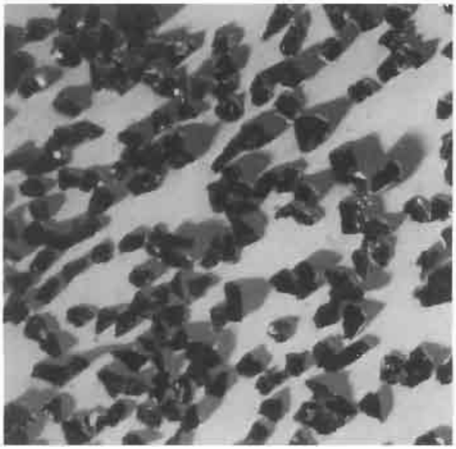


Figure 1.26 *Optical microscope picture of a metal-shadowed (shadowing angle 25° with focal plane) 37–53 µm fraction of ground silicon.*

Figure 1.27 *Scanning electron microscope picture of fine fraction of ground silicon: typical particle size 2–3 µm (Courtesy of W. C. Wedberg).*

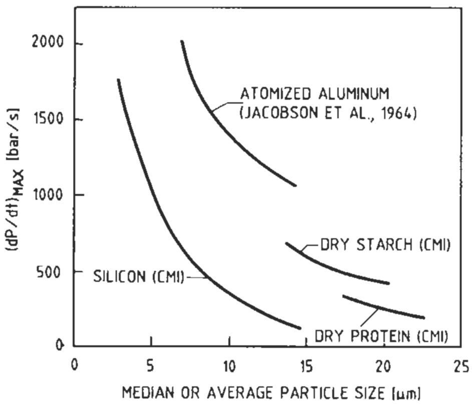


Figure 1.28 *$(dP/dt)_{max}$ in Hartmann bomb of clouds in air silicon dust, aluminum dust, and dust from natural organic materials, as functions of particle size (From Eckhoff et al., 1986).*

Figure 1.28 summarizes some data for the maximum rate of pressure rise for various dusts as functions of median or average particle size.

Figure 1.29 illustrates how the minimum explosible dust concentration is influenced by the particle size. The particles used in these experiments were close to monodisperse, that is, of narrow size distributions. In practice, the distributions may be quite wide, and simple relationships for monosized dusts may not be valid. Hertzberg and Cashdollar

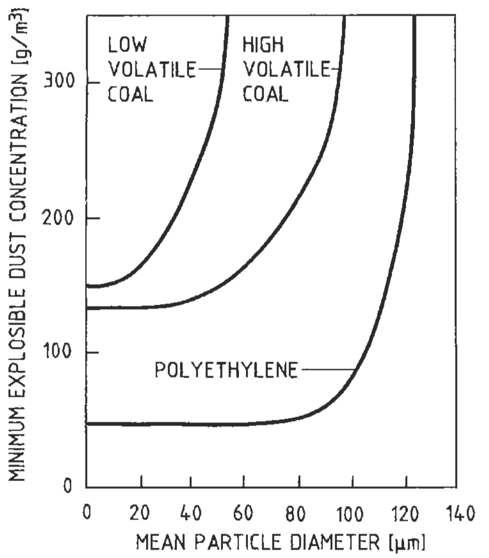


Figure 1.29 *Influence of mean particle diameter on minimum explosible concentration for three different dusts in a 20 liter USBM vessel (From Hertzberg and Cashdollar, 1987).*

(1987) interpreted the data in Figure 1.29 in terms of the existence of a critical particle size, above which the devolatilization process becomes the critical factor in the flame propagation process. Below this size, devolatilization is so fast that the combustion is controlled by gas mixing and gas combustion only. Note that the limiting particle size at the minimum explosible dust concentration is not necessarily the same as at higher concentrations, where the explosions are more violent.

Figure 1.30 shows how particle size influences the minimum ignition energy for three different dusts. The vertical scale is logarithmic, and it is seen that the effect is very strong.

Kalkert and Schecker (1979) developed a theory indicating that the MIE is proportional to the cube of the particle diameter, as illustrated in Figure 1.30 by their theoretical prediction of the relationship for polyethylene.

Investigations at the Chr. Michelsen Institute (CMI) showed that a 50–150 μm fraction of atomized aluminum powder could not be ignited as a cloud in air, even with a welding torch. This contradicts somewhat with the data in Figure 1.30. The discrepancy could be due to the presence of a fine particle size fraction in the powders used by Bartknecht (1978). This emphasizes the need for considering the entire size distribution rather than just a mean size.

Figure 1.31 gives some independent experimental results for MIE as a function of particle size for methyl cellulose, confirming the trends in Figure 1.30.

1.3.3
DEGREE OF DUST DISPERSION EFFECTIVE PARTICLE SIZE

In his experimental studies of burning times of pulverized fuels, Bryant (1973) found that persistent agglomeration was the reason for comparatively long burning times for apparently small particles. The situation is illustrated in Figure 1.32. A stable agglomerate behaves as a large single particle of the size of the agglomerate.

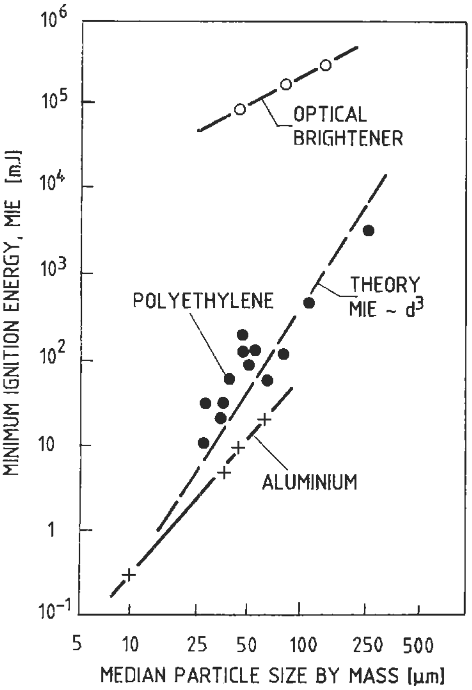


Figure 1.30 *Minimum electric spark ignition energy of clouds in the air of an optical brightener, polyethylene and aluminum, as functions of median particle size (From Bartknecht, 1987) and theoretical line for polyethylene (From Kalkert and Schecker, 1979).*

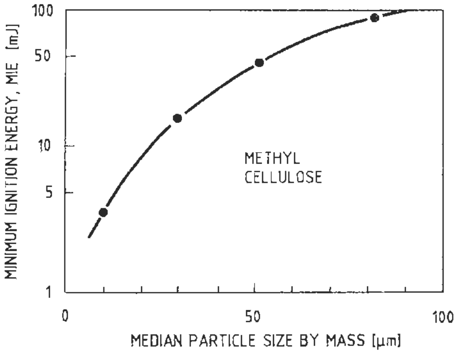


Figure 1.31 *Influence of median particle size of mass on the minimum ignition energy of clouds of methyl cellulose in air. Experiments performed at Chr. Michelsen Institute, Bergen.*

Eckhoff and Mathisen (1977/1978) investigated the influence of the degree of dispersion of maize starch grains on the rate of pressure rise during explosions in a 1.2 liter Hartmann bomb (see Chapter 7). As shown in Figure 1.22, maize starch consists of fairly monosized, close-to-spherical grains of typical diameters 10–15 μm. The degree of dispersion of the individual starch grains in the Hartmann bomb was studied by mounting a microscope slide with a double-sticky tape inside a specially made 1.5 liter dummy vessel that fitted to the dust dispersion cup of the Hartmann bomb (see Figures 7.4 and 7.5). Microscopic analysis of the dust deposited on the tape revealed a considerable fraction of stable agglomerates, which were probably formed during production of the starch. It was found that various qualities of maize starch had different degrees of agglomeration. This was reflected in differences in combustion rate, in agreement with Figure 1.32. Figure 1.33 shows a scanning electron micrograph of typical stable maize starch agglomerates found in a commercial maize flour purchased in Norway. Figure 1.34 shows the results of Hartmann bomb experiments with this flour, as purchased and after removal of the agglomerates retained by a 37 μm sieve, and a maize starch purchased in the United States, all of which passed a 37 μm sieve. Figure 1.34 shows a consistent increase of $(dP/dt)_{\max}$ as the effective particle size decreases.

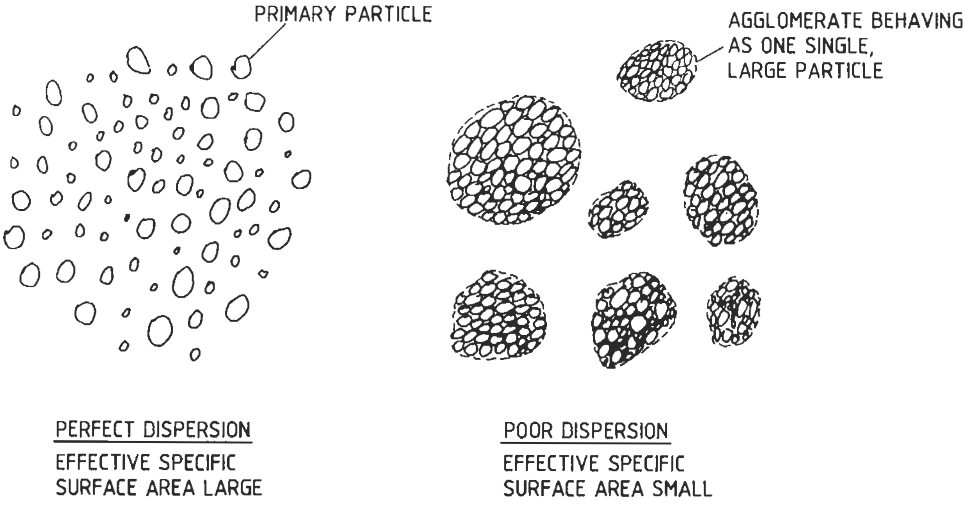


Figure 1.32 *Illustration of perfectly dispersed dust cloud and cloud consisting of agglomerates of much larger effective particle sizes than those of the primary particles.*

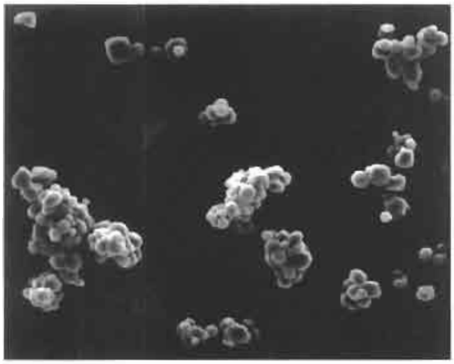


Figure 1.33 *Scanning electron microscope picture of stable agglomerates of primary maize starch grains. Diameters of primary grains are typically 10–15 μm (Courtesy of W. C. Wedberg).*

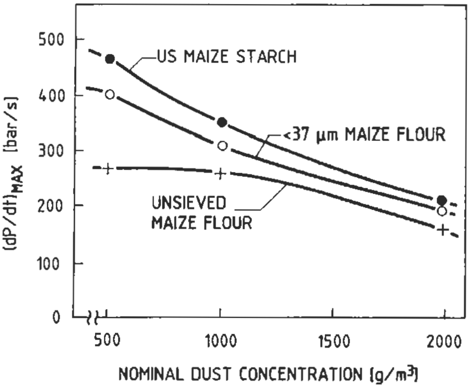


Figure 1.34 *Maximum rate of pressure rise of the 1.2 Hartmann bomb of maize starches containing different fractions of agglomerates (From Eckhoff and Mathisen, 1977/1978).*

The extent to which a certain powder or dust appears in agglomerated form when dispersed in a cloud, very much depends on the intensity of the dispersion process. This is discussed in detail in Chapter 3. In general, the tendency of powders and dusts to form agglomerates increases with decreasing particle size, in particular in the range below 10 μm.

1.3.4
DUST CONCENTRATION

Figure 1.3 illustrates the comparatively narrow explosible range of dust concentrations in air. However, neither ignition sensitivity nor explosion rate is constant within the explosible range. Typical patterns of variation with dust concentration are illustrated in Figure 1.35. C_l is the minimum explosible concentration, C_{stoich} the stoichiometric concentration, and C_u the maximum explosible concentration.

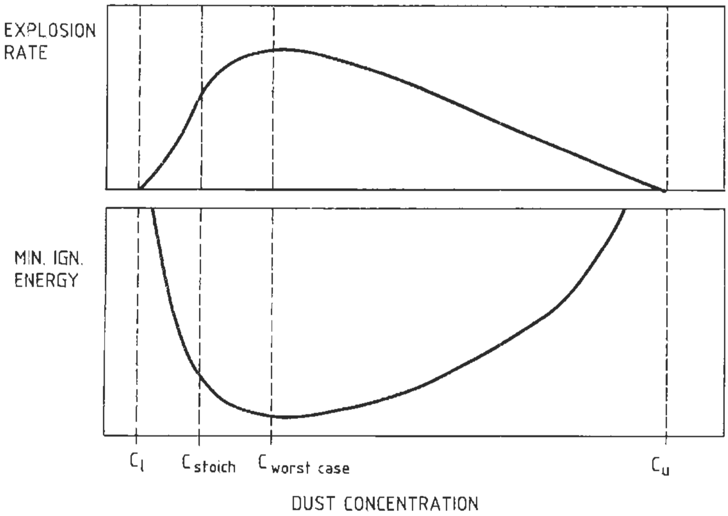


Figure 1.35 *Illustration of typical variation of explosion rate and minimum electric spark ignition energy with dust concentration within the explosible range.*

For maize starch of low moisture content in air at normal pressure and temperature, the minimum explosible concentration equals about 70 g/m^3, the stoichiometric concentration 235 g/m^3, the worst-case concentration about 500 g/m^3, and the maximum explosible concentration probably somewhere in the range 1500–2500 g/m^3. (Note: Figure 4.16 in Chapter 4 suggests a worst-case concentration equal to the stoichiometric concentration, based on laminar flame speed measurements. However, peak values of $(dP/dt)_{max}$ in closed bomb experiments most often seem to occur at higher concentrations than stoichiometric.) For metal dusts, the minimum explosible concentrations are normally considerably higher than for organic dusts and coals. For example, for zinc dust, it is about 500 g/m^3. The stoichiometric and worst-case concentrations then also are correspondingly higher.

Figure 1.36 shows a set of results from experiments with maize starch (11% moisture) in a 1.2 liter closed Hartmann bomb. The maximum rate of pressure rise peaks at about 400–500 g/m^3, whereas the maximum pressure reaches a fairly constant peak level in the range from 500 g/m^3 and upwards. Figure 1.37 shows some results from large-scale experiments with the same starch in a 22 m high experimental silo of volume 236 m^3 and vented at the top. The results indicate a peak in the maximum vented explosion pressure at a concentration range not very different from the one that gave the highest $(dP/dt)_{max}$ in the Hartmann bomb experiments. However, measuring the dust concentration distribution in the 236 m^3 silo was not straightforward and undue emphasis should not be put on this coincidence.

Figure 1.38 illustrates the influence of dust concentration on the ignition sensitivity by some experimental data from Bartknecht (1979).

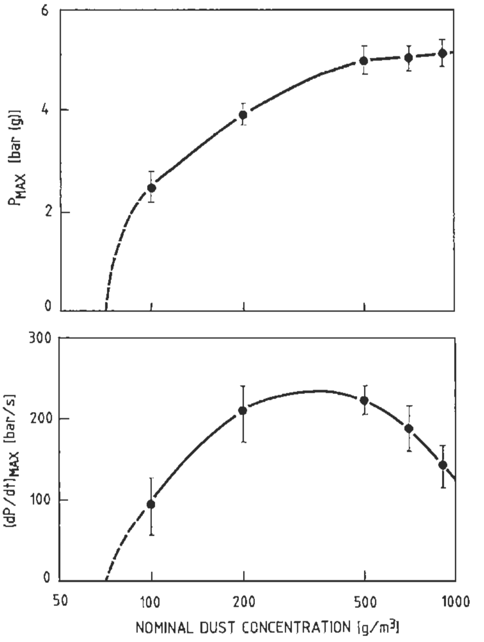


Figure 1.36 *Influence of nominal dust concentration in a Hartmann bomb on maximum explosion pressure and maximum rate of pressure rise. Maize starch containing 11% moisture. The bars through the points show ±1 standard deviation (From Eckhoff, Fuhre, and Pedersen, 1985).*

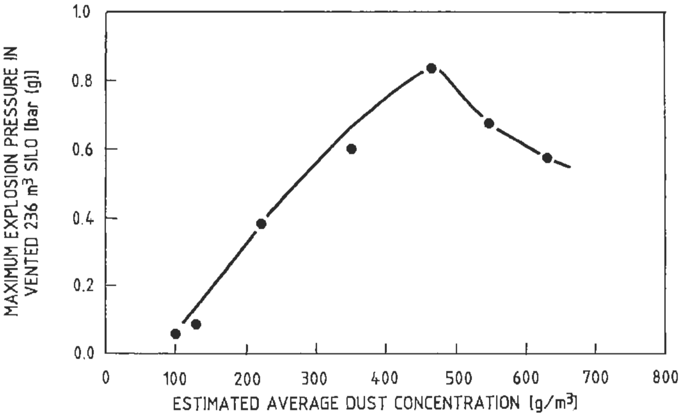


Figure 1.37 *Influence of estimated average dust concentration in exploding cloud in 236 m^3 silo of $L/D = 6$, on maximum explosion pressure in vented silo. Vent area at the top of the silo is 5.7 m^2. Maize starch contains 11% moisture. Ignition is close to the bottom of the silo (From Eckhoff et al., 1985).*

1.3.5
TURBULENCE

In practical terms, turbulence in the present context is a state of rapid internal, more or less random movement of small elements of the dust cloud relative to each other in three dimensions. If the cloud is burning, turbulence gives rise to mixing of the hot

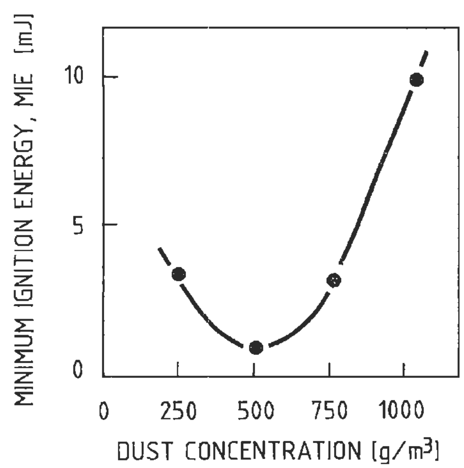


Figure 1.38 *The influence of average dust concentration in a 1 m^3 ISO standard vessel on the minimum electric spark ignition engery of clouds of an antioxidant in air (From Bartknecht, 1979).*

burned and burning parts of the cloud with the unburned parts, and the cloud becomes a kind of three-dimensional laminate of alternating hot burned or burning and cold unburned zones. Therefore, a turbulent cloud burns much faster than when a single plane flame sheet propagates through a quiescent cloud.

In the case of ignition of the dust cloud, whether by an electric spark or a hot surface, the turbulence disturbs the heat transfer by removing heat from the ignition zone by rapid convection. Therefore, ignition of a turbulent dust cloud generally requires higher energy or temperature than ignition of quiescent clouds.

In the context of dust explosions, two kinds of turbulence, differing by their origin, have to be considered. The first is turbulence generated by the industrial process in which the dust cloud is formed, whether an air jet mill, a mixer, a cyclone, a bag filter, a pneumatic transport pipe, or a bucket elevator. This kind of turbulence is often called *initial turbulence*. The second kind is generated by the explosion itself by expansion-induced flow of unburned dust cloud ahead of the propagating flame. The level of turbulence generated in this way depends on the speed of the flow and the geometry of the system. Obstacles, like the buckets in a bucket elevator leg, enhance the turbulence generation under such conditions.

In long ducts or galleries a positive feedback loop can be established, by which the flame can accelerate to very high speeds and even transit into a detonation. This is discussed in Chapter 4.

Figure 1.39 shows a characteristic example of the influence of initial turbulence on the rate of dust explosions in closed bombs. The dust cloud is generated in a closed vessel by dispersing a given mass of dust by a short blast of air.

In the early stages of dust dispersion, the dust cloud can be quite turbulent, but the turbulence fades away with time after the dispersion air has ceased to flow. Therefore, if explosion experiments with the same dust are performed in similar vessels at different delays between dust dispersion and ignition, they have different initial turbulence. As Figure 1.39 shows, the explosion violence, in terms of the maximum gradient of the pressure rise versus time, decreased markedly, by at least an order of magnitude, as the initial turbulence faded away. However, Figure 1.39 also shows that the maximum explosion

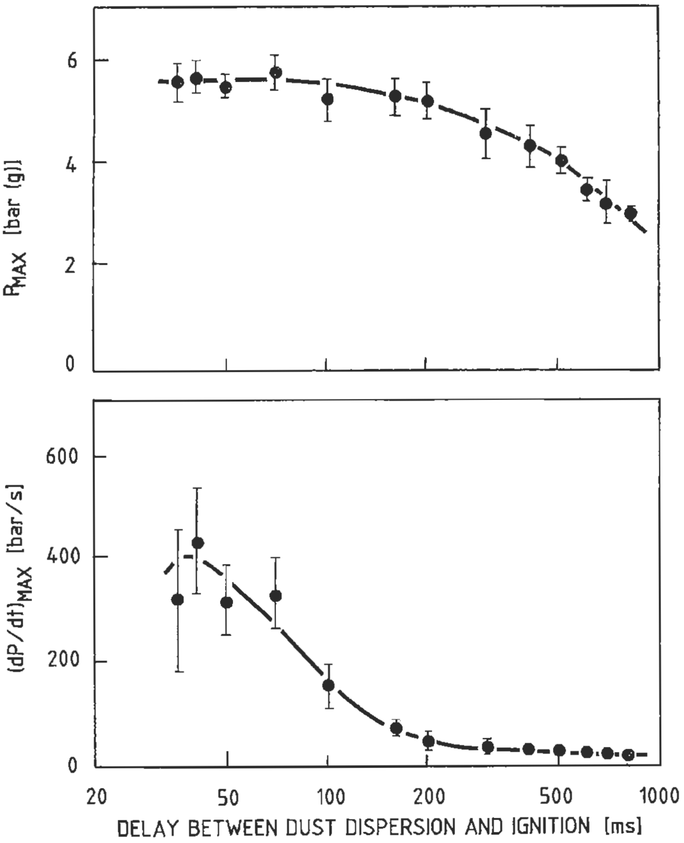


Figure 1.39 *Influence of initial turbulence on explosion rate of a dust cloud. Experiments with 420 g/m^3 of lycopodium in air in a 1.2 liter Hartmann bomb; five experiments per delay. Bars indicate ±1 standard deviation (From Eckhoff, 1977).*

pressure remained fairly constant up to about 200 ms. This reflects the fact that the maximum pressure is essentially a thermodynamic property, as opposed to the rate of pressure rise, which contains a strong kinetic component.

Christill et al. (1989), having developed a comprehensive model for predicting flame propagation and pressure development in gas explosions, implying the k-ϵ model of turbulence (see Section 4.4.1 in Chapter 4), suggested that similar models might be developed even for turbulent dust explosions. Other work along similar lines is discussed in Section 4.4.8 in Chapter 4.

Figure 1.40 shows the strong influence of initial turbulence on the minimum electric spark ignition energies of dust clouds. In this case, turbulence acts in the direction of safety, making it much more difficult to ignite the dust cloud compared with the quiescent state. The effect is quite dramatic, the minimum ignition energy increasing by several orders of magnitude. This is fortunate in the context of the possible generation of electrostatic discharges in the presence of explosible dust clouds, because such discharges are normally generated when the cloud is in turbulent motion. Section 5.3.4 in

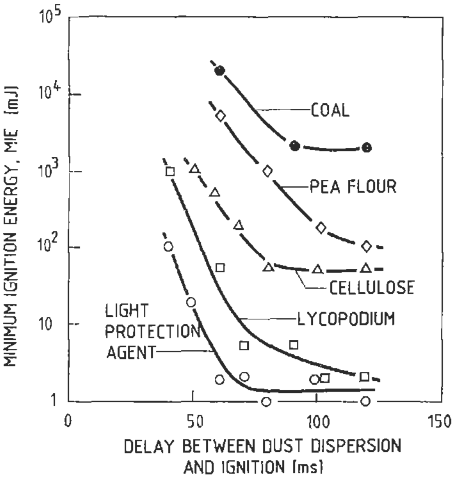


Figure 1.40 *The influence of initial turbulence on the minimum electric spark ignition of dust clouds. Experiments with various dusts in a 20 liter spherical explosion bomb (From Glarner, 1984).*

Chapter 5 gives some further information. Further analysis of the role of turbulence on propagation of dust flames is given in Section 4.4 in Chapter 4 and Section 9.2.4.4 in Chapter 9.

1.3.6
OXYGEN CONTENT OF OXIDIZER GAS

As one would intuitively expect, both the explosion violence and ignition sensitivity of dust clouds decrease with decreasing oxygen content of the gas in which the dust is suspended. Wiemann (1984) investigated the influence of the oxygen content of the gas (air + nitrogen) on the maximum pressure and maximum rate of pressure rise of coal dust explosions in a 1 m^3 closed vessel. The results, illustrated in Figure 1.41, show that both the explosion pressure and the rate of pressure rise decreased with decreasing oxygen content. Furthermore, the explosible dust concentration range was narrowed, in particular on the fuel-rich side. It is worth noting that a reduction of the oxygen content from that of air to 11.5% caused a reduction of the maximum rate of pressure rise by a factor of 10 or more, whereas the maximum pressure was reduced by less than a factor of 2. This illustrates the strong influence of the oxygen content on the kinetics of the combustion process. The reduction of the maximum pressure is approximately proportional to the reduction of the oxygen content, as would be expected from thermodynamic considerations.

Figure 1.42 shows some earlier results from the work of Hartmann (1948). The trend is similar to that of Wiemann's results in Figure 1.41. The maximum explosion pressure is approximately proportional to the oxygen content down to 16–17%, whereas the maximum rate of pressure rise falls much more sharply. For example, at 15% oxygen (i.e., 71% of that in air), $(dP/dt)_{max}$ is only 13% of the value in air.

The influence of the oxygen content in the oxidizing gas on the minimum explosible dust concentration was studied in detail by Hertzberg and Cashdollar (1987). Some results for a high-volatile-content coal dust are shown in Figure 1.43. For particles smaller than about 10 μm, a reduction of the oxygen content from that of air to 15.5% caused only a moderate increase, from 130 g/m^3 to 160 g/m^3, of the minimum

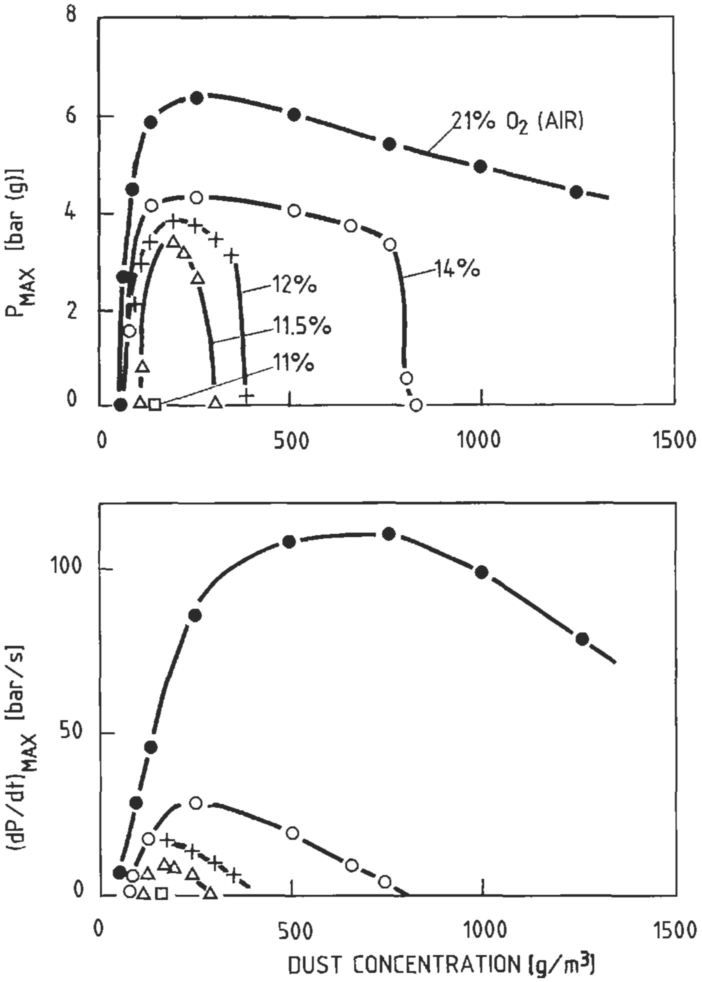


Figure 1.41 *The influence of oxygen content in the gas on the maximum explosion pressure and maximum rate of pressure rise of brown coal dust concentrations. Nitrogen as an inert gas is in a 1 m^3 ISO standard explosion vessel at 150°C and atm pressure (From Wiemann, 1984).*

explosible concentration. However, as the particle size increased, the influence of reducing the oxygen content became pronounced. At a mean particle size of 50 μm, 15.5% oxygen was sufficiently low to prevent flame propagation. It seems probable that the particle size fractions used by Hertzberg and Cashdollar (1987) were quite narrow. This can explain why particles of larger mean diameters than 100 μm did not produce explosions in air at all, irrespective of dust concentration. In practice, most powders and dusts involved in dust explosions have comparatively wide particle size distributions, and characterizing their fineness by only a mean particle size can be misleading in the context of dust explosibility assessment. It would be expected that many coal dusts of mean particle diameter larger than 100 μm would be explosible in air if they contain a significant "tail" of fine particles.

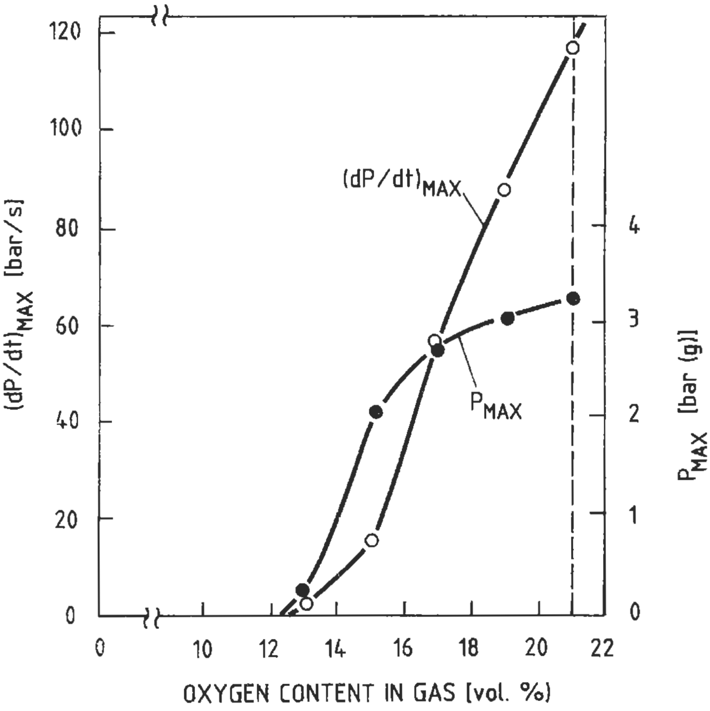


Figure 1.42 *The influence of oxygen content in gas on the maximum pressure and maximum rate of pressure rise in explosions of 100 g/m³ of <74 μm ethyl cellulose molding powder in a 1.2 liter Hartmann bomb (From Hartmann, 1948).*

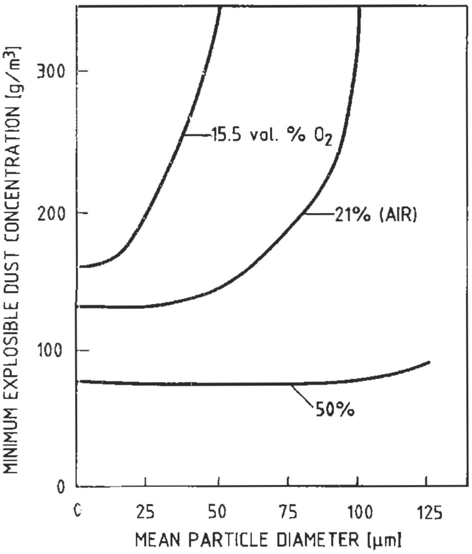


Figure 1.43 *The influence of oxygen content in gas on the minimum explosible concentration of coal dust (high volatile content) versus particle size (From Hertzberg and Cashdollar, 1987).*

Sweiss and Sinclair (1985) investigated the influence of particle size of the dust on the limiting oxygen concentration in the gas for flame propagation through dust clouds. Natural and synthetic organic dusts were studied. The results from experiments with narrow size fractions indicated that the limiting oxygen concentration decreased with decreasing particle size down to 100 μm. Below 100 μm, the limiting oxygen concentration was practically independent of particle size. However, addition of only 5% by mass of a fine dust ($\approx$60 μm) to a coarse main dust (200–1000 μm) reduced the limiting oxygen concentration by at least 60% of the difference between the values of the coarse dust only and the fine dust only.

Wiemann (1984) found that, for brown coal, dust particle size had a comparatively small influence on the limiting oxygen concentration for inerting. Therefore, at an initial temperature of 50°C and nitrogen as inert gas, the values were 11.8 vol% for a median particle size of 19 μm and 12.4 vol% for 52 μm.

The results in Figure 1.44, produced by Walther and Schacke (1986), show that the maximum permissible oxygen concentration for inerting clouds of a polymer powder was independent of the initial pressure over the range 1–4 bar (abs). For oxygen concentrations above this limit, the data in Figure 1.44 can be represented by the simple approximate relationship:

$$P_{\max}[\text{bar(g)}] = 0.35 \bullet P_o[\text{bar(abs)}] \bullet (\text{vol\%O}_2) \qquad (1.12)$$

where P_o is the initial pressure.

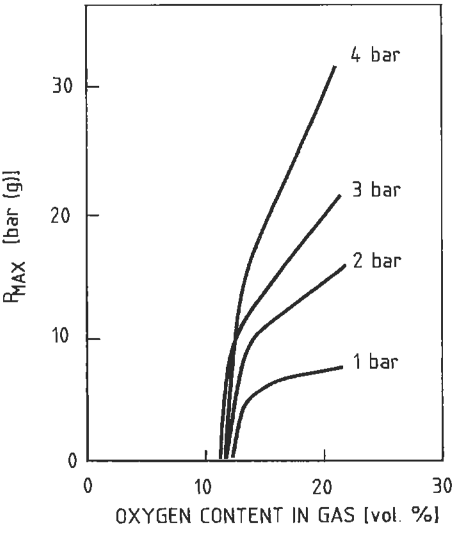


Figure 1.44 *The influence of oxygen content in gas on the maximum explosion pressure for a polymer powder for various initial pressures in a 1 m³ closed ISO vessel (From Walther and Schacke, 1986).*

Figure 1.45 illustrates the influence of the oxygen content of the gas on the minimum ignition temperature of a dust cloud. For <74 μm Pittsburgh coal dust, there is a systematic increase from 500°C in pure oxygen via 600°C in air to 730°C in 10 vol% oxygen.

The influence of the oxygen content in the gas on the minimum electric spark ignition energy of dust clouds is illustrated by the data in Figure 1.46 for a subatmospheric

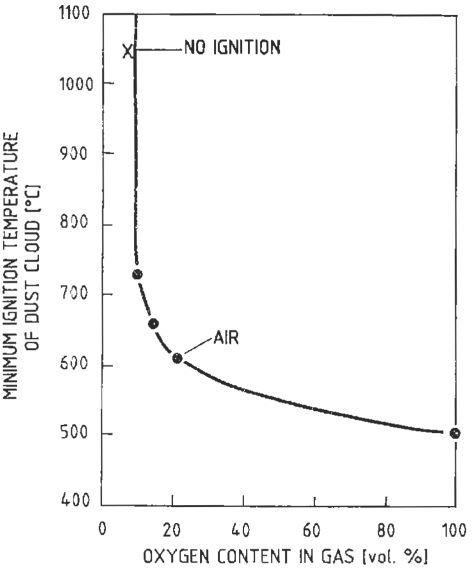


Figure 1.45 *The influence of oxygen content in gas on the minimum ignition temperature of <74 μm Pittsburgh coal dust in the Godbert-Greenwald furnace (From Hartmann, 1948).*

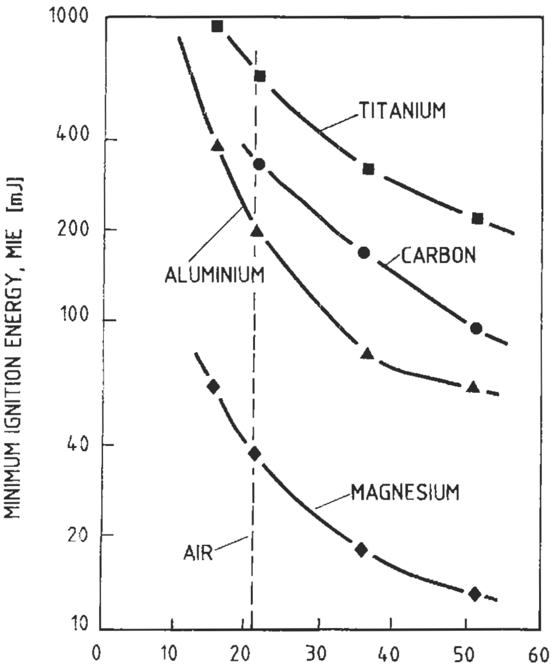


Figure 1.46 *The influence of oxygen content in atmosphere on minimum electric spark ignition energy of dust clouds of various materials. Initial pressure 0.2 bar (abs): mean particle diameter 40 μm, equivalence ratio 0.65 (i.e., excess oxygen for combustion), MIE defined for 80% probability of ignition (From Ballal, 1980).*

pressure of 0.2 bar (abs). A reduction from 21 vol% to 10 vol% increased the minimum ignition energy by a factor of about 2. This is on the same order as the relative increase found by Hartmann (1948) for atomized aluminum; namely, a factor of 1.4 from 21 vol% to 15 vol% oxygen and a factor of 2.0 from 21 vol% to 8.5 vol% oxygen. However, as the oxygen content approached the limit for flame propagation, a much steeper rise of the minimum ignition energy is expected. This is illustrated by Glarner's (1984) data for some organic dusts in Figure 1.47.

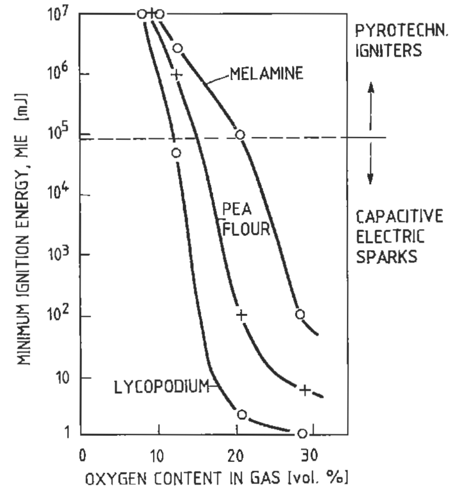


Figure 1.47 *The influence of oxygen content in gas of minimum ignition energy of dust clouds (From Glarner, 1984).*

It should finally be mentioned that Wiemann (1984) found that the maximum oxygen concentration for inerting clouds of a brown coal dust of median particle diameter 52 μm varied somewhat with the type of inert gas. For an initial temperature of 150°C, the values were 10.9 vol% for nitrogen, 12.3 vol% for water vapor, and 13.0 vol% for carbon dioxide. The influence of initial temperature was moderate in the range 50–200°C. Therefore, the value for nitrogen dropped from 12.4 vol% at 50°C to 10.4 vol% at 200°C. For carbon dioxide, the corresponding values were 14.0 and 12.5 vol%, respectively.

1.3.7

INITIAL TEMPERATURE OF THE DUST CLOUD

Figure 1.48 summarizes results obtained by Wiemann (1987) and Glarner (1983) for various coals and organic dusts, indicating a consistent pattern of decreasing minimum explosible dust concentrations with increasing initial temperature. Furthermore, as the minimum explosible concentration decreases toward zero with increasing temperature, the data seem to converge toward a common point on the temperature axis. For gaseous hydrocarbons in air, Zabetakis (1965) proposed linear relationships between the minimum explosible concentration and the initial temperature, converging toward the point 1300°C for zero concentration. For methane/air and butane/propane/air, Hustad and Sönju (1988) found a slightly lower point of convergence, 1200°C. However, linear plots of the data in Figure 1.48 yield points of convergence for zero minimum explosible

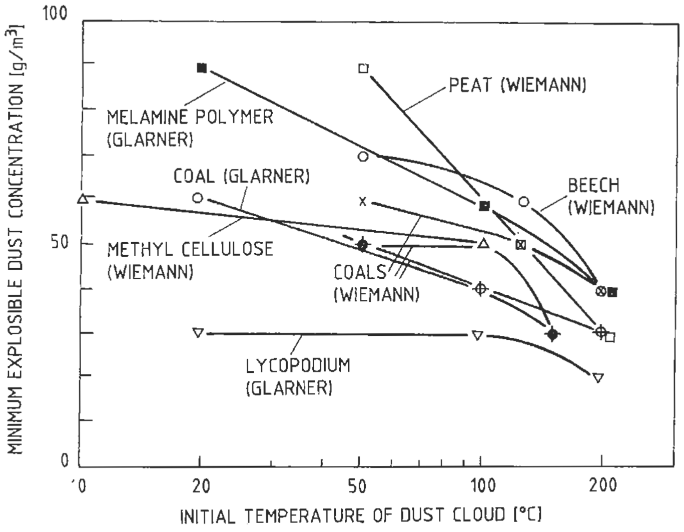


Figure 1.48 *The influence of initial temperature of dust clouds on minimum explosible dust concentration in air at 1 bar (abs) (Data from Wiemann, 1987, determined in a 1 m^3 closed vessel with 10 kJ chemical igniter, and from Glarner, 1983, determined in a 20 liter closed vessel with 10 kJ igniter).*

concentration in the range 300–500°C, much lower than the 1200–1300°C found for hydrocarbon gases. This indicates that the underlying physics and chemistry is more complex for organic dusts than for hydrocarbon gases.

The influence of the initial temperature of the dust cloud on the minimum electric spark ignition energy is illustrated in Figure 1.49, using the data of Glarner (1984). For the organic materials tested, a common point of convergence for the straight regression

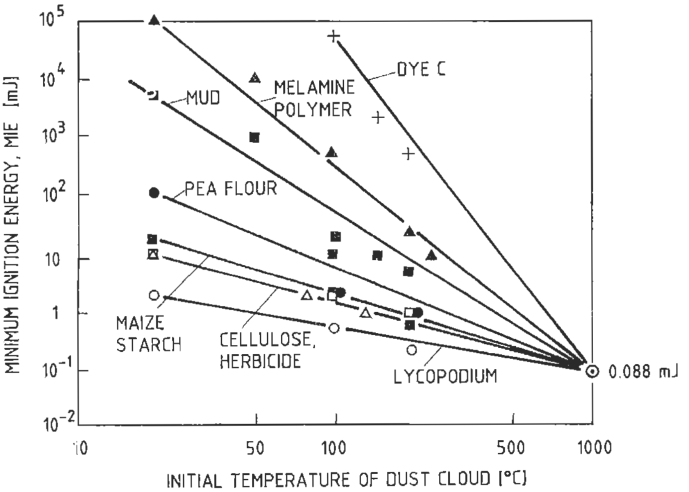


Figure 1.49 *The influence of the initial temperature of a dust cloud on the minimum electric spark ignition energy (From Glarner, 1984).*

lines at 1000°C and 0.088 mJ is indicated. This means that the MIE values for organic dusts at elevated temperatures can be estimated by linear interpolation between this common point and the measured MIE value at the ambient temperature.

Figure 1.50 shows how the initial temperature influences the maximum explosion pressure and rate of pressure rise. The reduction of P_{max} with increasing initial temperature is due to the reduction of the oxygen concentration per unit volume of dust cloud at a given initial pressure, with increasing initial temperature. The trend for $(dP/dt)_{max}$ in Figure 1.50 is less clear and reflects the complex kinetic relationships involved.

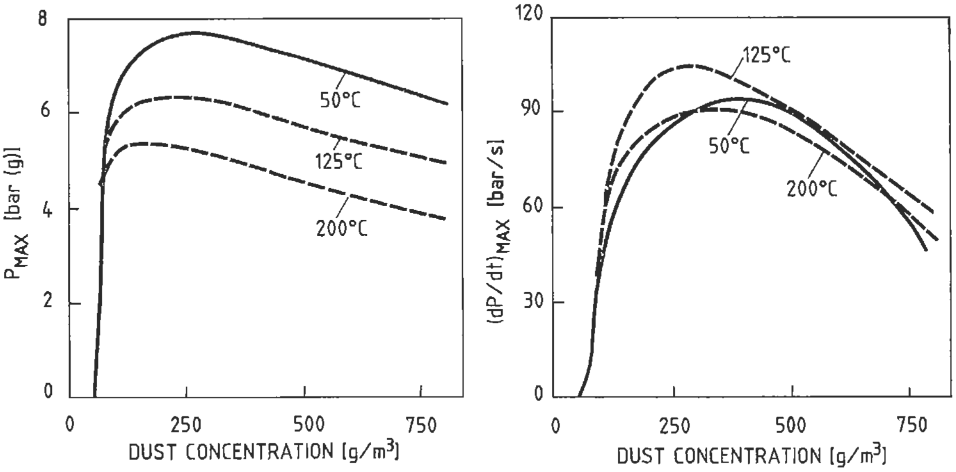


Figure 1.50 *The influence of the initial temperature of a dust cloud on the development in a 1 m³ closed vessel, using bituminous coal dust in air (From Weimann, 1987).*

Figure 1.51 indicates an approximately linear relationship between the reciprocal of the normalized initial temperature and the normalized maximum explosion pressure for some organic materials and coals.

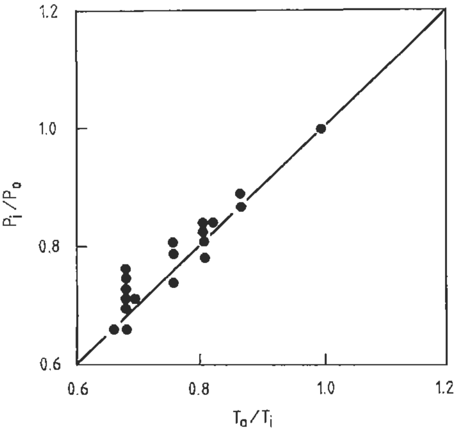


Figure 1.51 *Influence of normalized initial temperature (K) of dust clouds on normalized maximum explosion pressure (absolute). T_0 is the lowest initial temperature investigated for a given dust, mostly 323 K. T_i is the actual initial temperature. P_0 and P_i are the maximum explosion pressures for initial temperatures T_0 and T_i, respectively. Data are for coal, beech, peat, jelly agent, milk powder, methyl cellulose, and napthalic acid anhydride (From Wiemann, 1987).*

1.3.8
INITIAL PRESSURE OF A DUST CLOUD

Wiemann's (1987) data for brown coal dust in air in Figure 1.52 illustrate the characteristic pattern of the influence of initial pressure on the maximum explosion pressure in closed vessels (constant volume). Two features are apparent. First, the peak maximum pressure (abs) is close to proportional to the initial pressure (abs). Second, the dust concentration that gives the peak maximum pressure is also approximately proportional to the initial pressure, as indicated by the straight line through the origin and the apexes of the pressure-versus-concentration curves. This would indicate a given ratio of mass dust to mass air that gives the most efficient combustion, independent of initial pressure.

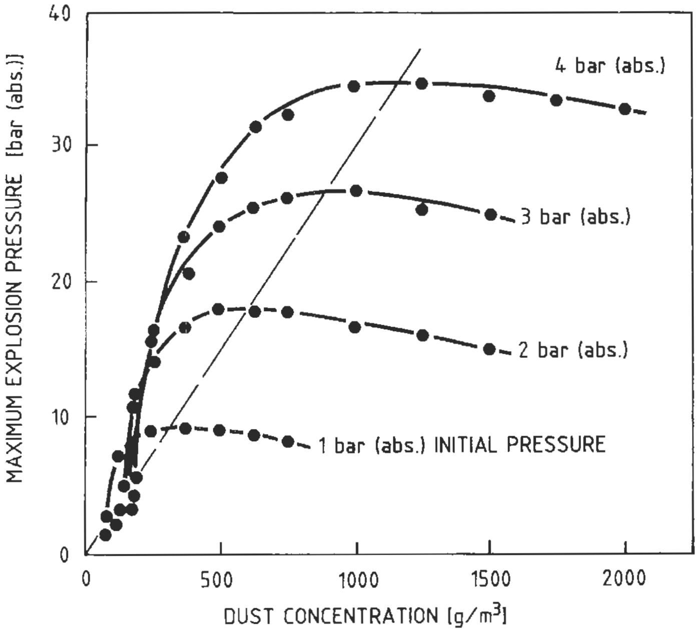


Figure 1.52 *Maximum explosion pressure in a 1 m^3 closed vessel as function of dust concentration for different initial pressures, using brown coal dust in air. A straight line through the origin passes through the apexes of the curves (From Wiemann, 1987).*

Walther and Schacke (1986) presented results for polymer powder/air explosions in a 20 liter closed vessel, revealing the same trends as Figure 1.52, from an initial pressure of 3 bar (abs) down to 0.2 bar (abs). These results are in complete agreement with the earlier results for starch presented by Bartknecht (1978), covering the initial pressure range 0.2–2.0 bar (abs). Figure 1.53 summarizes the results from the three investigations.

The results in Figure 1.54, obtained by Pedersen and Wilkins for higher initial pressures, indicate that the trend of Figure 1.53 extends at least to 12 bar (abs). This is in agreement with corresponding linear correlations found for methane/air up to 12 bar (abs) initial pressure, as shown by Nagy and Verakis (1983). For clouds of fuel mists in air, Borisov and Gelfand (personal communication, December 1989) found a linear correlation

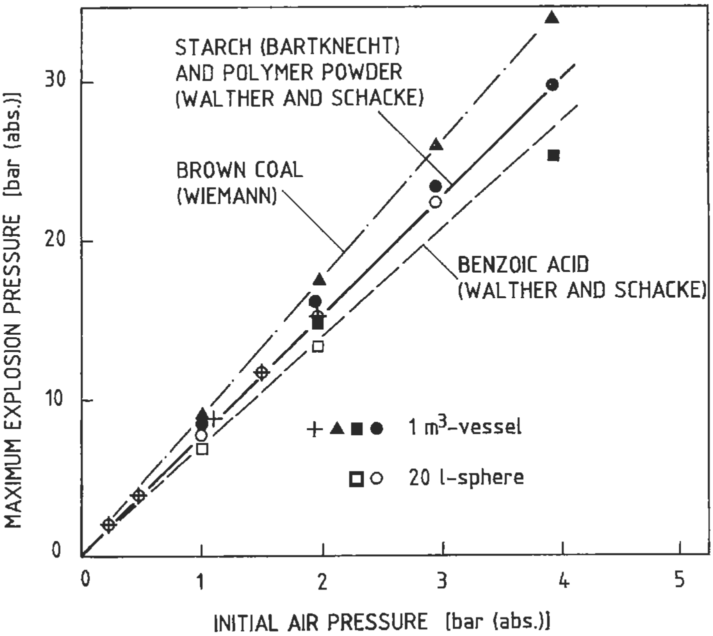


Figure 1.53 *The maximum explosion pressure at a constant volume as a function of initial air pressure (Data from Bartknecht, 1978; Walther and Schake, 1986; and Wiemann, 1987).*

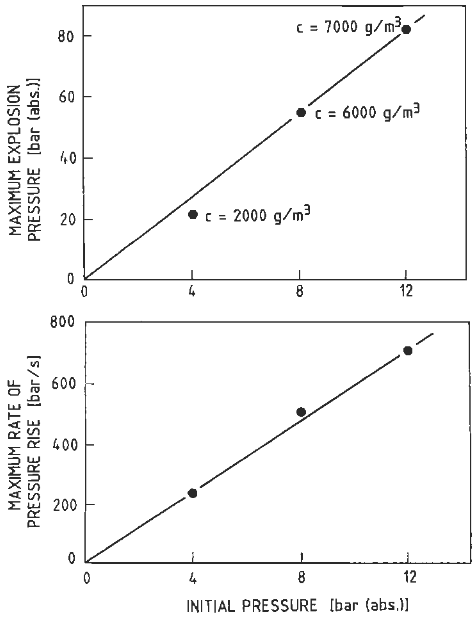


Figure 1.54 *The influence of initial pressure on maximum pressure and maximum rate of pressure rise in explosions of clouds of subbituminous coal dust in air in a 15 liter closed bomb: median particle size of mass is 100 µm (From Pedersen and Wilkins, 1988).*

between initial pressure and maximum explosion pressure up to very high initial pressures, approaching 100 bar.

Figure 1.54 also gives the maximum rate of pressure rise as a function of initial pressure. The excellent linear correlation is the result of somewhat arbitrary adjustment of the dust dispersion conditions with increasing quantities of dust to be dispersed.

The more arbitrary nature of the rate of pressure rise is reflected by the data in Figure 1.55, which show that in Wiemann's experiments $(dP/dt)_{\max}$ started to level out and depart from the linear relationship for initial pressures exceeding 2 bar (abs).

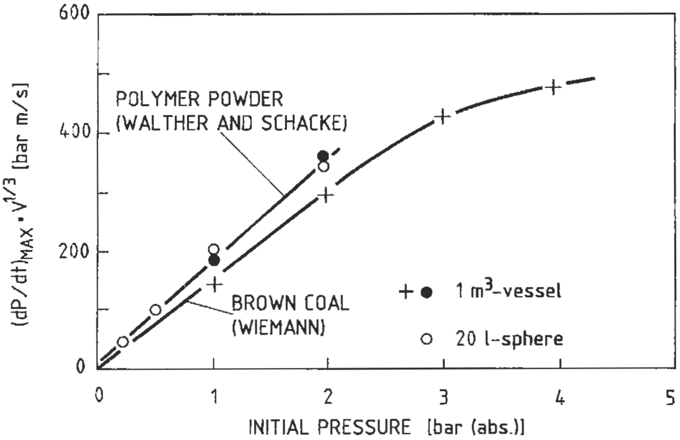


Figure 1.55 *Normalized highest $(dP/dt)_{max}$ as a function of initial pressure for explosions of polymer and brown coal dust in closed compatible 1 m^3 and 20 liter vessels (Data from Walther and Schacke, 1986, for polymer, and Wiemann, 1987, for brown coal).*

Figure 1.56 illustrates how the minimum explosible concentration of dusts increases systematically with increasing initial pressure. Hertzberg and Cashdollar (1988) attributed the close agreement between polyethylene and methane to fast and complete

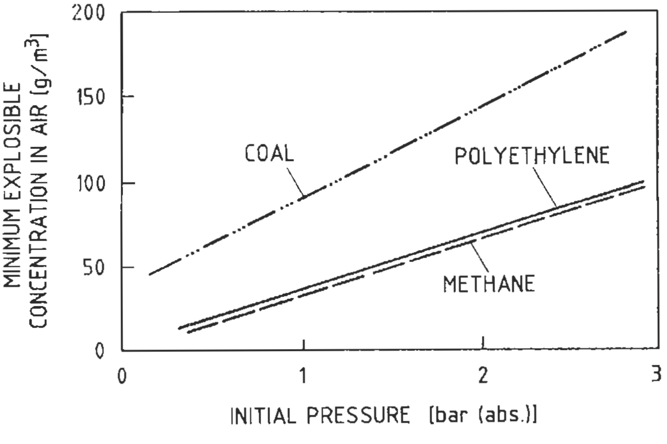


Figure 1.56 *Influence of initial pressure on the minimum explosible concentration of two dusts and methane in air (From Hertzberg and Cashdollar, 1988).*

devolatilization of polyethylene in the region of the minimum explosible concentration. In the case of coal, only the volatiles contribute significantly to flame propagation in this concentration range. A more detailed discussion of these aspects is given in Chapter 4.

1.3.9
COMBUSTIBLE GAS OR VAPOR MIXED WITH A DUST CLOUD ("HYBRID" MIXTURES)

It is not clear who was the first researcher to study the influence of comparatively small amounts of combustible gas or vapor on the ignitability and explosibility of dust clouds. However, more than a century ago, Engler (1885) conducted experiments in a wooden explosion box of 0.25 m^2 cross section, 0.5 m height, and essentially open at the bottom. The box was filled with a mixture of air and marsh gas (methane) of the desired concentration, and a cloud of fine charcoal dust, which was unable to produce dust explosions in pure air, was introduced at the container top by a vibratory feeder. Engler made the interesting observation that methane concentrations as low as 2.5 vol% made clouds of the charcoal dust explosible, whereas the methane and air alone, without the dust, did not burn unless the gas content was raised to 5.5–6 vol%. One generation later, Engler (1907) described a simple laboratory-scale experiment by which the hybrid effect could be demonstrated. The original sketch of the apparatus is reproduced in Figure 1.57.

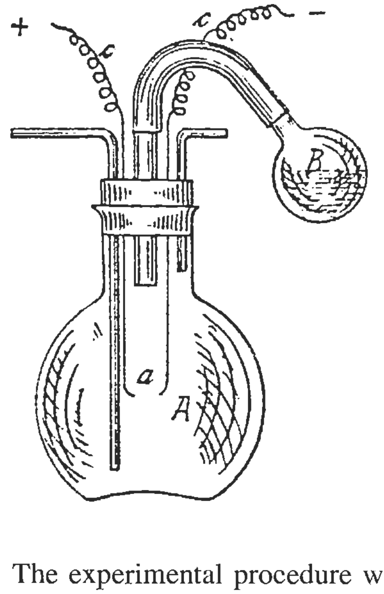


Figure 1.57 *Apparatus for demonstrating the hybrid interaction of combustible dust and gas: A is a glass explosion vessel of volume 250–500 cm^3, B is a glass dust reservoir connected to A via a flexible hose, b is the inlet tube for the dispersing air, and a is the gap for the spark ignition source (From Engler, 1907).*

The experimental procedure was first to raise reservoir *B* to allow an appropriate quantity of dust (unable to propagate a flame in pure air) to drop into vessel *A*. A continuous train of strong inductive sparks was then passed across the spark gap *a*, while a short blast of air was injected via *b* by pressing a rubber bulb, to generate a dust cloud in the region of the spark gap. With only air as the gaseous phase, no ignition took place.

The entire vessel *A* was then replaced by another one of the same size and shape but filled with a mixture of air and the desired quantity of combustible gas, and the experiment was repeated. Engler advised the experimenter to protect himself against the flying fragments of glass that could result in the case of a strong hybrid explosion.

Adding small percentages of combustible gas to the air influences the minimum explosible dust concentration, depending on the type of dust. This is illustrated by the data of Foniok (1985) for coals of various volatile contents, shown in Figure 1.58. The effect is particularly pronounced for dusts that have low ignition sensitivity and low combustion rate in pure air. A similar relationship for another combination of dust and gas is shown in Figure 1.59.

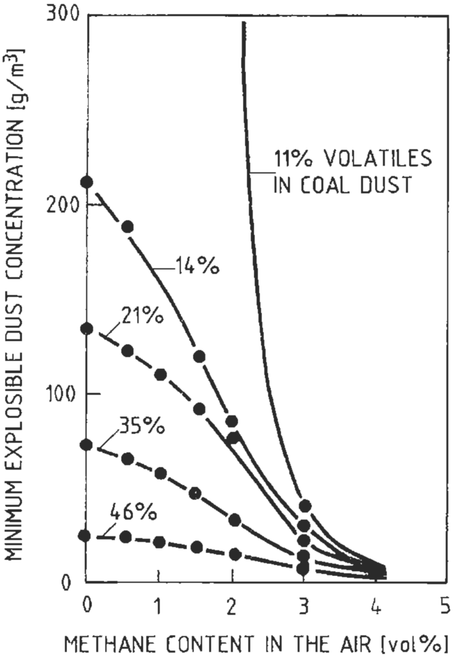


Figure 1.58 *The influence of methane content in the air on the minimum explosible concentration of coal dusts of different volatile contents. Average particle size 40 µm with 100% <71 µm, 4.5 kJ ignition energy (From Foniok, 1985).*

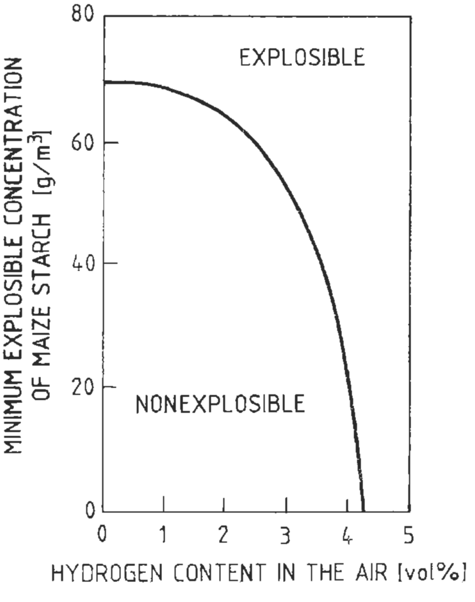


Figure 1.59 *The influence of small percentages of hydrogen in the air on the minimum explosible concentration of maize starch at normal ambient conditions (From Hertzberg and Cashdollar, 1987).*

Nindelt, Lukas, and Junghans (1981) investigated the limiting concentrations for flame propagation in various hybrid mixtures of dusts and combustible gases in air. The dusts and combustible gases were typical of those represented in the flue gases from coal powder plants.

Reeh (1979) determined the critical minimum contents of volatiles in coals and methane in the air for self-sustained flame propagation in clouds of coal dust in a 200 m experimental mine gallery. With no methane in the air, flame propagation was possible only for volatile contents above 14%. With 1 vol% methane in the air, the critical value was 13%; for 2% methane, about 12%; and for 3% methane, about 9% volatiles.

Cardillo and Anthony (1978) determined empirical correlation between the content of combustible gas (propane) in the air and the minimum explosible concentration of polypropylene, polyethylene, and iron. It is interesting to note that iron responded to the propane addition in the same systematic way as the organic dusts. For no propane in the air, the minimum explosible iron dust concentration was found to be 200 g/m^3, whereas for 1 vol% propane, it was 100 g/m^3.

The influence of small fractions of methane in the air on the minimum electric spark energy for igniting clouds of coal dusts was investigated systematically by Franke (1978). He found appreciable reductions in MIE, by factors on the order of 100, when the methane content was increased from 0 to 3 vol%.

Pellmont (1979) also investigated the influence of combustible gas in the air on the minimum ignition energy of dust clouds. A set of results, demonstrating a quite dramatic effect for some dusts, is given in Figure 1.60. Pellmont found that the most ignition sensitive concentration of the various dusts decreased almost linearly with increasing content of propane in the air. For example, for 20 μm PVC in pure air the most sensitive concentration was 500 g/m^3, whereas with 2 vol% propane in the air, it was 250 g/m^3. Figures 1.61 and 1.62 give some results presented by Foniok (1985). In agreement with the findings of Pellmont, Foniok observed that the dust concentration most sensitive to ignition, and at which the reported MIE values were determined, decreased systematically with increasing combustible gas content in the air. For example, for the 31% volatile dust, for which data are given in Figure 1.61, the most sensitive concentration was 750 g/m^3 with no methane in the air, whereas with 3.5% methane in the air, it dropped to 200 g/m^3.

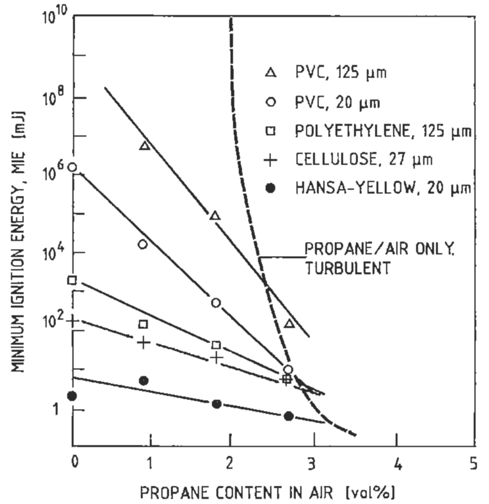


Figure 1.60 *The influence of small fractions of propane in the air on the minimum electric spark ignition energy of clouds of various organic dusts at normal ambient conditions (From Pellmont, 1979).*

Torrent and Fuchs (1989), probably using more incendiary electric sparks of longer discharge times than those used by Foniok (1985), found little influence of methane content in the air on MIE for coal dusts up to 2 vol% methane. For all the coal dusts tested but one, the MIE in pure air was <100 mJ. For one exceptional coal dust, containing 18% moisture and 12% ash, the MIE dropped from 300 mJ for no methane to about 30–50 mJ for 2% methane.

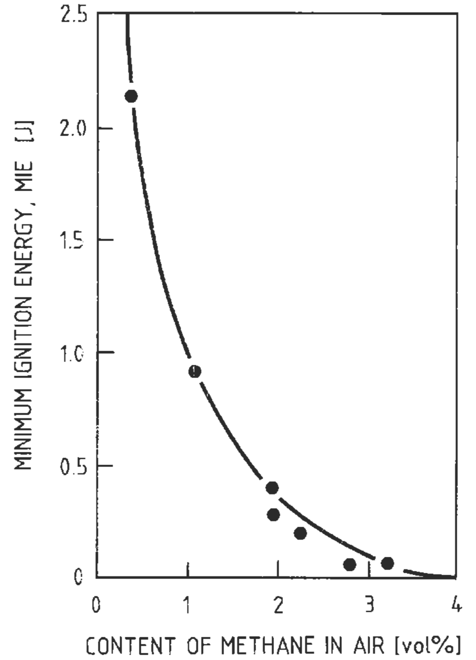


Figure 1.61 *The influence of methane content in the air on the minimum electric spark ignition energy of a coal dust of 31% volatile content. Average particle size is 40 μm. Note: This uses presumably short-duration sparks from a low-inductance, low-resistance capacitive discharge circuit (From Foniok, 1985).*

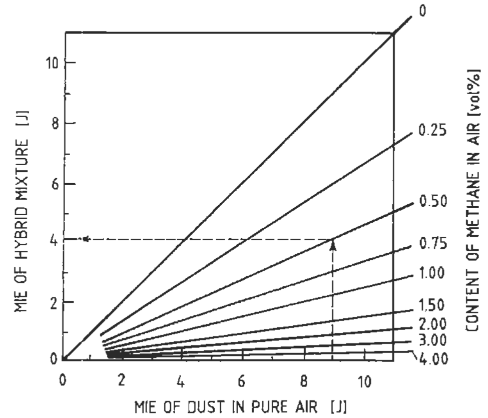


Figure 1.62 *Nomograph for minimum ignition energy of hybrid mixtures of dust and methane in air as a function of the methane content in the air and the minimum ignition energy of the dust in air only. Note: This uses a presumably short-duration capacitive circuit (From Foniok, 1985).*

It has been suggested that hybrid mixtures involving dusts that are very easy to ignite even without combustible gas in the air (MIE <10 mJ) may be ignited by electrostatic brush discharges, but definite proof of this has not been traced.

Figure 1.63 illustrates how the content of combustible gas in the air influences the percentage of inert dust required for inerting coal dust clouds.

One of the first systematic investigations of the influence of combustible gas in the air on the explosion violence of dust clouds was conducted by Nagy and Portman (1961). Their results are shown in Figure 1.64. The dust dispersion pressure is a combined arbitrary measure of the extent to which the dust is raised into suspension and dispersed and of the turbulence in the dust cloud at the moment of ignition. As can be seen, the maximum explosion pressure, with and without methane in the air, first rose, as the dust dispersion

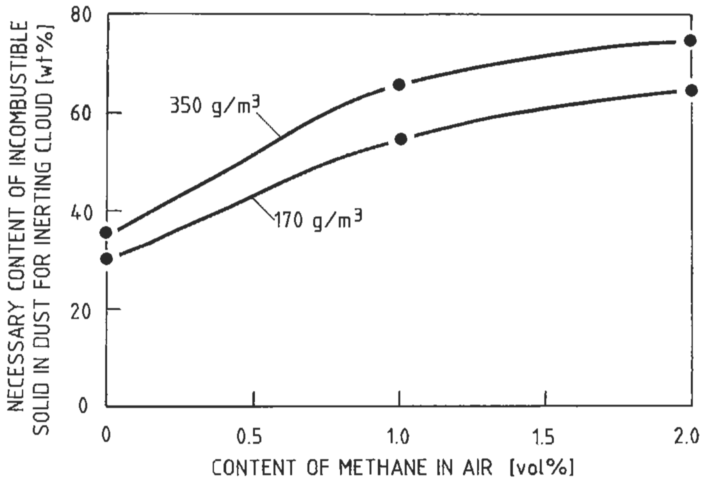


Figure 1.63 *The necessary mass percentage of incombustible solid material for clouds of dry coal dust of 38% volatiles and 10% ash in air containing various low percentages of methane (From Torrent and Fuchs, 1989).*

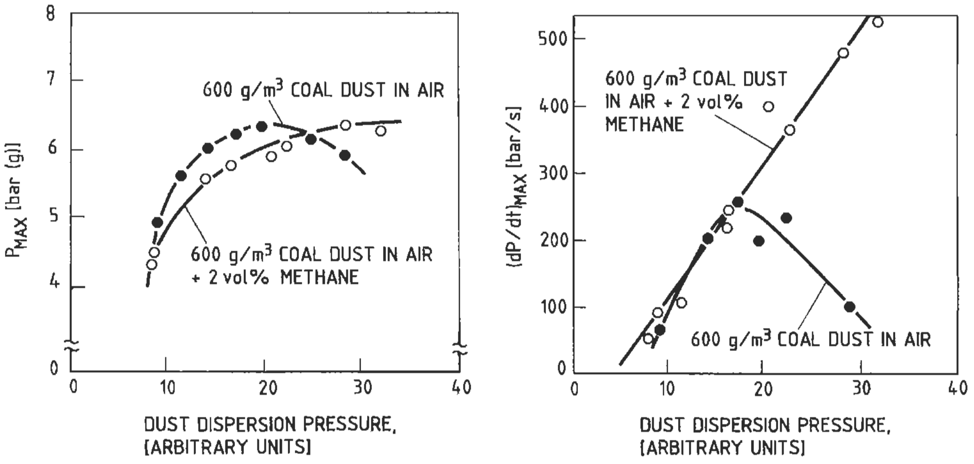


Figure 1.64 *Influence of 2 vol% methane in the air on maximum explosion pressure and maximum rate of pressure rise of coal dust in a 28 liter closed vessel at various levels of initial turbulence (From Nagy and Portman, 1961).*

was intensified. However, as the dust dispersion pressure was increased further, the dust without methane started to burn less efficiently, probably due to quenching by intense turbulence. In the presence of methane, this effect did not appear, presumably due to faster combustion kinetics. The influence of the methane was even more apparent for the maximum rate of pressure rise, which, for a dust dispersion pressure of 30 arbitrary units, dropped to less than 100 bar/s without methane, whereas with 2% methane, it increased further up to 500 bar/s. This comparatively simple experiment revealed important features of the kinetics of combustion of turbulent clouds of organic dusts. Ryzhik and Makhin (1978) also investigated the systematic decrease of the induction time for ignition of hybrid mixtures of coal dust/methane/air, in the methane concentration range 0–5 vol%.

Reeh (1978) conducted a comprehensive investigation of the influence of methane in the air on the violence of coal dust explosions. He concluded that the influence was strongest in the initial phase of the explosion. In the fully developed, large-scale, high-turbulence explosion, it made little difference whether gas or coal dust was the fuel.

Further illustrations of the influence of combustible gas or vapor in the air on the explosion violence are given in Figures 1.65 from Bartknecht (1978) and 1.66 from Dahn (1986). Dahn studied the influence of small fractions of xylene, toluene, and hexane in the air, on the maximum rate of pressure rise of explosions of a combustible waste dust in a 20 liter closed bomb. The waste dust originated from shredded materials, including paper and plastics. Its moisture content was 20% and the particle size <74 μm. Results for maize starch of 4–5% moisture content in hexane and air are also shown in Figure 1.66.

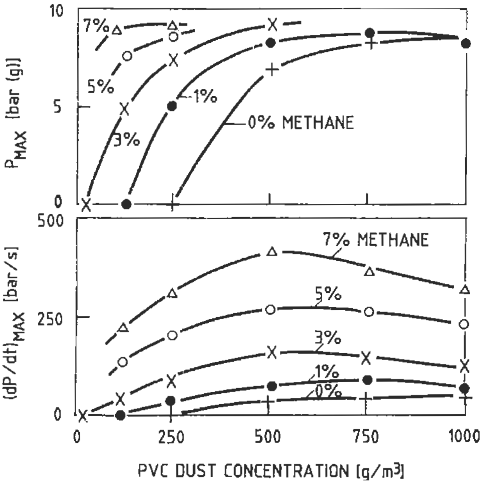


Figure 1.65 *The influence of small fractions of methane in the air on maximum explosion pressure and maximum rate of pressure rise in a 1 m^3 closed vessel, with a 10 kJ pyrotechnical igniter (From Bartknecht, 1978).*

Torrent and Fuchs (1989) found that both maximum explosion pressure and maximum rate of pressure rise of a dry coal dust of 38% volatiles and 10% ash in a closed 20 liter vessel, increased by 30% when 3 vol% methane was added to the air. There was a significant decrease of the dust concentrations that gave the most violent explosions, with increasing methane content, from 600–700 g/m³ without methane to about 300 g/m³ with 3 vol% methane. This agrees with the trend found by Foniok (1985) for the minimum ignition energy.

1.3.10
INERTING BY MIXING INERT DUST WITH COMBUSTIBLE DUST

This principle of inerting the dust cloud is of little practical interest apart from in mining. In coal mines, stone dust has been used extensively for this purpose for a long time.

Comprehensive information concerning that specific problem was provided by Cybulski (1975). Michelis (1984) indicated that satisfactory protection against propagation of coal dust explosions in mine galleries cannot be obtained unless the total content of combustible material in the mixture of coal dust and limestone is less than 20 wt%. This is

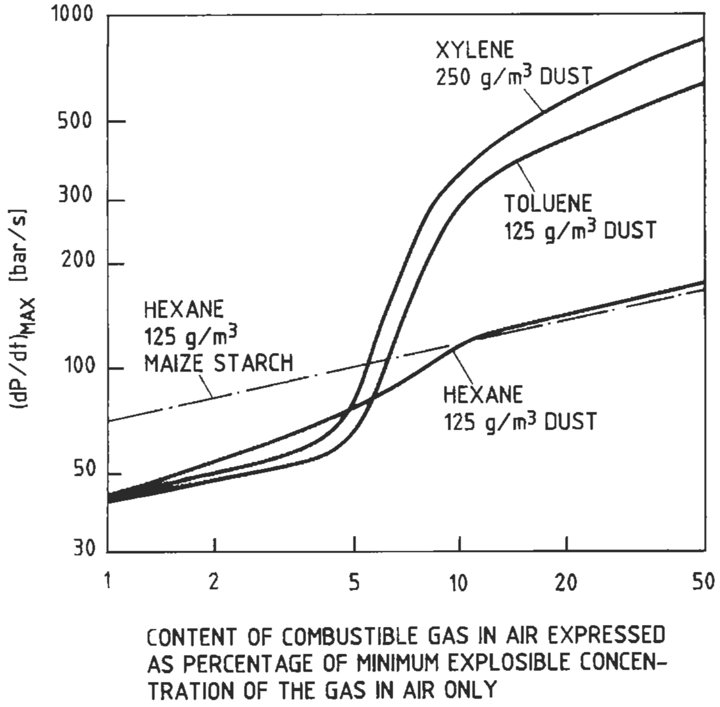


Figure 1.66 *Influence of low concentrations of various organic solvent vapors in the air on the maximum rate of pressure rise during explosions of organic dusts in a 20 liter closed vessel (From Dahn, 1986).*

not always easy to achieve in practice, and supplementary means of protection (water barriers etc.) must be employed.

A useful, more general analysis of the problem of inerting combustible dust clouds by adding inert dust was given by Bowes, Burgoyne, and Rasbash (1948).

Table A.3 in the Appendix gives some experimental data for the percentages of inert dusts required for inerting clouds in air of various organic dusts and coals.

1.3.11
CONCLUDING REMARKS

Section 1.3 is included primarily to bring into focus the various important parameters that influence ignitability and explosibility of dust clouds and to indicate main trends of their influence.

The extent to which the reader will find quantitative data that satisfy specific needs is bound to be limited. In particular, size distributions and specific surface areas of dusts of a given chemistry can vary considerably in practice. However, the quantitative information provided can help in identifying the type of more specific information needed in each case. In many cases, the required data have to be acquired by tailor-made experiments.

1.4
MEANS FOR PREVENTING AND MITIGATING DUST EXPLOSIONS

1.4.1
THE MEANS AVAILABLE: AN OVERVIEW

The literature on the subject is substantial. Many authors have written short, general surveys on the means of preventing and mitigating dust explosions in the process industry. A few examples are Gibson (1978); Scholl, Fischer, and Donat (1979); Kühnen and Zehr (1980); Field (1982b, 1987); Woodcock and Reed (1983); Siwek (1986, 1987); Swift (1987a, 1987b); and Bartknecht (1988). For more recent works, see Section 9.3.3. The books mentioned in Sections 1.1.1.5 and 9.1.2 also contain valuable information.

Table 1.9 gives an overview of the various means presently known and in use. They can be divided in two main groups, the means for preventing explosions and the means for their mitigation. The preventive means can again be split in the two categories, prevention of ignition sources and prevention of an explosible or combustible cloud. One central issue is whether preventing only ignition sources can provide sufficient safety, or is it also necessary, in general, to employ additional means of prevention or mitigation. In the following sections, the means listed in Table 1.9 are discussed separately.

Table 1.9 Means of preventing and mitigating dust explosions: a schematic overview

Prevention		
Preventing ignition sources	**Preventing explosible dust clouds**	**Mitigation**
a. Smoldering combustion in dust, dust flames	f. Inerting by N_2, CO_2, and rare gases	j. Partial inerting by inert gas
b. Other types of open flames (e.g. hot work)	g. Intrinsic inerting	k. Isolation (sectioning)
c. Hot surfaces	h. Inerting by adding inert dust	l. Venting
d. Electric sparks and arcs, electrostatic discharges	i. Dust concentration outside explosible range	m. Pressure-resistant construction
e. Heat from mechanical impact (metal sparks and hot spots)		n. Automatic suppression
		o. Good housekeeping (dust removal, cleaning)

1.4.2
PREVENTING IGNITION SOURCES

1.4.2.1
Introduction

The characteristics of various ignition sources are discussed in Section 1.1.4, and some special aspects are elucidated more extensively in Chapter 5. The test methods used for assessing the ignitability of dust clouds and layers, when exposed to various ignition sources are discussed in Chapter 7.

Several authors have written survey papers on the prevention of ignition sources in process plants. Kühnen (1978a) discussed the important question of whether preventing ignition sources can be relied on as the only means of protection against dust explosions. His conclusion was that this may be possible in certain cases but not in general. Adequate knowledge about the ignition sensitivity of the dust, both in cloud and layer form, under the actual process conditions, and proper understanding of the process, are definite preconditions. Schäfer (1978) concluded that relying on preventing ignition sources is impossible if the minimum electric spark ignition energy of the dust is in the region of vapors and gases (<10 mJ). However, for dusts of higher MIE, he specified several types of process plants that he considered could be satisfactorily protected against dust explosions solely by eliminating ignition sources.

In a more recent survey, Scholl (1989) concluded that the increased knowledge about ignition of dust layers and clouds permits the use of prevention of ignition sources as the sole means of protection against dust explosions, provided adequate ignition sensitivity tests have shown that the required ignition potential, as identified in standardized ignition sensitivity tests, is unlikely to occur in the process of concern. Scholl distinguished between organizational and operational ignition sources. The first group, which can largely be prevented by enforcing adequate working routines, includes

- Smoking.
- Open flames.
- Open light (bulbs).
- Welding (gas or electric).
- Cutting (gas or rotating disc).
- Grinding.

The second group arises within the process itself and includes

- Open flames.
- Hot surfaces.
- Self-heating and smoldering nests.
- Exothermic decomposition.
- Heat from mechanical impact between solid bodies (metal sparks or hot spots).
- Exothermic decomposition of dust via mechanical impact.
- Electric sparks and arcs and electrostatic discharges.

1.4.2.2

Self-Heating, Smoldering, and Burning of Large Dust Deposits

The tendency to self-heating in powder and dust deposits depends on the properties of the material. Therefore, the potential for self-heating should be known or assessed for any material before admitting it to storage silos or other parts of the plant where conditions are favorable for self-heating and subsequent further temperature rise up to smoldering and burning.

Possible means of preventing self-heating include

- Control of temperature, moisture content, and other important powder and dust properties before admitting powder or dust to, for example, storage silos.

- Adjustment of powder and dust properties to acceptable levels by cooling, drying, and the like, whenever required.
- Ensuring that heated solid bodies (e.g., a steel bolt heated and loosened by repeated impact) do not become embedded in the powder or dust mass.
- Continuous monitoring of temperature in the powder mass at several points by thermometer chains.
- Monitoring possible development of gaseous decomposition and oxidation products for early detection of self-heating.
- Rolling of bulk material from one silo to another, whenever the onset of self-heating is detected or as a routine after certain periods of storage, depending on the dust type.
- Inerting of bulk material in silo by suitable inert gas, such as nitrogen.

Thermometer chains in large silos can be unreliable because self-heating and smoldering may occur outside the limited regions covered by the thermometers.

Inerting by adding nitrogen or other inert gas may offer an effective solution to the self-heating problem. However, it introduces a risk of personnel being suffocated when entering areas that have been made inert. In the case of nitrogen inerting, the negative effects of lack of oxygen in the breathing atmosphere become significant in humans when the oxygen content drops to 15 vol% (air 21 vol%).

If inerting is adopted, it is important to take into account that the maximum permissible oxygen concentration for ensuring inert conditions in the dust deposit may be considerably lower than the maximum concentration for preventing explosions in clouds of the same dust. Walther (1989) conducted a comparative study with three different dusts, using a 20 liter closed spherical bomb for the dust cloud experiments and a Grewer furnace (see Chapter 7) for the experiments with dust deposits. In the case of the dust clouds, oxidizability was quantified in terms of the maximum explosion pressure at constant volume, whereas for the dust deposits, it was expressed in terms of the maximum temperature difference between the test sample and a reference sample of inert dust exposed to the same heating procedure. The results are shown in Figure 1.67. In the case of the pea flour, it is seen that self-heating took place in the dust deposit down to 5 vol% oxygen or even less, whereas propagation of flames in dust clouds was practically impossible below 15 vol% oxygen. Also, for the coals, there were appreciable differences.

Extinction of smoldering combustion inside large dust deposits, such as in silos, is a dual problem. The first part is to stop the exothermic reaction. The second, and perhaps more difficult part, is to cool down the dust mass. In general, the use of water should be avoided in large volumes. Limited amounts of water may enhance the self-heating process rather than quench it. Excessive quantities may increase the stress exerted by the powder or dust mass on the walls of the structure in which it is contained, and failure may result. Generally, addition of water to a powder mass, up to the point of saturation, reduces the flowability of the powder and makes discharge more difficult (see Chapter 3).

Particular care must be taken in the case of metal dust fires, where the use of water should be definitely excluded. Possible development of toxic combustion products must be taken into account.

The use of inert gases such as nitrogen and carbon dioxide has proven successful both for quenching the oxidation reaction and the subsequent cooling of smoldering combustion in silos. However, large quantities of inert gas are required, on the order of 10 tonnes or more, for a fair size silo. In the case of fine-grained products such as wheat

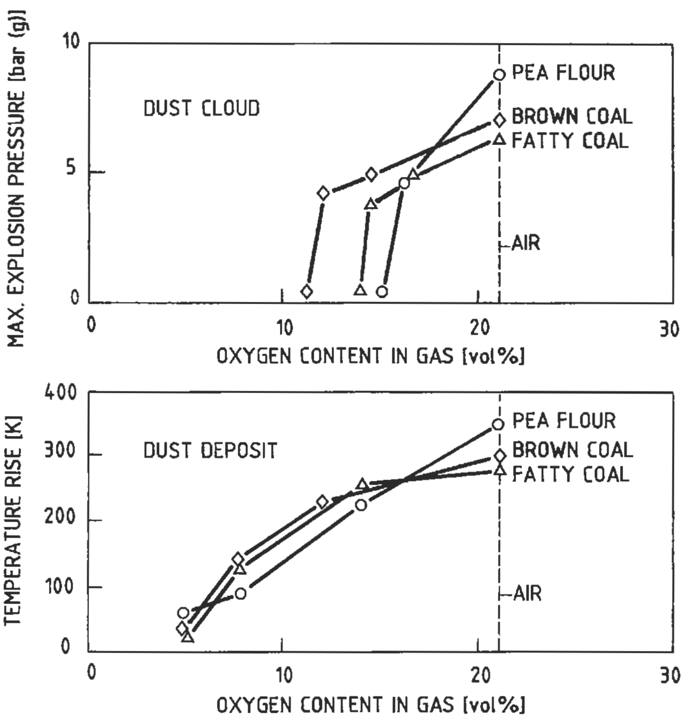


Figure 1.67 *Comparison of the influence of oxygen content in the gas on the oxidizability of dust clouds and dust deposits (From Walther, 1989).*

flour or corn starch, the permeability of the inert gas may be too low for efficient inerting of large bulk volumes.

Further details concerning the extinction of powder and dust fires are given by Palmer (1973a) and Verein deutscher Ingenieure (1986). The use of inert gas for extinction of smoldering fires in silos was specifically discussed by Dinglinger (1981) and Zockoll and Nobis (1981). Chapter 2 gives some examples of extinction of smoldering fires in practice.

Some synthetic organic chemicals, in particular cyclic compounds, can decompose exothermally and become ignited by a hot surface, a smoldering nest, frictional heat, or another ignition source. Such decomposition requires no oxygen, and therefore inerting has no effect. Zwahlen (1989) gave an excellent account of this special problem. He pointed out that this type of exothermic decomposition can be avoided only by eliminating all potential ignition sources. However, by taking other processing routes, one can eliminate or reduce the problem. Zwahlen suggested the following possibilities:

- Process the hazardous powder in a wet state, as a slurry or suspension.
- If wet processing is impossible, avoid processes involving internal moving mechanical parts that can give rise to ignition.
- If this is not possible, strictly control to prevent foreign bodies from entering the process. Furthermore, use detectors to observe early temperature and pressure rise and provide sprinkler systems. Adiabatic exothermal decomposition of bulk powder at constant volume, due to the very high powder concentration, can generate much higher pressures than a dust explosion in air.

- Generally, the processed batches of the powder should be kept as small as feasible.
- Use of additives that suppress the decomposition tendency may be helpful in some cases.

Section 9.3.5.2 in Chapter 9 gives further references to works on self-heating and smoldering.

1.4.2.3
Open Flames and Hot Gases

Most potential ignition sources of the open flame type can be avoided by enforcing adequate organizational procedures and routines. This, in particular, applies to the prohibition of smoking and other use of lighters and matches and to the enforcement of strict rules for performing hot work. Hot work must not be carried out unless the entire area that can come in contact with the heat from the work, indirectly as well as directly, is free of dust, and hazardous connections through which the explosion may transmit to other areas have been blocked.

Gas cutting torches are particularly hazardous, because they work with excess oxygen. This gives rise to ignition and primary explosion development where explosions in air would be unlikely.

In certain situations in the process industry, hot gaseous reaction products may entrain combustible dust and initiate dust explosions. Each such case has to be investigated separately and the required set of precautions tailored to the purpose in question.

Factory inspectors in most industrialized countries have issued detailed regulations for hot work in factories containing combustible powders or dusts.

1.4.2.4
Hot Surfaces

As pointed out by Verein deutscher Ingenieure (1986), hot surfaces may occur in industrial plants both intentionally and unintentionally. The first category includes external surfaces of hot process equipment, heaters, dryers, steam pipes, and electrical equipment. The equipment where hot surfaces may be generated unintentionally include engines, blowers and fans, mechanical conveyors, mills, mixers, bearings, and unprotected lightbulbs.

A further category of hot surfaces arises from hot work. One possibility is illustrated in Figure 1.10. During grinding and disk cutting, glowing hot surfaces are often generated, which may be even more effective as initiators of dust explosions than the luminous spark showers typical of these operations. This aspect has been discussed by Müller (1989).

A hot surface may ignite an explosible dust cloud directly or via ignition of a dust layer that subsequently ignites the dust cloud. Parts of glowing or burning dust layers may loosen and be conveyed to other parts of the process, where they may initiate explosions.

It is important to realize that the hot surface temperature in the presence of a dust layer can, due to thermal insulation by the dust, be significantly higher than it would normally be without dust. This both increases the ignition hazard and may cause failure of equipment due to the increased working temperature. The measures taken to prevent ignition by hot surfaces must cover both modes of ignition. The measures include

- Removal of all combustible dust before performing hot work.
- Prevention or removal of dust accumulations on hot surfaces.
- Isolation or shielding of hot surfaces.

- Use of electrical apparatus approved for use in the presence of combustible dust.
- Use of equipment with a minimal risk of overheating.
- Inspection and maintenance procedures that minimize the risk of overheating.

1.4.2.5
Smoldering Nests

Pinkwasser (1985, 1986) studied the possibility of dust explosions being initiated by smoldering lumps ("nests") of powdered material conveyed through a process system. The object of the first investigation (1985) was to disclose the conditions under which smoldering material that had entered a pneumatic conveying line would be extinguished, that is, cooled to a temperature range in which the risk of ignition in the downstream equipment was no longer present. In the case of >1 kg/m^3 pneumatic transport of screenings, low-grade flour and C3 patent flour, it was impossible to transmit a 10 g smoldering nest through the conveying line any significant distance. After only a few meters, the temperature of the smoldering lump had dropped to a safe level. In the case of lower dust concentrations, between 0.1 and 0.9 kg/m^3, that is, within the most explosible range, the smoldering nest could be conveyed for an appreciable distance, as shown in Figure 1.68, but no ignition was ever observed in the conveying line.

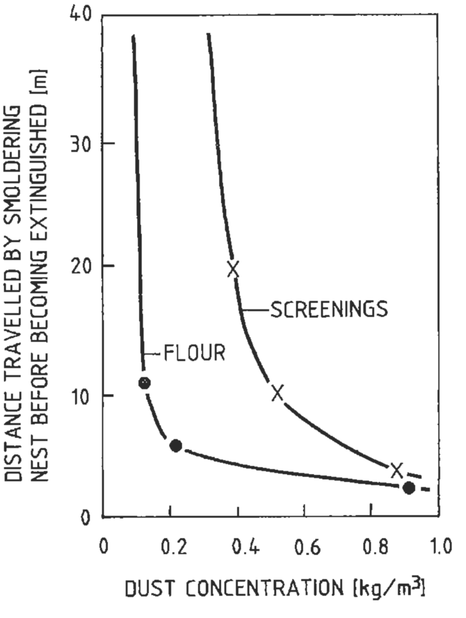


Figure 1.68 *The distance traveled in pneumatic transport by a smoldering nest before becoming extinguished, as a function of dust concentration in the pipe. The air velocity in the pipe is 20 m/s (From Pinkwasser, 1985).*

In the second investigation, Pinkwasser (1986) allowed smoldering nests of 700°C to fall freely through a 1 m tall column containing dust clouds of 100–1000 g/m^3 of wheat flour or wheat starch in air. Ignition was never observed during free fall. However, in some tests with nests of at least 25 mm diameter and weight at least 15 g, ignition occurred immediately after the nest had come to rest at the bottom of the test column. This may indicate the possibility that a smoldering nest, falling freely through a dust cloud in a silo without disintegrating during the fall, has a higher probability of igniting the dust cloud at the bottom of the silo than during the fall.

Jaeger (1989) conducted a comprehensive laboratory-scale investigation on formation of smoldering nests and their ability to ignite dust clouds. He found that only materials of flammability class larger than 3 (see Section A.1.2.9 in the Appendix) could generate smoldering nests. Under the experimental conditions adopted, he found that a minimum smoldering nest surface area of about 75 cm^2 and a minimum surface temperature of 900°C were required to ignite dust clouds of minimum ignition temperatures ≤600°C.

Zockoll (1989) studied the incendivity of smoldering nests of milk powder and concluded that such nests would not necessarily ignite clouds of milk powder in air. One condition for ignition by a moving smoldering nest was that the hottest parts of the surface of the nest were at least 1200°C. However, if the nest were at rest and a milk powder dust cloud settled on it, inflammation of the cloud occurred even at nest surface temperatures of about 850°C.

Zockoll suggested that, in the case of milk powder, the minimum size of the smoldering nest required for igniting a dust cloud is so large that carbon monoxide generation in the plant would be adequate to detect formation of the smoldering nests before the nests reach hazardous sizes.

Alfert, Eckhoff, and Fuhre (1989) studied the ignition of dust clouds by falling smoldering nests in a 22 m tall silo of diameter 3.7 m. They found that nests of low mechanical strength disintegrated during the fall and generated a large fire ball that ignited the dust cloud. Such mechanically weak nests cannot be transported any significant distance in, for example, pneumatic transport pipes before disintegrating. They further found that mechanically stable nests ignited the dust cloud either some time after having come to rest at the silo bottom or when broken during the impact with the silo bottom. However, as soon as the nest had come to rest at the silo bottom, it could also be covered with dust before ignition of the dust cloud got under way.

Infrared radiation detection and subsequent extinction of smoldering nests and their fragments during pneumatic transport, such as in dust extraction ducts, has proven an effective means of preventing fire and explosions in downstream equipment; for example, dust filters. One such system, described by Kleinschmidt (1983), is illustrated in Figure 1.69. Normally, the transport velocity in the duct is known, and this allows effective

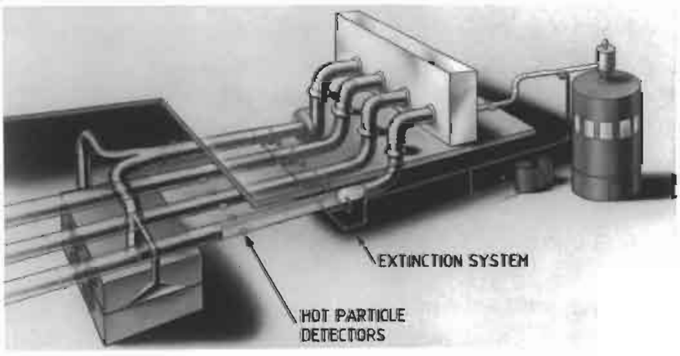


Figure 1.69 *An automatic system for detection and extinction of smoldering nests and their fragments, applied to a multiduct dust filter system (From Kleinschmidt, 1983).*

extinction by precise injection of a small amount of extinguishing agent at a convenient distance just when the smoldering or burning nest or fragment passes the nozzles. Water is the most commonly used extinguishing agent, and it is applied as a fine mist. Such systems are used mostly in the wood industries but also to some extent in the food and feed and some other industries. The field of application is not only to smoldering nests but also glowing or burning fragments from, say, sawing machines and mills. Further information is given in Sections 9.2.3.3, 9.3.5.2, and 9.3.5.3 in Chapter 9.

1.4.2.6
Heat from Accidental Mechanical Impact

Mechanical impacts produce two different kinds of potential ignition sources, small flying fragments of solid material and a pair of hot spots where the impacting bodies touch. Sometimes, such as in rotating machinery, impacts may occur repeatedly at the same points on one or both impacting bodies, and this may give rise to hot spots of appreciable size and temperature. The hazardous source of ignition then is a hot surface, and what has been said in Section 1.4.2.4 applies.

When it comes to single accidental impacts, there has been considerable confusion. However, research during the last decade has revealed that, in general, the ignition hazard associated with single accidental impacts is considerably smaller than often believed by many in the past. This applies, in particular, to dusts of natural organic materials, such as grain and feedstuffs, when exposed to accidental sparks from impacts between steel hand tools like spades or scrapers and other steel objects or concrete. In such cases, the ignition hazard is probably nonexistent, as indicated by Pedersen and Eckhoff (1987). The undue significance often assigned to "friction sparks" as initiators of dust explosions in the past, was also stressed by Ritter (1984) and Müller (1989).

However, if more sophisticated metals are involved, such as titanium or some aluminum alloys, energetic spark showers can be generated, and in the presence of rust, luminous, incendiary thermite flashes can result. Thermite flashes may also result if a rusty steel surface covered with aluminum paint or a thin smear of aluminum is struck with a hammer or another hard object. However, the impact of ordinary soft, unalloyed aluminum on rust seldom results in thermite flashes but just a smear of aluminum on the rust. For a given combination of impacting materials, the incendivity of the resulting sparks or flash depend on the sliding velocity and contact pressure between the colliding bodies (see Chapter 5).

Although the risk of initiation of dust explosions by accidental single impacts is probably smaller than believed by many in the past, there are special situations where the ignition hazard is real. It would in any case seem to be good engineering practice to

- Remove foreign objects from the process stream as early as possible.
- Avoid construction materials that can produce incendiary metal sparks or thermite flashes.
- Inspect work processes and remove the cause of impact immediately in a safe way whenever unusual noise indicating accidental impact(s) in process stream is observed.

Figures 1.70 and 1.71 show two examples of how various categories of foreign objects can be removed from the process stream before they reach the mills.

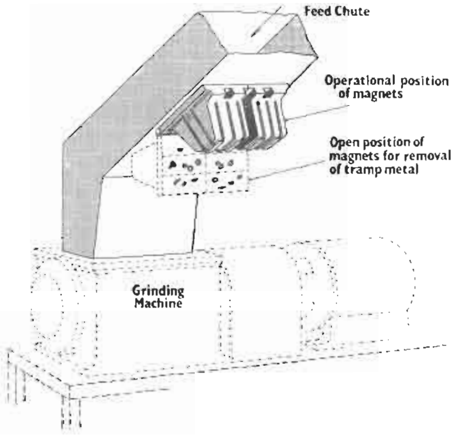


Figure 1.70 *A permanent magnetic separator fitted in the feed chute of a grinding mill to remove magnetic tramp metal (From Department of Employment and Productivity, 1970).*

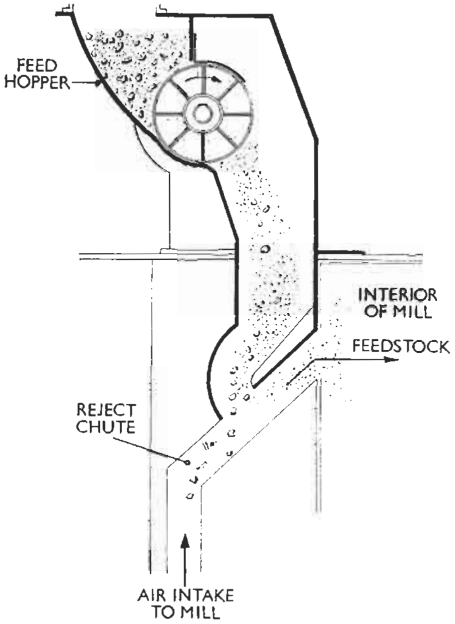


Figure 1.71 *A pneumatic separator can be used to remove most foreign bodies from the feed stock: the air current induced by the mill is adjusted to convey the feed stock and reject heavier foreign bodies (From Department of Employment and Productivity, 1970).*

1.4.2.7
Electric Sparks and Arcs and Electrostatic Discharges

The various types of electric sparks and arcs and electrostatic discharges are described in Section 1.1.4.6. Sparks between two conducting electrodes are discussed in more detail in Chapter 5. Sparks or arcs due to breakage of live circuits can occur when fuses blow, in rotating electric machinery, and when live leads are accidentally broken. The main rule for minimizing the risk of dust explosions due to such sparks and arcs is to obey the regulations for electrical installations in areas containing combustible dust. The electrostatic hazard is more complex and it has not always been straightforward to specify clearly defined design guidelines. However, Glor (1988) contributed substantially to developing a unified approach. As a general guideline, he recommends the following measures:

- Use conductive materials or materials of low dielectric strength, including coatings, (breakdown voltage across dielectric layer or wall, <4 kV) for all plant items that may accumulate very high charge densities (pneumatic transport pipes, dust deflector plates, and walls of large containers that may become charged due to ionization during gravitational compaction of powders). This prevents propagating brush discharges.

- Ground all conductive parts of equipment that may become charged. This prevents capacitive spark discharges from equipment.
- Ground personnel if powders of minimum ignition energies <100 mJ are handled. This prevents capacitive spark discharges from humans.
- Ground electrically conductive powders (metals, etc.) by using grounded conductive equipment without nonconductive coatings. This prevents capacitive discharges from conductive powder.
- If highly insulating material (resistivity of powder in bulk $>10^{10}$ Ωm) in the form of coarse particles (particle diameter >1 mm) is accumulated in large volumes in silos, containers, hoppers, or the like, electrostatic discharges from the material in bulk may occur. These discharges can be hazardous when a fine combustible dust fraction of minimum ignition energy <10–100 mJ is present simultaneously. So far, no reliable measure is known to avoid this type of discharge in all cases, but a grounded metallic rod introduced into the bulk powder will most probably drain away the charges safely. It is, however, not yet clear whether this measure is always successful. Therefore, the use of explosion venting, suppression, or inerting should be considered under these circumstances.
- If highly insulating, fine powders (resistivity of powder in bulk $>10^{10}$ Ωm) with a minimum ignition energy ≤10 mJ, as determined with a low-inductance capacitive discharge circuit, is accumulated in large volumes in silos, containers, hoppers, or the like, measures of explosion protection should be considered. There is no experimental evidence that fine powders with no coarse particles generate discharges from powder heaps, but several explosions have been reported with such powders in situations where all possible ignition sources, with the exception of electrostatic, have been effectively eliminated.

If combustible powders are handled or processed in the presence of a flammable gas or vapor (hybrid mixtures), the use of electrically conductive and grounded equipment is absolutely essential. Insulating coatings on grounded metallic surfaces may be tolerated, provided the thickness is less than 2 mm, the breakdown voltage is less than 4 kV at locations where high surface charge densities have to be expected, and the conductive powder cannot become isolated from the grounding by the coating. If the powder is nonconducting (resistivity of the powder in bulk $>10^6$ Ωm), measures of explosion prevention (e.g., inert gas blanketing) are strongly recommended. If the resistivity of the powder in bulk is less than 10^6 Ωm, brush discharges, which would be incendiary for flammable gases or vapors, can also be excluded.

Glor pointed out, however, that experience has shown that, even in the case of powders of resistivities in bulk $<10^6$ Ωm it is very difficult in practice to exclude all kinds of effective ignition sources when flammable gases or vapors are present. In such cases, large amounts of powders therefore should be handled and processed only in closed systems blanketed with an inert gas.

Further details, including a systematic step-by-step approach for eliminating the electrostatic discharge ignition hazard, were provided by Glor (1988). He also considered the specific hazards and preventive measures for different categories of process equipment and operations, such as mechanical and pneumatic conveying systems, sieving operations, and grinding, mixing, and dust collecting systems. Sections 9.2.3.4 and 9.3.5.4 in Chapter 9 give references to more recent works.

1.4.3
PREVENTING EXPLOSIBLE DUST CLOUDS

1.4.3.1
Inerting by Adding Inert Gas to the Air

The influence of the oxygen content of a gas on the ignitability and explosibility of dust clouds was discussed in Section 1.3.6. For a given dust and type of added inert gas, there is a certain limiting oxygen content, below which the dust cloud is unable to propagate a self-sustained flame. By keeping the oxygen content below this limit throughout the process system, dust explosions are excluded. As the oxygen content in the gas is gradually reduced from that of air, the ignitability and explosibility of the dust cloud is also gradually reduced, until ultimately flame propagation becomes impossible. Figure 1.72 shows some of the results from the experiments by Palmer and Tonkin (1973) in an industrial-scale experimental facility. Solid lines separate the experiments that yielded no flame propagation at all, flame propagation in part of the tube, and flame propagated the entire length of the tube.

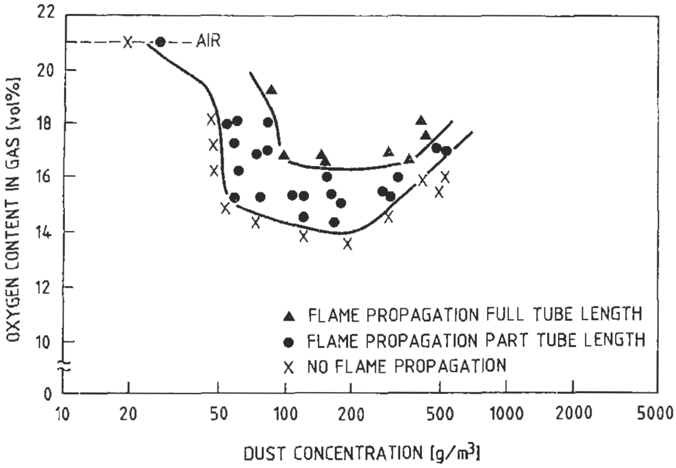


Figure 1.72 *Concentration range of flammability of clouds of phenol formaldehyde (15 μ is: CO_2. Experiments are in a vertical tube of diameter 0.25 m and length 5 m. Flame propagated upward (From Palmer and Tonkin, 1973).*

Schofield and Abbott (1988) and Wiemann (1989) have given useful overviews of the possibilities and limitations for implementing gas inerting in industrial practice. Five types of inert gases are in common use for this purpose:

- Carbon dioxide.
- Water vapor.
- Flue gases.
- Nitrogen.
- Rare gases.

Fischer (1978) also included halogenated hydrocarbons (halons) in his list of possible gases for inerting. However, due to the environmental problems caused by these substances, they may no longer be permitted for protecting against explosions and fires.

The choice of inert gas depends on several considerations, such as availability and cost, possible contaminating effects on products, and effectiveness. In the case of dusts of light metals, such as aluminum and magnesium, exothermic reactions with CO_2 and also in some situations with N_2 are known, and the use of rare gases may have to be considered in certain cases.

Table A.2 in the Appendix gives some data for the maximum permissible oxygen concentration in the gas for inerting clouds of various dusts.

The design of gas inerting systems depends on whether the process is continuous or of the batch type, the strength of the process equipment, and the type and source of inert gas. Two main principles are used to establish the desired atmosphere in the process:

- Pressure variation method.
- Flushing method.

The pressure variation method operates either above or below atmospheric pressure. In the former case, the process equipment, initially filled with air at atmospheric pressure, is pressurized to a given overpressure by inert gas. When good mixing of air and inert gas has been obtained, the process equipment is vented to the atmosphere and the cycle repeated until a sufficiently low oxygen content has been reached. The alternative is to first evacuate the process equipment to a certain underpressure, then fill with inert gas to atmospheric pressure, and repeat the cycle the required number of times. By assuming ideal gases, as shown by Wiemann (1989), there is a simple relationship between the oxygen content c_2 (vol%) at the end of a cycle and the content c_1 at the beginning, as a function of the ratio of the highest and lowest absolute pressures of the cycle.

$$c_2 = c_1(P_{\text{max}}/P_{\text{min}})^{1/n} \tag{1.13}$$

where $n = 1$ for isothermal and $n = C_p/C_v$ for adiabatic conditions.

The flushing method is used if the process equipment has not been designed for the significant pressure increase or vacuum demanded by the pressure variation method. It is useful to distinguish between two extreme cases of the flushing method, the replacement method (plug flow) and the through-mixing method (stirred tank). To maintain plug flow, the flow velocity of inert gas into the system must be low (<1 m/s) and the geometry must be favorable for avoiding mixing. In practice, this is very difficult to achieve; and the stirred tank method, using high gas velocities and turbulent mixing, is normally employed. It is essential that the instantaneous through mixing is complete over the entire volume; otherwise, pockets of unacceptably high, hazardous oxygen concentrations may form. Wiemann (1989) referred to the following equation relating the oxygen content c_2 (vol%) in the gas after flushing and the oxygen content c_1 before flushing:

$$c_2 = (c_1 - c_r)e^{-v} + c_r \tag{1.14}$$

where c_r is the content of oxygen, if any, in the inert gas used, and v is the ratio of the volume of inert gas used in the flushing process, and the process volume flushed. Leaks in the process equipment may cause air to enter the inerted zone. Air may also be introduced when powders are charged into the process. It is important, therefore, to control the oxygen content in the inerted region, at given intervals or sporadically, depending on the size and complexity of the plant. The supply of inert gas must also be controlled.

Oxygen sensors must be located in regions where the probability of hitting the highest oxygen concentrations in the system is high. A sensor located close to the inert gas inlet is unable to detect hazardous oxygen levels in regions where they are likely to occur. Wiemann (1989) recommended that the maximum permissible oxygen content in practice be 2–3 vol% lower than the values determined in standard laboratory tests (see Chapter 7 and Table A.2 in the Appendix).

Various types of oxygen detectors are in use. The fuel cell types are accurate and fast. However, their lifetime is comparatively short, of the order of 6 months–1 year, and they operate only within a comparatively narrow temperature range. Zirconium dioxide detectors are very sensitive to oxygen and cover a wide concentration range with high accuracy and fast response. They measure the partial pressure of oxygen irrespective of temperature and water vapor. However, if combustible gases or vapors are present in the gas, they can react with oxygen in the measurement zone and cause systematically lower readings than the actual overall oxygen content, which can be dangerous. There are also oxygen detectors that utilize the paramagnetic or thermomagnetic properties of oxygen. Even these detectors are sufficiently fast and accurate for monitoring inerting systems for industrial process plants. However, nitrogen oxides can cause erratic results.

Wiemann emphasized two limitations of the gas inerting method when applied to dust clouds. First, as already illustrated by Figure 1.67, inerting to prevent dust explosions does not necessarily inert against self-heating and smoldering combustion. Second, also mentioned earlier, the use of inert gas in an industrial plant inevitably generates a risk of accidental suffocation. The limit where significant problems start to arise is 15 vol% oxygen. If flue gases are used, there may also be toxic effects.

Fischer (1978) also mentioned several technical details worth considering when designing systems for inerting of process plants to prevent dust explosions. He discussed specific examples of protection of industrial plants against dust explosions by gas inerting. Heiner (1986) was specifically concerned with the use of carbon dioxide for inerting silos in the food and feed industry.

The actual design of gas inerting systems can take many forms. Combinations with other means of prevention and mitigation of dust explosions are often used. Figure 1.73 illustrates nitrogen inerting of a grinding plant. More recent works on inerting are reviewed in Section 9.3.6.1 in Chapter 9.

In Table 1.9, *partial inerting*, as opposed to the complete inerting discussed so far, is included as a possible means of mitigating dust explosions. This concept implies the addition of a smaller fraction of inert gas to the air than required for complete inerting. In this way, the ignition sensitivity, the explosion violence, and the maximum constant-volume explosion pressure all can be reduced appreciably, which means a corresponding reduction of the explosion risk. Partial inerting may be worth considering in combination with other means of prevention or mitigation when complete inerting is financially unacceptable. More recent works on partial inerting are reviewed in Section 9.3.7.4 in Chapter 9. See also Section 1.3.6.

1.4.3.2
Dust Concentration Outside the Explosible Range

In principle, one could avoid dust explosions by running the process in such a way that explosible dust concentrations are avoided (see Section 1.3.4). In practice, however, this is difficult in most cases, because the dust concentration inside process equipment most often varies in unpredictable and uncontrollable ways.

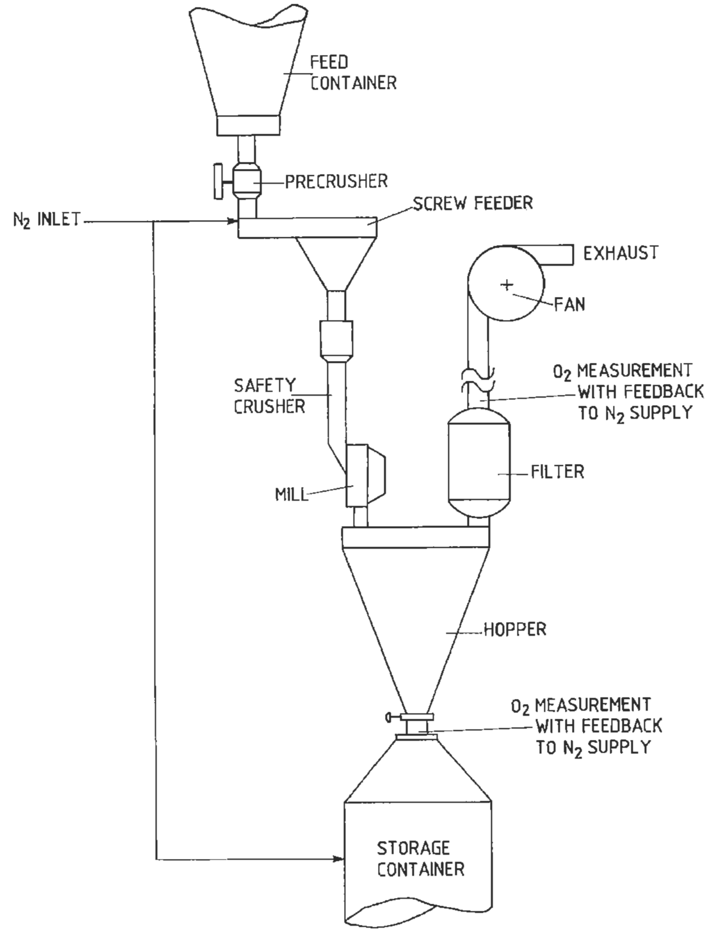


Figure 1.73 *Grinding plant inerted by nitrogen (Simplified version of illustration from Bartknecht, 1978).*

On the other hand, maintaining the powder or dust in the settled state by avoiding entrainment or fluidization in the air is one way of ensuring that the dust concentration is either zero or well above the upper explosible concentration. Good process design can significantly reduce the regions in which explosible dust concentrations occur, as well as the frequency of their occurrence. One example is the use of mass flow silos instead of the traditional funnel flow type (see Perry and Green, 1984).

In some special cases, it may be possible to avoid explosible dust clouds by actively keeping the dust concentration below the lower explosible limit. One such case is dust extraction ducts, another is cabinets for electrostatic powder coating, and the third is dryers. The second case is discussed in Section 1.5.3.5.

Ritter (1978) indicated that the measure of keeping the dust concentration below the minimum explosible concentration can also be applied to spray dryers, and Table 1.13 in Section 1.5.2 shows that Noha (1989) considered this a means of protection for several types of dryers. Noha also included dust concentration control when discussing explosion protection of crushers and mills (Table 1.12), mixers (Table 1.14), and conveyors and dust removal equipment (Table 1.15). However, in these contexts, the dust concentration is below the minimum explosible limit due to the inherent nature of the process rather than active control.

An essential requirement for controlling dust concentration is that the concentration can be adequately measured. Nedin et al. (1971) reviewed various methods used in the metallurgical industry in the USSR, based mostly on direct gravimetrical determination of the dust mass in isokinetically sampled gas volumes. Stockham and Rajendran (1984) and Rajendran and Stockham (1985) reviewed a number of dust concentration measurement methods with a view to dust control in the grain, feed, and flour industry. In-situ methods based on light attenuation or backscattering of light were found to be most suitable.

Ariessohn and Wang (1985) developed a real-time system for the measurement of dust concentrations up to about 5 g/m^3 under high-temperature conditions (970°C). Midttveit (1988) investigated an electrical capacitance transducer for measuring the particle mass concentration of particle/gas flows. However, such transducers are unlikely to be sufficiently sensitive to allow dust concentration measurements in the range below the minimum explosible limit.

Figure 1.74 shows a light attenuation dust concentration measurement station developed by Eckhoff and Fuhre (1975) and installed in the 6 in. diameter duct extracting dust from the boot of a bucket elevator in a grain storage plant. The long-lifetime light source is a conventional 12 V car lamp run at 4 V. A photoresistor and a bridge circuit were used to measure the transmitted light intensity at the opposite end of the duct diameter.

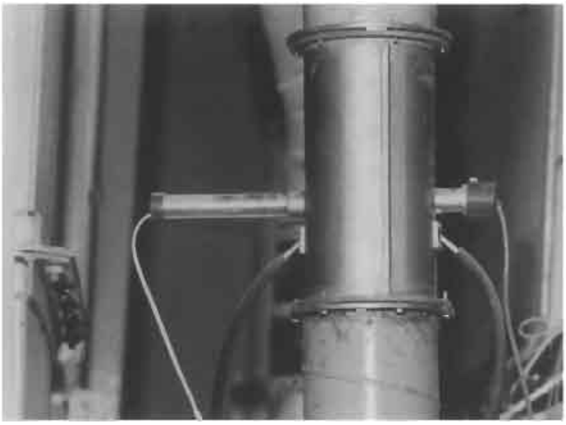


Figure 1.74 *Light attenuation dust concentration measurement station mounted in the dust explosion duct on a bucket elevator boot in a grain storage facility in Stavanger (From Eckhoff and Fuhre, 1975).*

The light source and photoresistor were protected from the dust by two glass windows flush with the duct wall. The windows were kept free from dust deposits by continuous air jets (the two inclined tubes just below the lamp and photoresistor in Figure 1.74).

Figure 1.75 shows the calibration data for clouds of wheat grain dust (10% moisture) in air. The straight line indicates that Lambert-Beer's simple concentration law for molecular species applies to the system used.

Figure 1.76 illustrates a type of light attenuation dust concentration measurement probe developed more recently, using a light emitting diode (LED) as light source and a photodiode

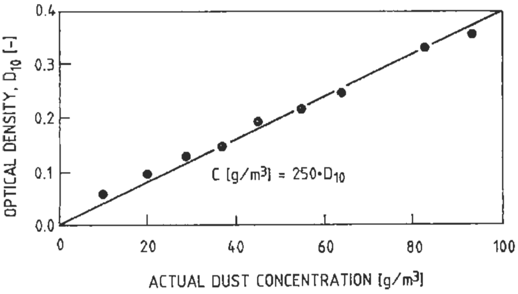


Figure 1.75 *Optical density of clouds in air of wheat grain dust containing 10% moisture, length of light path is 150 mm, optical density D_{10} is defined as*

$$\log_{10}\left(\frac{\text{incident light intensity}}{\text{light intensity after 150 mm}}\right)$$

(From Eckhoff and Fuhre, 1975).

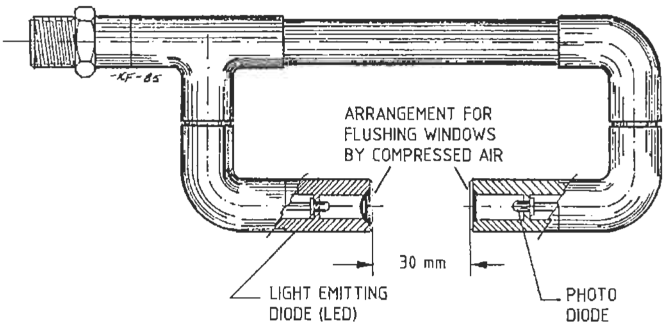


Figure 1.76 *Light attenuation probe for measurement of concentration of dust clouds, used by Eckhoff et al. (1985).*

for detecting transmitted light. This concept was probably first introduced by Liebman, Conti, and Cashdollar (1977), with subsequent improvement by Conti, Cashdollar, and Liebman (1982). The particular probe design in Figure 1.76 was used successfully by Eckhoff, Fuhre, and Pedersen (1985) to measure concentration distributions of maize starch in a large-scale (236 m^3) silo. The compressed air for flushing the glass windows of the probe was introduced via the metal tubing constituting the main probe structure.

However, in the case of dust explosions in the silo, the heat from the main explosion and from afterburns, required extensive thermal insulation of the probes to prevent damage.

A light path length of 30 mm was chosen to cover the explosible range of maize starch in air. The calibration data are shown in Figure 1.77. If this kind of probe is to be used for continuous monitoring of dust concentrations below the minimum explosive limit, such as in the range of 10 g/m^3, paths considerably longer than 30 mm are required to make the instrument sufficiently sensitive. Other dust materials and particle sizes and shapes may also require other path lengths. In general, it is necessary to calibrate light attenuation probes for each particulate dust and concentration range to be monitored.

The use of dust control in dust extraction systems is most likely to be successful if a small dust fraction is to be removed from a coarse main product, such as grain dust from grain or

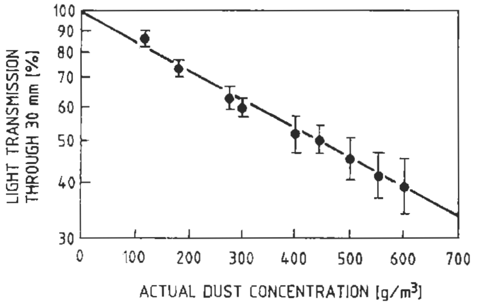


Figure 1.77 *Calibration data for light attenuation dust concentration probe in Figure 1.76 for native maize starch in air (From Eckhoff et al., 1985).*

plastic dust from pellets. By monitoring dust concentrations and controlling airflows, the desired level of dust concentration can be maintained. However, if the air velocities are too low to prevent dust deposits on the internal walls of the ducting over time, dust explosions may nevertheless be able to propagate through the ducts (see Section 1.3.4 and Chapter 4).

Possible dust entrainment and formation of explosible dust clouds by the air blast preceding a propagating dust explosion may also occur in mixers, conveyors, and the like, where sufficient quantities of fine dust are deposited. This means that, in many cases, dust concentration control is feasible for preventing only the primary explosion initiation, not propagation of secondary explosions. References to more recent works on minimum explosion dust concentrations are reviewed in Section 9.2.4.3 in Chapter 9.

1.4.3.3
Adding Inert Dust

This principle is used in coal mines, by providing sufficient quantities of stone dust either as a layer on the mine gallery floor or on shelves and the like. The blast that always precedes the flame in a dust explosion then entrains the stone dust and coal dust simultaneously and forms a mixture that is incombustible in air; and the flame, when arriving, is quenched.

In industries other than mining, adding inert dust is seldom applicable, due to contamination and other problems. It is nevertheless interesting to note the special wartime application for protecting flour mills against dust explosions initiated by high-explosive bombs, suggested by Burgoyne and Rashbash (1948). Table A.3 in the Appendix contains some data for the percentage inert dust required for producing inert dust clouds with various combustible materials.

1.4.4
PREVENTING EXPLOSION TRANSFER BETWEEN PROCESS UNITS VIA PIPES AND DUCTS: EXPLOSION ISOLATION

1.4.4.1
Background

There are three main reasons for trying to prevent a dust explosion in one process unit from spreading to others via pipes and ducts. First, there is always a desire to limit the extent of the explosion as far as possible.

Second, a dust flame propagating in a duct between two process units tends to accelerate due to flow-induced turbulence in the dust cloud ahead of the flame. For a sufficiently long duct, this may result in a vigorous flame jet entering the process unit at the downstream end of the duct. The resulting extreme combustion rates can generate very high explosion pressures, even if the process unit is generously vented. This effect was demonstrated in a dramatic way for flame-jet-initiated explosions of propane/air in a generously vented 50 m^3 vessel by Eckhoff et al. (1980, 1984), as shown in Figure 1.78. There is no reason not to expect very similar effects for dust explosions.

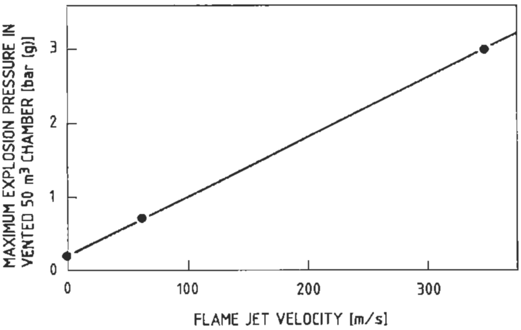


Figure 1.78 *Influence of flame jet ignition in the maximum explosion pressure for stoichiometric propane/air in a 50 m^3 vented chamber: vent orifice diameter 300 mm, vent 4.7 m^2, no vent cover (From Eckhoff et al., 1980).*

The third main reason for preventing flame propagation between process units is pressure piling. This implies that the pressure in the unburned dust cloud in the downstream process unit(s) increases above atmospheric pressure due to compression caused by the expansion of the hot combustion gases in the unit where the explosion starts and the connecting duct(s). As shown in Section 1.3.8, the final explosion pressure in a closed vessel is proportional to the initial pressure. Therefore, in a coupled system, higher explosion pressures than would be expected from atmospheric initial pressure can occur transiently due to pressure piling. This was demonstrated in a laboratory-scale gas explosion experiment by Heinrich (1989), as shown in Figure 1.79.

In spite of the marked cooling by the walls in this comparatively small experiment, the transient peak pressure in V_2 significantly exceeded the adiabatic constant volume pressure of about 7.5 bar(g) for atmospheric initial pressure. Extremely serious situations can arise if flame jet ignition and pressure piling occur simultaneously. See also Section 9.3.7.3 in Chapter 9.

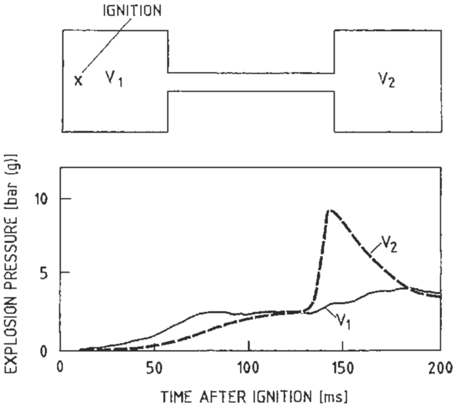


Figure 1.79 *Pressure development in two closed vessels of 12 liters each, filled with 10% methane in air at atmospheric initial pressure and connected with a 0.5 m long duct, following ignition at the location indicated (From Heinrich, 1989).*

1.4.4.2
Published Overviews of Methods for Isolation

Basically there are two categories of methods, the passive ones activated directly by the propagating explosion and the active ones, which require a separate flame or pressure sensor system that triggers a separately powered system to operate the isolation mechanism. For obvious reasons, the passive systems are generally preferable, if they function as intended and are otherwise suitable for the actual purpose.

Several authors have discussed the different technical solutions for interrupting dust explosions in the transfer system between process equipment. Walter (1978) concentrated on methods for stopping or quenching explosions in ducts. The methods included automatic, very rapid injection of extinguishing agent in the duct ahead of the flame front, and various kinds of fast response mechanical valves. Scholl et al. (1979) also included the concept of passive flame propagation interruption in ducts by providing a vented 180° bend system (see Figure 1.82). Furthermore, they discussed the use of rotary locks for preventing explosion transfer between process units or a process unit and a duct. Czajor (1984) and Faber (1989a) discussed the same methods as covered by Scholl et al. and added a few more. See also Section 9.3.7.3 in Chapter 9.

1.4.4.3
Screw Conveyors and Rotary Locks

One of the first systematic investigations described in the literature is probably that by Wheeler (1935). Two of his screw conveyor designs are shown in Figure 1.80.

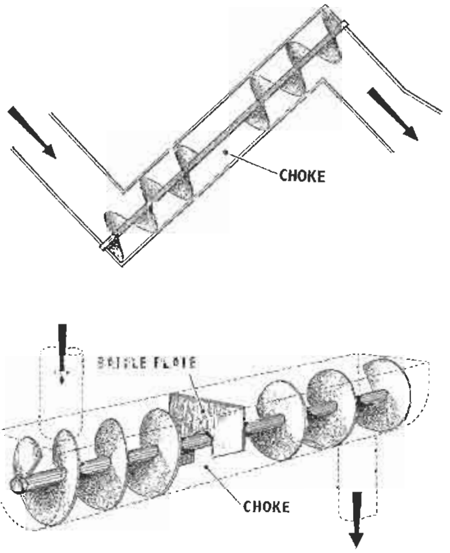


Figure 1.80 *Screw conveyors designed to prevent transmission of dust explosion (From Wheeler, 1935).*

The removal of part of the screw ensures that a plug of bulk powder or dust always remains as a choke. Wheeler conducted a series of experiments in which rice meal explosions in a 3.5 m^3 steel vessel were vented through the choked screw conveyors and through a safety vent at the other end of the vessel. Dust clouds were ejected at the downstream end of the conveyors but no flame.

Wheeler conducted similar experiments with rotary locks. A hopper section mounted on top of the rotary lock was connected to the 3.5 m^3 explosion vessel. Even when the hopper was empty of rice meal, there was no flame transmission through the rotary lock. When the hopper contained rice meal and the rotary lock was rotating, there was not even transmission of pressure, and the rice meal remained intact in the hopper.

In more recent years, Schuber (1989) and Siwek (1989a) conducted extensive studies of the conditions under which a rotary lock is capable of preventing transmission of dust explosions. Schuber provided a nomograph by which critical design parameters for explosion-transmission-resistant rotary locks can be determined. The minimum ignition energy and minimum ignition temperature of the dust must be known. However, the nomograph does not apply to metal dust explosions. Explosions of fine aluminum are difficult to stop by rotary locks. Schuber's work is described in detail in Chapter 4 in the context of the maximum experimental safe gap (MESG) for dust clouds. Figure 1.81 illustrates how a rotary lock may be used to prevent transmission of a dust explosion from one room in a factory to the next.

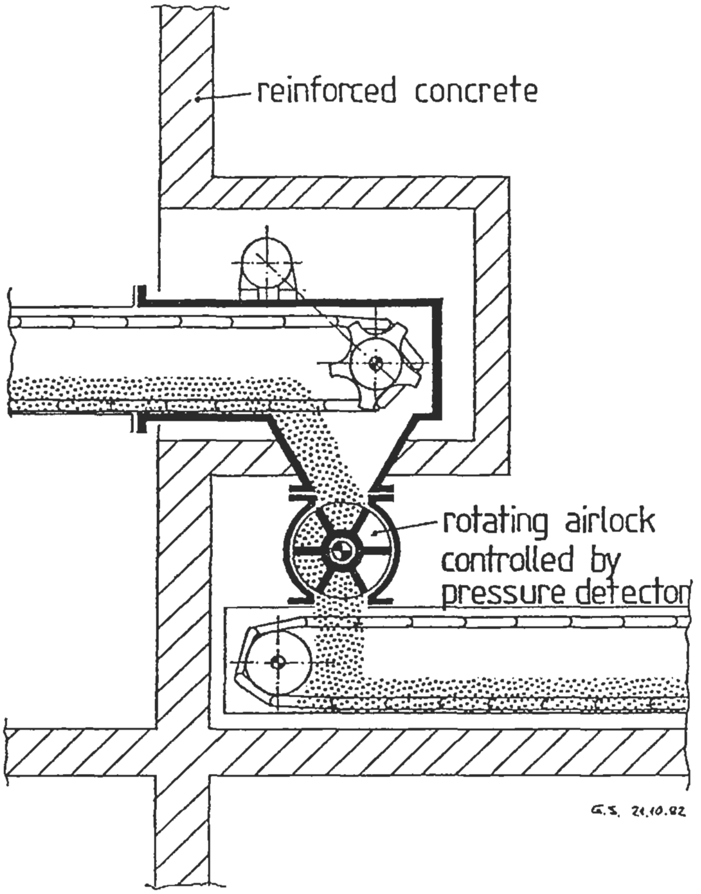


Figure 1.81 *Explosion isolation of two rooms using a rotary lock (Courtesy of T. Pinkwasser and G. Schuber, Bühler, Switzerland).*

1.4.4.4
Passive Devices for Interrupting Dust Explosions in Ducts

The device illustrated in Figure 1.82 was described relatively early by Scholl et al. (1979) and subsequently by others.

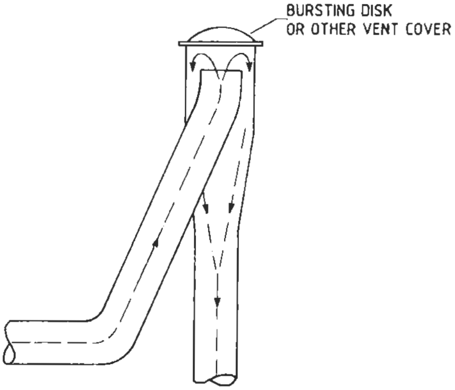


Figure 1.82 *Section through device for interrupting dust explosions in ducts by combining change of flow direction and venting. Flow direction may also be opposite to that indicated by arrows.*

The basic principle is that the explosion is vented at a point where the flow direction is changed by 180°. Due to the inertia of the fast flow caused by the explosion, the flow tends to maintain its direction rather than making a 180° turn. However, the boundaries for the applicability of the principle have not been fully explored. Parameters that may influence performance include the explosion properties of dusts, velocity of flame entering the device, direction of flame propagation, and direction, velocity, and pressure of initial flow in duct. Faber (1989) proposed a simplified theoretical analysis of the system shown in Figure 1.82, as a means of identifying proper dimensions. Figure 1.83 shows

Figure 1.83 *Device for interrupting dust (and gas) explosions in ducts by combining change of flow direction and venting (Courtesy of Fike Corporation, Blue Springs, MO, USA).*

a commercial unit. Figure 1.84 illustrates how the same basic principle may be applied to 90° bends at corners of buildings. Another passive device for interrupting dust (and gas) explosions in ducts is the Ventex valve described by Rickenbach (1983) and illustrated in Figure 1.85.

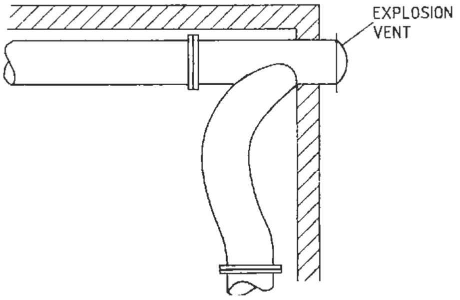


Figure 1.84 *Arrangement for interrupting or mitigating dust explosions in ducts by venting at 90° bends in corners of buildings.*

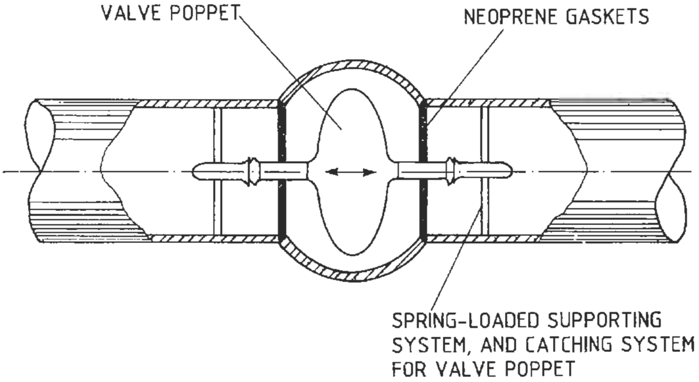


Figure 1.85 *Ventex valve for passive interruption of dust explosions in ducts (From Rickenbach, 1983).*

In normal operation, the dust cloud being conveyed in the duct flows around the valve poppet without causing any significant offset as long as the flow velocity is less than about 20 m/s. However, in an explosion in the duct, the preceding blast pushes the valve poppet in the axial direction until it hits the neoprene gasket, where it is held in position by a mechanical catch lock, which can be released from the outside. Because of the inserts, the Ventex valve is perhaps more suitable when the dust concentration is low than for clouds of higher concentrations.

Active Ventex valves are also being used. In this case, a remote pressure or flame sensor activates a separately powered system that closes the valve in the desired direction prior to arrival of the flame.

1.4.4.5
Active Devices for Interrupting Dust Explosions in Ducts

Bartknecht (1980, 1982), Ebert (1983), Brennecke (1987), and Chatrathi and De Good (1988) discussed the ability of various types of fast-closing slide valves to interrupt dust explosions in ducts. The required closing time depends on the distance between the remote pressure or flame sensor and the valve and on the type of dust. Often closing times as short as 50 ms, or even shorter, are required. This most often is obtained by using an electrically triggered explosive charge for releasing the compressed air or nitrogen that operates the valve. The slide valve must be sufficiently strong to resist the high pressures of 5–10 bar(g) that can occur on the explosion side after valve closure (in the case of pressure piling effects and detonation, the pressures may transiently be even higher than this).

Figure 1.86 shows a typical valve and compressed gas reservoir unit. Figure 1.87 shows a special valve triggered by a fast-acting solenoid instead of by an explosive charge. This permits nondestructive checks of valve performance. Bartknecht (1978)

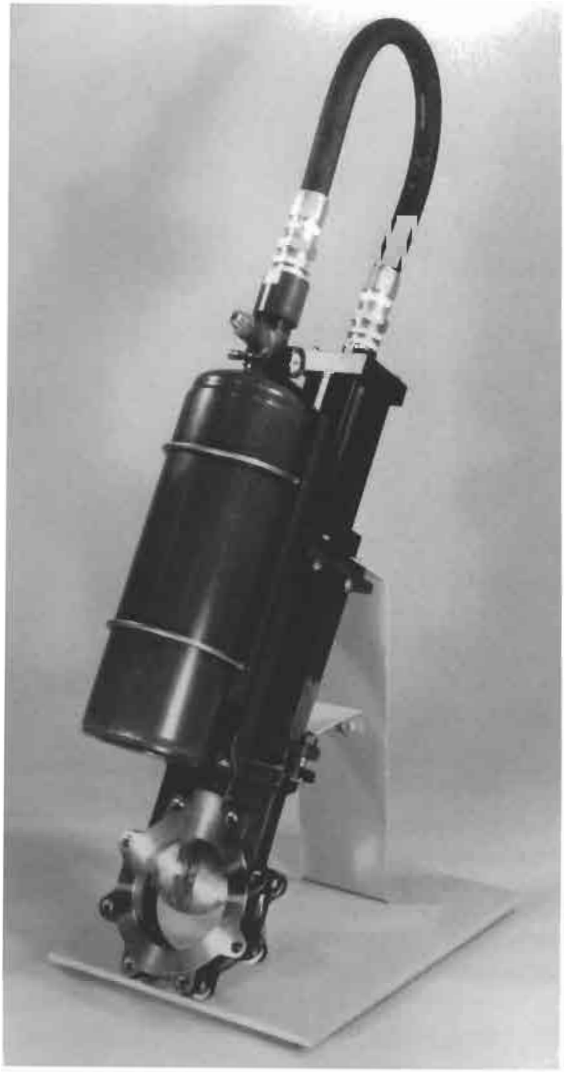


Figure 1.86 *Compressed-gas-driven, fast-clocking slide valve actuated by an explosive charge (Courtesy of Fike Corporation, Blue Springs, MO, United States).*

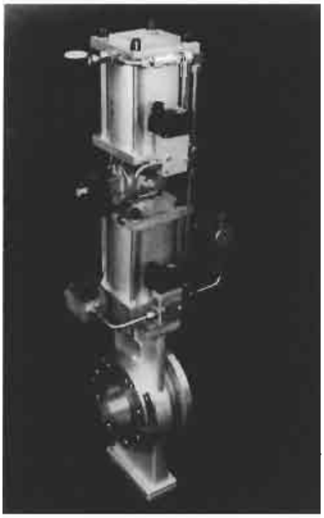


Figure 1.87 *Compressed-gas-driven, fast-closing slide valve actuated by a fast solenoid (Courtesy of IRS, Darmstadt, Germany).*

described successful performance of a fast-closing (30 ms) compressed-gas-operated flap valve, illustrated in Figure 1.88. Figure 1.89 illustrates an active (pressure sensor) fast-closing compressed-gas-driven valve that blocks the duct at the entrance rather than further downstream.

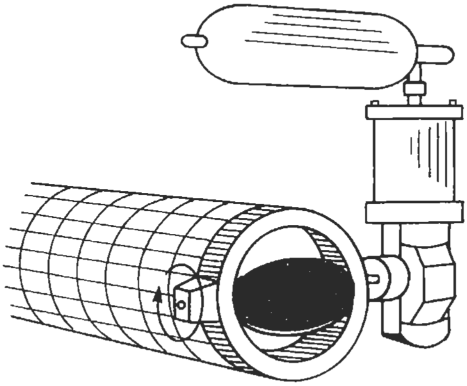


Figure 1.88 *A compressed-gas-driven, fast-closing flap valve.*

The last active isolation method of dust explosions in ducts and pipes to be mentioned is interruption by fast automatic injection of extinguishing chemicals ahead of the flame. The system is illustrated in Figure 1.90. This is a special application of the automatic explosion suppression technique, which is described in Section 1.4.7. Bartknecht (1978, 1987) and Gillis (1987) discussed this special application and gave some data for the design of adequate performance by such systems. Important parameters are the type of dust, initial turbulence in primary explosion, duct diameter, distance from vessel where primary explosion occurs, method used for detecting the onset of the primary explosion, and type, quantity, and rate of release of the extinguishing agent.

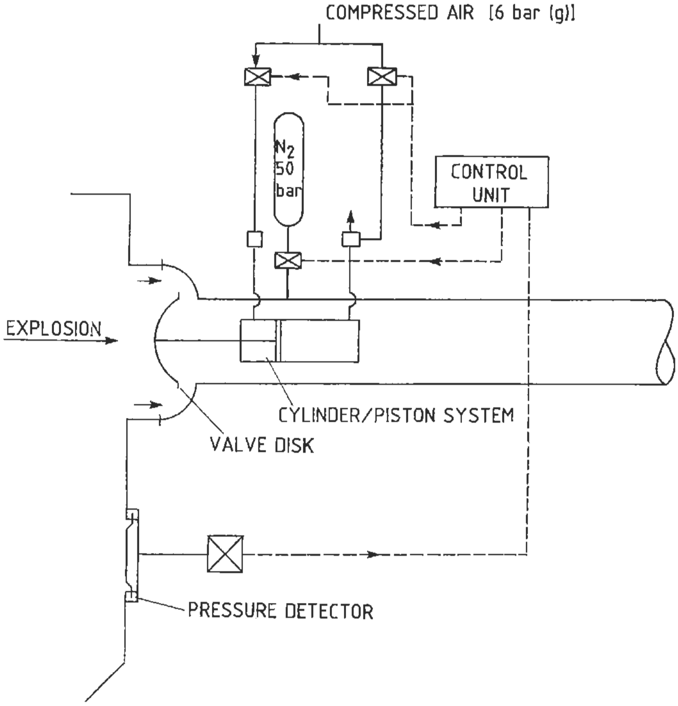


Figure 1.89 *Active fast-closing, compressed-gas-driven valve system for blocking the opening between the process unit where the primary explosion occurs and the duct or pipe. Nitrogen is injected into the duct or pipe simultaneously with the valve being closed, to obtain additional protection.*

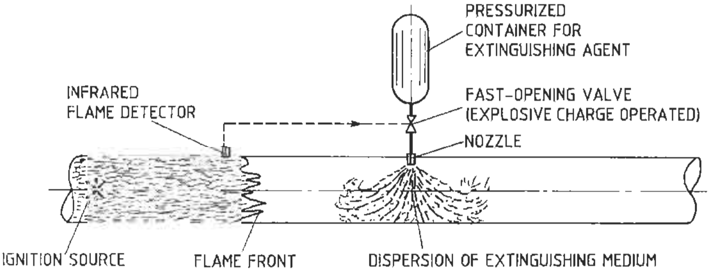


Figure 1.90 *A system for interrupting dust explosions in ducts by fast automatic injection of an extinguishing agent ahead of the flame.*

1.4.5
EXPLOSION-PRESSURE-RESISTANT EQUIPMENT

1.4.5.1
Background

If a dust cloud becomes ignited somewhere in the plant, a local primary dust explosion occurs. As discussed in Sections 1.4.6 and 1.4.7, the maximum explosion pressure in such a primary explosion can be effectively reduced to tolerable levels. However, in some cases, it is preferred to make the process apparatus in which the primary explosion occurs so strong that it can withstand the full maximum explosion pressure under adiabatic, constant volume conditions. Such pressures are typically in the range 5–12 bar(g) (see Table A1 in the Appendix. See also Sections 9.3.7.2 and 9.3.7.7 in Chapter 9.)

1.4.5.2
The "Explosion Strength" of a Process Unit

The development of a stringent philosophy for the design of process equipment that has to withstand dust explosions is to a large extent due to the work of Donat (1978, 1984). More recent summaries of the subject were given by Kirby and Siwek (1986), Pasman and van Wingerden (1988) and Margraf and Donat (1989).

Donat (1978) introduced the useful distinction between pressure-resistant design and pressure-shock-resistant design. The first applies to pressure vessels that must be capable of withstanding the maximum permissible pressure for long periods without becoming permanently deformed. In principle, this concept could be used to design explosion-resistant equipment, by requiring that the process unit be designed as a pressure vessel for a maximum permissible working pressure equal to the maximum explosion pressure to be expected. However, experience has shown that this is a very conservative and expensive design. Pressure-shock-resistant design means that the explosion is permitted to cause slight permanent deformation of the process unit, as long as the unit does not rupture. This means that, for a given expected maximum explosion pressure, a considerably less heavy construction is sufficient than is required for pressure vessels. The difference is illustrated in Figure 1.91, which applies to enclosures made of ferritic steels (plate steels). The pressure vessel approach would require that the apparatus be constructed so heavy that the maximum deformation during an explosion inside the vessel would not exceed two-thirds the yield strength or one-quarter the tensile strength. The pressure-shock-resistant approach allows the explosion pressure to stress the construction right up to the yield point.

For austenitic (stainless) steels the stress-versus-strain curve does not show such a distinct yield point as in Figure 1.91. In such cases, the pressure vessel approach specifies the maximum permissible working stress as two-thirds the stress that gives a strain of 1%, whereas for the pressure-shock-resistant design, the maximum permissible stress is

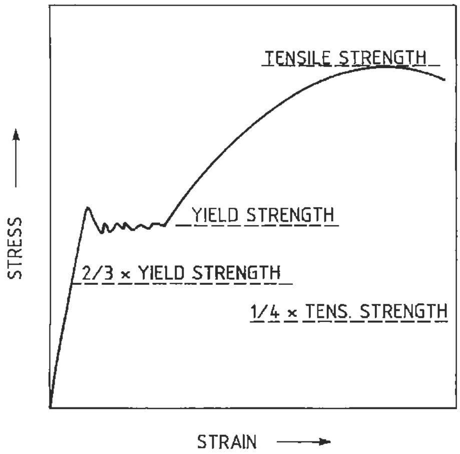


Figure 1.91 *Schematic stress-versus-strain curve for ferritic steel (From Kirby and Siwek, 1986).*

the one that gives a strain of 2%. However, in the latter case, repair of deformed process equipment must be foreseen, should an explosion occur.

If dust explosions in the plant of concern were fairly frequent events, one might consider the use of the pressure vessel design approach, because the deformations that often result with the pressure-shock-resistant design would be avoided. This is a matter of analyzing cost versus benefit. From the point of view of safety, the main concern is to protect personnel, that is, avoid the rupture of process equipment.

The field of structural response analysis has undergone substantial development over the past decades. Finite element techniques are now available for calculating stress and strain distributions on geometrically complex enclosure shapes, resulting from any given internal overpressure. Two examples are shown in Figures 1.92 and 1.93.

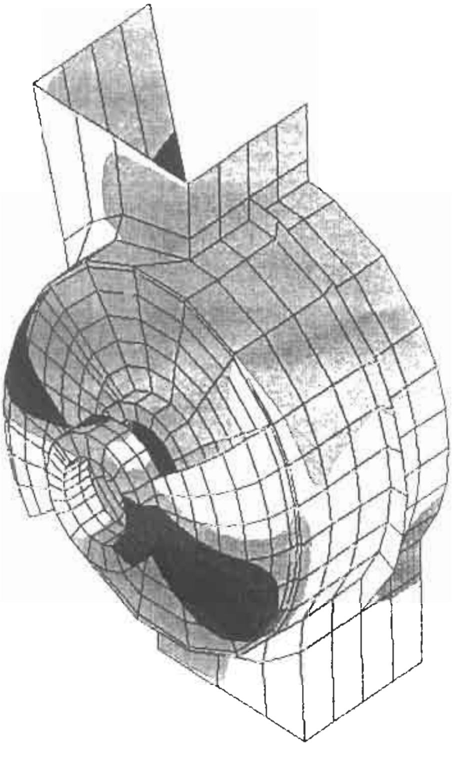


Figure 1.92 *Finite element design of a rotary lock housing capable of withstanding 10 bar(g) internal pressure (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

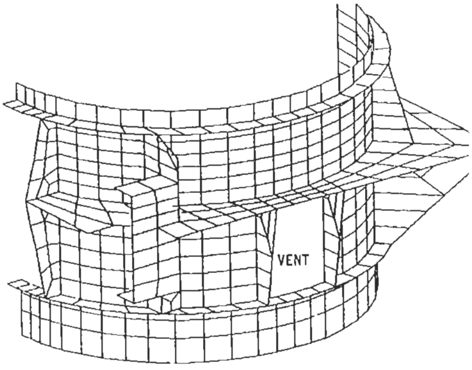


Figure 1.93 *Section of finite element network of cylindrical casing of a pneumatic unloaded tower, with explosion vent opening. The diameter of the tower is 2 m (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

1.4.5.3
The Influence of the Dynamics of the Explosion Load

Pasman and van Wingerden (1988) discussed the influence of the dynamic characteristics of the explosion load on the structural response. Typical dust explosion pressure pulses in industrial equipment have durations in the range 0.1–1.0 s. In general, the shorter the load pulse, the stiffer and stronger the equipment behave. Some quantitative data illustrating this were given by Kirby and Siwek (1986). However, the energy transfer from the dust cloud to the enclosure walls is enhanced if the load pulse frequency equals the characteristic resonance frequency of the enclosure system. In this case, acceleration and inertial forces become important, and the load exceeds the value that would result if the maximum explosion pressure were applied as a static load.

Pasman and van Wingerden conducted a series of propane/air and acetylene/air explosions in various equipment typical of the powder production and handling industry. These included bins, ducts, an elevator head, eight cyclones, and a fan housing. The observed structural response (deformation etc.) was correlated with the maximum explosion pressure and details of the construction of the equipment (number and dimensions of bolts in flanges, plate thicknesses). In spite of the complexity of the problem, it was possible to indicate some quantitative design criteria.

It nevertheless seems that direct explosion testing of full-scale process equipment prototypes will remain a necessity for some time. But, as illustrated in Figures 1.92 and 1.93, finite element techniques for structural response calculations are developing rapidly; and if these can be coupled to realistic dynamic explosion loads, the computer may replace full-scale explosion tests in a not too distant future.

Valuable further information concerning the response of mechanical structures to various types of explosion load was provided by Baker et al. (1983) and Harris (1983).

1.4.6
EXPLOSION VENTING

1.4.6.1
What Is Explosion Venting?

The basic principle of explosion venting is illustrated in Figure 1.94. The maximum explosion pressure in the vented explosion, P_{red}, is a result of two competing processes:

- Burning of the dust cloud, which develops heat and increases the pressure.
- Flow of unburned, burning, and burned dust cloud through the vent, which relieves the pressure.

The two processes can be coupled via flow-induced turbulence that can increase the burning rate.

The maximum permissible pressure, P_{red}, depends on the construction of the enclosure and whether a pressure vessel design or a pressure-shock-resistant design is adopted, as discussed in Section 1.4.5. Constructions of comparatively thin steel plates may require reinforcement to obtain the P_{red} required. An example is shown in Figure 1.95.

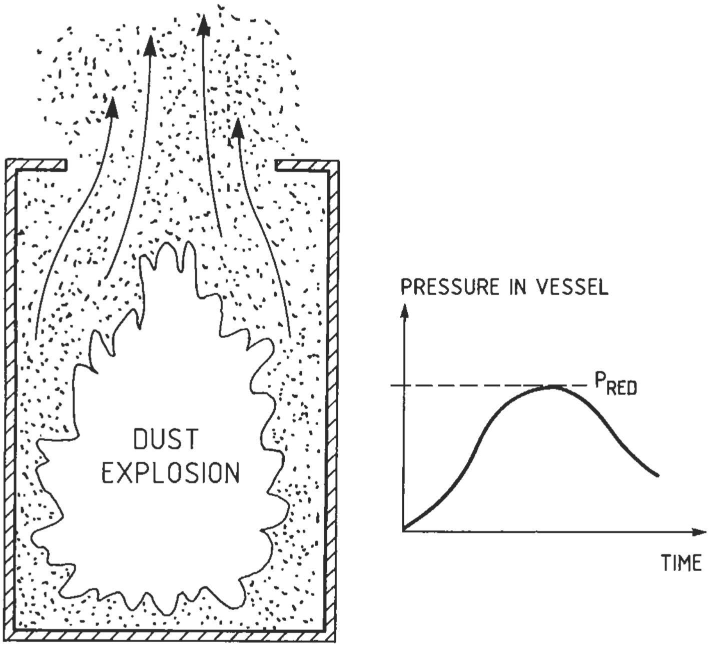


Figure 1.94 *The basic principle of dust explosion venting: Provision of an opening controlled discharge of unburned, burning, and burned dust cloud keeps the maximum pressure inside the vessel below a predetermined limit, P_{red}.*

Figure 1.95 *Reinforced vented 6 m^3 bag filter enclosure: P_{red} = 0.4 bar(g), pressure-shock-resistant construction. The vent cover is a 0.85 m^2 three-layer bursting panel (Courtesy of Infastaub Brilon, Rembe, Germany).*

1.4.6.2
Vent Area Sizing

Through the systematic work by Bartknecht (1978) and others, it has become generally accepted that the required area of the vent opening depends on the

- Enclosure volume.
- Enclosure strength (P_{red}).
- Strength of vent cover (P_{stat}).
- Burning rate of dust cloud.

For some time it was thought by many that the burning rate of the dust cloud was a specific property of a given dust, which could be determined once and for all in a standard 1 m^3 closed vessel test (K_{St} value, see Chapter 4).

However, some researchers, including Eckhoff (1982a), emphasized the practical significance of the fact that a given dust cloud at worst case concentration can have widely different combustion rates, depending on the turbulence and degree of dust dispersion in the actual industrial situation. The influence of the dust cloud combustion rate on the maximum vented explosion pressure is illustrated in Figure 1.96.

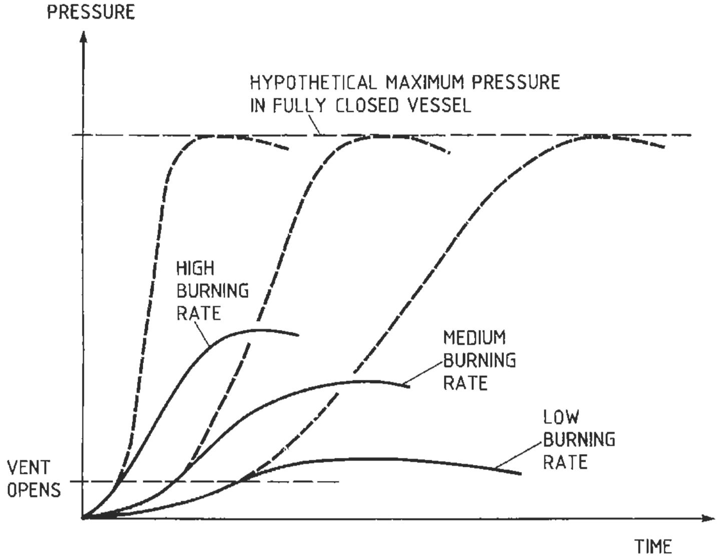


Figure 1.96 *Explosion pressure versus time in vented dust explosions with a given dust at worst case concentration in a given enclosure with a given vent, for three different dust cloud burning rates (different turbulence intensities and degrees of dust dispersion).*

During the 1980s, new experimental evidence in support of the differentiated view on dust explosion venting was produced, as discussed in detail in Chapter 6. Over the next decade, the differentiated nature of the problem has also become gradually accepted as a necessary and adequate basis for vent sizing. Sections 9.2.4.7 and 9.3.7.5 in Chapter 9 review the statistics per 2003.

As discussed in Chapters 4 and 7, a measure of the combustion rate of a dust cloud in air can be obtained by explosion tests in a standardized closed vessel. In these tests, the maximum rate of rise of the explosion pressure is determined as a function of dust concentration, and the highest value is normally used for characterizing the combustion rate. Eckhoff, Alfert, and Fuhre (1989) found that, in practice, it is difficult to discriminate between dusts of fairly close maximum rates of pressure rise; and it seems reasonable to work with a few, rather wide hazard classes of dusts. The classification used in the past in the Federal Republic of Germany comprises three classes. The first, St1, covers dusts that generate up to 200 bar/s in the 1 m^3 closed vessel test adopted by the International Standards Organization (1985). The second class, St2, covers the range 200–300 bar/s, whereas the most severe class, St3, comprises dusts of >300 bar/s. Pinkwasser (private communication, 1989) suggested that the large St1 class be split in two at 100 bar/s, which may be worth considering.

Various vent area sizing methods used in different countries are discussed in Chapter 6. Figure 1.97 summarizes what presently seems to be a reasonable compromise for dusts in the St1 class. The example shown is a 4.5 m^3 enclosure designed to withstand an internal pressure of 0.4 bar(g). If the process unit is a mill or other equipment containing highly turbulent and well-dispersed dust clouds, the vent area requirement is 0.48 m^2. If, however, the equipment is a silo, a cyclone, or a bag filter, the required vent area is smaller, in the range 0.1–0.25 m^3.

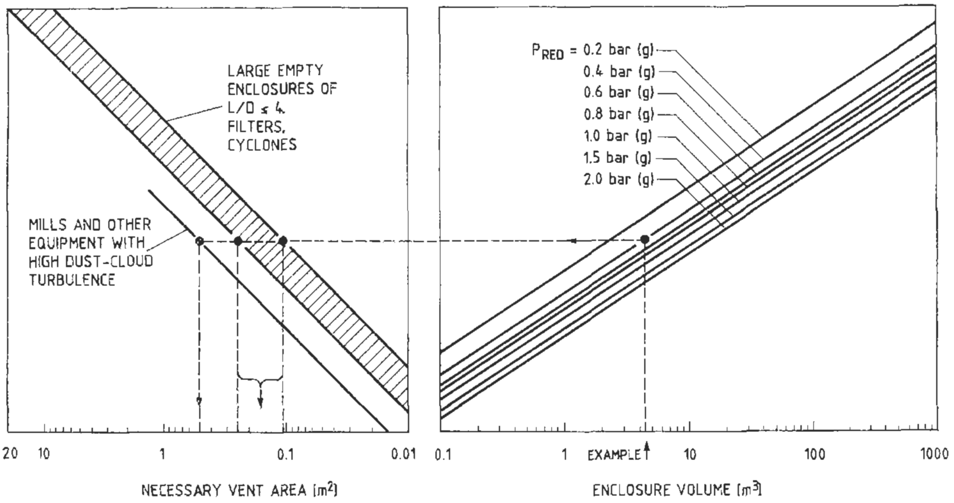


Figure 1.97 *Modified nomograph from VDI 3673 (1979) for St1 dusts (0 < K_{St} < 200 bar • m/s) and static vent cover opening pressures P_{stat} of ≤0.1 bar(g). Length of diameter ratio of enclosure ≤4. The example shown is an enclosure of volume 4.5 m^3 and strength P_{red} of 0.4 bar(g).*

Further details concerning vent area sizing, such as for enclosures of large length-to-diameter ratios, are given in Chapter 6. Vent areas may be scaled using approximate formulas, as also discussed in Chapter 6. See also Sections 9.2.4.7, 9.2.4.8, and 9.3.7.5 in Chapter 9.

1.4.6.3
Vent Covers

A wide range of vent cover designs are in use, as shown in the comprehensive overview by Schofield (1984). Some designs are based on systematic research and testing, whereas others are more arbitrary. Beigler and Laufke (1981) carried out a critical inventory of vent covers used in the Swedish process industries for venting of process equipment as well as workrooms. Their conclusion was that a number of the vent covers inspected would not have performed adequately in the event of an explosion. They emphasized the need for ensuring that the static opening pressure of the vent cover is sufficiently low and remains so over time and that the mass of the cover is sufficiently small to permit rapid acceleration once released. Beigler (1983) subsequently developed an approximate theory for the acceleration of a vent cover away from the vent opening.

One quite simple type of vent cover is a light but rigid panel, such as an aluminum plate, held in position by a rubber clamping profile as used for mounting windows in cars. The principle is illustrated in Figure 1.98.

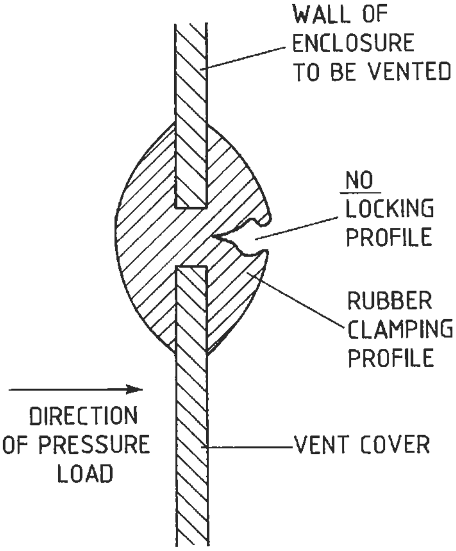


Figure 1.98 *Vent cover plate held in position by a rubber clamping profile.*

Other methods for keeping the vent cover in place include various types of clips. When choosing a method to secure the panel, it is important to make sure that the pressure, P_{stat}, needed to release the vent panel is small compared with the maximum tolerable explosion pressure, P_{red}. It is further important to anchor the vent panel to the enclosure to be vented; for example, by means of a wire or a chain. Otherwise, the panel may become a hazardous projectile in an explosion. Finally, it is important to make sure that rust formation or other processes do not increase the static opening pressure of the vent cover over time.

Bursting panels constitute a second type of vent covers. In the past, such panels were often "homemade," and adequate data for the performance of the panels were lacking. A primary requirement is that P_{stat}, the static bursting pressure of the panel, is considerably lower than the maximum permissible explosion pressure, P_{red}. Figure 1.99 shows a classic example of what happens if P_{stat} is higher than P_{red}. The enclosure bursts, whereas the explosion panel remains intact.

Today, high-quality bursting panels are manufactured by several companies throughout the world. Such panels burst reliably at the P_{stat} values for which they are certified. An example of such a panel is shown in Figure 1.100 (see also Figure 1.95).

Figure 1.99 *Damaged cyclone after a dust explosion. The vent cover was too strong to open before the cyclone itself ruptured (From Department of Employment and Productivity, 1970).*

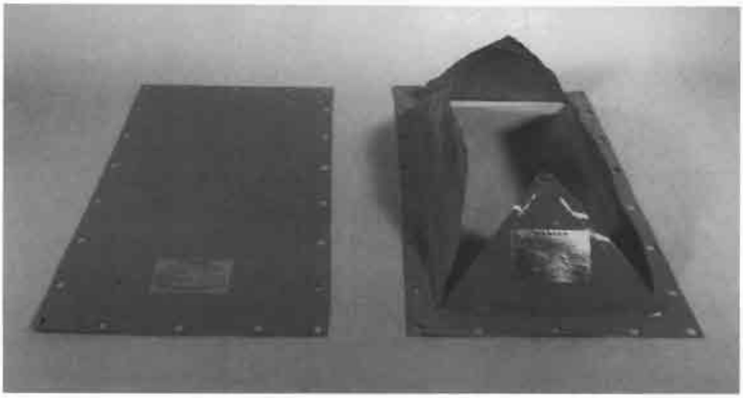


Figure 1.100 *Epoxy-coated explosion vent panel: (left) mounted on vent, (right) after having relieved an explosion (Courtesy of Fike Corporation, Blue Springs, MO, United States).*

Such panels are manufactured in a wide range of sizes and shapes, and coatings may be provided that allow permanent contact with various types of chemically aggressive atmospheres. Often, a backing film of Teflon is used as environmental protection, to prevent the vent panel from contaminating the product inside the enclosure that is equipped with the vent. However, the upper working temperature limit of Teflon is about 230°C. Brazier (1988) described special panels designed for service temperatures up to 450°C.

Figure 1.101 shows a bursting panel design originally developed for bucket elevators but that may have wider applications. It consists of the bursting panel itself, which is a 0.04 mm thick aluminum foil of P_{stat} 0.1 bar(g), supported by a 0.5 mm metal gauze and a second 0.5 mm metal gauze for further cooling of the combustion gases ("flame arrester"). Additional layers of metal gauze may be added as required for adequate cooling. The combustion gases should be cooled to the extent that unburned discharged dust and dust that may be whirled up in the building are not ignited. In an explosion, the explosion detection panel is blown out and operates a proximity switch that triggers whatever preprogrammed automatic actions that should be taken (closing of the plant or valves, automatic suppression, and so forth).

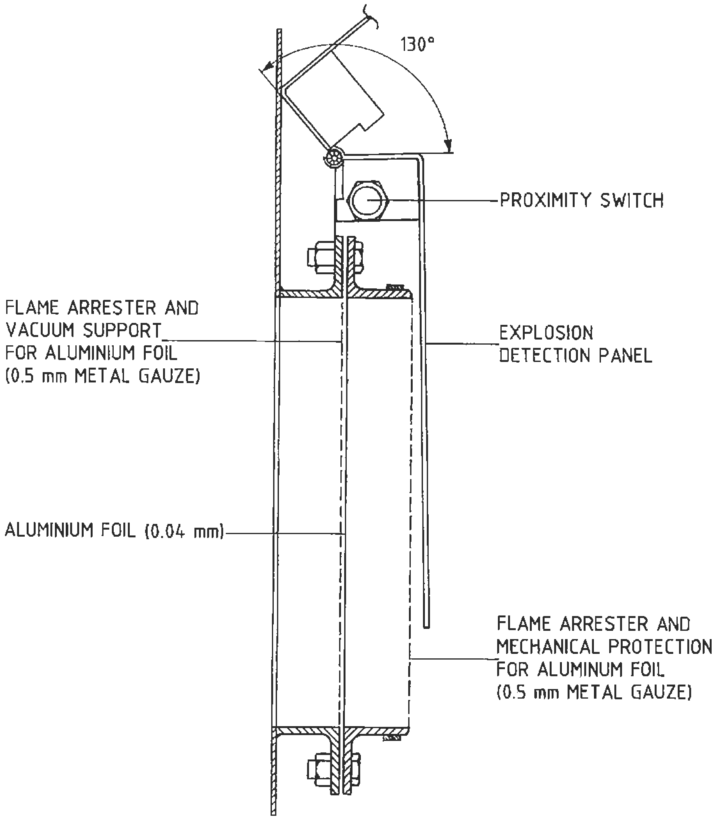


Figure 1.101 *Bursting panel combined with metal gauze for mechanical protection of vent panel and cooling of combustion gases. Displacement of explosion detection panel operates proximity switch (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

He Kuangguo et al. (1987) investigated the dynamic strength and venting characteristics of bursting disks of various materials. Reasonable agreement was found between experimental results and theoretical predictions.

Hinged explosion doors constitute a third category of vent covers. Such doors may take a variety of different forms, depending on the equipment to be vented and other circumstances. Various kinds of calibrated locking mechanisms to ensure release at the predetermined P_{stat} have been developed. Hinged doors may be preferable if explosions are relatively frequent. Figure 1.102 shows an example of the use of hinged doors as vent covers. Figure 1.103 shows the opened explosion doors on a milling plant similar to that in Figure 1.102, just after a dust explosion.

Donat (1973) discussed various advantages and disadvantages of bursting panels and hinged doors. Siwek and Skov (1989) analyzed the performance of hinged explosion doors during venting with and without vent ducts (see Section 1.4.6.5). Both theoretical and experimental studies were carried out and a computer model of the venting process developed.

The final category of vent covers to be mentioned are the reversible ones, that is, covers that close as soon as the pressure has been relieved. The purpose of such covers

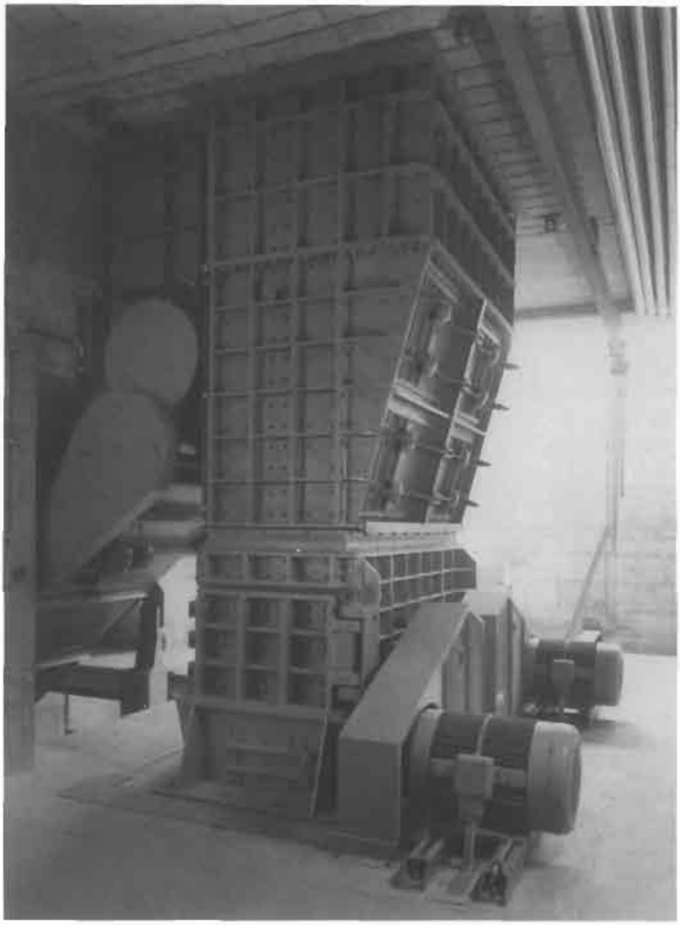


Figure 1.102 *Four hinged explosion doors of 0.8 m^2 each, with energy dissipation buffers, mounted on inlet hopper to a twin-rotor hammer mill for grinding household waste and bulky refuse: P_{red} = 1.0 bar(g) (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

is to prevent secondary air being sucked into the enclosure after the primary explosion has terminated, giving rise to secondary explosions and fires. The reversible vent covers include counterbalanced hinged doors and spring-loaded, axially traversing vent covers. One type of reversible hinged explosion vent cover is shown schematically in Figure 1.104.

The baffle plate is spring-loaded and acts as a shock absorber when hit by the vent cover. Additional shock absorption is provided by the air cushion formed between the vent cover and baffle plate during impact. The adjustable prestressing device sets the static opening pressure, P_{stat}, of the vent cover to the desired level. Figure 1.105 shows the type of dust explosion vent illustrated in Figure 1.104 installed in the roof of a silo. Käppeler (1978) discussed the successful use of reversible hinged explosion doors on dust filter enclosures.

One problem that can arise when using reversible explosion covers is implosion due to the internal underpressure that follows the cooling of the gases inside the enclosure, when sealed just after the explosion. Wiemann, Bauer, and Möller (1989) showed

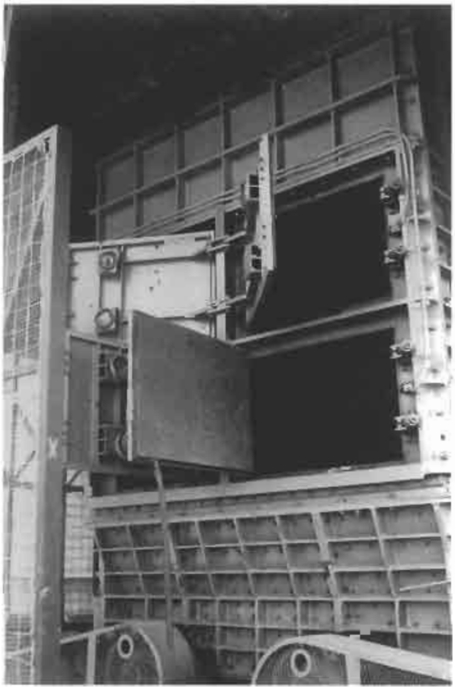


Figure 1.103 *Hinged vent doors on a mill similar to that in Figure 1.102, just after a dust explosion. Damaged shock absorbers are replaced by new ones after each explosion before the doors are closed (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

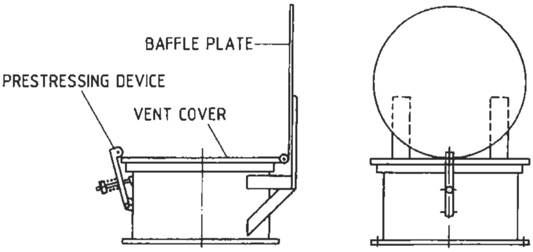


Figure 1.104 *Reversible low-mass hinged explosion door, which closes by gravity once the explosion has been relieved (Courtesy of Silo-Thorwestern, Beckum, Germany).*

experimentally and theoretically that the internal underpressure can be limited to a desired nondamaging level by providing a small opening through which the small quantity of air required for preventing implosion is allowed to enter the enclosure in a controlled manner. They presented a nomograph from which the necessary leak opening cross section can be determined from the vessel volume and the maximum permissible underpressure.

1.4.6.4
Potential Hazards Caused by Venting

Venting of dust explosions prevents rupture of the enclosure in which the explosion takes place. However, significant hazards still remain. These include

Figure 1.105 *Reversible, low-mass hinged explosion doors (see Figure 1.104) installed in the roof of a silo (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

- Ejection of strong flame jets from the vent opening.
- Emission of blast waves from the vent opening.
- Reaction forces on the equipment, induced by the venting process.
- Emission of solid objects (vent panels and parts that can be torn off by the venting process).
- Emission of toxic combustion products.

In general, flame ejection is more hazardous the larger the vent is and the lower the static opening pressure of the vent cover. This is because, with a large vent and a weak cover, efficient venting starts at an early stage in the combustion process inside the enclosure. Therefore, in the early stages of venting, large clouds of unburned dust are pushed out through the vent and subsequently ignited when the flame passes through the vent. The resulting, secondary fireball outside the vent opening can present a substantial hazard. If, on the other hand, the enclosure is strong, allowing the use of a small vent and a high P_{red}, only the combustion products are vented and the flame outside the vent is considerably smaller.

If a dust explosion is vented indoors, the blast waves and flame jet may generate serious secondary explosions in the workrooms (see Section 1.1.3). Some methods for preventing this are discussed in the following section.

1.4.6.5
Vent Ducts

One traditional solution to the flame jet problem is the use of vent ducts. This implies that a duct of cross-sectional area at least equal to the vent area is mounted between the vent and a place where a strong flame jet presents no hazard. The principle is illustrated in Figure 1.106.

Vent ducts generally increase the flow resistance and, therefore, the pressure drop to the atmosphere. Consequently, adding a vent duct increases the maximum explosion pressure

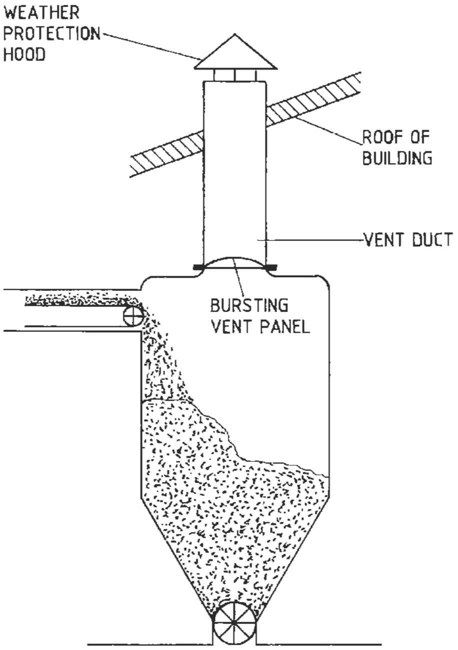


Figure 1.106 *The use of a vent duct for guiding discharged unburned dust cloud and flames to a safe place.*

in the vented vessel. Furthermore, the pressure increases with increasing duct length, increasing number of sharp bends, and decreasing duct diameter. These trends are confirmed by experiments.

Figures 1.107 and 1.108 give some results from small-scale experiments. The comparatively high pressures in Figure 1.107 for dextrin are due to the use of a smaller vent and duct diameters than those employed for acquiring the data in Figure 1.108. The same trend as exhibited by Figures 1.107 and 1.108 is found in larger scale, as shown by the data from TNO (1979) in Figure 1.109.

Walker (1982) analyzed available data at that time and proposed the general relationship for the maximum explosion pressure in a vented vessel with a duct as shown in Figure 1.110.

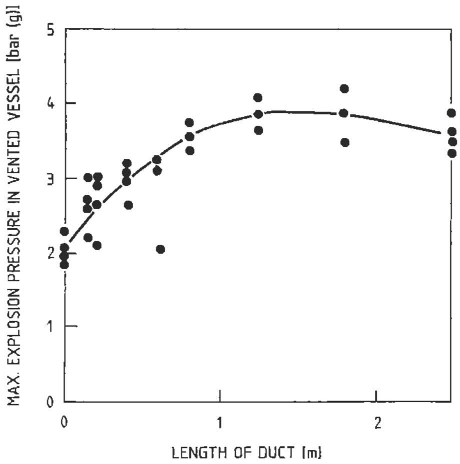


Figure 1.107 *The influence of the length of a straight vent duct of internal diameter 25 mm on the maximum pressure during explosions of dextrin/air in a 20 liter spherical vessel with no vent cover (From Kordylewski, Wach, and Wójcik, 1985).*

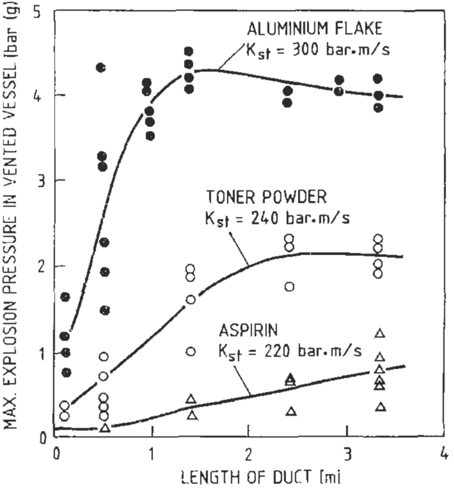


Figure 1.108 *The influence of the length of a straight vent duct of internal diameter 130 mm on the maximum pressure during explosions of three different dusts in air in a 20 liter spherical vessel with vent cover of diameter 130 mm and bursting strength 0.1 bar(g) between vessel and duct (From Crowhurst, 1988).*

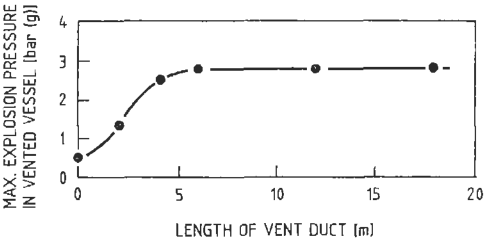


Figure 1.109 *The influence of the length of a straight vent duct of internal diameter 0.35 m on the maximum dust explosion pressure in a 1 m^3 vessel vented into the duct via a 0.35 m diameter bursting disk of bursting pressure 0.47 bar(g) (From TNO, 1979).*

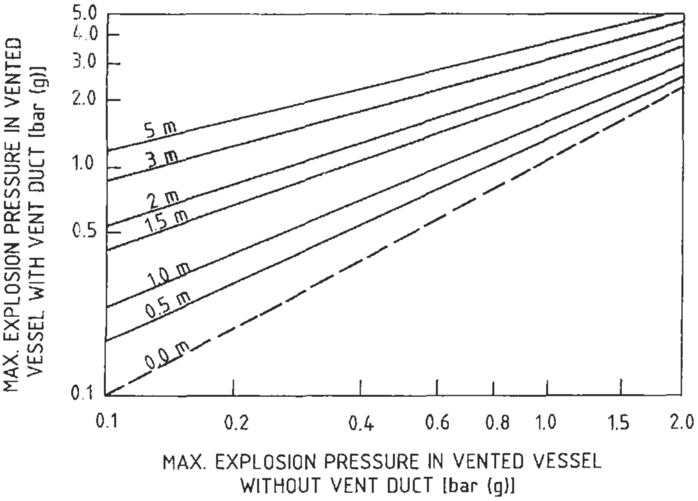


Figure 1.110 *Maximum pressure in a vented vessel with a vent duct as a function of maximum explosion pressure without a duct, for various duct lengths. The diameter of the duct equals the diameter of the vent. There are no sharp bends (From Walker, 1982).*

It is felt that this correlation still holds good as a first approximation. For example, the data in Figure 1.109 are reasonably well accounted for in Figure 1.110. However, as reviewed in Section 9.3.7.5 in Chapter 9, the length-to-diameter ratio of the duct is a more basic parameter than just the duct length.

Aellig and Gramlich (1984) studied the influence of various geometrical features of the vent duct design, in particular the details of the coupling between vessel, vent, and duct, and the geometry of the bends. They proposed an overall correlation that looks similar to that of Walker in Figure 1.110, but the ratio of duct volume to vessel volume was used as parameter instead of the duct length.

Pineau (1984a) conducted a comprehensive series of experiments with explosions of wheat flour and wood dust in vented vessels of 0.1 m^3 and 1.0 m^3 volumes connected to vent ducts of various diameters and lengths, with and without bends. Some experiments were also conducted with larger vessels of volumes 2.5–100 m^3 vented through ducts. In general, the main trends observed in the small-scale experiments were confirmed for the large-scale ones, and it was recommended that vent ducts be as short as possible and have a minimum number of sharp bends.

More recently, Lunn, Crowhurst, and Hey (1988) conducted a comprehensive theoretical and experimental study of the effect of vent ducts on the maximum explosion pressure in vented vessels. Experiments were performed in a 20 liter vessel (same experiments as Crowhurst, 1988), and in a large-scale 18.5 m^3 vessel. Figure 1.111 shows the 18.5 m^3 vessel fitted with a straight duct, whereas Figure 1.112 shows the same vessel during a coal dust explosion with a 90° bend at the end of the duct.

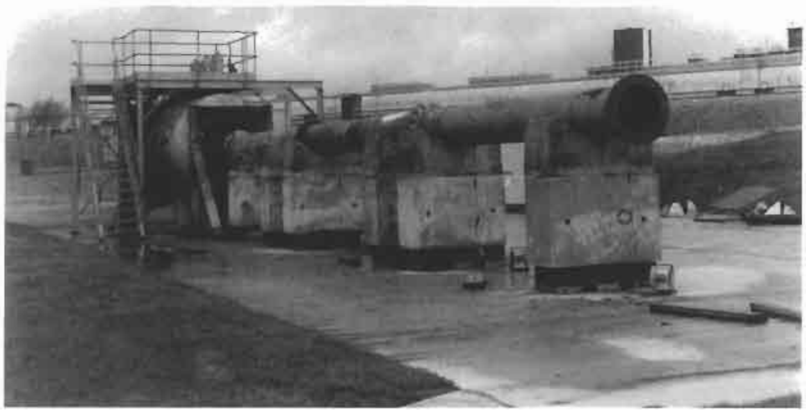


Figure 1.111 *18.5 m^3 vented explosion vessel connected to a straight vent duct (Courtesy of Health and Safety Executive, United Kingdom). For a much clearer picture, see Color Plate 1.*

In general, the trends of the experimental data for the five dusts—coal, aspirin, toner, polyethylene, and aluminum—used by Lunn et al. were similar to that in Figure 1.109. The maximum explosion pressure in the vessel increased systematically with duct length and the length-to-diameter ratio of the duct. The theoretical analysis generally confirmed this trend and yielded predictions in reasonable agreement with the experimental data, although some discrepancies were found. The theory developed by Lunn et al. may serve as a useful tool for estimating the influence of various types of vent ducts on P_{red}. The K_{St}

Figure 1.112 *Coal dust explosion in 18.5 m³ vessel vented through a duct with a 90° bend at the end (Courtesy of Health and Safety Executive, United Kingdom). For a much clearer picture, see Color Plate 2.*

value, which is numerically identical to the maximum rate of pressure rise in the standard 1 m³ ISO test, was used as a measure of the inherent explosibility of the dusts. The K_{St} values ranged from 144 bar·m/s for the coal to 630 bar·m/s for the aluminum.

1.4.6.6
The Quenching Tube

This promising new concept was developed by Alfert and Fuhre (1989) in cooperation with Rembe GmbH, Federal Republic of Germany (see also Anonymous, 1989). The main principle is illustrated in Figure 1.113.

If a dust explosion occurs in the enclosure to be vented, the bursting panel, which constitutes an integral part of the quenching tube assembly, bursts, and the explosion is vented

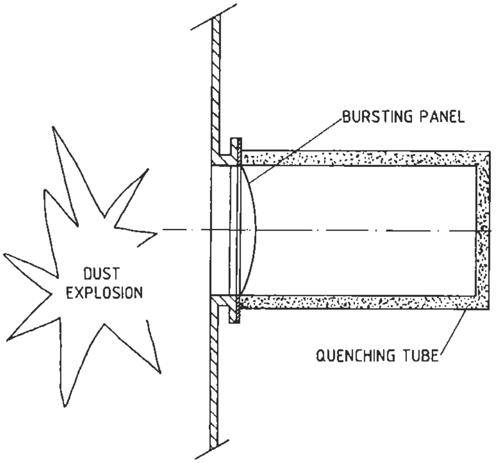


Figure 1.113 *A quenching tube for dust and flame-free venting of dust explosions*

through the comparatively large wall area of the quenching tube. The wall is designed to yield a low-pressure drop but high retention efficiency for dust particles and efficient cooling of combustion gases. This means that flame ejection from the vent is effectively prevented and the blast effects significantly reduced.

Furthermore, burning lumps of powder and other smaller objects that could be ejected through an open vent are retained inside the quenching tube. However, any toxic gaseous combustion products, such as carbon monoxide, escape to the atmosphere.

The increase of the maximum explosion pressure in the vented enclosure due to the flow resistance through the quenching tube wall is mostly moderate and can normally be compensated for by a moderate increase in the vent area.

Section 9.3.7.5 in Chapter 9 gives references to more recent work on this promising principle of dust explosion protection. Bucket elevator legs and silos in congested areas, where normal venting is prohibited, are likely areas of application. The very high temperatures of burning light metal dust clouds (magnesium, aluminum, silicon) place heavy demands on the design of the quenching tube wall, but there is no a priori reason for not assuming that even this problem will be solved. Whether the remaining problem of possible toxic gas emission can be tolerated, depends on the actual circumstances, and must be considered specifically in each particular case.

Figure 1.114 shows a commercial prototype of a quenching tube. Figure 1.115 shows venting of a 5.8 m^3 bag filter unit without and with the quenching tube. The white smoke in the lower picture is mostly condensed water vapor.

Figure 1.114 *Commercial prototype of a quenching tube (Courtesy of Rembe GmbH, Brilon, Germany).*

1.4.6.7
Reaction Forces and Blast Effects

Experience has shown that the reaction forces from dust explosion venting can increase significantly both the material damage and the extent of the explosion. Equipment can tilt and ducts be torn off, and secondary dust clouds can be formed and ignited. Whenever installing a vent, it is therefore important to assess whether the equipment to be vented can withstand the reaction forces from the venting, should an explosion occur. A very simple, static consideration says that the maximum reaction force equals the maximum

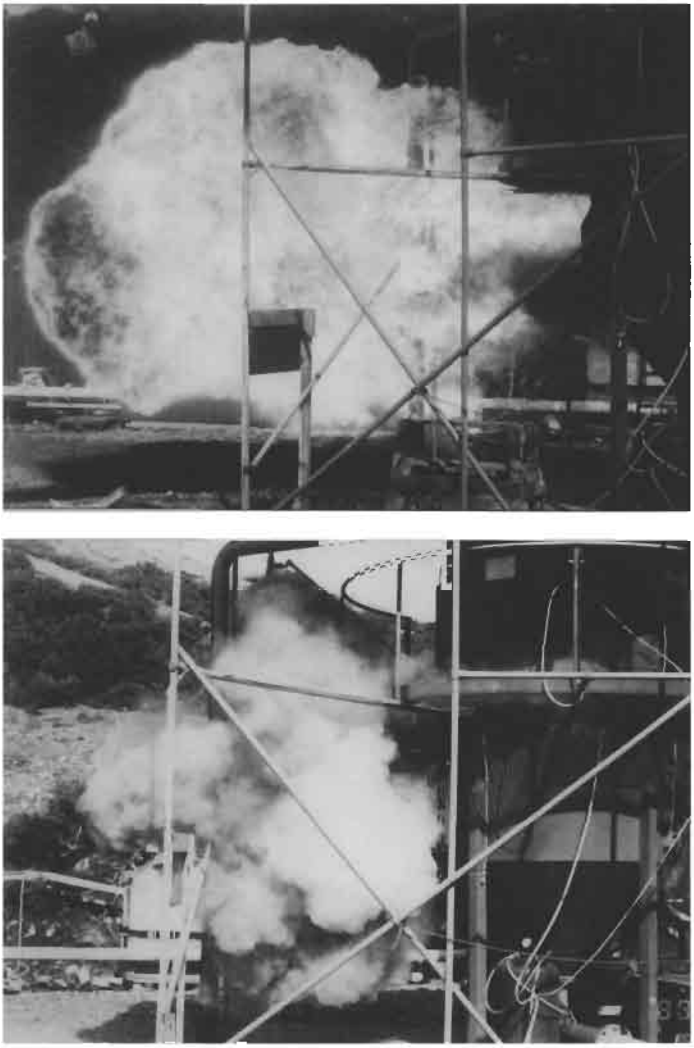


Figure 1.115 *Venting of a polypropylene/air explosion in a 5.8 m^3 bag filter unit without (top) and with (bottom) a quenching tube (Courtesy of F. Alfert and K. Fuhre, Chr. Michelsen Institute, Bergen, Norway). For a much clearer picture see Color Plate 3.*

pressure difference between the interior of the vessel being vented and the atmosphere, times the vent area. Careful experiments by Hattwig and Faber (1984) revealed that in actual explosion venting, the reaction force is about 20% higher than the value resulting from the simplified static consideration. The experimental relationship found by Hattwig and Faber is

$$F_{\max}\ (MN) = 0.12 \bullet A(\mathrm{m}^2) \bullet P_{\max}\ (\mathrm{bar(g)}) \tag{1.15}$$

This equation can be used for estimating maximum reaction forces expected in practice. P_{max} is then the maximum permissible pressure P_{red} for which the vent is designed. Brunner (1983) found that the experimental reaction force was reduced by about 6% by vent ducts.

As discussed in Section 1.4.5.3, a given pressure pulse interacts with the mechanical structure exposed to it. This is also a relevant aspect in the present context. As pointed out by Pritchard (1989), the strength of some materials, including structural steels, is highly sensitive to the strain rate. This means that the stress at which plastic deformation starts depends on the rate of loading. On the other hand, the damage to a structure also depends on how quickly the structure responds to the pressure loading. The natural period of vibration of the mechanical structure is normally used as a measure of the response time. If the duration of the pressure peak is long compared with the natural period of vibration, the loading can be considered essentially a static load. If, on the other hand, the pressure pulse is short compared with the response time of the structure, the damage is determined by the impulse, that is, the time integral of pressure. Pritchard (1989) provided a qualitative illustration of these relationships, shown in Figure 1.116.

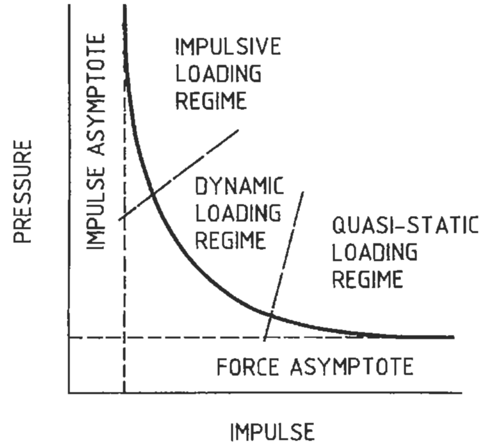


Figure 1.116 *Pressure-impulse diagram for a single-degree-of-freedom elastic structure leaded with an ideal blast wave (From Pritchard, 1989).*

Brunner (1983, 1984) performed a detailed theoretical and experimental study of the structural response of supports and buildings due to the reaction forces from dust explosion venting of a vessel. An analysis of experimental explosion pressure versus time revealed two different regimes: $P_{max} < 0.9$ bar(g) and $P_{max} > 0.9$ bar(g). In the first regime, the pressure pulses generally had several peaks, whereas in the high-pressure regime, there was normally only one main peak. Theoretical equations for pressure versus time were developed for both regimes.

Brunner considered both linear and nonlinear models for the structures subjected to the reaction forces and developed response spectra for both fully elastic and ductile systems. The theoretical strain predictions were in good agreement with experimental results. Some practical guidelines for safe design of structures subjected to reaction forces from explosion venting were proposed.

Hattwig (1980) investigated the blast peak pressure, P_{blast}, outside a vented dust and gas explosion as a function of the distance D from the explosion and found that

$$P_{\text{blast}} = \frac{A \bullet P_{\max} \bullet 1\ \text{m}}{D\ (\text{m})} \tag{1.16}$$

where the dimensionless parameter A is given by

$$\log_{10} A = -\frac{0.26}{F\ (\text{m}^2)} + 0.49 \tag{1.17}$$

and $P_{\max}$ is the maximum explosion pressure inside the vented enclosure. Both P_{blast} and $P_{\max}$ are gauge pressures.

According to Kuchta (1985), the static, or "side-on," gauge pressure of a blast wave front is

$$\Delta P_s = P_o \frac{2\gamma(M_o^2 - 1)}{(\gamma - 1)} \tag{1.18}$$

where P_o is the ambient absolute pressure, γ the specific heat ratio of air, and M_o the ratio of the actual wave front velocity to the velocity of sound. However, the total blast pressure sensed by an object exposed to a blast wave is the sum of the static gauge pressure and the dynamic pressure $\frac{1}{2}\rho V^2$ due to the gas flow (V is the gas velocity and ρ the gas density). Strehlow (1980) gave an instructive overview of the nature of blast waves and their damaging potential. A useful review was also given by Pritchard (1989).

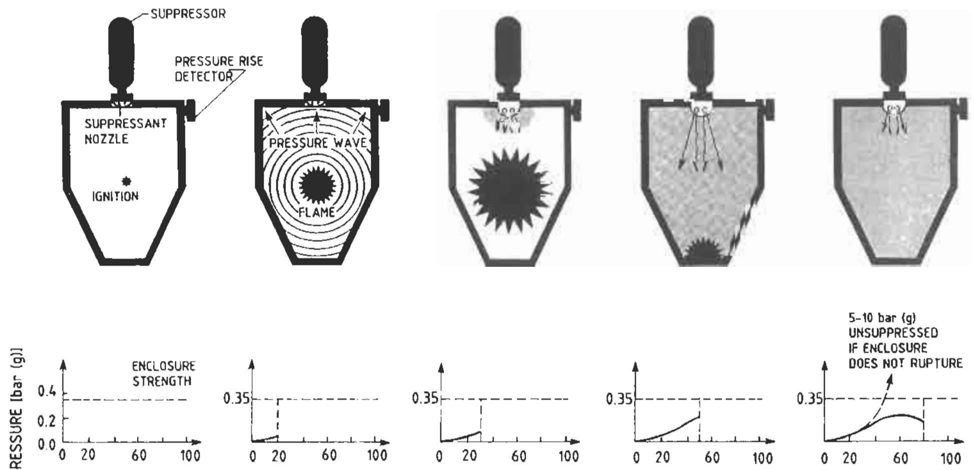
1.4.7
AUTOMATIC SUPPRESSION OF DUST EXPLOSIONS

1.4.7.1
General Concept

According to Dorn (1983), the first patent for a fast fire suppression system, a "rapid dry powder extinguisher," was allotted to a German company as early as 1912. The Second World War accelerated the development. The British Royal Air Force found that 80% of the total losses of aircraft in combat were due to fire. Based on this evidence, a military requirement was issued specifying a lightweight high-efficiency fire extinguishing system for protecting aircraft engines and their fuel systems. A similar situation arose in Germany. As a result new, fast-acting fire extinguishers were developed based on three main principles:

- The extinguishing agent is permanently pressurized.
- The discharge orifice is large in diameter.
- The valve for immediate release of extinguishing agent by means of an explosive charge opens very fast.

These principles, combined with a fast-response flame or pressure-rise detection system, form the basis for even today's automatic explosion suppression systems. Figure 1.117 illustrates the operation of a dust explosion suppression system.



1. Ignition
Time: 0 ms
Pressure: 0 bar (g)

2. Pressure rise detector triggers suppressors
Time: 20 ms
Pressure: 0.035 bar (g)

3. Suppressant injection starts
Time: 30 ms
Pressure: 0.085 bar (g)

4. Suppressant injection continues
Time: 50 ms
Pressure: 0.2 bar (g)

5. Suppression complete
Time: 80 ms
Pressure: 0.15 bar (g)

Figure 1.117 *The sequence of events and typical time scale of automatic suppression of dust explosions in process equipment. Actual figures apply to a starch explosion in a 1 m^3 vessel (Courtesy of Kidde-Graviner, Colnbrock, United Kingdom).*

The suppressor contains a suitable extinguishing agent (suppressant) and a driving gas, normally nitrogen at 60–120 bar. The onset of pressure rise in the vessel due to the growing dust flame is detected and an electric signal triggers the explosive charge that opens the suppressor valve. A special nozzle design ensures that the suppressant is distributed evenly throughout the vessel volume. In principle, the pressure sensor can be made sensitive enough to detect even a very small initial flame. However, if the pressure rise for triggering the opening of the suppressor valve is chosen so small that similar pressure variations may occur in normal plant operation, false activation of the suppression system becomes likely. This is not desirable and therefore the triggering pressure is normally chosen sufficiently high to avoid false alarms. The use of two pressure detectors oriented at 90° to each other can make it easier to discriminate between pressure rise due to explosions and other disturbances. Figure 1.118 shows a pressure detector of the membrane type, which is the most common type used in automatic dust explosion suppression systems.

Ultraviolet or infrared optical flame sensors may be used instead of pressure sensors for detecting the initial explosion. However, careful consideration is required before doing so, because explosible dust clouds have high optical densities even at distances of only 0.1 m. This can make it difficult to sense a small initial flame in a large cloud. Optical detectors may be used in advance inerting systems (see later) for detecting flames entering ducts between process units. Figure 1.119 shows a typical suppressor unit with pressure gauge for controlling the driving gas pressure, and suppressant dispersion nozzle. Figure 1.120 shows a very large suppressor developed for suppressing explosions in large volumes of several hundred cubic meters.

Figure 1.121 shows a special explosion suppression unit that is completely self-contained, even with respect to power supply. This gives great flexibility with respect to

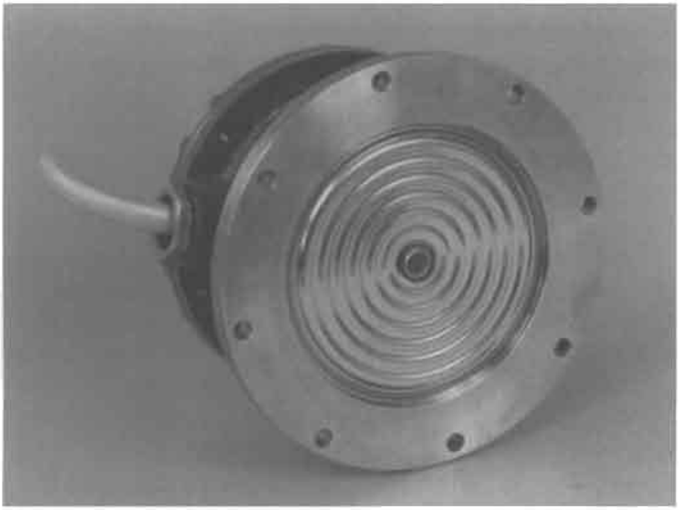


Figure 1.118 *A pressure sensor of the membrane type used for activating automatic dust explosion suppression systems. The diameter of the membrane is about 100 mm (Courtesy of Kidde-Graviner, Colnbrock, United Kingdom).*

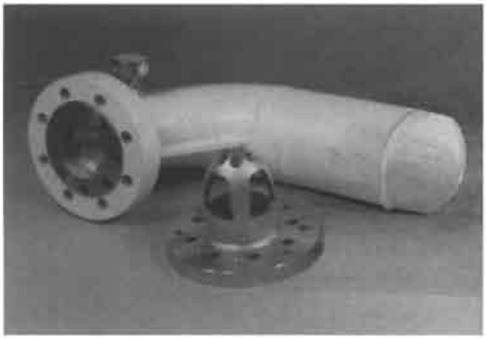


Figure 1.119 *Typical suppressor and nozzle system (Courtesy of Fike Corp., Blue Springs, MO).*

mounting the unit at any desired location. However, regular inspection and testing of power supply and the like is required. This unit was originally designed for using halon as suppressant, but transfer to powder suppressants is probably not too difficult.

The status on explosion suppression technology has been reviewed repeatedly in the literature. A fairly early paper discussing large-scale experimental research in France in the late 1960s was presented by Winter (1970). Bartknecht (1978) has a comprehensive discussion of extensive research in the Federal Republic of Germany and Switzerland in the 1970s. A summary covering similar evidence was given by Scholl (1978). Singh (1979) summarized theoretical and experimental work from various countries including the United Kingdom, United States, Federal Republic of Germany, and Switzerland. Moore (1981) discussed the results of his own comprehensive experimental and theoretical research, which resulted in a basis for systematic design of industrial suppression systems. He introduced the concept of critical mass M_t of suppressant that is just sufficient for suppressing the flame when being evenly distributed throughout the

Figure 1.120 *Large 45 liter high-rate suppressor for very fast discharge of 35 kg of $MH_4H_2PO_4$ powder. The diameter of the explosive charge-operated valve is 127 mm (5 in.) and the driving gas is nitrogen at 60 bar (Courtesy of Kidde-Graviner, Colnbrock, United Kingdom).*

Figure 1.121 *A self-contained automatic explosion suppression unit (X-PAS) consisting of a pressurized spherical suppressant container with an explosive charge-operated valve, a pressure detector, and a long-life lithium battery power unit (Courtesy of Fenwal Inc., Ashland, MA).*

flame volume. He assumed a critical minimum mass concentration of any given suppressant for suppressing a flame of a given dust and that a suppressant cloud of this concentration or higher must occupy at least the flame volume for successful suppression. It then follows that the critical mass M_t increases with time, because the flame volume increases with time.

A similar line of thought was applied to the mass of suppressant actually delivered at any time after onset of flame development. Successful suppression would result if $M_{t,\mathrm{delivered}} > M_{t,\mathrm{required}}$. This is illustrated in Figures 1.122 and 1.123.

Moore, Watkins, and Vellenoweth (1984) reviewed the status in the early part of the 1980s, including industrial experience with a number of automatic dust explosion suppression installations. More recently, Hürlimann (1989) presented a detailed, comprehensive review of dust explosion suppression, in general, and the research conducted by Ciba Geigy, Switzerland, in particular. Siwek (1989b) discussed then-recent research on explosion suppression in large vessels as well as explosion isolation by automatic suppression systems.

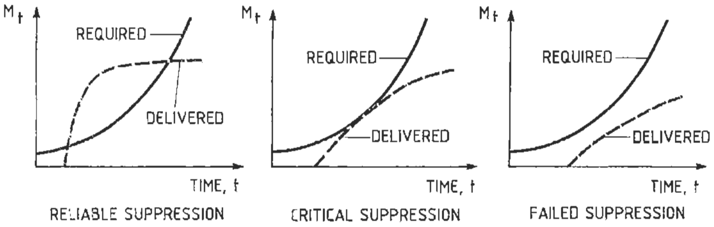


Figure 1.122 *Mass of suppressant required and delivered as functions of time, for reliable suppression, critical suppression, and failed suppression (From Moore 1981, 1987).*

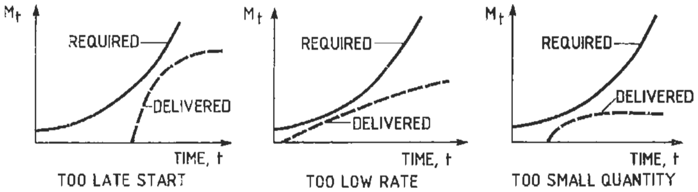


Figure 1.123 *How failed suppression can result from too late a start of suppressant injection, too low an injection rate, and too small a quantity of suppressant injected (From Moore, 1981, 1987).*

Automatic dust explosion suppression has proven feasible for organic dusts of the maximum rate of pressure rise in the standard 1 m^3 closed ISO-vessel of up to 300 bar/s (i.e., K_{St} = 300 bar m/s, see Chapter 4). It remained uncertain, however, whether the method could also be used for aluminum dusts of K_{St} in the range 300–600 bar m/s. Moore and Cooke (1988) investigated this experimentally in a 18.5 m^3 vessel, using aluminum flakes of K_{St} = 600 bar m/s. A special powdered suppressant, consisting essentially of $NaHCO_3$ (ICI Dessicarb^{TM}), proved to be the most effective for suppressing aluminum dust explosions and was therefore used in all experiments.

However, they found that, for aluminum flakes of K_{St} = 320 bar m/s, even under optimum conditions for suppression, it was difficult to ensure lower suppressed explosion pressures than about 2 bar(g). In the case of dusts of natural organic materials and plastics of K_{St} up to 300 bar m/s, the corresponding suppressed explosion pressures would have been 0.2–0.4 bar(g).

Moore and Cooke (1988) concluded that reliable suppression of aluminum flake explosions is difficult. However, they showed that a combination of explosion suppression and venting can reduce the maximum explosion pressure to a level significantly lower than the level from venting only. For an aluminum flake cloud of K_{St} = 600 bar m/s and a static opening pressure of the vent cover of 0.5 bar(g), venting only (about 1 m^2 vent area) yielded 8.2 bar(g). When combined with optimal suppression, the maximum pressure was 3.8 bar(g). However, although this is considerably lower than 8.2 bar, it is still a high pressure.

It should be mentioned that Senecal (1989), over the range 240 to 340 bar m/s investigated, found that the correlation between K_{St} and reduced explosion pressure in similar suppression experiments, was rather poor.

1.4.7.2
Design of Dust Explosion Suppression Systems

As discussed by Moore et al. (1984), one distinguishes among three different suppression strategies:

- *Advance inerting.* Detect the explosion, identify its location, activate the appropriate suppressors, and establish suppressant barriers to prevent explosion spread to other process units.
- *Local suppression.* Detect the initial explosion, identify its location, and activate the appropriate suppressors for ensuring no flame propagation beyond explosion kernel.
- *Total suppression.* Detect the explosion and deluge the entire system with suppressant to ensure that the explosion is totally suppressed.

The design of any particular industrial suppression system depends on the suppression strategy chosen, the type of suppressant, the chemical and explosibility properties of the dust, the nature of the process and enclosure to be protected (mill, cyclone, silo, etc.), the volume and shape of the enclosure, and other actions taken to prevent or mitigate against dust explosions in the plant. Moore and Bartknecht (1987) conducted dust explosion suppression experiments in large vessels of volumes up to 250 m^3 and could show that successful suppression of explosions in clouds of organic dusts is possible even in such large volumes. However, as the vessel volume increases, more suppressant and faster injection are required for successful suppression. The actual design of suppression systems depends very much on the specific design of the suppressors and other details, which vary somewhat from supplier to supplier. Therefore, it is difficult to specify generally applicable quantitative design criteria. Figure 1.124 gives an example of a design guide developed by one specific equipment supplier, based on the experiments with organic dusts by Moore and Bartknecht (1987).

As can be seen, three standardized types of suppressors were employed. The smallest type, of volume 5.4 liters, was used for vessel volumes up to 5 m^3, whereas 20 liter suppressors were used in the range 5 to 30 m^3, and the very large 45 liter type for the larger volumes. The large-volume range was verified experimentally only up to 250 m^3, for which 10 of the 45 liter suppressors were required for successful suppression of St2 dust explosions (organic dusts). For St1 dusts, seven such suppressors were sufficient.

Moore (1989) compared venting and suppression, referring to Figure 1.124, and showed that the two explosion protection methods are to a great extent complementary. In practice, cost effective safety is achieved by using either one of the two methods, or a combination of both.

Moore et al. (1984) provided a number of specific examples of automatic dust explosion suppression systems in industrial practice. One of these is shown in Figure 1.125.

Kossebau (1982) discussed the particular problem of suppressing dust explosions in bucket elevators, as illustrated in Figure 1.126. Schneider (1984) was concerned with applying the suppression method to dust explosions in milling and grinding plants.

1.4.7.3
Influence of Type of Suppressant (Extinguishing Agent)

Traditionally halogenated hydrocarbons (halons) were used as suppressants in automatic dust explosion suppression systems. However, long before the environmental

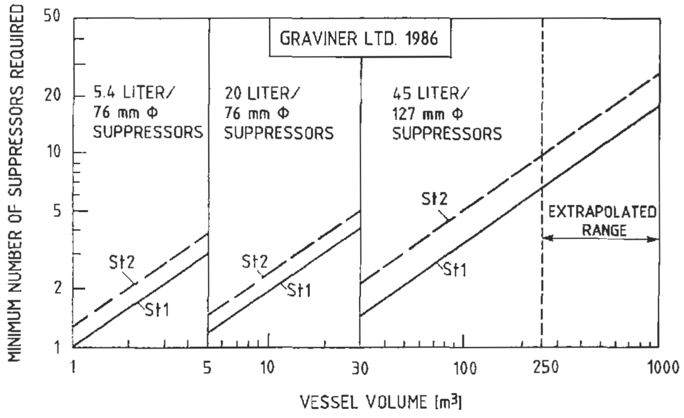


Figure 1.124 *Guide for designing dust explosion suppression systems for vessels of various volumes, based on the Graviner suppressor system:*

Pressure resistance of vessel: ≥ 1.0 *bar(g)*
Explosion of pressure detection level: ≤ 0.1 *bar(g)*
Suppressant: $NH_4H_2PO_4$
Driving gas pressure: *60 bar*

St1 means dusts that cause maximum rates of pressure rise in the standard closed 1 m^3 *ISO vessel of up to 200 bar/s* ($K_{St} = 200$ *bar m/s). St2 means dusts that cause 200–300 bar/s* ($K_{St} = 200$–300 *bar m/s). (From Moore and Bartknecht, 1987).*

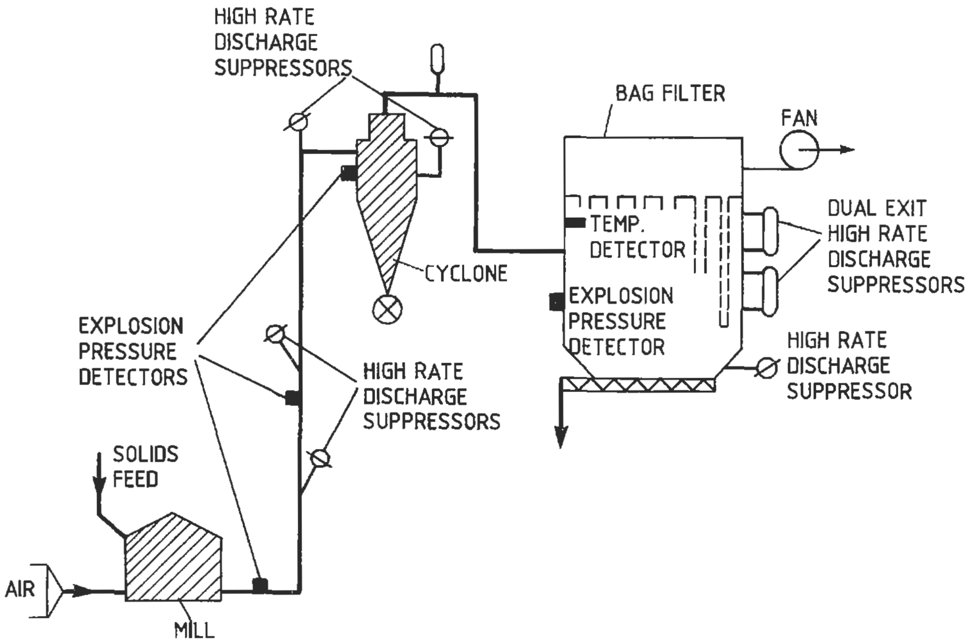


Figure 1.125 *Dust explosion protection of a grinding plant consisting of a mill, a cyclone, and a bag filter, using a comprehensive automatic explosion suppression system (From Moore et al., 1984).*

Figure 1.126 *Application of automatic dust explosion suppression to bucket elevators (Courtesy of T. Pinkwasser, Bühler, Switzerland). For a much clearer picture, see Color Plate 4.*

problems caused by these chemicals became a major issue, Bartknecht (1978) showed that powder suppressants, such as $NH_4H_2PO_4$, in general, were much more effective for suppressing dust explosions than halons. Therefore, powder suppressants have been used to suppress dust explosions for many years. But powders differ in their suppressive power, and efforts have been made to identify the most effective ones.

Figure 1.127 shows that the addition of only 30 weight% of $NH_4H_2PO_4$ powder is required to prevent flame propagation in dust clouds in air of Pittsburgh bituminous coal, whereas with $CaCO_3$ dust (limestone), 70 weight% is needed.

Similar systematic investigations were undertaken by Szkred (1983). He used a coal dust of 38% volatiles, 7% moisture, and 38 μm mean particle size as fuel and found that

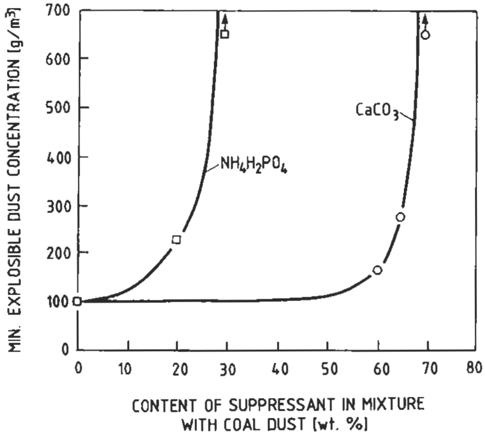


Figure 1.127 *The influence of the chemistry of inorganic powder suppression on mass percentage required for suppressing coal dust explosions: 400 J ignition source and 20 liter closed explosion vessel (From Hertzberg et al., 1984).*

25 weight% $NH_4H_2PO_4$, 35 weight% NaCl, and 80 weight% $CaCO_3$ were required to suppress flame propagation.

As already mentioned, the new powdered suppressant Dessicarb (>98.5% $NaHCO_3$) so far has proven the most effective agent for suppressing aluminum dust explosions. Furthermore, this material is suitable for use even in the food industry. It is soluble in water and can therefore be removed effectively by water only. Recently, superheated steam (water at >180°C) has also been used as a nonpolluting suppressant. Further, more recent works on automatic suppression are reviewed in Section 9.3.7.6 in Chapter 9.

1.4.8

CONTROL AND INTERLOCKING SYSTEMS TO PREVENT AND MITIGATE DUST EXPLOSIONS IN INTEGRATED PROCESS PLANTS

1.4.8.1

Overview

The subject has been discussed in two papers by Faber (1985, 1989b). A wide range of sensors for automatic measurement of a number of physical and chemical process variables are in use. Microprocessor technology has made it simple to utilize the signals from the sensors for control and interlocking purposes in a variety of ways.

The variety of process variables measured or detected includes

- Rotational speed, position, and translatory motion of mechanical objects, level of dusts and powders in silos, filter hoppers, and so forth.
- Temperature in powder and dust deposits, bearings and electrical motors, and gas flows.
- Gas pressure in process equipment and connecting ducts.
- Concentration of specific components in gases, such as oxygen in inert atmospheres and carbon monoxide in the case of self-heating.
- Presence of flames and hot gases.
- Concentration of dust suspended in a gas.
- Simple, digital quantities, such as whether an explosion vent door has opened or remains closed.

A comprehensive account of physical and chemical principles used for measuring such quantities and instruments using these principles has been given by Bentley (1988).

Faber (1989b) mentioned three objectives for monitoring process variables:

- Normal process control.
- Warning in case of abnormal process conditions.
- Triggering and control of measures for mitigating hazardous process conditions, such as dust explosions.

1.4.8.2

A Practical Example

Faber (1985, 1989b) used the plant for grinding and drying of coal shown in Figures 1.128 and 1.129 as an example. Such plants produce the fuel for pulverized-coal fired power plants.

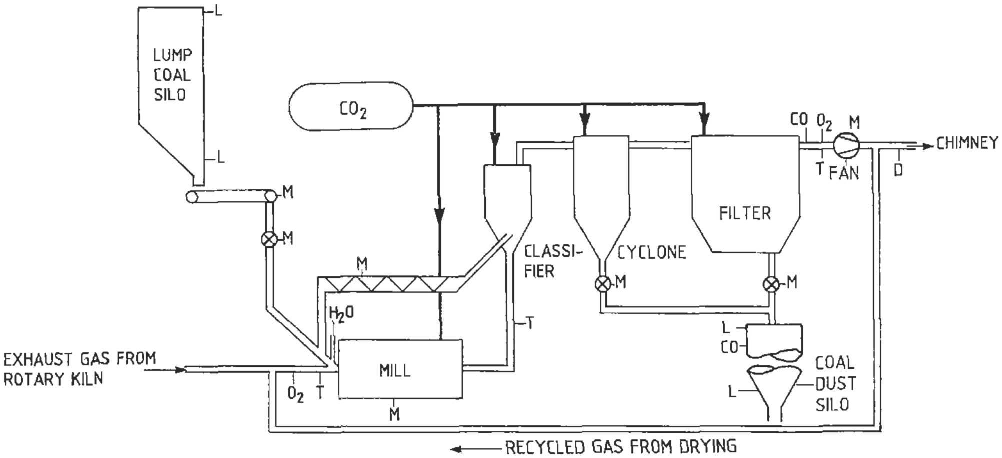


Figure 1.128 *Comprehensive sensor system for monitoring, controlling, and interlocking a process for milling and drying coal. The explosion protection is based on inerting* CO_2:

CO = carbon monoxide concentration sensors.
D = dust concentration sensor.
L = level sensors for coal and coal dust in silos.
M = movement sensors for mechanical components.
O_2 *= oxygen concentration sensors.*
T = temperature sensors.

(From Faber, 1985, 1989b with minor adjustments).

The basic process is simple. Lump coal is fed via a belt conveyor and a rotary lock to a rotary mill, which is flushed with gas to dry the coal and pneumatic transport of ground material to a gas classifier. The classifier separates the conveyed ground coal into a coarse fraction, which is returned to the mill, and a fine product fraction, which is removed from the gas in a cyclone and a subsequent filter. The coal dust collected in the cyclone and filter is conveyed to a coal dust silo.

Figures 1.128 and 1.129 show how the plant can be protected against damaging dust explosions utilizing two alternative measures, inerting and venting. The instruments for monitoring, controlling, and interlocking the process varies somewhat with the protective measure chosen.

In the case of inerting, one relies on keeping the plant inerted. To achieve this, as Figure 1.128 shows, continuous monitoring and control of a range of process variables is recommended. Automatic alarms can be activated as soon as a variable attains an unacceptable value. Interlocking by automatically turning off the power to the mill, the fan, the conveyor, and the rotary locks, should the oxygen level become too high, adds to the safety. Should the temperature of the gas from the mill become unacceptably high, water can be added automatically to the mill feed, as indicated. Development of carbon monoxide in the coal dust silo or filter indicates smoldering combustion, and this should also lead to automatic closedown of the plant.

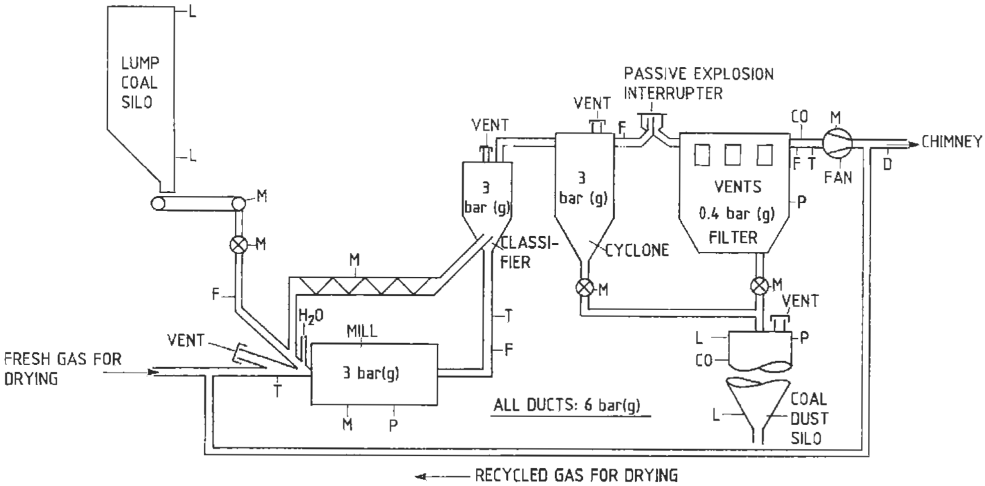


Figure 1.129 *Comprehensive sensor system for monitoring, controlling, and interlocking a process for milling and drying coal. The explosion protection is based on venting and explosion shock-resistant design:*

CO = carbon monoxide concentration sensors.
D = dust concentration sensor.
F = flame sensor.
L = level sensors for coal and coal dust in silos.
M = movement sensors for mechanical components.
P = pressure sensors.
T = temperature sensors.

(From Faber, 1985, 1989a with minor adjustments).

If venting and explosion shock-resistant design is the basic measure against damaging dust explosions (Figure 1.129), the probability of ignition is higher than with inerting. The plant is therefore designed to be able to withstand dust explosions without becoming damaged, but such events are clearly undesirable. Therefore, continual monitoring and control of a series of process variables is again recommended. In addition to the sensors in Figure 1.128, Figure 1.129 indicates sensors for detection of abnormal pressure rise in the mill, the filter, and the coal dust silos and detectors for flames in the ducts from the mill. On the other hand, measurement of oxygen concentration is of less interest in this case, because one has to accept that the oxygen content can be as high as in air (21 vol%).

In addition to stopping the mill, the fan, the rotary locks, and the conveyors, the pressure and flame sensors can be used to activate various kinds of active isolation devices in the ducting between the various process units that are not already isolated by the rotary locks, a screw conveyor, or a passive explosion interrupter (see Section 1.4.4).

It may be argued that the instruments suggested in Figures 1.128 and 1.129 is excessive. This is a matter of discussion in each case. The main purpose has been to indicate the possibilities that exist and from which one should select the appropriate measures to suit a specific application.

1.4.9
PREVENTION AND REMOVAL OF DUST ACCUMULATIONS OUTSIDE PROCESS EQUIPMENT: GOOD HOUSEKEEPING

1.4.9.1
General Outline

The main prerequisite for disastrous secondary explosions in factories is that sufficient quantities of combustible dust have accumulated outside the process equipment to permit development of large secondary dust clouds (see Section 1.1.3). In other words, the possibility of extensive secondary explosions can be eliminated if the outside of process equipment and shelves, beams, walls, and floors of workrooms are kept free of dust.

Significant quantities of dust may accumulate accidentally outside process equipment due to discrete events, such as bursting sacks or bags or erratic discharge from silos or filters. In such cases, it is important that the spilled dust be removed immediately. In case of large dust quantities, the main bulk may be sacked by hand using spades or shovels, but industrial, explosion-proof vacuum cleaners should be used for the final cleaning. In the case of moderate spills, dust removal may be accomplished by vacuum cleaning only.

Effective dust extraction should be provided in areas where dust occurs as part of normal operation, such as bagging machines.

Considerable quantities of dust can accumulate outside process equipment over time due to minor but steady leaks from process equipment. The risk of such leaks is comparatively large if the working pressure inside the process equipment is higher than the ambient pressure, whereas running the process at slightly lower than ambient pressure reduces the leaks.

It is important that process equipment be inspected regularly to discover and seal off obvious accidental leak points as early as possible. However, often one has to accept a certain unavoidable level of dust leaks from process equipment. It is then important to enforce good housekeeping routines by which accumulations of explosible dust outside process equipment are removed at regular intervals, preferably by explosion-proof vacuum cleaning.

Use of compressed air to blow away spilled dust should be prohibited. By this method, dust is not removed, only transferred to another location in the same room. In addition, dust explosions can result if the dust concentration in the cloud so generated is in the explosible range and an ignition source exists in the same location.

1.4.9.2
Industrial Explosion-Proof Vacuum Cleaners

The subject of industrial explosion-proof vacuum cleaners was discussed by Kühnen (1978b), Wibbelhoff (1984), and Beck and Jeske (1989). Beck and Jeske listed the requirements for mobile type 1 vacuum cleaners recommended in the Federal Republic of Germany for removal of combustible dusts:

- The fan must be on the clean side and protected against impact by foreign bodies.
- The electric motor and other electric components must satisfy the general requirements for such components to be used in areas containing explosible dusts. Motors must be protected against short circuit and overheating.

- The exhaust from the vacuum cleaner must be guided in such a way that it does not hit dust deposits and generate dust clouds.
- All electrically conducting parts of the equipment, including the hose and mouthpiece, must be grounded with a resistance to earth of less than 1 MΩ.
- Vacuum cleaner housings must be constructed of materials that are practically nonflammable. Aluminum and aluminum paints must not be used.
- A clearly visible sign saying "No suction of ignition sources" should be fitted to the housing of the vacuum cleaner.

Figure 1.130 shows an example of a large mobile vacuum cleaner for combustible dusts in industry.

Figure 1.130 *Large mobile vacuum cleaner for explosible dusts in industry. The vessels and connecting ducts are designed to withstand internal pressures of 9 bar(g). The power requirement is 45–55 kW (Courtesy of Edelhoff Polytechnik GmbH, Iserlohn, Germany).*

Sometimes it can be useful to install stationary vacuum cleaning systems rather than having mobile ones. Figure 1.131 is a schematic illustration of the main principle. A central dust collecting station with a suction fan is connected to a permanent tube system with a number of plug-in points for the vacuum cleaning hose at strategic locations.

The importance of good housekeeping is sometimes overlooked. Always remember that clean workrooms exclude the possibility of extensive secondary explosions. Further, cleanliness improves the quality of the working environment in general.

1.4.10
DUST CONTROL BY THE ADDITION OF LIQUID

As discussed in Chapter 3, adding liquids to dusts can give rise to particle enlargement by the formation of agglomerates held together by liquid bridges or capillary forces. Furthermore, if the main product is coarse, such as grains of wheat or oats, adding a suitable

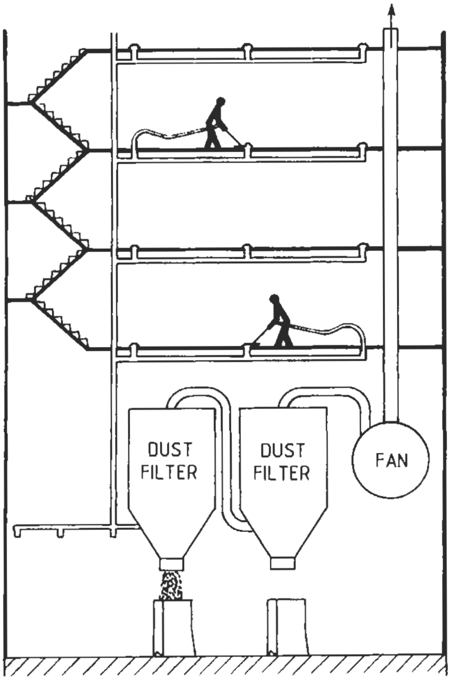


Figure 1.131 *A central stationary vacuum cleaning system with a number of alternative plug-in points for vacuum cleaning hoses.*

liquid may soften the grain surface and reduce dust formation by rubbing and abrasion during handling and transport. Adding liquids for controlling dust formation and dusting has been used primarily in the grain and feedstuffs industries. However, it is not unlikely that the method may also find other applications.

In grain handling and storage plants, the addition of small quantities of refined mineral oil, vegetable oils, or lecithin to the grain has turned out to be effective for suppressing dust cloud generation. The method was investigated by Lai et al. (1981, 1986). One type of system used in practice is illustrated in Figure 1.132.

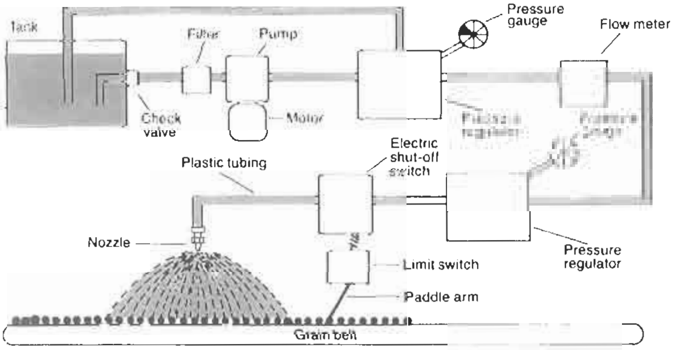


Figure 1.132 *System for spraying small quantities of oil onto grain on a belt conveyor (Courtesy of American Soybean Association).*

The oil may be sprayed onto the grain stream by conventional spraying equipment used in agriculture. The drop size should be sufficiently small to ensure even distribution of oil across the entire grain stream but not so small that the oil becomes airborne (aerosol). This would indicate an optimal drop size diameter somewhere in the range 0.1–1.0 mm. The oil may wet and penetrate into the surface of the grain. This counteracts formation of new fine dust by rubbing and impact. The oil layer on the grain surface may also act as an adhesive for fine dust particles. The oil further causes agglomeration of the fine primary dust particles to larger effective particles.

The relative significance of the two mechanisms, grain surface wetting and adhesion of dust and dust agglomeration, to some extent depends on the way in which the oil is applied. If oil is sprayed while the grain rests on a belt conveyor, the grain wetting mechanism may play a main role. If, however, the oil is applied inside the inclined feed duct to a bucket elevator bottom, where the high turbulence in the airflow causes most of the dust to be in suspension, direct agglomeration of dust particles is the more likely main result of adding the oil.

The latter configuration was used successfully by Johansen (1989). When handling various kinds of grain (wheat and barley, containing 700–800 g dust per tonne of grain), application of only 100 g soybean oil per tonne of grain was sufficient to reduce the dust level outside the process equipment substantially. The amount of dust, per tonne of grain, collected in the dust filters for the process stream was nearly the same as with no oil added. This was because of high airflow rates in the dust extraction system, which ensured collection of practically all the dust. However, the content of fine, unagglomerated particles in the collected dust, was considerably reduced by adding oil, as shown in Table 1.10.

Table 1.10 Influence of treatment of wheat grain with soybean oil on the effective particle size, ignitability, and explosibility of the grain dust resulting from handling the grain (115–230 g of oil per tonne of grain)

	Weight % of particles				Minimum electric spark ignition energy [mJ]	Minimum ignition temperature of dust cloud [°C]	K_{St} [bar\c·m/s]	P_{max} [bat(g)]
	<125 μm	<63 μm	<32 μm	<10 μm				
Without oil	75	60	50	25	10–100	430	115	7
With oil	50	40	30	10	100–1000	430	80	7

Source: Johansen, 1989, and personal communication with A. H. Johansen, Norwegian Grain Corporation.

The oil treatment method does not eliminate the dust explosion hazard. However, it reduces the hazard significantly in two ways. First, the quantity of the airborne fine dust that normally escapes from the process equipment and accumulates in workrooms, galleries, and the like is substantially reduced. Second, the clouds of agglomerated dust inside the process equipment have lower ignition sensitivity and explosibility than the clouds of unagglomerated dust that would be inside the equipment in the absence of oil treatment. Some figures for dust collected in grain handling plants with and without oil treatment are given in Table 1.10. The independence of the minimum ignition temperature on oil treatment is in accordance with this parameter being rather insensitive to changes in particle size for organic dusts.

According to Johansen (1989), the oil spraying dust control method, when applied to a grain storage and handling plant, in fact reduced the running cost of the plant, in addition to reducing the dust explosion hazard.

In the case of products that are fine in themselves, such as wheat flour and tapioca, oil addition for suppressing dust is less suitable than in the case of a coarse main product containing a small dust fraction. However, in some cases, circumstances permit addition of larger amounts of oil, up to several percent, which can give a significant reduction of dust emission even for such fine products.

1.4.11

CONSTRUCTION AND LAYOUT OF BUILDINGS

It is important to distinguish between ideal requirements and realistic possibilities. In all circumstances, it is strongly recommended that the dust explosion problem be taken into account as early as possible in the planning process, whether a completely new plant is to be constructed or an existing plant rebuilt.

Ideally, any factory in which dust explosions may occur should be located a safe distance from other buildings. Furthermore, the various parts of the factory should be separate to enable effective isolation of the explosion to the section of the factory where it starts.

Buildings should be one story whenever otherwise suitable. If multistory buildings have to be used, the parts of the plant representing the greatest explosion hazard should be located as high up as possible, preferably on the roof. Alternatively, the hazardous plant items can be located in special, isolated, well-vented niches, as illustrated in Figure 1.133. Depending on the location, the floor and roof of the niche may also have to be explosion proof.

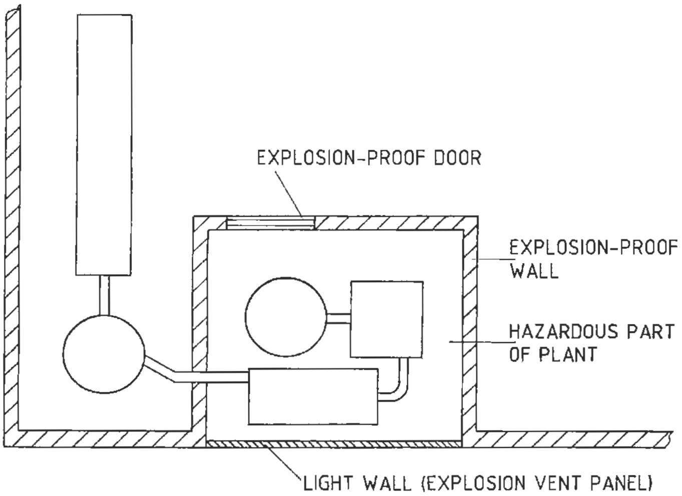


Figure 1.133 *Top view of location of hazardous part of plant in an isolated, well-vented niche within the factory building.*

In modern facilities for grain, feed, and flour, the bucket elevator legs are sometimes mounted on the outside of the buildings rather than inside. The elevator legs can then be vented outdoors.

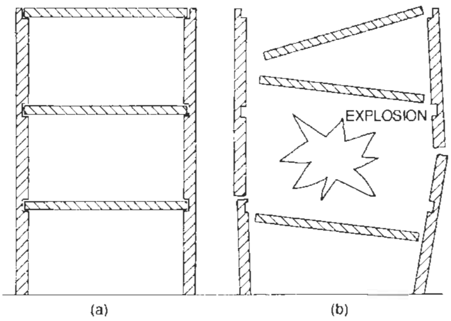


Figure 1.134 *Hazardous construction of factory buildings. Minor overpressures due to an internal dust explosion displace and break the weak walls and cause the roof and floors to fall.*

In the past, floors and roofs of factory buildings were often supported by recesses in comparatively weak walls with no reinforcement, as illustrated in Figure 1.134(a). In the case of an explosion, the walls were displaced outward, even at very modest overpressures, and the floors and roof fell down into the building, as illustrated in Figure 1.134(b). Clearly, under such circumstances the consequences of even minor dust explosions in the building could be catastrophic.

However, if the building is constructed of reinforced concrete, it can be made sufficiently strong to enable the windows to serve as vents. Figure 1.135 shows an actual example of successful venting of an explosion inside a building through the windows. It is important, however, to ensure that flying pieces of glass present no hazard to humans. To avoid this hazard, it may be necessary to replace glass panes with anchored, transparent plastic panes.

Figure 1.135 *Result of malted barley dust explosion in grain silo facility in Oslo, Norway, in 1987. The windows provided sufficient venting to prevent destruction of building, which is of reinforced concrete (Courtesy of A. F. Johansen, Oslo Port Silo, Norway).*

As long as there are no special reasons for choosing other solutions, it is recommended that factory buildings in which dust explosions may occur, be constructed as indicated in Figure 1.136. The basic principle is that the roof and intermediate floors are supported by a strong frame structure. The walls are lightweight panel sections that function as vent covers, should an explosion occur. If required, the panels may be anchored to the frame structure (see Figure 2.7).

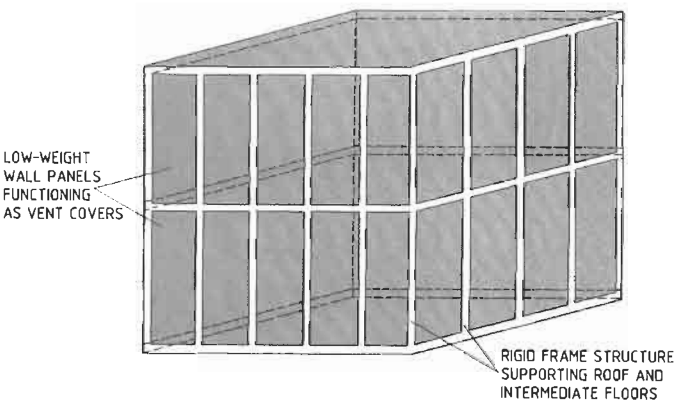


Figure 1.136 *Recommended construction of factory buildings to prevent collapse of building in a dust explosion.*

Some final points to be taken into account when planning the layout and construction of factory buildings to reduce the explosion and fire hazard, include

- Safe escape routes in case of explosion and fire.
- Fire-resistant construction materials.
- Fire-resistant doors.
- Electrical installations according to latest regulations and recommendations.

1.4.12
THE "HUMAN FACTORS"

Proper construction and maintenance of an integrated system for preventing and mitigating dust explosions very much depends on human relations and human behavior.

A number of different personnel categories may be involved, including

- Workers and foremen in the plant.
- Workers from the maintenance department.
- Plant engineers.
- Safety engineers.
- Purchasing department officers.
- Safety manager.

- Middle management.
- Top management.
- Suppliers of equipment.
- Dust explosion experts and consultants.

Adequate prevention and mitigation of dust explosions cannot be realized unless there is meaningful communication among the various categories of personnel involved. If such communication is lacking, the result can easily become both unsatisfactory and confusing, as illustrated in Figure 1.137.

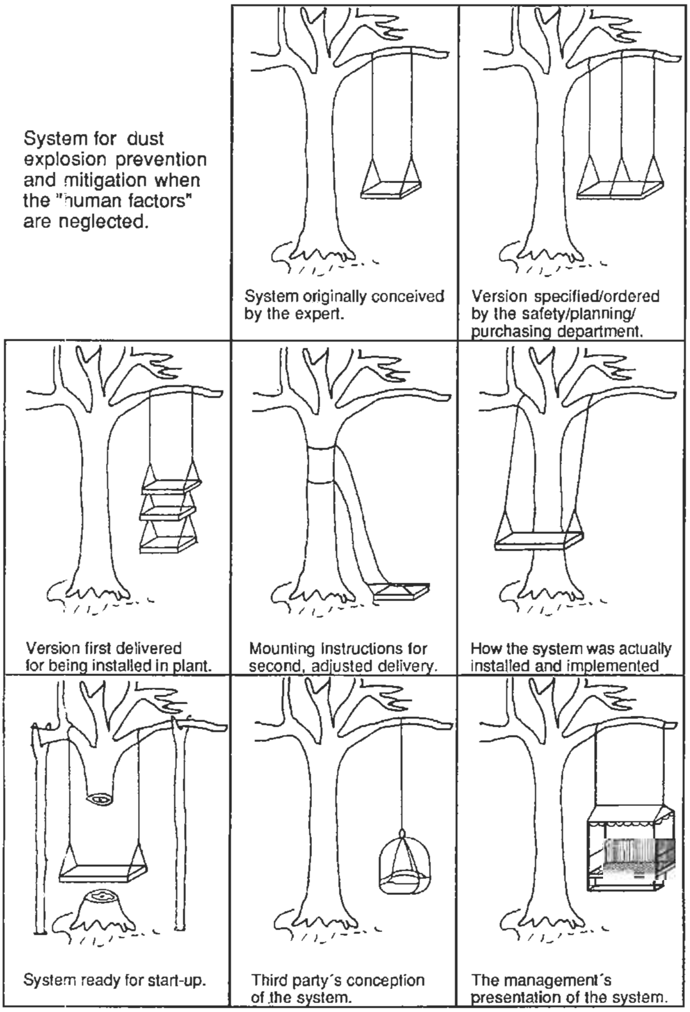


Figure 1.137 *Implementation of system for dust explosion prevention and mitigation when "human factors" are neglected (Adapted version of original by Klapp, 1977).*

In general terms, *meaningful communication* may be defined as the conveyance and proper receipt and appreciation of adequate information whenever required. However, to receive, appreciate, and use the information in a proper way, one must have

- Adequate knowledge.
- Adequate motivation.
- Adequate resources and deciding power.

Knowledge about dust explosions can be acquired by reading, listening to lectures, talking to experts, and the like, although experience from actual explosion prevention and mitigation work is perhaps the best form of knowledge.

Genuine motivation is more difficult to achieve. It seems to be a law of life that people who experienced serious explosion accidents possess the highest level of motivation, in particular if the accident caused injuries and perhaps even loss of life. This applies to workers as well as top management. However, high levels of motivation can also result from good demonstrations of real explosions, including their initiation by various ignition sources, as well as their propagation and damaging effects. Video and film can help, if used properly.

The final element, adequate resources and the authority to put the good plans into practice, is in reality controlled by the top management. Verhaegen (1989) concluded from this that the real responsibility for establishing and running a proper safety assurance system always lies on the top management. Summarizing the experience of a large, multinational chemical company, Verhaegen suggested that the following 10 essential elements be involved to ensure proper safety management:

- Top management responsibility.
- Safety statement (explicit commitment from top management).
- Objectives and goals (specification of long- and short-term expectations).
- Stated standards (written guidelines and rules).
- Safety committees (a dedicated organization for handling safety issues at all levels).
- Safety audits (regular reexamination of work practices).
- Accident records (written analyses of accidents: Why did they happen? How can similar accidents be prevented?).
- Safety personnel (qualified specialists are essential as advisers, but responsibility remains with top management).
- Motivation (by information and involvement and so on).
- Training (a continual process, courses are essential, the message must get through!).

Verhaegen emphasized the problem that a good safety organization is in reality often kept active by one or two dedicated individuals. If they change position within the company, or even leave, the safety organization may suffer. Management should foresee this problem and provide a workable solution.

Burkhardt (1989) gave an informative, more theoretical psychological analysis of the role of human factors in accident prevention in general. Atkinson (1988) and Proctor (1988) discussed various aspects of the training of safety personnel.

1.5
SELECTING APPROPRIATE MEANS FOR PREVENTING AND MITIGATING DUST EXPLOSIONS

1.5.1
BASIC PHILOSOPHY, COST ESTIMATION, AND RISK ANALYSIS

1.5.1.1
The Optimal Solution, or Striking the Balance

The extensive menu of means of preventing and mitigating dust explosions, summarized in Table 1.9, is discussed in Section 1.4.

Noha (1989) emphasized that the concepts of "primary" and "secondary" means of protection against dust explosions, used in the Federal Republic of Germany in the past, can be misleading, by indicating that mitigation is of secondary importance as compared to prevention. The rational approach is to seek an optimal combination of means of both categories for each specific application. In doing so, Noha suggested the need to break down the problem and evaluate specifically

- The efficacy of the protective means.
- The technical feasibility.
- The environmental acceptability.
- The financial acceptability.

Figure 1.138 illustrates the situation.

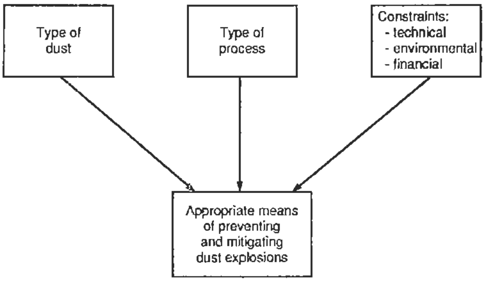


Figure 1.138 *The appropriate set of means for preventing and mitigating dust explosions depends on type of dust, type of process, and the boundary conditions in terms of plant layout, type of building(s), environmental constraints, financial constraints, and so forth.*

One pitfall related to assessing the efficacy of the protective means is the selection of the dust sample on which the assessment is to be based. Noha (1989) mentioned as an example a comparatively coarse polypropylene powder to which <1% of fine calcium stearate had been added to increase flowability. Such additives have large specific surface areas and correspondingly low minimum ignition energies. But, as long as they are homogeneously mixed with the polypropylene, the small fraction of additive has little influence on the ignitability and explosibility of the polypropylene powder as a whole. However, if segregation occurs, the fine, reactive additive may accumulate in certain areas of the process, for example, in a filter. This can create a much more hazardous situation than would have been anticipated on the basis of the properties of the polypropylene powder. In such cases, it may be wise to base the assessment of the efficacy of the protective means on the properties of the additive rather than the main product. This, not in the least, applies to the incendivity of the dusts in terms of their minimum ignition energies.

The protective means to be used must be technically and financially feasible. For example, there is no point in installing vents on an enclosure that is so weak that it could not withstand the maximum pressure to be expected, even with the largest vent area that can be provided.

Traditional venting may sometimes be unacceptable due to the inevitable emission of unburned, burning, and burned dust. This is particularly so in congested urban areas and for some special synthetic organic powders like pesticides, pharmaceuticals, and dye stuffs. However, the further development of the quenching tube for dust and flame-free venting of dust explosions (see Section 1.4.6.6) may alter this situation and make venting a feasible means of mitigating dust explosions even in some of these situations.

In the case of very reactive dusts, of K_{St} values $\gg$300 bar m/s, automatic explosion suppression must most often be excluded because the injection of the suppressant is too slow to produce any significant mitigating effect on the explosion development. Inerting is feasible only if sufficient inert gas is available at an acceptable cost, whereas reinforcement of process equipment to an explosion shock-resistant standard may often be both technically and financially unacceptable.

Figure 1.139 outlines a general approach to fighting the dust explosion hazard in industry. Sometimes, the required ignitability and explosibility data for the dust(s) in question are available from earlier test work or from the literature. However, most often, specific laboratory testing is needed.

1.5.1.2
Cost Considerations

Ritter (1978) compared the cost of the various means of dust explosion prevention and mitigation by means of cost indices. The index for proper elimination of ignition sources was, by definition, set equal to unity and used as a basis for cost comparison for all types of plant units except milling plants. Ignition source elimination included use of approved electrical equipment in all areas, grounding of all conducting equipment to avoid static electricity, avoidance of overheating by friction, safe maximum temperatures on all heated surfaces, and avoidance or elimination of smoldering nests. A summary of Ritter's figures is given in Table 1.11.

Table 1.11 Relative costs for various means of preventing and mitigating dust explosions using the costs of eliminating ignition sources as a basis for comparison

Plant type	Elimination of ignition sources	Inerting	Pressure resistant at 7 bar(g)	Venting: pressure resistant at 2 bar(g)	Automatic suppression: pressure resistant at 2 bar(g)	Dust concentration $<C_{min}$
Silo plant	1.0	1.3–1.5	3.0	1.5–1.7	2.1–2.6	Not possible
Spray dryer	1.0	1.7	3.1	1.7	2.0	1.1
Milling plant*	Not possible	1.3	1.8	1.4	1.5	Not possible
Bag filter	1.0	1.5	2.3	1.8	1.7	Not possible
Fluidized bed dryer	1.0	1.4	2.8	1.5	1.5	Not possible

*Ignition sources cannot be eliminated in mills, and therefore the cost of the plant itself is used as the cost basis of index 1.0.
Source: Ritter, 1978.

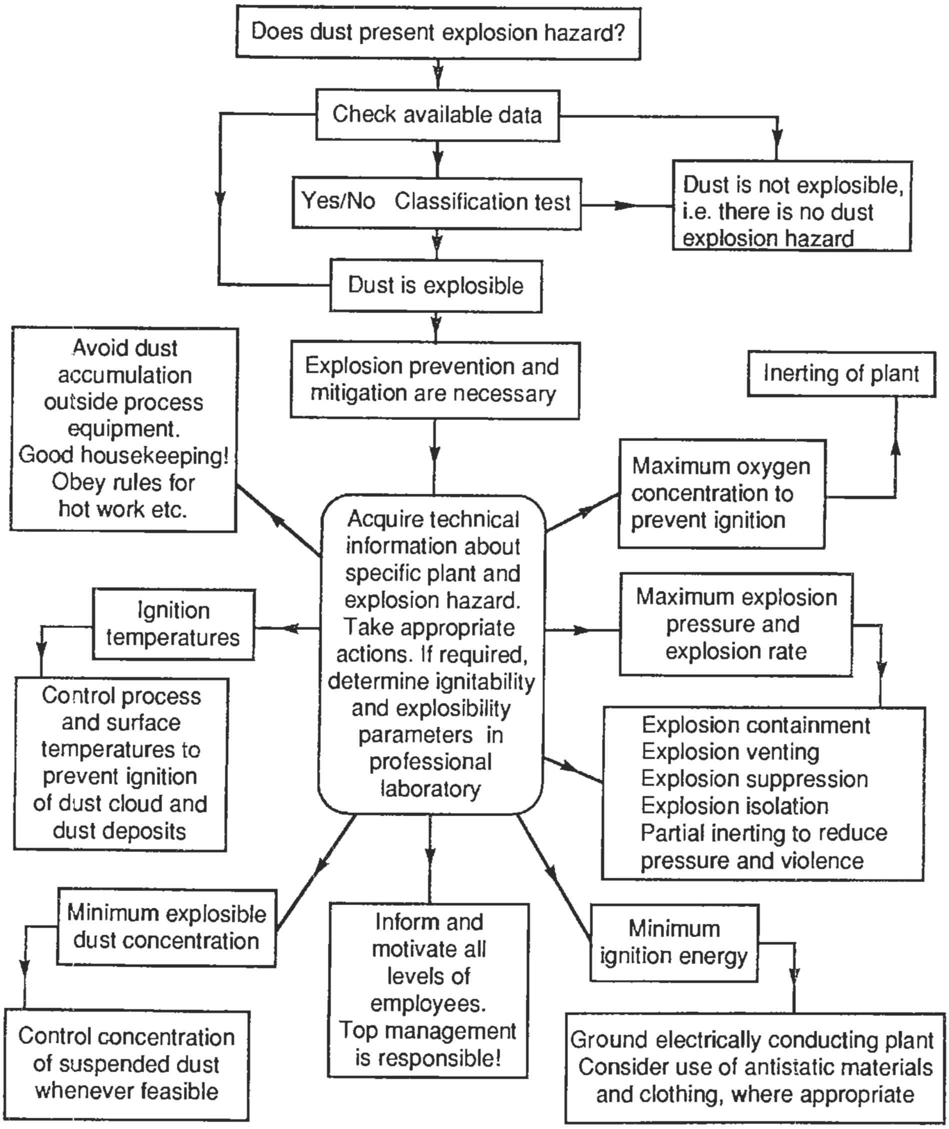


Figure 1.139 *A general approach to practical dust explosion protection (Modified, extended version of scheme suggested by Field, 1982a).*

Table 1.11 indicates that the use of pressure-resistant equipment is generally comparatively expensive. However, the cost of pressure shock-resistant equipment is significantly lower. The relative costs in Table 1.11 of inerting, venting, and automatic suppression are fairly equal, perhaps with a slight increase in the order mentioned. However, technology has changed somewhat since 1978, and the more liberal vent area requirements justified by more recent research (see Chapter 6) suggest that venting may be somewhat cheaper than indicated by Table 1.11. Table 1.11 should rather serve as an illustration of the usefulness of systematic cost comparison, than as a final, generally valid ranking of costs.

1.5.1.3
Hazard Analysis

Hazard analysis is a large subject in itself, covered by a substantial quantity of published information. The term *hazard analysis* comprises a number of different systematic methods for identifying, and sometimes also quantifying, the hazards associated with a given process or plant. In principle, such analyses can also be used as a basis for optimizing the selection of means to prevent and mitigate dust explosions.

Cox (1986, 1987) presented an informative summary of the various techniques in use for hazard analysis, which is quoted more or less literally, under the following five headings.

Hazard Surveys or Inventories These methods are essential preliminaries to many safety studies. The survey consists of making an inventory of all stocks of hazardous material or energy and noting relevant details of storage conditions. When carried out at the conceptual stage of a project, such a survey can contribute to layout optimization and may suggest process changes to reduce stored quantities. It generates information that can be used in a preliminary risk assessment, but the hazard survey itself is little more than a "screening" exercise designed to identify problem areas.

Hazard and Operability Studies (HAZOP) and Failure Modes and Effects Analysis (FMEA) These two techniques have very similar objectives and methods of approach. The purpose is to identify systematically all the possible ways in which the system investigated could fail, evaluate these, and formulate recommendations for preventive and mitigating measures.

FMEA is the simpler of the two techniques. The procedure is to take each plant item and component in turn, list all possible failure modes and consider the consequences of each. The results are recorded in a standard format in which recommendations for action can be included. The weakness of FMEA is that there is no specified method for identifying the failure modes and their effects. The engineer is expected to do this from first principles or past experience, and the only discipline imposed on him or her is that of the reporting format itself.

HAZOP overcomes this difficulty by introducing a systematic method for identifying failure modes. This involves scrutiny of a large number of possible deviations from normal operating conditions, which are generated by applying guide words such as *more*, *less*, and *reverse*, to each parameter describing process conditions in each component, plant item, or line in the plant. However, HAZOP in its original form has disadvantages, and some industrial companies have modified the way in which the results of the study are handled. Instead of "recommendations," the output is "identified problems," which leaves more room for a coordinated rational design revision, which is not only cheaper but probably safer also.

Analysis of Systems Reliability by Fault Tree Analysis This method is applied to complex systems, whether the complexity is due to the nature of the process itself or the instruments required to run the process. In the basic technique, the fault tree analysis, the failure modes must first be identified, such as by HAZOP. These failure modes are named *top events*. An example of a top event could be a dust explosion in a milling plant.

For each top event, the analyst must identify all those events or combinations of events that could lead directly to the failure. The precise logical relationship between cause and effect is expressed by AND or OR gates and is usually presented in diagrammatic form. The immediate causes of the top event have their own contributory causes, and these can be presented in a similar way, so that a complete fault tree is built up. The process ceases when all the causative factors at the bottom of the tree are of a simple kind for which frequencies of occurrence or probabilities can be estimated.

The synthesis of fault tree is a job that is best done by an engineer with good experience in the type of system under consideration; it is much easier to teach such a person how to construct a fault tree than to teach a reliability specialist everything about the system. However, the quantitative analysis of a fault tree is a separate activity in which the reliability specialist plays the dominant role.

An illustrative example of a quite comprehensive fault tree for a grain dust explosion in a grain storage facility was given by National Materials Advisory Board (1982).

Risk Analysis by Event Tree Analysis Risk analysis consists of four major steps: identification of a representative set of failure cases, calculation of consequences, estimation of failure probabilities, and assessment of overall impact.

Failure cases are identified first by establishing the location of the main inventories of hazardous material and then by detailed scrutiny of the process flow and instrumentation diagrams using checklist methods or HAZOP.

Once the failure cases have been identified, the consequences of the failure must be calculated. Event tree analysis is a useful method in this process. An event tree is the reverse of a fault tree, starting with the initial or "bottom events" and exploring all possible "top events" that can result from it. Each outcome has further outcomes, and all these can be related by means of decision gates. At each gate, the conditional probabilities must be estimated for each of the alternative branches. On this basis, the probabilities of the final hazard, or "top event," can be calculated.

Criteria have been suggested whereby calculated risks can be judged. Almost all criteria proposed so far are based on the concept of comparability with the existing general risk background. Cost/benefit and "risk perception" arguments have been advanced, but they have not yet been developed to a practical and accepted form for being used in risk analysis.

Risk analysis has been criticized by pointing at

- Inaccurate mathematical models.
- Incomplete analysis of actual practical problem.
- Inaccurate primary failure probability data.
- Inadequate acceptability criteria.
- Difficulty of checking final result.
- Complexity and laboriousness of method.

Hawksley (1989) discussed the conditions under which the various elements of quantitative risk analysis are useful in the assessment of risks in practice.

Safety Audits Once a plant enters operation, hardware and procedures start to change from those originally established by the commissioning team. Usually, there are good reasons for this: The plant engineers and operators may find simpler or more economic procedures, and the operational requirements themselves may change. However, it is also quite possible that safety standards fall off with time because experience of satisfactory operation leads to overconfidence and a false sense of security.

For these reasons, safety audits are used in many operating companies. These may vary from a half-day tour by the works manager to a review lasting several weeks carried out by a team of engineers covering different disciplines and independent of the regular operational management of the plant. For the most penetrating audits, the study should not be announced in advance.

In practice, the assessment of dust explosion hazards is bound to be subjective, because the problem is too complex for quantitative analytical methods to yield an indisputable answer. In Figure 1.140, four different scenarios for a given industrial plant are indicated.

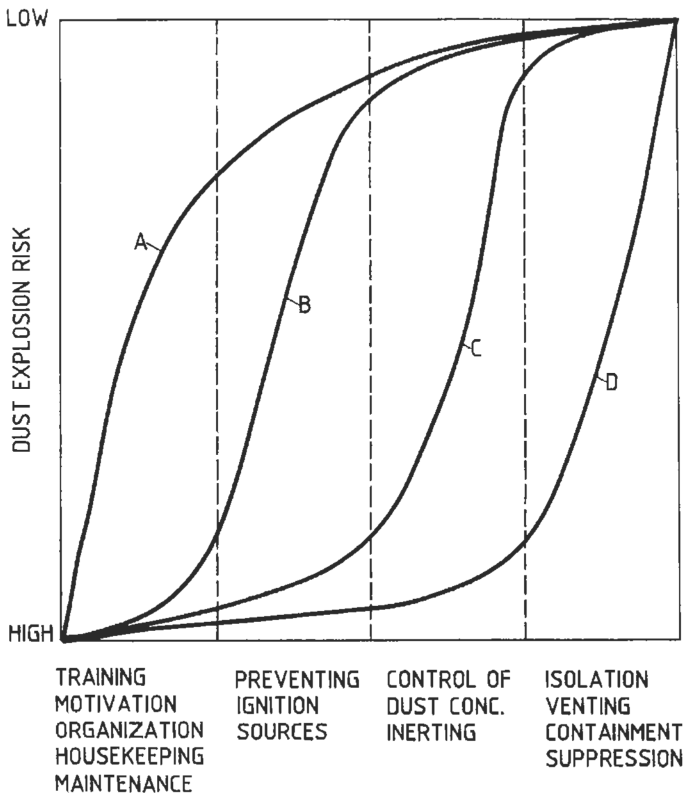


Figure 1.140 *Effect of various means of preventing and mitigating dust explosions. Four different scenarios for a given plant. Extended and generalized presentation based on an original scenario (A) by Pinkwasser and Häberli (1987).*

Scenario A, which was assumed by Pinkwasser and Häberli (1987) for the grain, feed, and flour industry, suggests that most of the dust explosion hazard can be eliminated by "soft" means, such as training, motivation, improving the organization, good housekeeping, and proper maintenance. The alternative scenario (B) suggests that concentrating on preventing ignition sources gives the greatest benefit. Scenarios C and D focus on keeping the dust cloud nonexplosive and using mitigating measures, respectively. Other scenarios can easily be envisaged.

However, experience suggests that some scenarios, depending on the type of powder or dust and plant, are more credible than others. For example, it can be argued that a plant producing or handling fine aluminum flake is well represented by Scenario C in Figure 1.140, because inerting by nitrogen would probably reduce the dust explosion risk from high to acceptably low.

In spite of the objections that can be raised against the use of the various hazard analysis methods, several authors have suggested that risk analysis and other methods be adopted specifically for reducing the dust explosion hazard in the process industry, including grain, feed, and flour storage plants. These include Beck (1974, 1985); Sorgdrager (1985); Kameyama et al. (1982); Lai, Shenoi, and Fan (1985); and Piotrowski, Mrzewinski, and Proskurmicki (1988).

1.5.2

SELECTION SCHEME SUGGESTED BY NOHA FOR THE CHEMICAL PROCESS INDUSTRY

1.5.2.1

General Background

Noha (1989) restricted his analysis to four groups of process equipment:

- Crushing and milling equipment.
- Dryers.
- Mixers.
- Conveyors and dust removal equipment.

Informative descriptions and illustrations of the various kinds of process equipment typical of powder producing and handling plant are provided by Perry and Green (1984).

Before deciding how a given plant should be protected against dust explosions, it is necessary to evaluate the extent to which protection is really necessary. This requires knowledge of ignitability and explosibility parameters of representative dust samples as well as information about the plant design, layout, and operation. It may be necessary to investigate the possibility of generation of hybrid mixtures (dust + explosible gas or vapor).

Tables 1.12, 1.13, 1.14, and 1.15 give Noha's suggestions for selecting appropriate means for preventing and mitigating dust explosions in four categories of process equipment in the chemical process industry. The symbol X indicates the most appropriate means of protection, whereas (X) implies that the use of the means indicated is possible, but that it is not implemented very often in practice.

Noha emphasized that a given plant item, for example, a specific dryer, should not be considered in isolation. It is always necessary also to consider the entire plant or the part of it likely to become involved in a dust explosion in the system. Identification of probable ignition sources and ignition points is an important part of the analysis.

Table 1.12 Appropriate means for preventing and mitigating dust explosions in a chemical process plant: crushing and milling equipment

Means of explosion prevention/ mitigation Crushing and milling equipment	Dust concentration <minimum explosion concentration	Inerting by adding inert gas	Intrinsic inerting	Evacuation of process equipment	Addition of inert solids	Elimination of ignition sources	Explosion-resistant equipment	Explosion venting	Automatic explosion suppression	Explosion isolation
Ball mills		X		(X)	(X)		X	(X)		
Vibratory mills		(X)			(X)		X	(X)		
Crushers	X					(X)	X	(X)	(X)	
Roll mills	X					(X)				
Screen mills		(X)				X	(X)			
Air jet mills		(X)				X	(X)			
Pin mills		(X)			(X)		X	(X)	(X)	
Impact mills					(X)		X	(X)	(X)	
Rotary knife cutters	(X)						X	(X)	(X)	
Hammer mills		(X)			(X)		X	(X)	(X)	

Source: Noha, 1989.

Table 1.13 Appropriate means for preventing and mitigating dust explosions in a chemical process plant: powder dryers

Means of explosion prevention/ mitigation Powder dryers	Dust concentration <minimum explosion concentration	Inerting by adding inert gas	Intrinsic inerting	Evacuation of process equipment	Addition of inert solids	Elimination of ignition sources	Explosion-resistant equipment	Explosion venting	Automatic explosion suppression	Explosion isolation
Spray dryers (nozzle)	X	(X)	X			X		(X)	(X)	
Spray dryers (disc)	X	(X)	X					(X)	(X)	
Fluidizd bed dryers		(X)	(X)			X	(X)	(X)	(X)	
Stream dryers	(X)	(X)				X	(X)	(X)		
Spin-flash dryers						(X)	X	(X)	(X)	
Belt dryers	X					(X)				
Plate dryers	X					(X)				
Paddle dryers	X	X		(X)	(X)	X	(X)	(X)	(X)	

Source: Noha, 1989.

Table 1.14 Appropriate means for preventing and mitigating dust explosions in a chemical process plant: powder mixers

Means of explosion prevention/mitigation Powder mixers	Dust concentration <minimum explosion concentration	Inerting by adding inert gas	Intrinsic inerting	Evacuation of process equipment	Addition of inert solids	Elimination of ignition sources	Explosion-resistant equipment	Explosion venting	Automatic explosion suppression	Explosion isolation
With mixing tools: High-speed	(X)	X		(X)			X	(X)	(X)	
Low-speed	(X)	(X)		(X)		X	(X)	(X)	(X)	
Without mixing tools: Drum mixers		(X)		(X)		X	(X)			
Tumbling mixers		(X)		(X)		X	(X)			
Double cone mixers		(X)		(X)		X	(X)			
Air flow mixers: Fluidized bed mixers						X	(X)	(X)		
Air mixers						X	(X)	(X)		

Source: Noha, 1989.

1.5.2.2
Crushing and Milling Equipment

The justification for some of the suggestions in Table 1.12 for crushing and milling equipment are as follows. In crushers and roll mills, the concentration of fine dust that can produce explosions is mostly below the minimum explosible concentration, just because of the nature of the process itself. In the case of screen mills and air jet mills, the probability of ignition sources can be regarded as low. Inerting is most common in the case of batch mills, whereas other mill types are often made strong enough to withstand an internal dust explosion.

Mayerhauser (1978) considered the dust explosion protection of mills and air classifiers specifically. He concluded that pressure-resistant or pressure shock-resistant construction and inerting the two most suitable methods for these kinds of equipment.

Ruttmann (1989) described the systematic design of one specific plant, in which inerting was used to protect a combined milling and mixing system against dust explosions.

Whenever possible, one should use mill types that minimize dust cloud formation and generation of ignition sources by high-speed impact. Figure 1.141 shows a type of open slow-speed screw shredder that, to an increasing extent, replaces enclosed high-speed hammer mills. The slow motion minimizes both dust cloud formation and the probability

Table 1.15 Appropriate means for preventing and mitigating dust explosions in a chemical process plant: powder and dust conveyors and dust removal equipment

Means of explosion prevention/mitigation Powder/dust conveyors and dust removal equipment	Dust concentration <minimum explosion concentration	Inerting by adding inert gas	Intrinsic inerting	Evacuation of process equipment	Addition of inert solids	Elimination of ignition sources	Explosion-resistant equipment	Explosion venting	Automatic explosion suppression	Explosion isolation
Screw conveyors	(X)	(X)				(X)	X	(X)		
Chain conveyors	(X)						X	(X)	(X)	
Bucket elevators		(X)				(X)	X	X	(X)	
Conveyor belts	X									
Shaker loaders						X		(X)		
Rotary locks		(X)				X	X	(X)		
Pneumatic transport equipment	(X)	(X)				X	(X)			(X)
Dust filters and cyclones		(X)				X	X	(X)	(X)	
Industrial vacuum cleaning installations	X					X				

Source: Noha, 1989.

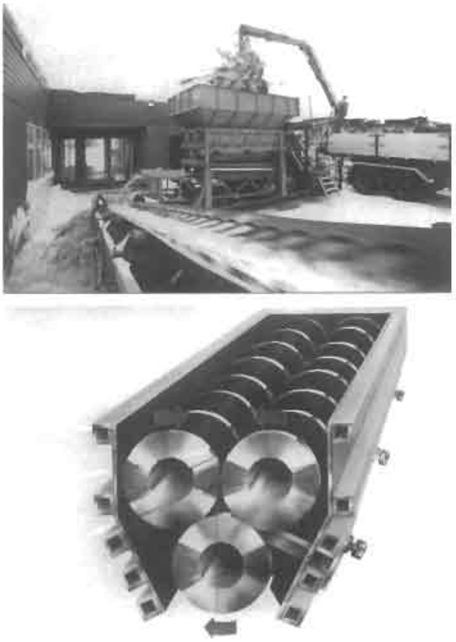


Figure 1.141 *Open slow-speed screw shredder for size reduction of combustible waste materials: (top) complete installation in operation, (bottom) the shredding screw section in the lower part of the installation (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

of ignition source generation. Furthermore, the open construction provides generous venting should an explosion nevertheless occur.

In Table 1.12, Noha also indicated that adding inert dust to the explosible dust is a means of preventing dust explosions in crushers and mills, in principle. However, as pointed out in Section 1.4.3.3, most often this method is not feasible in practice, due to contamination of the product by the inert additive.

1.5.2.3
Dryers for Powders and Granular Materials

In the case of dryers (Table 1.13), the special protective method "intrinsic inerting" can be a good solution in some cases, particularly for spray dryers. This method implies that the required quantity of inert gas is generated in the plant itself by controlled combustion in the hot-gas generator and recirculation of the gas. Such hot gases consist mainly of nitrogen, carbon dioxide, and water vapor. The residual concentration of oxygen is kept at a sufficiently low level to ensure inert conditions. Intrinsic inerting of dryers was discussed specifically by Hammer (1978) and Klais (1989).

Spray dryers normally operate at dust concentrations significantly below the lower explosible limit, which clearly adds to safety. However, dust deposits are often generated on walls and the like and smoldering nests may develop, depending on the local temperature and oxygen concentration. Klais (1989) emphasized that oxygen concentrations as low as 4 vol%, which exclude dust explosions for most organic powders, may still be too high to prevent certain autooxidation processes in the dried powder when deposited as a layer or a heap (see also Figure 1.67 in Section 1.4.2.2). If a smoldering nest loosens and gets carried away with the product stream, it can initiate a dust explosion in downstream cyclones and silos.

In the case of disc type spray dryers, one cannot fully exclude the possibility that a disk that flies away and impacts the walls of the dryer generates a hot spot of sufficient size and temperature to initiate a dust explosion.

The powder and dust in belt and plate dryers are mostly in deposited form. In paddle dryers, the dust concentration normally is expected to exceed the upper explosible limit in the areas where occurrence of an ignition source might be envisaged.

Gibson, Harper, and Rogers (1985) evaluated the fire and explosion risk in powder dryers with particular emphasis on the detection of exothermic decomposition. Their conclusion was that existing methods for evaluating dust explosion risk, combined with an adequate method for characterizing the exothermic decomposition properties of the powder, provide a means of specifying safe drying conditions. Most often, control of the atmosphere to keep the dust cloud nonexplosive or the use of venting, automatic suppression, or explosion- (shock-)resistant equipment is required. However, in certain cases, safety can be based solely on avoidance of decomposition and ignition.

1.5.2.4
Powder and Dust Mixers

In mixing equipment (Table 1.14), ignition sources may be avoided as long as there are no fast-moving mixing tools. Inerting by adding, for example, nitrogen or another inert gas is feasible in batch mixers, whereas continuous mixers may preferably be designed to withstand the pressure rise caused by a possible dust explosion.

Radandt (1969) discussed the dust explosion protection of mixing silos and containers and concluded that the choice of means to prevent and mitigate dust explosions depends on the specific equipment and process design.

1.5.2.5
Powder and Dust Conveyors and Dust Removal Equipment

As Table 1.15 for conveyors and dust removal equipment shows, Noha recommended the use of explosion-resistant construction whenever fast-moving mechanical elements constitute part of the system. This, for example, applies to bucket elevators, which can preferably be equipped with cylindrical, pressure-resistant legs, vented to a safe place via the elevator top. In some cases, elevator legs can be mounted along the wall outside the building and vented directly to the atmosphere.

Some materials collected in filters may form consolidated plugs in the dust discharge hopper at the filter bottom. This may give rise to frictional heating and self-ignition, which can result in dust explosions. Provided that the main enclosure as well as the filter bag supports are properly grounded, incendiary electrostatic discharges would not normally be expected in filters. (In the case of hybrid mixtures, the situation may be different.) However, if the equipment upstream of the filter, such as mills and spray dryers, can generate ignition sources that may be conveyed to the filter, the filter must be protected against possible explosions. By adopting a cylindrical or conical body shape, the use of pressure shock resistant filter enclosures is a feasible possibility.

According to Noha (1989), industrial vacuum cleaners operate mostly at dust concentrations below the lower explosible limit. The fan is normally located on the clean side of the filter and therefore constitutes no ignition hazard. However, the possibility of internal dust explosions in industrial vacuum cleaners cannot be fully excluded in generally; therefore, such equipment is often designed to be explosion- (shock-)resistant. Various aspects of preventing and mitigating dust explosions in pneumatic and other systems for conveying powders and dusts were discussed by Palmer (1973b) and Eckhoff (1982ab). Pinkwasser (1985) described the extinction of smoldering powder nests in a dust cloud during pneumatic transport, and Göpfert (1981) discussed means of dust explosion prevention and mitigation in continuous conveying equipment in general. Palmer (1975) paid specific attention to dust explosions in dust collecting plant including cyclones and filters.

1.5.2.6
Conclusion

Noha (1989) emphasized that Tables 1.12–1.15 should be regarded as a starting point for discussion rather than as a final answer. The solution ultimately adopted must be the result of detailed analysis of the relevant factors in each specific case. General guidelines are useful as a point of departure, but the end result will always be tailor-made.

1.5.3
SPECIAL ASPECTS FOR SOME SPECIFIC GROUPS OF POWDERS AND DUSTS: A BRIEF LITERATURE SURVEY

1.5.3.1
Grain and Feed Dusts and Flour

The literature on preventing and mitigating dust explosions in the grain, feed, and flour industry is substantial. This is easy to understand in view of the large losses of life and property caused by dust explosions in this branch of industry. One of the earliest contributions, by Weber (1878), is still relevant in many respects. In particular, he emphasized the marked influence of the moisture content of the dust or flour on the explosion hazard. Almost a century later, Theimer (1972) gave his well-known summary of causes and means of prevention of dust explosions in grain storage facilities and flour mills.

A useful summary of existing knowledge and experience at that time was collected during an international symposium arranged by National Materials Advisory Board of the United States (1978). Aldis and Lai (1979) reviewed literature related to the engineering aspects of grain dust explosions. The National Materials Advisory Board (1982) produced a set of well-structured recommendations for the selection of adequate means to prevent and mitigate dust explosions in grain storage facilities and flour mills. The reason why soybean oil is used to reduce dust formation in grain storage facilities (see Section 1.4.10) was not mentioned but is simple. The potential of this very promising method of dust control was just not known at that time. This illustrates that knowledge and technology change continuously, necessitating regular updating of sources of information.

A most informative document was issued by the Committee on Agriculture (1982), of the U.S. House of Representatives. A number of witnesses, including both people from industry and scientists, were asked to express their views on how to reduce the probability of dust explosions in the U.S. grain industry. Several witnesses emphasized the need for improved dust control.

Solymos (1985) discussed various "dry" methods of dust control as a means of preventing dust explosions in grain storage facilities. Erling (1984) outlined the very comprehensive system for preventing and mitigating fires and dust explosions in the rebuilt Roland flour mill in the Federal Republic of Germany. The mill suffered a catastrophic explosion and fire in 1979.

Radandt (1987) reviewed the prevention and control of dust explosions in the grain, feed, and flour industry in the Federal Republic of Germany in general; Zhang Fenfen and Zhang Chunxiao (1987) considered grain dust explosions and their prevention in grain storage facilities in the Peoples Republic of China.

Tesler and Semyonov (1988, 1989) discussed new concepts for reducing the dust explosion hazard in grain storage facilities, with particular reference to the situation in the USSR. The latter paper included schemes of explosion protection systems for integrated grain storage facilities and quantitative methods for design of equipment, structures, and buildings.

The venting of large silos in the grain, feed, and flour industry has been a topic for discussion for a long time. Experimental full-scale work conducted in Norway and discussed in Chapter 6 provides some evidence. Pinkwasser and Häberli (1987) described specific designs of relief panels in the roof of large silo cells.

Bucket elevators are well-known sites of primary dust explosions. Wilcoxen (1981) reported on an actual dust explosion in a grain storage facility in which the bucket elevators were in part located outdoors and fitted with explosion vents. Due to the vents in the elevator legs, the extent of the explosion and resulting damage was comparatively minor. It was concluded that the design adopted had proven successful.

The French organization for standardization, Afnor (1986), issued a recommendation for mitigating dust explosions in the grain, feed, and flour industry by venting. However, in view of the fast development in the field, one may wish to revise the recommendation at some points by including recent experimental evidence.

The ignitability and explosive characteristics of dusts influence the choice and design of means of dust explosion prevention and mitigation. Ignitability and explosibility, in turn, depend on basic dust chemistry, effective particle size (see Section 1.3.3), and moisture content. Contributions elucidating various relationships for grain, feed, and flour dusts were written by Hartmann, Cooper, and Jacobson (1950); Jacobson et al. (1961); Eckhoff (1977/1978); Eckhoff and Mathisen (1977/1978); Enright and Bullock (1983a, 1983b); Chiotti and Yoshizaki (1983); and Ambroziak (1985)

1.5.3.2
Milk Powder, Fish Meal, and Sugar

According to Beever (1984), the number of reported fires and explosions in operations involving spray drying of milk increased during the early 1980s. Spray drying of milk is known in particular to generate self-heating and charring of the dried product. In milk spray dryers, there will always be some regions containing explosible dust clouds. The question is only whether an ignition source is also present. Self-heating and charring in deposited dried milk powder can generate effective ignition sources, and Beever (1984) concluded that glowing or burning powder deposits were the most likely source of ignition in milk spray dryers. She estimated the minimum thicknesses for self-ignition of deposits of various types of milk powders at 7–14 mm for 200°C ambient temperature and 100–320 mm for 100°C.

Following an extensive explosion in a milk spray dryer in France, Pineau (1984b, 1985) conducted a comprehensive study of the self-ignition properties of milk powders and their ignitability and explosive properties in cloud form.

Fish meals constitute another product group that can give rise to dust explosions. One example is given in Chapter 2. The self-heating properties of fish meals as functions of meal chemistry, moisture content, and so forth were discussed by Dreosti (1980). Eckhoff (1980) gave some further data for the ignitability and explosibility of fish meals.

In a series of full-scale sugar dust explosion experiments in the dust removal plant of a disused sugar factory, Scholl (1973) demonstrated the potential of this material to give rise to serious dust explosions. Meek and Dallavalle (1954) tried to correlate explosibility properties of various types of sugar (C_{18}, C_{12}, and C_6) with molecular structure and particle size. However, possibly due to a very weak ignition source and nonhomogeneous dust clouds, this was only partly successful.

1.5.3.3
Wood, Cellulose, and Peat Dusts

The fire and explosion hazards in the production of chipboard, hardboard, and wood powder have been recognized for a long time. As new insight and technology have become available, the methods of preventing and mitigating the hazards have been improved.

Thelning and Laufke (1970) mainly focused on mitigation, in particular by venting and automatic suppression of explosions, and fire extinction by carbon dioxide and water vapor. Schmid (1972) gave detailed recommendations for both fire, explosion and environmental protection of chip board producing plants. He included prevention of ignition sources by recommending removal of foreign stone and metal objects before admitting the raw material to the process, and avoidance of overheating. The specific processes of chip preparation, pressing and cutting of the board, and the final finishing of the board surface were considered separately.

Arvidsson, Back, and Östman (1977) conducted a very comprehensive investigation of the explosion and fire hazards in the production of chipboard. They summarized their recommendations for preventive and mitigating measures in a list of 59 specific points, paying particular attention to removal of foreign objects in the plant feed, transport, storage, and further size reduction of undried wood chip, drying of the chip, storage of the dried chip, milling of the dried chip, finishing of the board, and general housekeeping. Special attention was paid to the chip drying process. Continuous control of the oxygen concentration in the drying gas, maintaining it as low as possible, was strongly recommended.

The work of Arvidsson et al. (1977) was presumably not known to Drossel (1984), who suggested a similar list of means to prevent and mitigate dust explosions and fires in chipboard production. However, Drossel included automatic extinction of potential ignition sources in the form of small glowing wood or board fragments in gas and dust extraction ducts as an additional element. This method, which resulted from newer technological development, has proven particularly useful in the wood industry and was described in greater detail by Schröder (1984) (see also Section 1.4.4).

Scholl (1975) investigated the flame development following ignition inside mobile vacuum collectors for wood dust and wood chips. He found that only smoldering or open fires occurred, but no dust explosions. Furthermore, fire was only initiated if the ignition source was comparatively energetic, and the dust/chip mixture contained an appreciable fraction of fine dust ($<100\ \mu m$). May et al. (1981) concentrated on the prevention of fire and explosion in wood chip dryers. They found that considerable overall improvement could be achieved by adequate process control and energy economization. Pfeiffer, Kühnen, and Armbruster (1985) investigated particle size distributions of airborne dusts from wood sawing and finishing operations. The particle size at which 30% of the dust mass was finer varied between 22 μm and 10 μm depending on operation and wood type. The mass fractions of very fine dust ($<7\ \mu m$) varied between 20 and 2%.

Natural cellulosic dusts that can give rise to explosions are also generated in the cotton and linen textile industries. A catastrophic linen dust explosion in Harbin, Peoples Republic of China, is discussed in Chapter 2. Kuczynski (1987) suggested a comprehensive scheme for protecting cotton processing plants against dust explosions. Particular attention should be paid to dust collecting systems and systems for storage of raw materials. Early detection of self-heating and self-ignition in deposits of dust and raw material and adequate systems for extinction were recommended. It was found that automatic injection of $NH_4H_2PO_4$ in ducts connecting to other plant sections provided effective isolation of the primary explosion (see Section 1.4.4).

As a result of the country's large peat resources, the use of peat as fuel has become a major concern in Finland. The ignitability and explosibility of peat dust depend on the origin and decomposition of the peat and its moisture content and particle size distribution. Weckman et al. (1981) investigated the possibilities for reducing the fire and explosion hazard in Finnish peat handling plants, with particular reference to peat power plants. They concluded that every effort should be made to prevent ignition, but it would also be necessary to take mitigating actions, should explosions nevertheless be initiated. The recommended means of mitigation were use of pressure- (shock-)resistant equipment, explosion venting, automatic explosion suppression, and isolation.

1.5.3.4
Coal Dust and Pulverized Coal (Excluding Mines)

The literature on the ignitability and explosibility of coal dust is extensive. Originally, the objective was limited to reducing the dust explosion hazard in coal mines and associated activities, as discussed in detail by Cybulski (1975). However, as pulverized coal has become an increasingly important fuel both for general heat production in power plants and other purposes (cement furnaces, for example), the coal dust explosion problem has also become an important issue in these areas.

The influences of the chemical composition, particle size, and moisture content of coal dust on its ignitability and explosibility has been studied systematically since early in the last century. Much information was collected by Nagy, Dorsett, and Cooper (1965) and Cybulski (1975). Ignitability and explosibility properties of coal dust have also been investigated by Carpenter and Davies (1958), Scholl (1981), Bracke (1984), Enright (1985), Nettleton (1986), Wall et al. (1988), and Woskoboenko (1988). Torrent, Armada, and Pedreira (1988) found a good statistical correlation between two canonical variables representing the explosibility properties and the chemical composition of coal dusts, respectively. Some further data related to the combustion of coal dust are given in Chapter 4 and Table A.1 in the Appendix.

Self-heating leading to self-ignition can be a significant problem when storing coal powder or dust in bulk. This problem and its prevention and mitigation have been discussed by Korotov and Polferov (1978); Heinrich (1981); Thatcher (1982); Chauvin, Lodel, and Philippe (1985); Wiemann and Scholl (1985); and Braun (1987). Schlieper (1984) was particularly concerned with self-ignition of pulverized coal during transport by rail and road.

The extinction of coal dust explosion flames by various gaseous and pulverized solid additives was studied by Rahimian, Choi, and Essenhigh (1982) in a laboratory-scale jet-stirred reactor. Most additives tested were just thermal heat sinks; NaCl and $NH_4H_2PO_4$ also caused chemical reaction chain termination. Rae and Thompson (1979) investigated the effectiveness of various halogenated hydrocarbons as inerting agents and suppressants for coal dust explosions. However, due to the negative environmental effects of such substances, they are currently being replaced by other extinguishing agents.

Scherrer (1984) and Wehland (1984) discussed prevention of self-ignition in dust deposits and explosions in dispersed dust in plants for the production and storage of pulverized coal, by inerting with combustion gases, nitrogen, or carbon dioxide.

The overall dust explosion protection of coal pulverizing plants was discussed by Birolini and Sammartin (1979), Wibbelhoff (1981), Diliberto (1983), Carini and Hules (1987), and Dansk Brandvaerns-Komité (1987). Fire and explosion protection of systems for the conveyance and storage of pulverized coal was treated by Körner (1984) and Chauvin et al. (1987), whereas dust removal from pulverized coal plants was considered by Parpart (1979). Mullinger (1987) was concerned with fire and explosion protection of pulverized firing systems, and Egesoe (1978) discussed dust explosion prevention in systems for preparing and burning coal dust in cement kilns. Patzke (1984) considered venting of dust explosions in plants for milling and drying coal.

Finally, Ruygrok et al. (1983) were concerned with the prevention and mitigation of coal dust explosions in surface facilities for the transport, storage, and handling of coal. The possibility of gas explosions due to release of methane from the coal, in particular from anthracites, was also investigated.

1.5.3.5
Polyester and Epoxy Powders for Electrostatic Powder Coating

Electrostatic powder coating, to an increasing extent, is replacing traditional liquid paint spraying systems for painting industrial metal products. The basic principle is that the metal object is first covered with an even layer of electrostatically bound epoxy/polyester powder. By subsequent treatment in an oven, the powder melts and hardens to an even, strong protective, decorative coating.

In the actual process, the powder is transported pneumatically from a powder hopper to an electrostatic spraying gun. As the powder particles flow through the spraying gun, they become electrostatically charged by passing a strong electrostatic field on the order of tens of kilovolts. The charged particles are then attracted to and deposited on the grounded workpiece. The powder continues to be deposited on the grounded workpiece until, at a certain powder layer thickness, the layer acts as an insulator and prevents further deposition of powder. Powder not deposited on the workpiece is normally collected in a powder recovery unit by a dust extraction system.

As technology developed and knowledge increased, the overall concepts of preventing and mitigating dust explosions in electrostatic powder coating systems were revised periodically. An early summary was given by Eckhoff and Enstad (1975). One of the preventive measures recommended was to keep the dust concentration in the spraying boot lower than the minimum explosible concentration. In a later paper, Liere (1983) omitted this possibility, concentrating instead on inerting, automatic flame extinction, and isolation. Bartknecht (1986) and Liere (1989) conducted realistic full-scale explosion experiments in a powder spraying cabin and showed that dust flames in clouds of concentrations just above the minimum explosible concentrations are weak and slow. Bartknecht and Liere also determined ignitability and explosive properties of typical polyester and epoxy powders used for electrostatic powder coating. Eckhoff, Pedersen, and Arvidsson (1988) were unable, in a subsequent investigation, to reproduce the lowest minimum explosible dust concentrations of 15 g/m^3 reported by Bartknecht. In view of the fact that the minimum explosible concentration of typical hydrocarbon gases in air is about 35 g of gas per m^3 of air and gas phase combustion is the basic flame propagation process for organic dusts, the value of 15 g/m^3 seems unrealistically low. Eckhoff et al. further found that, in up to 50 wt% of noncombustibles, the minimum explosible dust concentration increased systematically with increasing proportions of noncombustibles in the powder, in such a way that the minimum explosible concentration of the combustible fraction was constant, in the range of 32–35 g/m^3. A dust containing 50 wt% noncombustibles, therefore, had a minimum explosible concentration of 65–70 g/m^3.

Both Bartknecht (1986) and Eckhoff et al. (1988) observed that some coating powders had exceptionally low minimum electric spark ignition energies, of <3 mJ.

CENELEC (1989) issued a comprehensive European standard for electrostatic powder coating, where keeping the dust concentration in the spraying cabinet and dust extraction system below the minimum explosible concentration was reintroduced as a central preventive measure. Another preventive measure was use of antistatic materials to avoid accumulation of electrostatic charge. Mitigating measures included interlocking systems and use of noncombustible construction materials.

1.5.3.6
Aluminum and Magnesium Powder and Dust

The fire and explosion hazards associated with production and handling of aluminum and magnesium powders has been the subject of extensive research for many years. As for metal powders in general, the hazard increases with decreasing particle size, right down into the range below 1 μm. Dust clouds in air of very fine aluminum and magnesium powders have exceptionally low electric spark minimum ignition energies and produce exceptionally violent explosions (see Appendix 1). On the other hand, coarser aluminum powders, such as particle diameters of 100 μm, present only a moderate explosion hazard. However, if a comparatively coarse aluminum powder contains a fine dust fraction, even if it represents only a few percent by mass, the explosion hazard is considerably increased. For metal dusts like aluminum, it is particularly true that keeping a watch on the explosion hazard to a large extent means keeping a watch on particle size.

Beck, Foerster, and Faber (1984) discussed the prevention and mitigation of dust explosions in aluminum grinding plants. By using wet grinding (e.g., water), the aluminum particles can be collected as a slurry and the dust explosion problem eliminated altogether. Alternatively, the grinding operation itself can be dry, with the fine metal dust collected in a liquid either immediately after the grinding point or in a separate wet collector further downstream. In general, the need for measures to prevent and mitigate dust explosions depends on the extent to which the process is dry.

Beck et al. (1984) recommended several types of measures, adapted to the nature of the actual process. The list included interlocking systems to prevent grinding without dust extraction or sufficient liquid (water) supply, location of fans in dust-free areas, prevention of mechanical and electric sparks and hot surfaces, no smoking, and good housekeeping (cleanliness) in the workrooms.

Reinke (1987) described the safety measures taken in a plant for the production of comparatively coarse atomized aluminum powder (63–1200 μm). The fine fraction, <63 μm, representing the most severe explosion hazard, was separated out in an air jet filter.

A high-speed automatic isolation valve was installed in the duct between the filter and the other parts of the process, and the filter enclosure was equipped with a vent. Detectors for airflow and pressure were integrated in the interlocking system.

In plants producing very fine aluminum and magnesium powders, extensive gas inerting is necessary. For aluminum, nitrogen is normally suitable as inert gas, whereas a rare gas (helium or argon) is required for magnesium. However, to enable the particle surface to become oxidized and thus avoid extreme reactivity when the powder or dust is later exposed to air, a certain fraction of oxygen, normally between 3 and 5 vol%, should remain in the inerting gas. The National Fire Protection Association (1987) discussed inerting and other necessary measures more extensively.

Eckhoff and Alfert (1988) reviewed the influence of particle size on the ignitability and explosibility properties of aluminum powders.

1.5.3.7
Silicon, Silicon Alloys, and Other Metals

As indicated by Table 1.1 in Section 1.1.2, silicon dust has the potential to generate nearly the same explosion strength as aluminum dust of the same particle size. This has been confirmed in practice. Fine silicon dust has given rise to catastrophic explosions in production and handling plants (see Chapter 2). Like magnesium and aluminum dust clouds, clouds of silicon in air burn at a very high temperature, and thermal radiation from the burning cloud represents a severe threat to personnel.

If silicon is alloyed with iron, ignitability and explosibility is generally reduced as the iron content increases. On the other hand, the presence of magnesium in silicon alloys significantly increases the explosion hazard. In particular, the minimum electric spark ignition energy drops significantly if the magnesium content approaches 5–10 wt% or more. In general, understanding the influence of various alloy compounds on the ignitability and explosibility of silicon alloys is incomplete, and specific investigation is often required.

Eckhoff et al. (1986) investigated the ignitability and explosibility of silicon dust clouds in air and confirmed that the minimum electric spark ignition energy decreases and the explosion violence increases systematically with decreasing particle size. However, very fine powders and dusts of particle sizes in the range of 1 μm and even smaller may be difficult to disperse completely into primary particles and therefore behave as if they were coarser. This can complicate the correlation of primary particle size with ignitability and explosibility data (see Chapters 3 and 9 for further details on dust dispersion).

In manganese and ferromanganese, flashes that can initiate flame propagation in dust clouds are easily produced by mechanical impact of lumps of the material or in crushing operations. (This particular feature has also been observed with ferro-silicon-magnesium.) Clouds of fine manganese dust in the air can have very low minimum electric spark ignition energies, on the order of 1 mJ. On the other hand, flame propagation in clouds in the air of dusts of manganese and manganese alloys is comparatively slow and the flame temperature comparatively low. Qian Qiyong, Wang Taisheng, and Xiao Hechai (1987) studied how dust explosions and fires in the cyclone separator of a ferromanganese milling plant could be prevented, despite unavoidable flashes in the crushing and milling units. As part of the work, they also studied ignition of layers of ferromanganese dusts on a hot plate. Even for a layer thickness of only 2 mm, the minimum ignition temperature was as low as 320°C.

Allenbach (1984) proposed a special system for classifying the fire and explosion hazards associated with dusts of various metals and ferro alloys in industrial plants. He introduced three combustibility classes based on observation of the flame development in clouds of freshly ground <44 μm dust fractions in a laboratory-scale explosion vessel:

- Class 1. Very active: Very violent flame propagation.
- Class 2. Active: Quite fast flame propagation.
- Class 3. Combustible: Slow propagation of weak flame.

The hazard of a particular powder or dust was evaluated by combining the flammability class of the ground <44 μm dust sample and the actual particle size of the product. Allenbach provided a list of the combustibility class ratings of a wide range of ferro alloys and other metals. All listed calcium alloys and most alloys containing aluminum and magnesium were of Class 1. The other metals and alloys tested, including boron alloys, chromium and chromium alloys, manganese and its alloys, and silicon and silicon alloys were of Class 2 or Class 3.

Allenbach did not provide sufficient information about the experimental apparatus and procedure to permit further evaluation of his proposed classification system.

Ma et al. (1987) and Xiao et al. (1987) produced kinetic data and mathematical models for the oxidation of calcium silicon alloys, which may prove useful in future modeling of dust explosions involving these materials.

1.5.3.8
Miscellaneous Powders and Dusts

Baklygin and Nikitina (1978) investigated the minimum explosible dust concentration and minimum ignition temperature (dust layer) of various dust mixtures generated in the mixing plant of the Moscow Tyre Works.

Gehring, Friesenhahn, and Rindner (1978) studied the explosiveness of clouds in air of dust of a propellant containing 84% nitrocellulose, 10% dinitrotoluene, 5% dibutylphthalate, and 1% diphenylamine. For a <75 μm fraction of this particular propellant, the minimum explosible dust concentration in air was 100–200 g/m^3, whereas the minimum electric spark ignition energy of dust clouds was about 150 mJ. This means that, when dispersed as clouds in air, such materials exhibit ignitability and explosibility properties similar to, or even less severe than, those of normal organic solid fuels like starch and proteins of the same particle size. However, the pressure and temperature waves generated by the initial dust explosion may in some cases initiate more hazardous secondary exothermal reactions in adjacent condensed propellant deposits.

The fire and dust explosion hazard connected with mine blasting of oil shale has been considered by several authors, including Cashdollar, Hertzberg, and Conti (1984); Richmond and Beitel (1984); Weiss, Cashdollar, and Sapko (1985, 1986); Miron and Lazzara (1985); Sapko, Weiss, and Cashdollar (1986); and Hertzberg and Cashdollar (1988). Karim, Bardon, and Hanafi (1979), in a more basic investigation, studied the combustion of oil sand fragments in hot, flowing, oxidizing gas.

Dust explosions can also result from mining sulfide ores containing substances like pyrite, pyrrhotite, arsenopyrite, sphalerite, and galena. The hazards of sulfide dust explosions also include the toxic effects of the combustion products. Various aspects of sulphide ore dust explosions were discussed by Polikarpov (1984), Enright (1984a, 1984b), and Amaratunga (1988).

Finally, a quite special dust explosion hazard arises when burned-out fuel rods in nuclear power plants are cut in reprocessing plants and fine zircaloy dust is generated. Zircaloy is essentially zirconium with small percentages of antimony, iron, and nickel. It is used as cladding for nuclear fuel rods. Because of the hazardous radioactivity of the zircaloy dust, very special precautions must be taken when assessing the ignitability and explosibility properties of the dust. Andriessen et al. (1987), Hensel (1988), and Hattwig et al. (1988) discussed the methods used and results obtained and suggested possible means of preventing and mitigating zircaloy dust explosions in reprocessing plants.

1.5.4
STANDARDS, RECOMMENDATIONS, AND GUIDELINES

Most industrialized countries have their own official codes of practice for preventing and mitigating dust explosions in industry. Examples include Germany, the United Kingdom, France, Holland, Sweden, Norway, the United States, and Russia. Normally, the official national factory inspectorate or health and safety inspectorate is the responsible authority issuing the codes and controlling whether they are practiced.

In addition, independent bodies in many countries issue their own regulations, some of which are in reality considered authoritative. Examples of such bodies are the National Fire Protection Association (NFPA) in the United States and the Verein deutscher Ingenieure (VDI) in Germany. Sometimes, various industrial branches in a country, such as the grain, feed, and flour industry or the ferro alloy industry, issue their own set of specific guidelines. It is important that these comply with the general authoritative codes of the country.

Codes and standards are also issued on an international level, through cooperation among many countries. Examples of international organizations set up for such work are the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), and European Community bodies (CEN, CENELEC).

All the various codes, standards, regulations, and guidelines are, or should be, periodically revised to keep pace with the development of knowledge and technology. One should therefore always make sure that the document at hand is the latest, valid version. Some recent standards and guidelines are mentioned in Chapters 8 and 9.

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Chapter 2

Case Histories

2.1
INTRODUCTION

Experience has shown that "learning by doing" is an effective way of acquiring new knowledge. Unfortunately, this also applies to learning about dust explosions. Those who have experienced a dust explosion in their own plant, whether workers or management, have a much more profound appreciation of the reality of this hazard than those who only heard or read about dust explosions in general terms. Real understanding, in turn, produces the proper motivation for minimizing the probability of occurrence of such events in the future.

Clearly, accidental dust explosions are highly undesirable in any plant, and one therefore seeks less dramatic means of transferring knowledge and motivation. One way is the use of case histories, that is, fairly detailed accounts of dust explosions that actually occurred elsewhere.

The number of well-documented dust explosions worldwide is considerable and only a small fraction can be covered in this text. Because of my close cooperation with Norwegian industry in investigating accidental dust explosions for nearly 20 years, I have access to detailed information on many explosions that have occurred in Norway through the years. It is natural, therefore, to include some of this information in the present book.

On the other hand, it is considered appropriate also to include accidents in countries other than Norway. However, some well-known explosions described extensively elsewhere in the open literature have not been included; for example, the catastrophic wheat flour explosion in the Roland Mill in Bremen, Federal Republic of Germany, which was discussed in detail by the Fire and Police Authorities of Bremen (1979). Also, many of the large dust explosions in the United States after 1975 have been discussed in detail by Kauffman (1982, 1987) and Kauffman and Hubbard (1984). A few of these nevertheless are included in the present account. Section 9.5 in Chapter 9 gives references to reports of more recent accidents.

2.2
THE EXPLOSION IN A FLOUR WAREHOUSE IN TURIN ON DECEMBER 14, 1785

This is probably the most-frequently quoted of all dust explosions that occurred. However, only very rarely are details of Count Morozzo's (1795) fascinating account mentioned. It is therefore appropriate to start this sequence of case histories with the full original account of the wheat flour explosion in Mr. Giacomelli's bakery in Turin. The explosion was a comparatively minor one, but there is still much to learn from Count Morozzo's analysis. The considerations related to the low moisture content of the flour due to dry weather are important and still relevant. The same applies to the primary explosion causing a secondary explosion by entrainment of dust deposits.

> LIV. Account of a violent Explosion which happened in a Flour-Warehouse, at Turin, December the 14th, 1785; to which are added some Observations on spontaneous Inflammations; by Count Morozzo.
>
> From the Memoirs of the Academy of Science of Turin.
>
> The Academy having expressed a desire to have a particular account of the explosion which I mentioned to them a few days after it happened, I have made all possible haste to fulfil their desires, by ascertaining, with the utmost attention, all the circumstances of the fact, so as to be able to relate it with the greatest exactness.
>
> I shall take the liberty to add to it a short account of several spontaneous inflammations, which have happened to different substances, and which have been the cause of very great misfortunes. Although the greater number of these phenomena is already well known to philosophers, I trust the collecting them together in this place will not be displeasing, as it is impossible to render too well known facts which so strongly interest the public utility.
>
> On the 14th of December, 1785, about six o'clock in the evening, there took place in the house of Mr. Giacomelli, baker in this city, an explosion which threw down the windows and window-frames of his shop, which looked into the street; the noise was as loud as that of a large cracker, and was heard at a considerable distance. At the moment of the explosion, a very bright flame, which lasted only a few seconds, was seen in the shop; and it was immediately observed, that the inflammation proceeded from the flour-warehouse, which was situated over the back shop, and where a boy was employed in stirring some flour by the light of a lamp. The boy had his face and arms scorched by the explosion; his hair was burnt, and it was more than a fortnight before his burns were healed. He was not the only victim of this event; another boy, who happened to be upon a scaffold, in a little room on the other side of the warehouse, seeing the flame, which had made its passage that way, and thinking the house was on fire, jumped down from the scaffold, and broke his leg.
>
> In order to ascertain in what manner this event took place, I examined, very narrowly, the warehouse and its appendages; and, from that examination, and from the accounts of the witnesses, I have endeavoured to collect all the circumstances of the event, which I shall now describe.
>
> The flour-warehouse, which is situated above the back shop, is six feet high, six feet wide, and about eight feet long. It is divided into two parts, by a wall; an arched ceiling extends over both, but the pavement of one part is raised about two feet higher than that of the other. In the middle of the wall is an opening of communication, two feet and a half wide, and three feet high; through it the flour is conveyed from the upper chamber into the lower one.
>
> The boy, who was employed, in the lower chamber, in collecting flour to supply the bolter below, dug about the sides of the opening, in order to make the flour fall from the upper chamber into that in which he was; and, as he was digging, rather deeply, a sudden fall of a great quantity took place, followed by a thick cloud, which immediately caught fire, from the lamp hanging to the wall, and caused the violent explosion here treated of.
>
> The flame shewed itself in two directions; it penetrated, by a little opening, from the upper chamber of the warehouse, into a very small room above it, where, the door and windowframes being well closed and very strong, it produced no explosion; here the poor boy, already mentioned, broke his leg. The greatest inflammation, on the contrary, took place in the smaller chamber, and, taking the direction of a small staircase, which leads into the back shop, caused a violent explosion, which threw down the frames of the windows which looked into the street. The baker himself, who happened then to be in his shop, saw the room all on fire some moments before he felt the shock of the explosion.
>
> The warehouse, at the time of the accident, contained about three hundred sacks of flour. Suspecting that this flour might have been laid up in the warehouse in a damp state, I thought it right to enquire into that circumstance. I found, upon examination, that it was perfectly dry; there was no appearance of fermentation in it, nor was there any sensible heat.
>
> The baker told me that he had never had flour so dry as in that year [1785], during which the weather had been remarkably dry, there having been no rain in Piedmont for the space of five or six months: indeed, he attributed the accident which had happened in his warehouse to the extraordinary dryness of the corn.

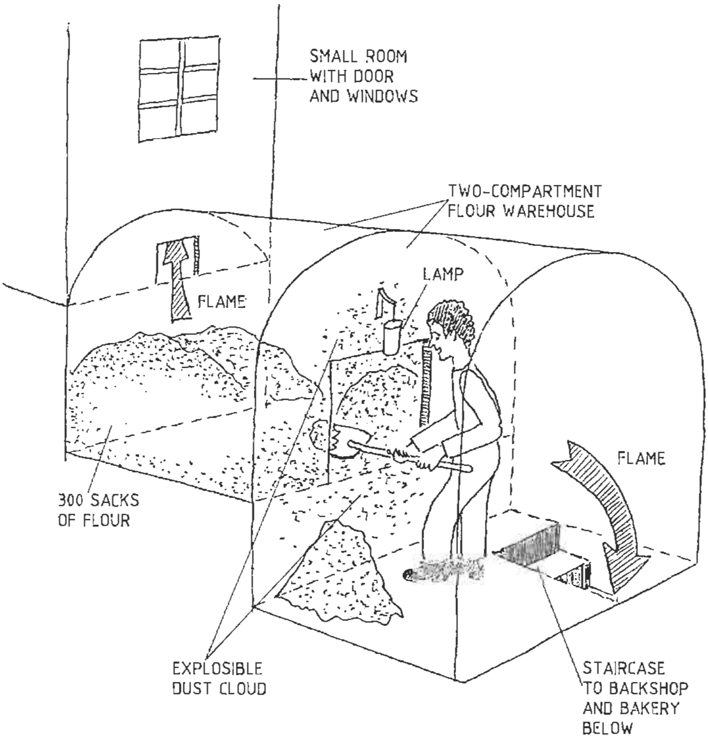

Figure 2.1 *Reconstruction of possible scene of wheat flour explosion in Mr. Giacomelli's bakery on December 14, 1785, as described by Count Morozzo (1795).*

The phænomenon, however striking at the time it happened, was not entirely new to the baker, who told me that he had, when he was a boy, witnessed a similar inflammation; it took place in a flour-warehouse, where they were pouring flour through a long wooden trough, into a bolter, while there was a light on one side; but, in this case, the inflammation was not followed by an explosion.

He mentioned to me several other instances, which I thought it my duty to enquiry into; amongst them, one which had happened to the widow Ricciardi, baker in this city, where (there being, on the other side of the wall of the flour-warehouse, a lock-smith's forge) the flour was heated to such a degree, that a boy who went into the warehouse could not remain there, so much were his feet scorched by the heat; this flour was of a dark brown colour, and whilst the people were examining it, sparks began to appear, and fire spread itself around, without producing any flame, like a true *pyrophorus**.

He also informed me, that an inflammation like that above-mentioned had happened at the house of a baker in this city, called Joseph Lambert; it was occasioned by shaking some large sacks, which had been filled with flour, near a lighted lamp, but the flame, though pretty brisk, did not do any mischief.

According to the foregoing accounts, it appears to me, that it is not difficult to explain the phænomenon in question. The following is the idea I have conceived of it: as the flour fell down, a great quantity of inflammable air, which had been confined in its interstices, was set free; this, rising up, was inflamed by the contact of the light; and, mixing immediately with a sufficient quantity of atmospheric air, the explosion took place on that side where there was the least resistance. As to the burning of

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* I was very anxious to ascertain by experiments, whether it were possible to bring flour alone into the state of pyrophorus, but it was in vain; for though I calcined flour with a strong heat, in a small retort, with the same precautions as used in making other pyrophori, I never could succeed in making it take fire by exposure to the air. By joining alum with it I obtained a true pyrophorus, as Lemery had already done.

> the hair, and the skin, of the boy who was in the warehouse, the cause of it must be attributed to the fire of the fine particles of the flour, which, floating in the atmosphere, were kindled by the inflammable air, in the same manner as the powder from the stamina of certain vegetables, (particularly of the pine, and of some mosses,) when thrown in the air, takes fire if any light is applied to it.
>
> But it may be objected, that as the flour was not at all damp, and had not any sensible degree of heat, there should not be any fermentation in it, and consequently no inflammable air should be produced: to this I answer,
>
> First. That flour is never entirely free from humidity, as is evidently shewn by distillation.
>
> Secondly. That although the degree of heat was not so great as to set free inflammable air by fermentation, a sufficient quantity was set free, by what may be called a mechanical mean, to inflame upon the contact of light; and to disengage, at the same time, all that which communicated with the atmospheric air.
>
> Thirdly. We must recollect that flour also furnishes alkaline inflammable air, which is produced from the glutinous vegeto-animal part of the corn; and we know that this kind of inflammable air is of a very active nature.
>
> After having described this singular event, I shall beg leave to collect together, in this place, all the known facts respecting spontaneous inflammations produced by different substances. A circumstantial account of these phænomena cannot but be very interesting to those concerned in government; not only as it may tend to prevent the unhappy accidents which result from them, but also as it may sometimes hinder the suspicion and persecution of innocent persons, on account of events which are produced merely by natural causes.

2.3
GRAIN DUST EXPLOSIONS IN NORWAY

2.3.1
WHEAT GRAIN DUST, STAVANGER PORT SILO, JUNE 1970

The explosion, which was discussed by Astad and Mo (personal communications from A. Astad, director, Stavanger Port Silo, and A. Mo, Norwegian Grain Corporation, 1970), occurred in Norway's largest and newly built import grain silo in Stavanger on a hot, dry summer day. Fortunately, no persons were killed, but some workers suffered first-degree burns. Although the extent of flame propagation was considerable, the material damage was moderate, due to the comparatively strong reinforced concrete structure of the buildings and the venting through existing openings.

The entire event lasted for a period of about 25–30 seconds, during which a sequence of six or seven distinct, major explosions were heard. In the middle of this sequence was an interval of 10–12 seconds. The flame propagated a total distance of about 1500 meters, through a number of bucket elevators, horizontal conveyors, ducting, filters, and rooms in the building. Dust explosions occurred in six of the large, cylindrical storage silos of total volume 2000 m^3 each, in one large, slightly smaller silo, in seven of the slimmer, intermediate silos of capacities 400 or 1000 m^3, in one 150 m^3 silo, and in seven loading-out silos with capacities of 50 m^3 each. The six largest silos had no venting, whereas the explosions in the large silo of slightly smaller volume and in all the intermediate and loading-out silos were vented through 0.4 m^2 manholes, which had their covers flung open.

It is of interest to note that only one silo was damaged in the incident, namely, one of the six unvented, large storage silos, which had its roof blown up, as shown in Figure 2.2. It is therefore clear that the maximum explosion pressures in all the other 21 silos, vented and unvented, were lower than about 0.2 bar(g), which would be required to blow up the actual type of silo roof.

Figure 2.2 *Damaged silo roof after the wheat grain dust explosion in Stavanger in June 1970 (Courtesy of Egil Eriksson).*

Almost all the windows, except those in the offices, were blown out, as was a large provisional light wall at the top of the head house, as shown in Figure 2.3. The legs of all five bucket elevators (0.65 m × 0.44 m cross section) were torn open from bottom to top. The dust extraction ducts were also in part torn open.

The source and site of initiation of the explosion were never fully identified. However, two hypotheses were put forward. The first was self-ignition of dust deposited in the boot of the elevator in which the explosion was supposed to start. The self-ignition process was thought to have been initiated by a bucket that had been heated by repeated impacts until it finally loosened and fell into the dust deposit in the elevator boot. The second hypothesis is that the chain of events leading to ignition started with welding on the outside of the grain feed duct to one of the elevator boots. Due to efficient heat transfer through the duct wall, self-heating could then have been initiated in a possible dust deposit on the inside of the duct wall (see Figure 1.10 in Chapter 1). Lumps of the smoldering deposit could then have loosened and been conveyed into the elevator boot and initiated an explosion in the dust cloud there.

Figure 2.3 *Provisional lightweight wall acting as vent during the wheat grain dust explosion in Stavanger in June 1970 (Courtesy of Egil Eriksson).*

2.3.2

WHEAT GRAIN DUST, NEW PART OF STAVANGER PORT SILO, OCTOBER 1988

The explosion was described by Olsen (personal communication from O. Olsen, 1989). Because of effective mitigation by explosion suppression and venting, both the extent of and damage caused by the explosion were minor. There were neither fatalities nor injuries. The incident deserves attention, however, because the chain of events leading to explosion initiation was identified and the incident illustrates that proper measures for explosion mitigation are effective.

The explosion occurred in a bucket elevator head immediately after termination of transfer of Norwegian wheat grain between two silo cells. At the moment of explosion, the transport system was free of grain. In this new part of Stavanger Port Silo, the bucket elevator legs are cylindrical and mounted outdoors, along the wall of the head house. A number of vents are located along the length of the legs. The vent covers on the elevator legs involved were blown out, which undoubtedly contributed to reducing the extent of the explosion. There was no significant material damage, either by pressure or by heat.

Figure 2.4 illustrates the head of the bucket elevator in which the explosion occurred. Because of a slight offset, the steel cover plate for the felt dust seal for the pulley shaft touched the shaft and became heated by friction during operation of the elevator. The hot steel plate, in turn, ignited the felt seal, from which one or more glowing fragments dropped into the wheat grain dust deposit on the inclined surface below and initiated smoldering combustion in the deposit. Figure 2.5 shows the burned, charred felt seal when investigated just after the explosion. Just after the elevator had stopped, presumably still enough dust was in the air to be ignited by the smoldering dust and be able to propagate a flame. Alternatively, some of the smoldering dust may have slid down the inclined surface and become dispersed into an explosible dust cloud. Just after the explosion, some smoldering dust was still on the inclined plate below the elevator pulley.

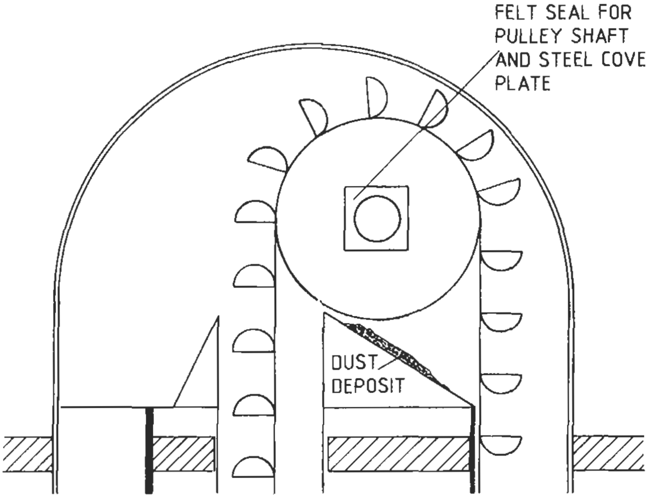

Figure 2.4 *Head of bucket elevator at new part of Stavanger Port Silo, where the minor 1988 wheat grain dust explosion was initiated (Courtesy of O. Olsen, Stavanger Port Silo, Norway).*

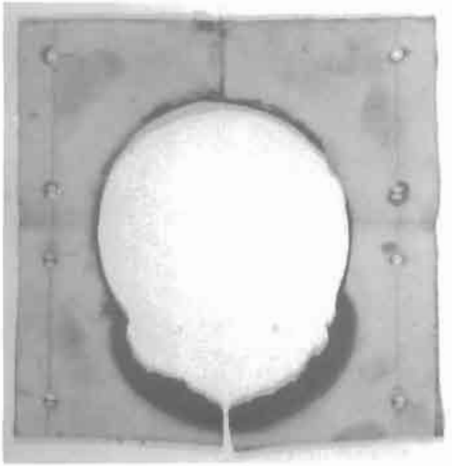

Figure 2.5 *Burned, charred felt seat of the elevator pulley shaft at Stavanger Port Silo (Courtesy of O. Olsen, Stavanger Port Silo, Norway).*

2.3.3

GRAIN DUST (BARLEY/OATS), HEAD HOUSE OF THE SILO PLANT AT KAMBO, JUNE 1976

This explosion, described by Storli (personal communication, K. Storli, Norwegian factory in reply to inspectorate, 1976), caused considerable material damage but, due to fortunate circumstances, neither fatalities nor significant injuries. The dust involved was from Norwegian barley or oats.

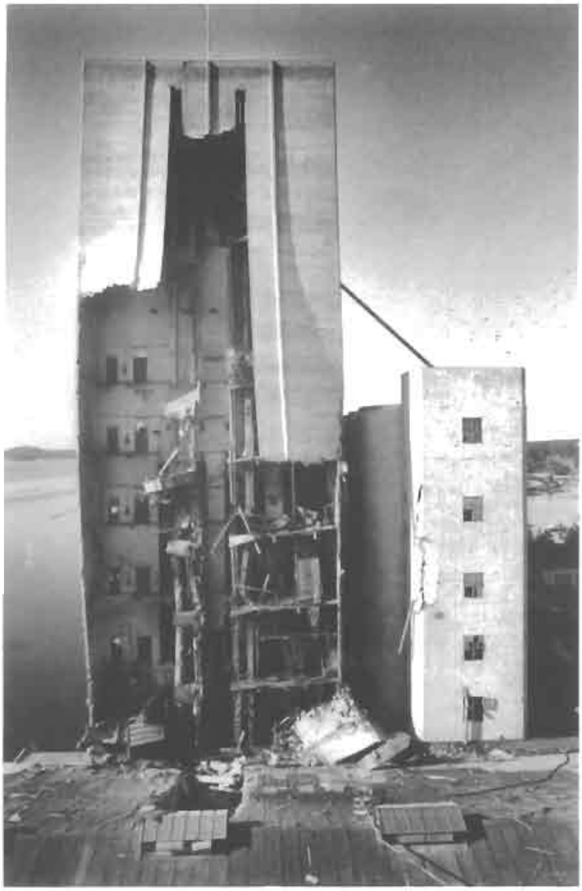

Figure 2.6 *Damaged silo head house after a grain dust explosion at Kambo, Norway, in June 1976 (Courtesy of Scan Foto, Oslo, Norway).*

The explosion probably started in a bucket elevator, initiated by burning or glowing material from an overheated hammer mill. The primary explosion developed into a secondary explosion in the head house itself, which pushed out most of the front wall of the head house, as shown in Figure 2.6.

Two of the bucket elevators had bulged out along the entire length and the dust extraction ducting had become torn apart; this gave rise to the secondary explosion. Because the floors were supported by the wall and the connections between wall and floors were weak, the entire wall sheet was pushed out at quite low explosion pressure, leaving the floors unsupported at the front (see Figure 1.134 in Chapter 1).

After the explosion, the head house was reconstructed, utilizing the principle illustrated schematically in Figure 1.136 in Chapter 1. The floors were supported by a rigid framework, with the lightweight wall elements serving as vent covers, should an explosion occur again. The reconstructed head house is shown in Figure 2.7.

Figure 2.7 *Reconstructed head house (1977) after the grain dust explosion at Kambo, Norway, in June 1976. The entire house front is covered with lightweight wall elements that can serve as explosion vent panels (Courtesy of J. Kosanovic, Kambo, Norway).*

2.3.4
MALTED BARLEY DUST, OSLO PORT SILO, JULY 1976

The explosion, described by Johansen (1976), occurred in an old silo building in the central harbor area of Oslo at about 7:30 on a dry summer morning. The material damage was extensive, and much debris was thrown into the surroundings. However, due to several fortunate circumstances, there were neither loss of life nor severe injuries.

The dust involved was from malted barley, of only 5–6% moisture content. The ignition source was not identified, but the explosion probably started in a silo cell and propagated to other cells through the common dust extraction system. The primary explosions in the silo cells blew up the cell roofs, which were part of the floor of the silo loft, and gave rise to an extensive secondary explosion in the loft, blowing up the entire silo roof. The result is shown in Figure 2.8. The damage was so extensive that the entire building had to be demolished.

2.3.5
MALTED BARLEY DUST, OSLO PORT SILO, JUNE 1987

The explosion, described by Johansen, Johansen, and Mo (1987), occurred on a warm, dry summer day during unloading of malted barley from a ship. There were neither fatalities nor injuries and no damage to the building, apart from broken window panes and a broken silo cell roof.

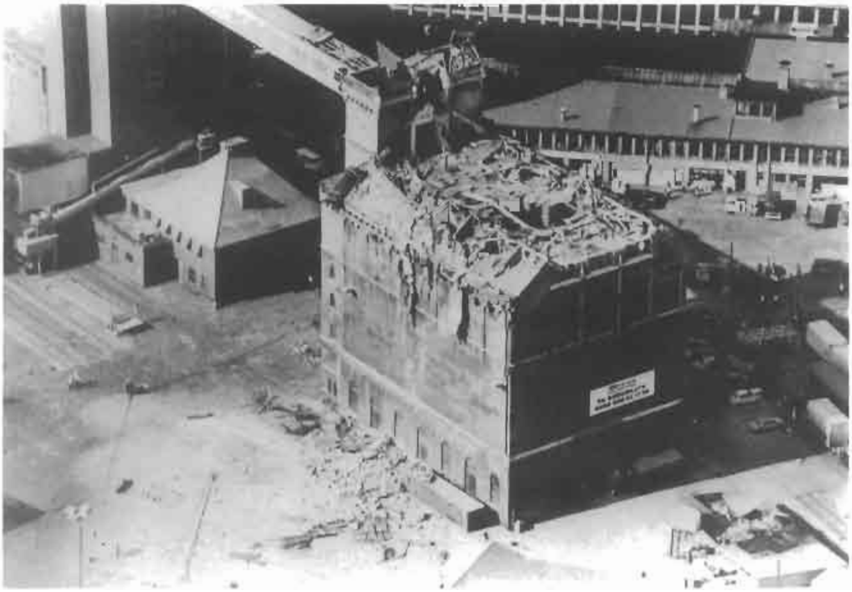

Figure 2.8 *Damaged silo building after malted barley dust explosion at Oslo Port Silo in July 1976 (Courtesy of A. F. Johansen, Oslo Port Silo, Norway).*

As in the 1976 explosion (Section 2.3.4), the malted barley was quite dry, containing only a few percent of moisture. The explosion probably started in a main dust filter, in which smoldering combustion had developed due to frictional heating caused by packing dust in the unloading screw at the filter bottom. Due to buildup of explosion pressure in the filter, the airflow in the dust extraction duct to the filter was reversed, and the explosion propagated upstream to the silo cell to which the duct was connected. The resulting explosion in the silo cell blew up the part of the concrete floor of the loft that was also the roof of that particular silo cell, and a fairly strong explosion occurred in the loft. The explosion also propagated from the filter to a bucket elevator that was torn open, which gave rise to a secondary explosion in the room. Furthermore, the explosion propagated to the truck loading station of the silo plant.

As Figure 1.135 in Chapter 1 shows, the windows of the main building served as vents and probably prevented damage to the main structure of the building.

2.4
FOUR GRAIN DUST EXPLOSIONS IN THE UNITED STATES, 1980–1981 (Source: Kauffman and Hubbard, 1984)

2.4.1
INLAND GRAIN TERMINAL AT ST. JOSEPH, MISSOURI, APRIL 1980

The explosion, which occurred in the middle of the day, killed one person and injured four. Material damage was estimated at US$ 2 million.

The explosion probably started in a dust cloud in a silo cell used for the receipt and delivery of grain. The probable ignition source was an electric arc between the electric wires of the lower-level indicator in the silo. Repeated filling and discharge of grain had pulled the level indicator from the wall and the electric arc occurred between the bare wires that had been pulled out of their conduit.

Severe structural damage occurred to almost all the silos in the head house and moderate damage to most of the head house structure. Most of the head house silo roofs were blown up, destroying the spout floor and the top of the cleaner floor. Rupture of the silos around the edge of the head house caused failures in the outside wall. The casings of all bucket elevators, steel as well as concrete, had opened up in many places. A silo complex comprising 18 cells suffered severe explosion damage to the gangway connecting it to the head house, to the gallery, to the far end of the tunnel, and to a small group of silos centered around an air shaft approximately one-third of the way along the gallery. At the location of the air shaft, the gallery wall and roof had been completely destroyed. Beyond this point the explosion damage to the gallery was still significant but not as severe. The exterior concrete silo walls had been extensively shattered, in many places leaving only the reinforcing rods. Figure 2.9 presents a detailed view down the air shaft made after the grain was removed. As can be seen, the concrete fragments were quite small and much concrete had been removed from the steel reinforcement. Concrete fragments from this area of the plant had been thrown about a hundred meters into the adjacent railway yard.

Figure 2.9 *Air shaft along the damaged walls of reinforced concrete silo cells of the grain terminal at St. Joseph, Missouri, 1980 (Courtesy of C. W. Kauffman, University of Michigan).*

2.4.2
RIVER GRAIN TERMINAL AT ST. PAUL, MINNESOTA, JUNE 10, 1980

The explosion occurred just before lunchtime. There were no fatalities, but 13 persons were injured. The material loss was estimated at about US$ 0.3 million.

The probable cause of the explosion was that an electrician was repairing live electrical equipment in a truck-receiving cross tunnel, while the elevator was unloading grain trucks. The ignition source probably was electric arcing in an open electric junction box located within an explosible dust cloud.

The blast and flame front moved in one direction along the tunnel into the head house basement. There were open spouts to the bucket elevators, and with the secondary explosion in the basement initiated by the cross tunnel explosion, the explosion was carried into all the bucket elevators and the dust extraction systems. The building was of structural steel with nonsupporting metal clad walls, and this allowed rapid pressure relief by blowing out the wall panels (see Figure 1.136 in Chapter 1). Therefore, the blast that went out of the head house and up one of the bucket elevators did not do much damage to the galleries. This was fortunate because, as Figure 2.10 shows, the level of housekeeping in the gallery at the moment of the explosion was rather poor. With a stronger blast entering the gallery and a flame following, a serious secondary gallery explosion could have resulted.

Figure 2.11 shows another example of unacceptably large quantities of accumulated dust. Kauffman (1982) used this photograph as a reminder when emphasizing that even

Figure 2.10 *Accumulation of dust in the gallery of a river grain terminal at St. Paul, Minnesota, 1980 (Courtesy of C. W. Kauffman, University of Michigan).*

Figure 2.11 *Dust accumulation on the floor in the head house of a grain silo plant in the United States (Courtesy of C. W. Kauffman, University of Michigan).*

a dust layer only 0.5 mm thick may propagate a dust flame when being entrained by the blast wave preceding a propagating dust flame. This experience has been transformed into a simple rule of thumb, saying that, if footprints are visible, the dust layer is unacceptably thick.

During the explosion at St. Paul, the flame front and pressure wave from the primary cross-tunnel explosion also traveled into the three tunnels under the grain storage tanks. However, these tunnels were clean, the blast was unable to pick up sufficient dust to sustain the flame propagation, and the explosion dissipated. However, the pressure wave continued down the three tunnels, sweeping away objects in its path, and finally damaging the aeration fans before venting itself to the atmosphere at the tunnel ends.

2.4.3
TRAIN-LOADING COUNTRY GRAIN TERMINAL AT FONDA, IOWA, JULY 15, 1980

This explosion, which occurred in the early afternoon, caused neither fatalities nor injuries. The material loss was modest, estimated at US$ 0.03 million.

The probable cause of the explosion was electrical welding on a bucket elevator. However, the ignition source was not the welding spot itself, but probably a hot spot in the casing of the elevator boot caused by poor electrical contact between the grounding

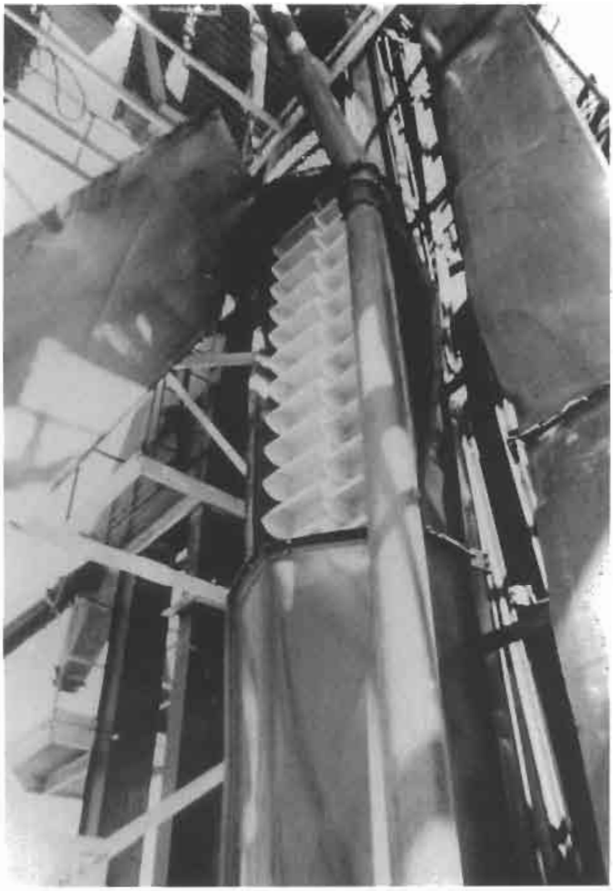

Figure 2.12 *Damaged bucket elevator following a corn dust explosion in a grain terminal at Fonda, Iowa, 1980 (Courtesy of C. W. Kauffman, University of Michigan).*

clamp and the grounded elevator casing. The hot spot either ignited the corn in the elevator boot, which in turn ignited the corn dust cloud or the dust cloud was ignited directly by the hot spot.

The explosion was transmitted to a second bucket elevator and blast waves and flames propagated upward in the legs of both elevators, bursting the casings. Figure 2.12 shows one of the elevator legs after the explosion.

Kauffman (1982) emphasized the essential role played by bucket elevators in 14 carefully investigated grain dust explosions in the United States. In 5 of the 14 accidents, the explosion originated in the bucket elevator. In six other accidents, bucket elevators were able to effectively amplify and propagate the explosion, although the combustion process did not originate there. Only in 3 of the 14 cases, the bucket elevators were not involved. Kauffman (1982) also discussed why the bucket elevator is so frequently involved in the explosions. When in operation, the elevator contains an explosible dust cloud that is confined.

Potential ignition sources can result fro, "Once a combustion process enters a bucket elevator, things can only get worse."

Fortunately, in the Fonda explosion in 1980, the bucket elevator explosions did not result in secondary explosions in the head house. Proper housekeeping could be one reason for this.

2.4.4
LARGE EXPORT GRAIN SILO PLANT AT CORPUS CHRISTI, TEXAS, APRIL 1981

In this catastrophic explosion, 9 persons lost their lives and 30 were injured. The material loss was also substantial, estimated at US$ 30 million.

The probable cause of ignition was smoldering lumps of sorghum that entered a bucket elevator together with the grain and ignited the dust cloud in the elevator. The sorghum was being unloaded from hopper-bottom railway cars. The grain had been stored in these cars for 30 days, and the weather had been quite warm. A fine screen had been put over the rail dump to prevent the larger lumps of the sorghum from entering the elevator. However, smaller lumps of smoldering sorghum nevertheless probably entered one of the operating bucket elevators and ignited the dust cloud there.

From this elevator the explosion propagated into the other elevators and eventually broke into the head house basement, through the dust control system, spout mixers, or the head house silos. It then traveled from the basement into a tunnel to the basement of a large concrete silo complex, where the combustion process entered the hooded conveyors and found more than sufficient dust to sustain the combustion process. As it traveled within this enclosure, the flame accelerated and generated a pressure wave moving ahead of it. Approximately halfway down the basement of the silo complex, the conveyor hoods blew up, throwing a large cloud of dust throughout the basement. The trailing flame front then arrived at this dust cloud and a very rapid combustion process developed. This explosion then vented itself in four different directions. It blew out the north basement wall, it went upward through the grain silo cells, westward through the dog house, and eastward back into the head house, which eventually exploded. The explosion then propagated further through the dust extraction system and into the hooded conveyors in the middle of the basement of the second large concrete silo complex, through which it was channeled to the railway dump area on the north and the shipping gallery on the south. The explosion in the basement of the second silo complex was vented through the basement windows.

Figure 2.13 shows the silo plant just after the explosion. The entire gallery of the nearest large silo complex was totally demolished, and some of the silo cells had blown out along the entire length. The head house was also badly damaged.

The extensive destruction of the railway dump area is shown in Figure 2.14. The wall cover sheets of the shelter have been shattered and blown away from the frame structure.

According to Kauffman and Hubbard (1984), the housekeeping in the Corpus Christi plant was excellent. Therefore, the only explanation for the extensive flame propagation is accumulation of large dust quantities inside the process and dust extraction equipment, including the ducting.

Figure 2.13 *Demolished Corpus Christi grain silo plant after major grain dust explosion in 1981 (Courtesy of C. W. Kauffman, University of Michigan).*

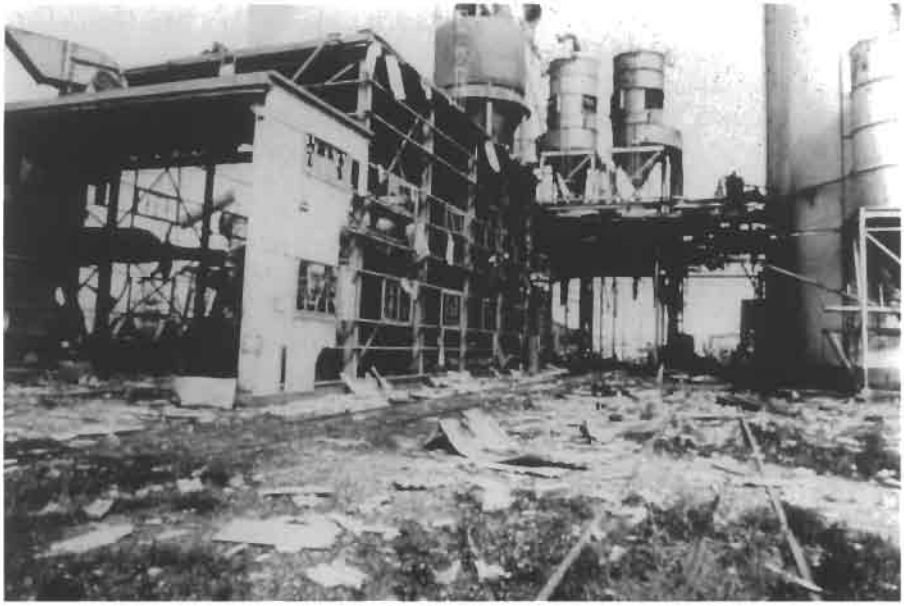

Figure 2.14 *Destroyed dump area of the Corpus Christi grain silo plant after major grain dust explosion in 1981 (Courtesy of C. W. Kauffman, University of Michigan).*

2.5

A DUST EXPLOSION IN A FISH MEAL FACTORY IN NORWAY IN 1975

The explosion, described by Eckhoff (1980), took place at the end of a hot, dry day in August 1975, in one of the many fish meal factories located along the Norwegian west coast. A young worker lost his life due to severe burns, and another was injured. At the time of the explosion, the Norwegian factory inspectorate had just about released its very first set of rules for fighting industrial dust explosions. Hence, the general appreciation of the dust explosion hazard in Norwegian industry was still meager.

The part of the factory involved in the explosion was the fish meal grinding plant, illustrated in Figure 2.15. This plant was located in a 30 m tall building that also contained several fairly large storage and mixing silos. A photograph of the building, taken just after the explosion and showing the damaged roof, is given in Figure 2.16.

The three silos indicated on Figure 2.15, which played a key role in the development of the explosion, were 12 m high with diameters of about 3 m. The wooden floor of the loft of the building also served as the common roof of the three silos. Close to the top of the silos there were 0.1 m × 1 m open slots in the common wall between silos no. 1 and no. 2, and no. 2 and no. 3. The original purpose of the three silos was to store the production of fish meal accumulated during the night shift, allowing the screening operation to be limited to the day shift. However, the hopper parts of the silos were not properly

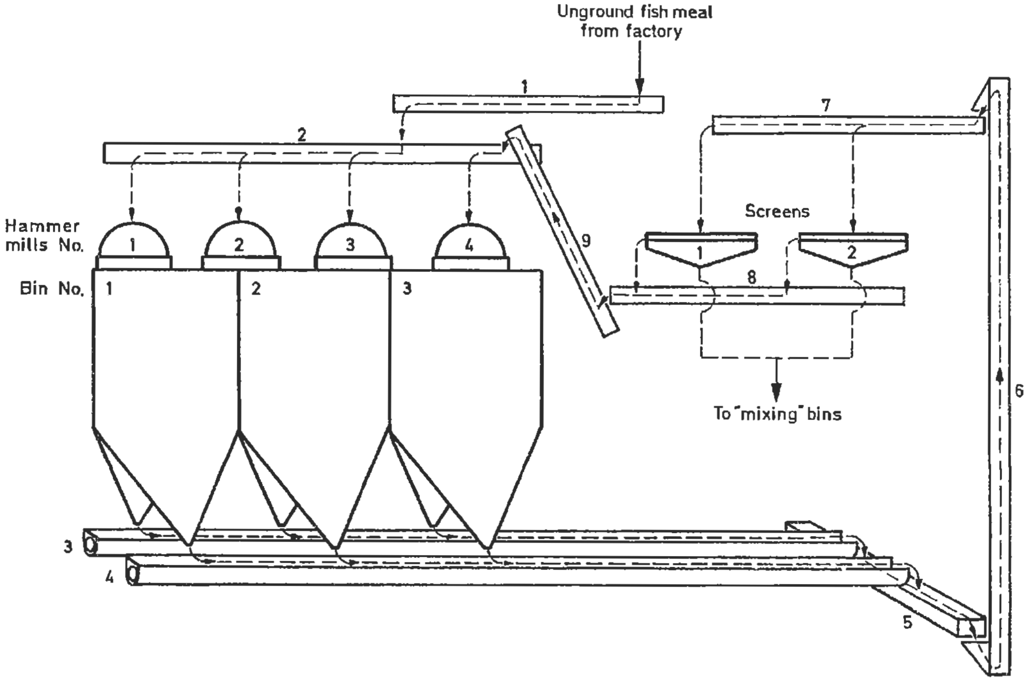

Figure 2.15 *The fish meal grinding plant afflicted with a dust explosion in 1975.*

Figure 2.16 *The building of the fish meal factory in Norway afflicted with a dust explosion in 1975.*

designed, and severe flow problems were encountered when attempting to discharge the fish meal by means of the screw conveyors at the hopper outlets. Therefore, the use of the silos as buffer stores had to be abandoned. But instead of feeding the output from the hammer mills directly to the screens, the long transport loop via the large silos was maintained, the silos being mostly empty because of the large capacity of the screws at the hopper outlets. Nevertheless, arching problems still occurred across the hopper outlet just above the screw conveyors, and breaking such arches became part of the regular duties of the staff operating the plant.

Although the grinding of the fish meal in the hammer mills in the loft produced large quantities of fine dust, no dust extraction system had been installed. As a consequence, the interior of the three large, empty silos acted as dust collectors, and considerable quantities of dust accumulated on the internal walls. Furthermore, appreciable amounts of dust escaped to most other parts of the building. In addition to having a much larger specific surface area than the main fish meal product, in periods of hot and dry weather, as on the day of the explosion, this fine dust would become quite dry. Because of the heat liberated by the production process itself, the temperature in the loft of the silo building would frequently be in the range 25–30°C. On the exceptionally hot day of the explosion, the temperature in the loft in the middle of the day was 45°C.

One particular feature of the screw conveyors of this plant was that the bolts fixing the screw blades to the shaft (bolts of lengths 110–120 mm and diameters 12–16 mm) broke fairly regularly, presumably as a result of material fatigue. Figure 2.17 shows part of one of the screws with three bolt heads.

In spite of frequent bolt failures, the plant made no provision for trapping tramp metal, such as broken bolts, before it reached the hammer mills. Neither were there any instructions for controlling the screws to replace defective bolts in advance. As a consequence, the entrance

Figure 2.17 *Part of a screw conveyor in the exploded fish meal plant showing fixing bolts.*

of broken bolts and other tramp metal into the hammer mills was a fairly frequent event. The presence of bolts in the mills created a most unpleasant noise, which warned the operators of the plant. The normal procedure for removal of bolts from the mill was to open the 250 mm × 180 mm door in the mill chute, shown by the arrow in Figure 2.18, and wait until the foreign metal object eventually found its way out of the opening.

Just prior to the explosion, as part of the routine during startup of the night shift, a worker went up to the loft, where he at once heard, by the sound from the mills, that foreign objects had entered several of them. By means of the usual procedure, bolts were first removed from mills 2 and 4. However, the noise of foreign objects continued, and the source was mill no. 1. As soon as the door in the mill chute was opened, a rapidly growing cloud of "sparks" (probably burning fish meal particles) was discovered. At the same time, flames just below mill no. 1 were observed through a narrow slot close to the mill. The main explosion occurred immediately after these observations had been made, blowing the hatch off the manhole and ejecting a strong flame through the loft room and against the roof of the building. According to the observer, the flame was bluish in color, similar to that of a brazing lamp. This first blast was followed by a kind of whistling or howling that moved in the direction from mill no. 1 to mill no. 4. This may have been flame propagation from silo no. 1 via silo no. 2 to silo no. 3 through the 0.1 m × 1 m slots at the top of the common wall between two neighboring silos. At this moment, the witness found his way out and escaped from the loft, which was now on fire.

The explosion was also observed from the outside by two persons who just happened to pass by. One distinct and fairly strong explosion could be heard. This was followed by a large pyramidal flame lasting for 30–45 seconds and extending 4–5 m above the roof of the building. The explosion was sufficiently strong to blow out windows in the building even in other parts than the loft.

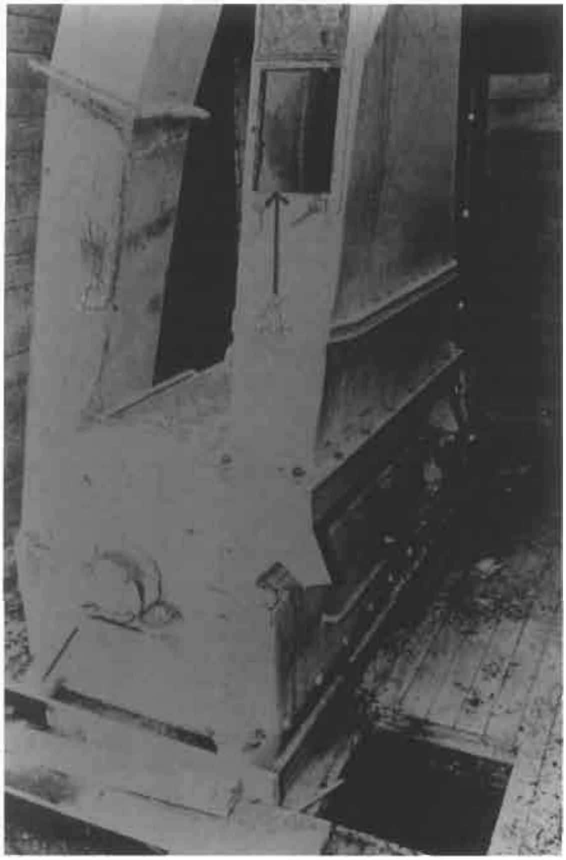

Figure 2.18 *View of hammer mill no. 1, in which the fish meal explosion started, the door in the mill chute, and the manhole in the floor. The manhole acted as vent for the explosion in silo no. 1.*

It seems highly probable that the ignition took place in hammer mill no. 1 and the ignition process was closely related to the presence of tramp metal in the mill. It seems unlikely that sparks struck between two steel objects would be able to ignite clouds of the fish meal in the mill. However, a metal object can be heated, even to glowing, by repeated impact or friction and thus act as a hot surface for direct initiation of dust explosion in a cloud. It is not unlikely that this latter process was in operation in the actual case, because after the explosion it was discovered that a 14 × 7 mm strip of steel was wedged into one of the 3 mm slots of the bottom screen plate of mill no. 1. In view of the high rotation speed of the mill (25 rev/s), such an object could easily have been heated to appreciable temperatures by repeatedly being struck by one of the mill hammers.

This accident shows that normal fish meals can, under unfavorable circumstances, give rise to quite severe dust explosions, even though the explosions produced by such materials in standard laboratory tests are relatively weak compared with those produced by many other dusts. Because the pressure needed to blow up very weak structures, like the wooden floor of the loft, is low, even a modest dust explosion is hazardous under such circumstances. The housekeeping was very poor. There was neither any dust extraction system nor any routine for frequent and regular removal of the considerable amounts of fine dust accumulated throughout the plant and building. This dust certainly was the main source of the extensive secondary explosion and fire sweeping through the entire loft. Because of the dry weather, the dust moisture content was probably low and the dust easy to entrain and disperse. The process design was inadequate, in that the large silos below the hammer mills did not serve their purpose and merely acted as large potential dust explosion bombs.

Also prevention of potential ignition sources was inadequate. In the grinding plant, no provision was made for removing foreign metal objects before they entered the hammer mills. Allowing tramp metal into the hammer mills at all created a considerable risk of potential ignition sources being introduced. Furthermore, the procedure for removing broken conveyor screw bolts from the hammer mills by opening the door in the mill chute was indeed questionable.

Hence, the three key ingredients needed for generating a serious dust explosion were present: large enclosures that were empty apart from explosible dust clouds, large quantities of dust throughout the entire building, and an ignition source.

2.6

SMOLDERING GAS EXPLOSION IN A SILO PLANT IN STAVANGER, NORWAY, IN NOVEMBER 1985

This accident, described by Braaten (1985), was not primarily a dust explosion but an explosion of combustible gases released from a solid organic material during self-heating in a silo cell. At first glance, such an event may seem out of place in the context of dust explosions. However, smoldering combustion is most often related to powders and dusts; therefore, the initial smoldering gas explosion, in most cases, entrains combustible dust and the explosion can easily develop into a normal dust explosion.

The cause of events was in accordance with Figure 1.9 in Chapter 1. The explosion occurred in a fairly modern reinforced concrete silo complex used to store various feedstuffs. Pellets of Canadian rape seed flour had been stored in one of the silos for some time, when it was discovered that the material in the bottom part of the silo had become packed to a solid mass and could not be discharged through the silo exit. Some time later, one week before the explosion, flames were observed in the silo. The fire brigade was called and covered the pellets in the silo with foam from above. Various unsuccessful attempts were then made at discharging the pellets mass at the silo bottom. During this phase there was considerable development of smoke, which mixed with the air, not only in the silo cell in question but also in the silo loft above the cells. It is probable that the smoke contained combustible gases, such as CO, and that the strong explosion, which occurred just after the top of the pellets had been covered with foam once more, was mainly a gas explosion. However, any dust deposits in the loft may also have been involved. The entire roof of the building was blown up, and debris was thrown into the surrounding area (see Figure 2.19). Because the explosion occurred in the middle of the night (3:00 A.M.), just after the fire brigade had left, nobody was killed or hurt.

Figure 2.19 *View of damaged loft of silo plant in Stavanger, Norway, after smoldering gas explosion in November 1985 (Courtesy of Øyvind Ellingsen, Stavanger Aftenblad, Norway).*

2.7
SMOLDERING GAS EXPLOSIONS IN A LARGE STORAGE FACILITY FOR GRAIN AND FEEDSTUFFS IN TOMYLOVO, KNIBYSHEV REGION, USSR

This extensive series of explosions were of the same nature as the smoldering gas explosion discussed in Section 2.6. The report of the event was provided by Borisov and Gelfand (personal communication from A. Borisov and B. Gelfand, USSR Academy of Science, Moscow,1989).

The large storage facility for grain and feedstuffs consisted of four sections of 60 silo cells each, that is, 240 silo cells altogether. As indicated in Figures 2.20 and 2.21, each cell had a 3 m × 3 m square cross section and 30 m height. The first explosion occurred in December 1987 in a silo cell containing moist sunflower seed, which was not supposed to be stored in such silos due to the risk of self-heating. However, this had nevertheless been done, and the resulting self-heating developed into extensive smoldering decomposition, during which methane and carbon monoxide were produced and mixed with the air in the empty top part of the silo, above the powder bed surface. It is reasonable to believe that the primary explosion was in this mixture of explosive gas and air and that the ignition source was the smoldering combustion when it penetrated to the powder bed top surface, as illustrated in Figure 1.9 in Chapter 1. However, dust deposits on the internal silo walls and roof may well have become entrained by the initial blast and involved in the explosion. This was only the first of a large series of 20–30 subsequent explosions that took place in the same facility, in one silo cell after the other, during 1988 and 1989.

Figure 2.20 *Corner of the silo complex in Tomylovo, USSR, damaged by smoldering gas explosions, 1987–1989 (Courtesy of A. Borisov and B. Gelfand, USSR Academy of Science, Moscow).*

There are two main reasons for this continued explosion activity in the silo complex. The most important is the heat transfer from a silo cell in which smoldering combustion is taking place to the neighboring cells. Such heat transfer is facilitated by the large contact surface area between the cells provided by the square cross section. Furthermore, the prefabricated construction elements used throughout the entire facility, as shown in Figures 2.20 and 2.21, may have been comparatively poor heat insulators.

The second main reason for the repeated explosions was that sunflower seed was not the only material in the facility that was not supposed to be stored there. Some of the silo cells contained buckwheat and wheat grain of higher moisture contents than the maximum permissible limits for storage in such facilities.

During the period of repeated explosions, attempts were made to break the unfortunate chain of events. Cells were opened at the top for inspection. However, this admitted fresh air to the smoldering mass and enhanced the combustion process. Attempts also were made to quench and cool the powder mass with liquid nitrogen, but this was only partly successful.

Figure 2.21 *Central part of the silo complex in Tomylovo, USSR, damaged by smoldering gas explosions, 1987–1989 (Courtesy A. Borisov and B. Gelfand, USSR Academy of Science, Moscow).*

It was agreed that the use of water to extinguish the smoldering combustion in the silo cells was not feasible. Limited quantities of water would probably enhance the self-heating process rather than quench it, whereas use of extensive quantities would increase the load on the silo walls and cause collapse of the structure.

At one stage, it was discussed whether the whole facility could be blown up to put an end to the problem. However, this was considered too hazardous. The final solution chosen was to just leave the entire facility to itself and await a natural termination of the problem over time.

In addition to obeying the rules specifying which materials can be stored in silos, systematic use of portable gas analyzers for early detection of hydrogen, methane, and carbon monoxide in the silo cells was suggested as the best means for preventing similar accidents in the future.

2.8

SMOLDERING GAS EXPLOSION AND SUBSEQUENT SUCCESSFUL EXTINCTION OF SMOLDERING COMBUSTION IN PELLETIZED WHEAT BRAN IN A SILO CELL AT NORD MILLS, MALMÖ, SWEDEN, IN 1989

A cross-section of the silo is shown in Figure 2.22. The course of events, as recorded by Templin (personal communication from G. Templin, Nord Mills, Malmö, Sweden, 1990), was as follows:

> Saturday 28th January, 0700: The night shift stopped the production for the weekend according to schedule, and all activity in the grain silo plant terminated.
>
> Saturday 28th January, 1000: According to Nord Mills' safety procedures, the safety guard team made its inspection round through the entire plant. Nothing special was observed. No persons were encountered.
>
> Saturday 28th January, 2300: A bang, muffled by the noise of strong winds, was heard in the neighborhood, but no action was taken.

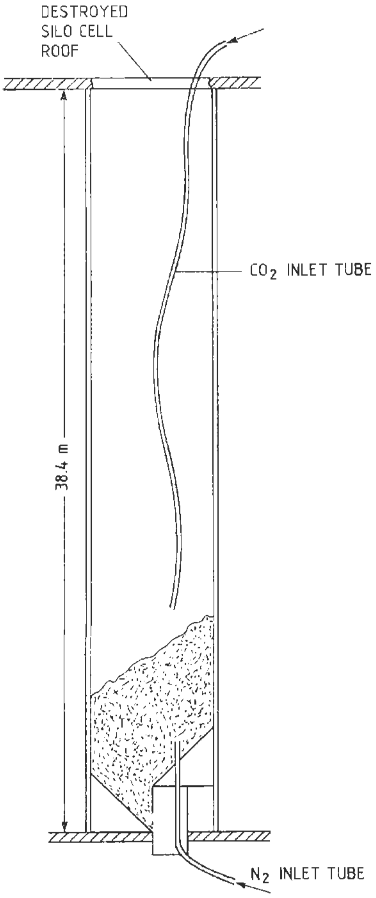

Figure 2.22 *Cross section of the silo in Malmö, Sweden, in 1989, with smoldering wheat bran pellets, showing inlets for carbon dioxide and nitrogen for extinction and cooling (Courtesy of G. Templin and B. Persson, Nord Mills, Sweden).*

Sunday 29th January, 0930: During its scheduled inspection round, the safety guard team discovered fragments of shattered window panes spread over the entire yard. Inspection of the roof of the silo building revealed that the roof of an intermediate star cell had blown up, as shown in Figure 2.23, and dense smoke was emerging from the open cell top. The height of the cell involved was about 36 m and its cross-sectional area about 20 m^2. Most of the silo was empty, the pelletized wheat bran occupying only the first 7 m above the cell bottom.

Sunday 29th January, rest of day: Fire brigade and other personnel were called, and the entire plant area was cordoned off. About 2000 kg of gaseous carbon dioxide was pumped into the burning silo from above through a long vertical pipe extending right down to the surface of the smoldering pellets.

Monday 30th January, early morning: The discharge valve at the cell bottom was removed, and discharge of the pellets mass, using a mobile suction unit, was started. This gave rise to increased smoke production, and at 03.30, more carbon dioxide was loaded into the silo cell from above.

Tuesday 31st January: The discharge operation was interrupted. Carbon dioxide was emerging through the bottom silo exit, and more was loaded into the silo at the top.

Wednesday 1st February: More carbon dioxide was loaded into the silo at the top. From 03:00 to 12:50, the smoke development was enhanced by vibrations due to operation of another silo cell. The smoke temperature just above the pellets was 96°C and just above the silo top, 45°C.

Thursday 2nd February–Wednesday 8th February: Smoke development and temperature rise was suppressed temporarily by loading several tonnes of carbon dioxide into the silo from the top, but there was only slow permanent progress. Temperature rise was observed in the material stored in the four larger adjacent silo cells.

Thursday 9th February–Saturday 11th February: Holes were drilled through the silo bottom and at intervals a total of several tonnes of nitrogen were pumped into the pellets from below, while carbon dioxide was charged from above.

Monday 13th February–Wednesday 15th February: Some 6000 kg of carbon dioxide and 3000 kg of N_2 was injected into the burning pellets. Temperatures in the burning and adjoining cells and contents of oxygen, CO, and CO_2 in the gas above the pellets were monitored regularly.

Monday 20th February: The smoldering combustion in the wheat bran pellets had finally been brought to an end.

This case history illustrates that fighting smoldering combustion in large silo complexes is not only a matter of quenching, or terminating, the oxidation reaction but also indeed a matter of cooling massive bulks of poor heat conductors to a temperature level at which the combustion process will not start again once air is readmitted to the system.

2.9

LINEN FLAX DUST EXPLOSION IN HARBIN LINEN TEXTILE PLANT, PEOPLES REPUBLIC OF CHINA, IN MARCH 1987

2.9.1

GENERAL OUTLINE

In the middle of the night (2:39 A.M.), on March 15, 1987, the spinning section of the large linen textile plant in Harbin, Peoples Republic of China, was afflicted with a catastrophic dust explosion. The losses were substantial. Out of the 327 women and men working the night shift in the spinning section when the explosion occurred, 58 lost their lives and 177 were injured; 13,000 m^2 of factory area was demolished.

This explosion accident has been discussed in detail by Xu Bowen (1988) and Zhu Hailin (1988). Xu Bowen et al. (1988) reconstructed a possible course of the explosion

Figure 2.23 *Damaged silo roof after a smoldering gas explosion resulting from smoldering wheat bran pellets in a 39 m tall concrete silo in Malmö in 1989 (Courtesy of G. Templin and B. Persson, Nord Mills, Sweden).*

development on the basis of a seismic recording of the explosion by the State Station of Seismology, located only 17 km from the Harbin Linen Textile Plant.

2.9.2
EXPLOSION INITIATION AND DEVELOPMENT, SCENARIO 1

Figure 2.24 illustrates the 13,000 m^2 spinning section through which the explosion swept and the possible locations and sequence of the nine successive explosions that constituted the event according to Xu Bowen (1988) and Xu Bowen et al. (1988). These workers based their reconstruction of the explosion on three independent elements of evidence. First, they identified the location of the various explosion sites throughout the damaged plant. Second, they ranked the relative strengths of the local explosions by studying the extent and nature of the damage. Third, they arranged the various local explosions in time by means of the relative strengths of the nine successive explosions, identified by decoding the seismic recording of the event.

Figure 2.25(A) shows a direct tracing of the amplitude-modulated seismic signal actually recorded 17 km from the explosion site. Figure 2.25(B) shows the sequence of nine energy pulse impacts on the earth at the location of Harbin Linen Textile Plant, deduced from the signal in Figure 2.25(A). Figure 2.25(C) finally shows the theoretical prediction of the seismic signal to be expected from the sequence of explosions in Figure 2.25(B). The agreement between the (A) and (C) signals is striking, which supports the validity of the energy impact pulse train (B).

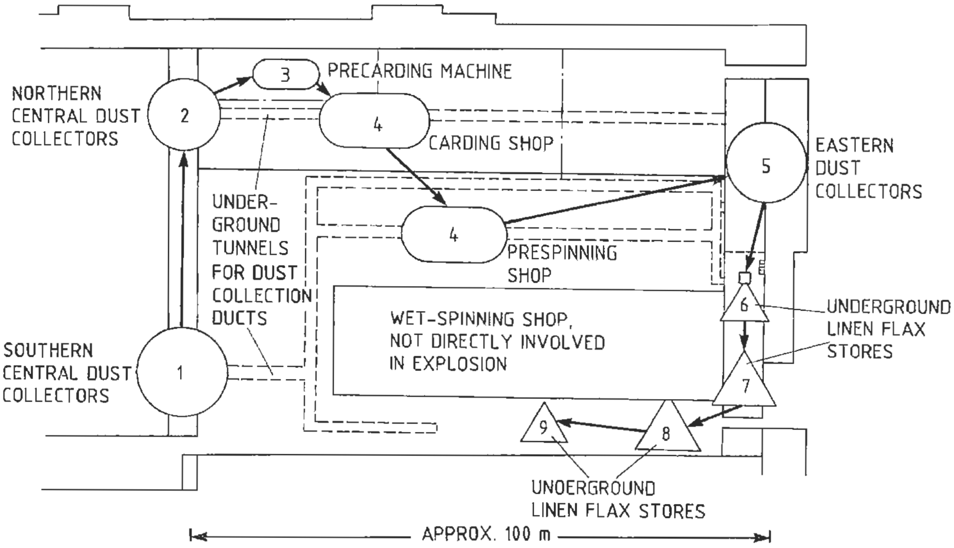

Figure 2.24 *The 12,000 m^2 spinning section of the Harbin Linen Textile Plant, Peoples Republic of China, that was afflicted with a catastrophic dust explosion on March 15, 1987. Numbered circles, ovals, and triangles indicate location and sequence of a postulated series of nine successive explosions (From Xu Bowen et al., 1988).*

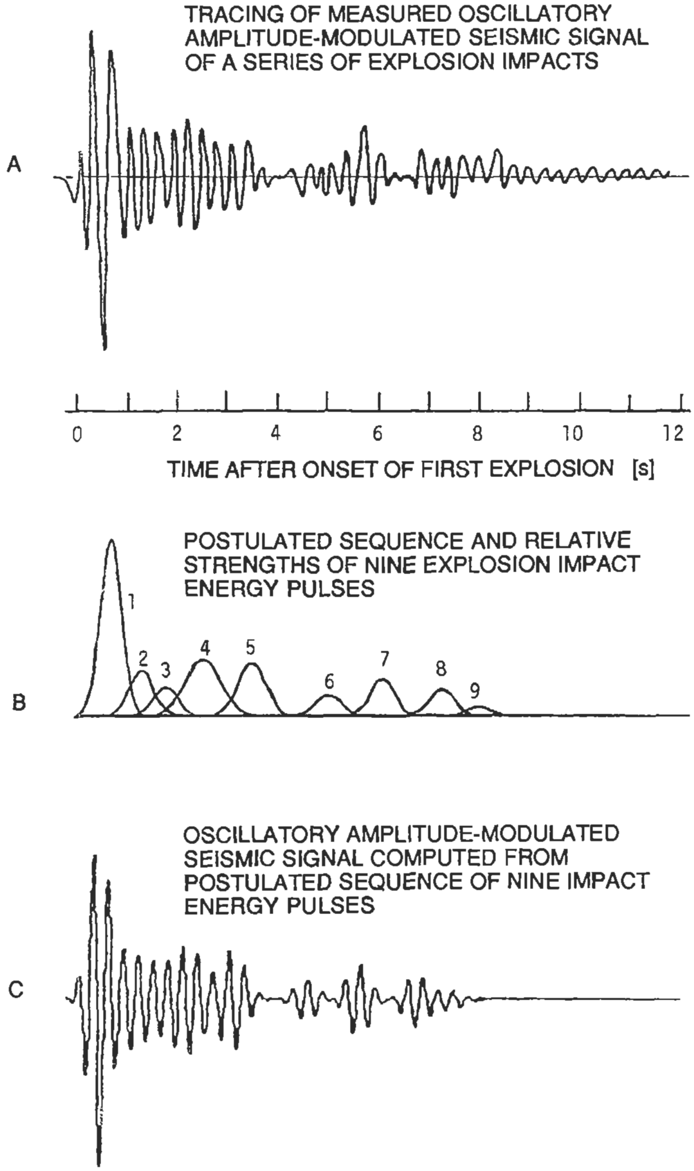

Figure 2.25 *Sequence of nine impact energy pulses from nine successive explosions in the Harbin Linen Textile Plant, Harbin, Peoples Republic of China, March 15, 1987, postulated on the basis of a seismic record of the event (From Bowen et al., 1988).*

Table 2.1 Sequence, relative strengths, and locations of nine successive dust explosions in the Harbin Linen Textile Plant, Harbin, Peoples Republic of China, March 15, 1987, postulated on the basis of damage analysis in the plant and a seismic recording of the explosion

Explosion number	Onset of explosion (s)	Seismic energy (T erg)	Location of explosion in plant
1	0.0	50.7	Southern central dust collector
2	0.6	5.4	Northern central dust collector
3	1.2	2.5	Precarding machine
4	1.6	7.6	Carding and prespinning shops
5	3.0	6.8	Eastern dust collectors
6	4.8	1.4	Underground linen flax stores
7	6.0	3.9	
8	7.3	2.2	
9	8.2	0.45	

Source: Bowen et al., 1988.

Table 2.1 summarizes the findings of Xu Bowen et al. (1988) that led to the suggestion of the explosion development indicated in Figure 2.24. According to this scenario, the explosion was initiated in one of the nine units in the central dust collector system. All nine units were connected by ducting. The ignition sources were not identified, but an electrostatic spark was considered a possibility, a local fire or glow another. The initial flame was transmitted immediately to the next dust collecting unit and both units (1) exploded almost simultaneously, giving rise to the first major impact pulse in Figure 2.25(B). The explosion then propagated through the other seven dust collecting units in the central collecting plant (2), and into the precarding area, where the blast wave preceding the flame generated an explosible dust cloud in the room, which was ignited by the flame jet from the dust collectors (3). The room explosion propagated further to the carding and prespinning shops (4), right up to the eastern dust collectors, where another distinct explosion (5) occurred. The final four explosion pulses were generated as the explosion propagated further into the underground linen flax stores, where it finally terminated after having traveled a total distance of about 300 m. The chain of nine explosions lasted for about 8 seconds.

2.9.3

EXPLOSION INITIATION AND DEVELOPMENT, SCENARIO 2

This alternative scenario originates from the investigation of Zhu Hailin (1988), who found evidence of an initial smoldering dust fire caused by a live 40 W electrical portable light lamp lying in a flax dust layer of 6–8 cm thickness in a ventilation room. He also found evidence of flame propagation through the underground tunnels for the dust collection ducting. On the basis of his analysis, Zhu suggested that the explosion was initiated in the eastern dust collectors (5 in Figure 2.24) from which it transmitted to nine units of the central dust collecting plant (1 and 2 in Figure 2.24) via the ducting in the underground tunnels. Severe room explosions were initiated when the ducting in the tunnel ruptured, and the resulting blast dispersed large quantities of dust in the workrooms into explosible clouds that were subsequently ignited. From the eastern dust collectors, the explosion also propagated into the underground flax stores. It is not unlikely that even this scenario could be developed further in such a way as to agree with the evidence from the seismic recording.

2.9.4
ADDITIONAL REMARKS

The investigation of the Harbin disaster exposed the great difficulties in identifying the exact course of events of major explosions creating massive damage. In addition to causing pain and grief, loss of life also means loss of eyewitnesses. Besides, the immediate need for fire-fighting and rescue operations changes the scene before the investigators can make their observations. Also, the explosion itself often erases evidence, such as of the ignition source. This problem was shared by the experts who investigated the Harbin explosion, and it seems doubtful that the exact course of events will ever be fully resolved.

However, the Harbin disaster unambiguously demonstrated the dramatic consequences of inadequate housekeeping in industrial plants where fine dust that can give dust explosions, is generated.

2.10
FIRES AND EXPLOSIONS IN COAL DUST PLANTS

2.10.1
METHANE EXPLOSION IN 17,000 m^3 COAL SILO AT ELKFORD, BRITISH COLUMBIA, CANADA, IN 1982

As mentioned in Section 1.5, the handling and storage of coal can, in addition to the dust explosion hazard, present a gas explosion risk, due to release of methane from some types of coal. An account of such an explosion was given by Stokes (1986).

The silo of height 48 m and diameter 21 m that exploded was used for storage and load-out of cleaned, dried metallurgical coal. The capacity of the silo was 15,000 tonnes.

Prior to the explosion, a methane detector had been installed in the roof of the silo. The detector activated a warning light in the silo control room when a methane concentration of 1% was detected, and an alarm light was activated when detecting 2% methane. A wet scrubber was located in the silo head house to remove dust from the dust-laden air in the silo during silo loading. A natural ventilation methane stack was also located in the silo roof to vent any buildup of methane gas from the silo.

The explosion occurred early in the morning on May 1, 1982, devastating the silo roof, head house, and conveyor handling system. Witnesses stated that a flash was noticed in the vicinity of the head house, followed seconds later by an explosion that displaced the silo top structures. This was followed by an orange-colored fireball that rolled down the silo walls and extinguished prior to reaching the base of the silo. Fortunately, neither injury nor death resulted and damage to surrounding structures was minimal, although large blocks of concrete and reinforcing steel had been thrown several hundred meters from the silo. However, the plant itself suffered substantial damage.

The silo was full of coal 24 hours prior to the explosion. During the evening before the explosion, 10,000 tonnes of coal were discharged. At the same time, conveying of deep-seam coal into the silo commenced and continued until the explosion occurred. At the time of the explosion, approximately 12,300 tonnes of coal were in the silo, of which 7,600 tonnes were deep-seam coal. Testing had shown that this quality of coal has a high methane emission rate and produces a low volatile coal dust. Clouds in air of this dust could not be ignited unless the air was mixed with methane.

The ignition source was not identified, but the following three possible sources were considered:

- Spontaneous combustion of the stored coal.
- An electrical or mechanical source.
- Hot coal from the thermal dryer.

During 10 years of operation, with coal being stored in different environments for varying lengths of time, spontaneous combustion had never presented a problem and, consequently, was not considered a probable source of ignition. During demolition of the damaged silo, all electrical and mechanical components were recovered and inspected; they showed no evidence of being the ignition source. Stokes (1986) did not exclude the remaining possibility that hot coal from the thermal dryer was the source of ignition.

2.10.2

METHANE/COAL DUST EXPLOSION IN A COAL STORAGE SILO AT A CEMENT WORKS IN SAN BERNARDINO COUNTY, CALIFORNIA

This incident was reported by Alameddin and Foster (1984). A fire followed by an explosion occurred inside a coal silo of 900 tonnes capacity while the silo was nearly empty, and the remaining 85 tonnes of coal were being discharged. Prior to the explosion, a hot spot of 0.6 m × 1.0 m had been detected on the lower part of the silo wall by means of an infrared heat detector. The hot spot originated from smoldering combustion in the coal in the silo. This process liberated methane, carbon monoxide, and other combustible gases from the coal. The explosion probably resulted from ignition of a mixture of combustible gas and airborne coal dust in the space above the bulk coal by the smoldering fire or glow when it reached the surface of the coal deposit (see Figure 1.9 in Chapter 1).

It was concluded that the supply of carbon dioxide from the top, which was used to suppress the fire and prevent explosion, was insufficient to prevent the development of an explosible atmosphere in the space above the bulk coal.

To prevent similar accidents in the future, it was recommended that a carbon dioxide system be installed in both the top and bottom of the coal silo. Sufficient inerting gas should be added for development of a slight positive pressure inside the silo. The inerting gas must be of sufficient quantity to ensure a nonexplosible atmosphere above the coal and sufficient pressure to prevent a sudden inrush of fresh air into the silo.

2.10.3

GAS AND DUST EXPLOSION IN A PULVERIZED COAL PRODUCTION/COMBUSTION PLANT IN A CEMENT FACTORY IN LÄGERDORF, FEDERAL REPUBLIC OF GERMANY, IN OCTOBER 1980

According to Patzke (1981), who described this explosion accident, the explosion occurred while coal of about 30% volatiles was milled at a rate of 55 tonnes per hour. The startup of the cement burner plant followed a compulsory break of at least 20 minutes of the milling operation to allow all airborne dust to settle out. A few seconds after the main gas valve had been opened, there was a violent explosion. The probable reason was a failure in the system for electric ignition of the gas. Within the period of 6 seconds before the gas valve was reclosed automatically, about 1 m^3 of gas had been discharged to the atmosphere of the hot combustion chamber and become mixed with the air to form an explosible gas cloud. The temperature of the walls of the chamber was sufficiently high to ignite the gas, and a gas explosion resulted. The blast and flame jet from this comparatively mild initial explosion was vented into the milling system, where a large, turbulent dust cloud was generated and ignited, resulting in a violent secondary dust explosion.

Various parts of the milling plant, some unvented and some vented, had been designed to withstand the pressure generated in an extensive dust explosion. Furthermore, a passive device for explosion isolation of the type shown in Figure 1.82 in Chapter 1 had been installed upstream of an electrostatic dust filter.

Apart from the deformation of some explosion vent doors, the dip tubes of two cyclones, and the coal feeder upstream of the mill, the plant had been able to withstand the explosion without damage. The passive explosion isolation device effectively protected the electrostatic filter from becoming involved in the system.

2.10.4

FURTHER EXPLOSION AND FIRE INCIDENTS INVOLVING COAL

Andersson (1988) gave a step-by-step account of the process of extinction of a smoldering fire in a 50 m^3 coal dust silo in Arvika, Sweden, in August 1988. It was necessary to pay attention to the risk of explosion of combustible gases driven out of the coal by the heat from the fire.

First, gaseous carbon dioxide was loaded into the silo at the top to build up a lid of inert atmosphere immediately above the coal deposit. Then, all the coal was discharged carefully through the exit at the silo bottom. In this particular case, supply of carbon dioxide at the silo bottom was considered superfluous.

Wibbelhoff (1981) described a dust explosion in a coal dust burner plant of a cement works in the Federal Republic of Germany, in March 1981. Prior to the explosion, an electrical fault had caused failure of an air blower. The explosion occurred just after restart of the repaired blower. During the period in which the blower was out of operation, dust had accumulated on the hot surfaces inside the furnace and ignited; and as soon as the blower was restarted, the glowing and burning dust deposits were dispersed into a dust cloud that exploded immediately.

Pfäffle (1987) reported on a dust explosion in the silo storage system of a pulverized coal powder plant in Düsseldorf, Federal Republic of Germany, in July 1985. The explosion occurred early in the morning in a 72 m^3 coal dust silo. The silo ruptured and burning material thrown into the surroundings initiated a major fire, which was extinguished by water. Fortunately, no persons were killed or injured in this primary accident. However, during the subsequent cleaning-up process, a worker was asked to free the damaged silo of ashes by hosing it down with water. It then appeared that a glowing fire had developed in the dust deposit covered by the ashes. The worker had been warned against applying the water jet directly to the smoldering fire, but for some reason he nevertheless did this. The result was an intense dust flame that afflicted him with serious third degree burns. The smoldering fire was subsequently extinguished by covering its surface with mineral wool mats and subsequently soaking the whole system with water containing surface-active agent.

2.11

DUST EXPLOSION IN A SILICON POWDER GRINDING PLANT AT BREMANGER, NORWAY, IN 1972

In this serious explosion accident, five workers lost their lives and four were severely injured. The explosion, which occurred in the milling section of the plant, was extensive, rupturing or buckling most of the process equipment and blowing out practically all the wall panels of the factory building. Figure 2.26 is a flowchart of the plant.

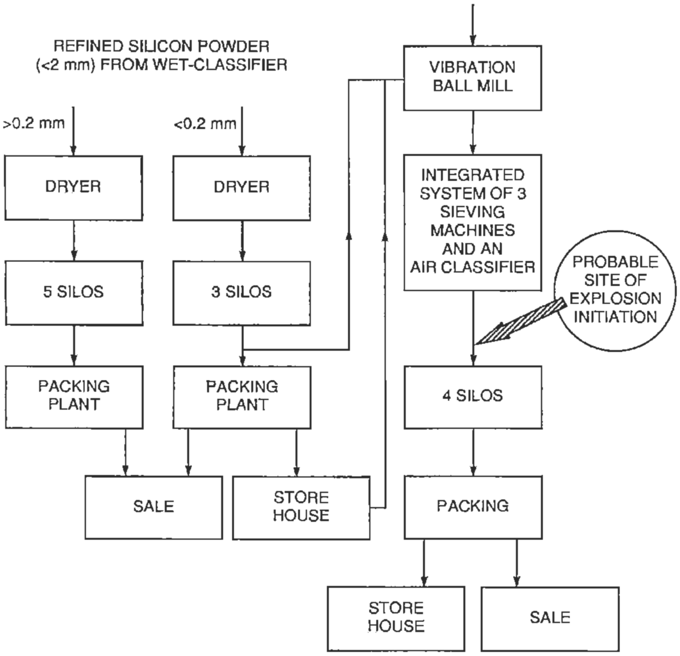

Figure 2.26 *The dry part of the plant for production of refined silicon products at Bremanger, Norway. The grinding plant that was totally damaged in the explosion in 1972 is shown to the right in the chart.*

Figure 2.27 *Totally destroyed milling section of silicon powder production plant at Bremanger, Norway, after the dust explosion in October 1972.*

Figure 2.28 *Detailed view of the extensive material damage cause by the silicon dust explosion at Bremanger, Norway, October 1972.*

Figure 2.27 shows the total damage of the entire grinding plant building, and Figure 2.28 gives a detailed view of the extensive damage.

Eyewitnesses reported that the flame was very bright, almost white. This is in accordance with the fact that the temperature of silicon dust flames, like flames of aluminum and magnesium dust, is very high due to the large amounts of heat released in the combustion process per mole of oxygen consumed (see Table 1.1 in Chapter 1). Because of the high temperature, the thermal radiation from the flame is intense, which was a main reason for the very severe burns that the nine workers suffered.

The investigation after the accident disclosed a small hole in a steel pipe for conveying Si powder from a mechanical sieve to a silo below. An oxygen/acetylene cutting torch with both valves open was found lying on the floor about 1 m from the pipe with the hole.

According to Kjerpeseth (personal communication from E. Kjerpeseth, Elkem-Bremanger, Svelgen, Norway, 1990), there was strong evidence of the small hole having been made by the cutting torch just at the time when the explosion occurred. At the moment of the explosion, part of the plant was closed down for various repair work. However, the dust extraction system was operating, and this may in part explain the rapid spread of the explosion throughout the entire plant. The interior of the perforated pipe had probably not been cleaned prior to the perforation. In view of the high temperature and excessive thermal power of the cutting torch, and not least that it supplied oxygen to the working zone, a layer of fine dust on the internal pipe wall may well have become dispersed and ignited as soon as the gas flame had burned its way through the pipe wall. The blast from the resulting primary silicon dust explosion then raised dust deposits in other parts of the plant into suspension and allowed the explosion to propagate further until it eventually involved the entire silicon grinding building. The grinding plant was not rebuilt after the explosion.

2.12
TWO DEVASTATING ALUMINUM DUST EXPLOSIONS

2.12.1
MIXING SECTION OF PREMIX PLANT OF SLURRY EXPLOSIVE FACTORY AT GULLAUG, NORWAY, IN 1973

The main source of information concerning the original investigation of the accident is Berg (personal communication from E. Berg, Dyno Industries, Gullaug, Norway, 1989). The explosion occurred during the working hours, just before lunch, while 10 workers were in the same building. Five of these lost their lives, two were seriously injured, two suffered minor injuries, only one escaped unhurt. A substantial part of the plant was totally demolished, as illustrated by Figure 2.29.

The premix preparation plant building was completely destroyed. Debris was found up to 75 m from the explosion site. The explosion was followed by a violent fire in the powders left in the ruins of the plant and in an adjacent storehouse for raw materials.

The explosion occurred when charging the 5.2 m^3 batch mixer, illustrated in Figure 2.30. It appeared that about 200 kg of very fine aluminum flake, sulfur, and some other ingredients had been charged at the moment of the explosion. The total charge of the formulation in question was 1200 kg.

The upper part of the closed vertical mixing vessel was cylindrical, and the lower part had the form of an inverted cone. The feed chute was at the bottom of the vessel. The mixing device in the vessel consisted of a vertical rubber-lined screw surrounded by a rubber-lined grounded steel tube. The powders to be mixed were transported upward by the screw, and when emerging from the top outlet of the tube, they dropped to the surface of the powder heap in the lower part of the vessel, where they were mixed with other powder elements and eventually retransported to the top.

Figure 2.29 *Scene of total demolition after aluminum dust explosion in the premix plant of a slurry explosive factory at Gullaug, Norway, in August 1973 (Courtesy of E. Berg, Dyno Industries, Gullaug, Norway).*

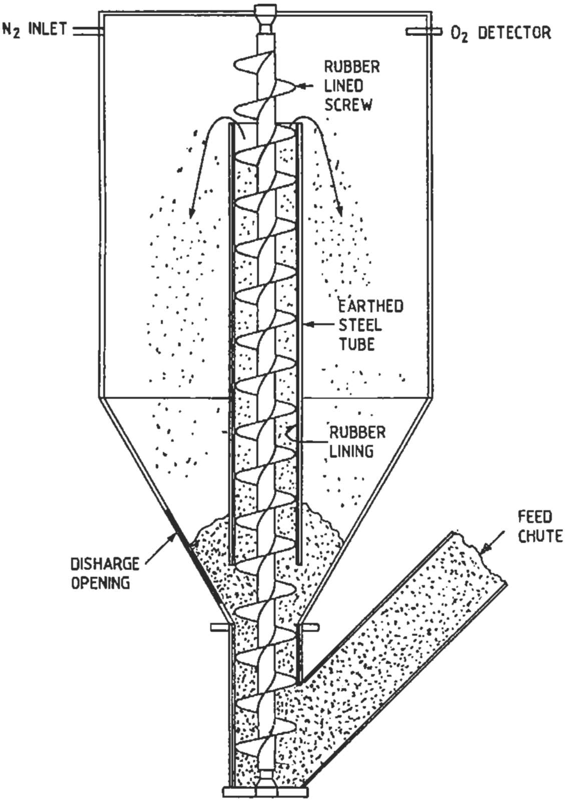

Figure 2.30 *Cross section of the mixer for production of dry premix for slurry explosives at Gullaug, Norway, in 1973 (Courtesy of E. Berg, Dyno Industries, Gullaug, Norway).*

The construction materials of the mixer had been selected to eliminate the formation of mechanical sparks. This was probably why both the screw and the internal wall of the surrounding grounded steel tube were lined with rubber.

During operation, the 5.2 m^3 vessel was flushed with nitrogen, the concentration of oxygen in the vessel being controlled by a direct reading oxygen analyzer. According to the foreman's statement, the oxygen content at the moment of explosion was within the specified limit.

After the explosion, the central screw part of the mixer, with the mixer top, was retrieved, as shown in Figure 2.31, about 12 m away from the location that the mixer had prior to the explosion. More detailed investigation of the part of the screw shielded by the steel tube revealed, as shown in Figure 2.32, that the screw wings had been

Figure 2.31 *Top of 5.2 m^3 premix and 3.3 m long mixing screw with surrounding steel tube (see Figure 2.30), as found after the explosion 12 m away from location of the mixer prior to the explosion (Courtesy of E. Berg, Dyno Industries, Gullaug, Norway).*

Figure 2.32 *Section of screw after splitting and removal of surrounding steel tube, showing bidirectional deformation of the screw wings from the explosion center. Part of rubber lining of steel tube removed from upper half of tube (Courtesy of E. Berg, Dyno Industries, Gullaug, Norway).*

deformed bidirectionally, as if an explosion in the central part had expanded violently in both directions. This evidence was considered a strong indication of the explosion having been initiated inside the steel tube surrounding the screw.

The blast and flame from this primary explosion, in turn, generated and ignited a larger dust cloud in the main space inside the mixer; and finally the main bulk of the powder in the mixer was thrown into suspension and ignited when the mixer ruptured, giving rise to a major explosion in the workrooms.

Subsequent investigations at the Chr. Michelsen Institute, Bergen, Norway, revealed that clouds in air of the fine aluminum flake powder was both extremely sensitive to ignition and exploded extremely violently. The minimum electric spark ignition energy was on the order of 1 mJ, and the maximum rate of pressure rise in the Hartmann bomb, 2600 bar/s. Both values are extreme. The thickness of the aluminum flakes was about 0.1 μm, which corresponds to a specific surface area of about 7.5 m^2/g (see Section 1.1.1.3 in Chapter 1).

The investigation further disclosed that the design of the nitrogen inerting system of the mixer was inadequate. First, the nitrogen flow was insufficient to enable reduction of the average oxygen concentration to the specified maximum level of 10 vol% within the time allocated. Second, even if the flow had been adequate, both the nitrogen inlet and the oxygen concentration probe were located in the upper part of the vessel, which rendered the measured oxygen concentration unreliable as an indicator of the general oxygen level in the mixer. It is highly probable that the oxygen concentration in the lower part of the mixer, and in particular in the space inside the tube surrounding the screw, was considerably higher than the measured value. This explains why a dust explosion could occur in spite of the use of a nitrogen inerting system.

The final central concern of the investigators was identification of the probable ignition source. In the reports from 1973, it was concluded that the primary explosion in the tube surrounding the screw was probably initiated by an electrostatic discharge. However, this conclusion was not qualified in any detail. In more recent years, the knowledge about various kinds of electrostatic discharges has increased considerably (see Section 1.1.4.6). It now seems highly probable that the ignition source in the 1973 Gullaug explosion was a propagating brush discharge, brought about by the high charge density that could be accumulated on the internal rubber lining of the steel tube surrounding the screw, because of the grounded electrically conducting backing provided by the steel tube itself. The discharge could then have occurred through a hole in the lining (see Figure 1.14).

2.12.2
ATOMIZED ALUMINUM POWDER PRODUCTION PLANT AT ANGLESEY, UNITED KINGDOM, IN 1983

This accident was discussed in detail by Lunn (1984), and the following brief summary is based on Lunn's account.

The explosion occurred on a Saturday evening in July 1983. Only three employees were working on the site at the time of the explosion. Two of these were injured whereas the third escaped unhurt. The plant was substantially damaged. Figure 2.33 shows the basic layout of the plant.

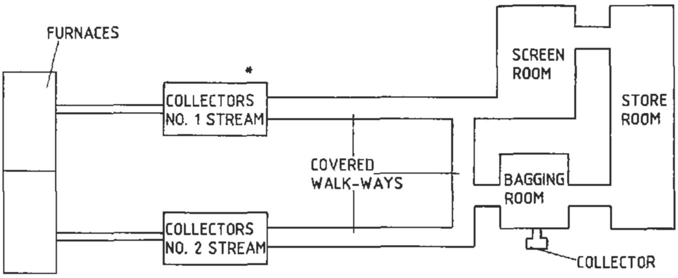

Figure 2.33 *Layout of plant for atomized aluminum powder production, in Anglesey, United Kingdom, damaged by an extensive dust explosion in July 1983. Ignition probably occurred in the no. 1 stream collector system marked with * (From G. Lunn, 1984).*

Molten aluminum from the furnaces was broken into small droplets by a jet of air. The aluminum powder so formed was carried by a current of air along sections of horizontal ducting at ground level before entering a riser that delivered it to a two-stage collecting system. There were two parallel collector streams, as shown in Figure 2.33. After the powder had been separated out in the collectors, the air passed through a fan and out to the atmosphere via a vertical stack. The powder dropped through rotary valves into a "Euro-bin," one for each stream. When full, the bins were transported along a covered walkway from beneath the collector to the screen room, where the aluminum powder was separated into particle-size fractions. The fractions were bagged in the bagging room, and the bagged powder was taken through a short corridor to the storeroom.

The explosion swept through almost the entire plant. Examples of the extensive damage are given in Figures 2.34 and 2.35. Figure 2.34 shows the no. 2 stream collector plant and Figure 2.35 the screen room.

According to Lunn (1984), neither the ignition source nor the location of the point of ignition was identified conclusively, but the fact that only no. 1 stream was in operation at the moment of the explosion would indicate that the explosion started there. The damage picture suggested that ignition could have occurred either before or within the first stage of the no. 1 stream collectors. Air blasts from the initial explosions then stirred up dust deposits in the walkways and screen room, allowing the flame to propagate into these areas.

The combination of a turbulent aluminum dust cloud ejected at a relatively high pressure from the no. 1 stream collectors and a large, energetic, and turbulent ignition source provided by the flames ejecting from the open vents generated ideal conditions for a dust explosion in the space between the no. 1 and no. 2 stream collectors capable of generating significant blast overpressure. In fact, the damage to the no. 2 stream collectors (Figure 2.34) suggested that overpressure had been exerted downward, collapsing the structure. However, the evidence also suggested that a relatively violent explosion inside the no. 2 stream collectors had taken place. Air movement from an external explosion and collapse of the structure could be sufficient to disperse dust inside the collectors. Ingress of flame from the external explosion into the collectors through tears in the bodywork caused by the collapse would provide multiple ignition sources.

An external explosion occurring some distance from the ground between the two collectors would also explain the damage to the cladding on the furnace room and the covered walkway

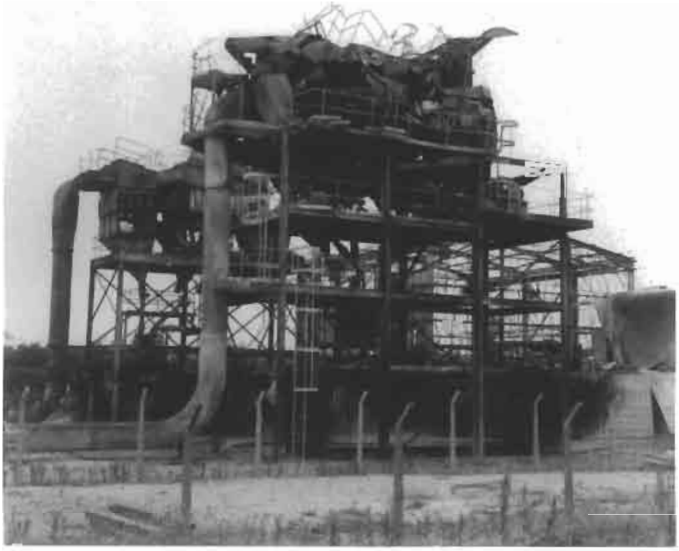

Figure 2.34 *Damaged no. 2 stream collectors after a dust explosion in an aluminum powder production plant at Anglesley, United Kingdom, in 1983 (Courtesy of G. Lunn, Health and Safety Executive, United Kingdom).*

Figure 2.35 *Damaged screen room after a dust explosion in an aluminum powder production plant at Anglesley, United Kingdom, in 1983 (Courtesy of G. Lunn, Health and Safety Executive, United Kingdom).*

beneath the no. 2 stream collectors. The cladding on the furnace room had not been blown out by an internal explosion but must have been pulled away from its fastenings by suction. This could have been caused by air movement generated by an explosion in the open air between the collectors. Similarly, cladding on the walkway was pulled away rather than blown out.

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Chapter 3

Generation of Explosible Dust Clouds by Reentrainment and Redispersion of Deposited Dust in Air

3.1
BACKGROUND

The dust concentration range, within which flames can propagate through a cloud of combustible dust in air, spans from the order of 50 g/m^3 to a few kg/m^3. The bulk density of powders and dusts, when settled in a layer or a heap, range from a few hundred kg/m^3 and upward. Therefore, there is a gap of a factor of at least 100 between the maximum explosible dust concentration and the bulk density in the settled state. Consequently, for an explosible dust cloud to be formed, the dust must be suspended in the air to the extent that the concentration of dust per unit volume of cloud drops into the explosible range.

In dust explosion research, the important role played by this resuspension process has often been overlooked or underestimated. It is realized that particle size plays a key role both with respect to the ignition sensitivity and the explosibility of dust clouds. However, it has not always been realized that fine, cohesive powders cannot be dispersed in a gas as individual primary particles unless particle agglomerates are exposed to very high shear or tensile stresses. This means that the effective particle size in a dust cloud can be much larger than the size of the primary particles.

It is interesting to note that Professor Weber, one of the pioneers of dust explosion research, stressed the importance of dust cohesion and dispersibility more than 100 years ago. In his excellent paper on the ignitability and explosibility of flour, Weber (1878) emphasized that the "cohesion of the flour, which is caused by inter-particle adhesion, plays an important role with respect to the ability of the flour to disperse into explosible dust clouds." Weber suggested that two large dust explosion disasters, one in Szczecin (Stettin) and one in Munich, were due mainly to the high dispersibility of the flours. He also demonstrated, using simple but convincing laboratory experiments, that the dispersibility or dustability of a given flour increased with decreasing moisture content in the flour.

In some special situations, such as in air jet mills, explosible dust clouds may be generated in situ; that is, the dust particles become suspended in the air as they are produced. However, in most cases, explosible dust clouds are generated by reentrainment and redispersion of powders and dusts produced at an earlier stage and allowed to accumulate as layers or heaps. Such accumulation may be either intentional, as collection of powders and dusts in silos, hoppers, and bag filters, or unintentional, as deposition of dust on beams, external surfaces of process equipment, or walls and floors of work and storage rooms.

Resuspension and redispersion of dust may either occur intentionally, such as by handling and transport in various process equipment (powder mixers, bucket elevators, pneumatic transport, etc.), or unintentionally, by bursting of sacks and bags that contain powder, leaks of dust from process equipment, or sudden blasts of air generated by an explosion that started elsewhere in the plant.

The characterization of the "state" of a dust cloud is far more complicated than characterizing the "state" of a premixed quiescent gas mixture. For a quiescent gas, the thermodynamic state is completely defined by the chemical composition, the pressure, and the temperature. For a dust cloud, however, the state of equilibrium is complete separation, with all the particles settled out at the bottom of the system.

In the context of dust explosions, the relevant state therefore always is dynamic. In various industrial environments as well as in experiments with dust clouds, gravity and other inertia forces act on the dust particles, giving rise to a complex dynamic picture. In the ideal static dust cloud, all the particles are located in fixed positions, either ordered or at random. The closest approximation to the ideal dust cloud that can be encountered in practice is probably a cloud in which the particles are settling in quiescent gas under the influence of gravity alone.

3.2
STRUCTURE OF THE PROBLEM

Formation of explosible dust clouds from powder deposits implies that particles originally in contact in the powder deposit must be separated and distributed in the air to give concentrations within the explosible range. There are two aspects to consider. The first is the spectrum of forces originally acting on and between the particles in the deposit, resisting the separation of the particles. The second aspect is the forces and energy required for the separation process under various conditions.

Eckhoff (1976) suggested that a global dispersibility parameter for a powder deposit may be defined by considering these two aspects. A given mass of powder at equilibrium with the ambient atmosphere contains a finite number of interparticle bonds, each of which requires a specific amount of work to be broken. The total minimum work W_{min} needed to break all these bonds in one unit mass of powder could, in principle, be calculated by integrating the work required for breaking all the individual interparticle bonds. The influence of gravity would depend on whether the particles have to be raised into suspension or whether dispersion is downward. One could then define a theoretical upper limit value of the dispersibility for that specific powder deposit by

$$D_{max} = \frac{1}{W_{min}} \tag{3.1}$$

When defined in this way, the "dispersibility" has the dimension mass per unit of energy or work and is therefore a measure of the quantity of powder that can be completely dispersed by spending one unit of energy from external sources in the process. However, no realistic dispersion process can be 100% efficient. This can be accounted for by incorporating an efficiency factor, K:

$$D_{\mathrm{real}} = \frac{K}{W_{\mathrm{min}}}, \quad 0 < K < 1 \tag{3.2}$$

The particle size distribution of the powder has a great influence on W_{min} at a given powder bulk density. It also is well known that powders consisting of small particles are compressible. The reason is that the various interparticle forces other than gravity are stronger than the gravity forces and therefore permit the formation of loosely packed particle arrangements that would have collapsed had gravity been the only force in operation. This means that the number of interparticle bonds per unit mass of cohesive powder can be increased by compacting the powder, that is, by increasing the bulk density of the powder deposit. Therefore, W_{min} also increases with the degree of compaction. Moisture influences W_{min} by influencing the strength of certain types of interparticle bonds.

The logical link between W_{min} and the nature and number density of the interparticle bonds in a powder has given rise to detailed studies of various types of interparticle bonds. Attempts have further been made at predicting aggregated powder/mechanical strength properties from microscopic interparticle structure and forces. This kind of work is concerned with the quantity D_{max} (equation (3.1)).

However, the efficiency factor $0 < K < 1$ in equation (3.2) allows D_{real} to have any value between 0 and D_{max}, depending on the way in which the work W_{min} is applied to the powder to be dispersed. This, in turn, depends on the geometrical arrangement of the powder and the form of the mechanical energy available for the dispersion process. If a comparatively coarse noncohesive powder is charged into a silo from a hopper at the silo top, for example, the potential energy of the powder, when transformed to kinetic energy in the gravity field, may be sufficient to generate a well-dispersed explosible dust cloud in the silo. The same applies if deposits of this powder falling from shelves and beams in a factory workroom. However, very energetic airflows may be required to raise deposits of such a powder on the factory floor into explosible suspensions.

When considering the other end of the scale, cohesive powders composed of very small particles, interparticle forces play a major role and interparticle bonds may not be broken unless the particle agglomerates are exposed to large shear forces. This means that complete dispersion into primary particles is possible only in high-velocity flow fields or if the particles are exposed to high-velocity impacts.

Consequently, the understanding of how explosible dust clouds can be generated requires knowledge both of the nature of the powder (W_{min}) and of the actual dispersion process (K). The dispersion process, in turn, depends very much on the actual industrial situation, which is different in bucket elevators, pneumatic transport systems, fluidized beds, various kinds of mills, driers, mixers, cyclones, filters, and silos. Therefore, intimate knowledge of the nature of the industrial environment is required.

It has not been possible to trace any comprehensive theory of the generation of dust clouds leading from the properties of the powder deposit via the nature of the energy available for dispersion to the structure of the dust cloud. However, in view of the wide variation in possible boundary conditions in industrial practice, one would not expect to find one single, unified theory covering all possible situations. On the contrary, each situation needs to be analyzed separately. Much work has been conducted on various limited elements inherent in the total problem complex. Some of this is reviewed in the following sections in sufficient detail for the genuine nature of the various problems to become visible. This is considered important in a text on dust explosions because, in the past, dust explosion research was often conducted without paying appropriate attention to the central role played by powder mechanics and particle technology. Section 9.2.2 in Chapter 9 reviews some further works on dust cloud generation processes.

3.3
ATTRACTION FORCES BETWEEN PARTICLES IN POWDER OR DUST DEPOSITS

Two categories of interparticle forces exist, one that operates even in dry powders and one due to the presence of a viscous liquid. Useful summaries have been given by Green and Lane (1964), Corn (1966), Rumpf (1974), Schubert (1979), and Enstad (1980).

3.3.1
VAN DER WAALS FORCES

The van der Waals force F_w between two spherical particles has been estimated theoretically by integrating London-van der Waals forces over all interacting pairs of molecules. The resulting expression is

$$F_w = \frac{A}{a^2} \frac{x_1 x_2}{(x_1 + x_2)} \tag{3.3}$$

where A is a constant, a the smallest distance between the sphere surfaces, and x_1 and x_2 the diameters of the two spheres.

Van der Waals forces between particles are of significance as long as $x < 100$ nm. If $x_1 \gg x_2$, the force is determined by the size of only the smallest particle, and equation (3.3) reduces to

$$F_w = \frac{A}{a^2} x_2 \tag{3.4}$$

Most particles in real life are not smooth spheres but of irregular shape and surface topography. Schubert (1979) showed that F_w between a plane surface and a point on an irregular particle of diameter x, having a small elevation of radius r that touches the plane surface, is

$$F_w = A \bullet \left(\frac{x}{(r + a_0)^2} + \frac{2r}{a_0^2} \right) \tag{3.5}$$

The distance, a_0, is the smallest distance that can exist between two bodies in touch, and it is estimated at 0.4 nm.

3.3.2
ELECTROSTATIC FORCES

When considering electrostatic forces, one distinguishes between electrically conducting and nonconducting particles. In the case of conducting particles, electrostatic interparticulate attraction between touching particles may occur even if the particles did not initially carry any net excess charge, provided their electron work functions are different. Electrons then are transferred from one particle to the other. Different electron work functions can occur in particle systems of apparently identical materials, due to differences in impurities, oxide layers, and the like. Provided the smallest distance a between the two surfaces is shorter than 100 nm, that is, the particles are in electric contact, the electrostatic contact attraction force between the two conducting particles is

$$F_{e,c} = \pi \epsilon_1 \epsilon_0 \bullet \frac{U^2}{a} \bullet \frac{x_1 x_2}{(x_1 + x_2)} \tag{3.6}$$

Here ϵ_0 is the permittivity of vacuum and ϵ_1 the dielectric constant of the gas surrounding the particles; U is the contact potential between the two particle surfaces.

For electrically nonconducting particles, such as plastics, the electrostatic contact force is negligible. In this case, electrostatic attraction between particles is caused by excess charges on the particle surfaces, acquired triboelectrically during the preceding production and handling. The attraction force between two nonconducting particles having total excess opposite charges on the surfaces of q_1 and q_2 equals

$$F_{e,n} = \frac{q_1 q_2}{4\pi \epsilon_1 \epsilon_0} \bullet \frac{1}{\left(\frac{x_1 + x_2}{2} + a \right)^2} \tag{3.7}$$

For $a \gg (x_1 + x_2)$, equation (3.7) reduces to Coulomb's equation for attraction between two opposite point charges. If a is much smaller than the diameter of the largest particle, $F_{e,n}$ essentially is independent of a.

Equations (3.3)–(3.7) are concerned with the attraction between two single particles under idealized conditions. It is clear, therefore, that these equations are of limited value for predicting interparticle attraction forces in real powders and dusts, where many particles interact and the particle shape and surface properties may be complex. In the case of electrostatic forces, realistic assessment of the particle charges q_1 and q_2 is also difficult, even for idealized particle geometries.

In industrial practice the relative humidity of the air has different values, and this influences the strength of the electrostatic attraction forces between particles in powders. This influence was investigated by Nguyen and Nieh (1989). They proposed a general mechanism of charge elimination in flowing powders in humid air by "hydrated ion clusters" $(H_2O)_nH^+$ and $(H_2O)_nOH^-$ and their polymers.

Ross (1988), working with clouds of lycopodium in air, was able to significantly reduce electrostatic agglomeration of particles, as well as electrostatic adhesion to the wall of an experimental flame tube, when the air was ionized by means of an alpha emitter mounted on the flame tube wall.

3.3.3
INTERPARTICLE FORCES DUE TO LIQUIDS

It is a common experience from practice in industry that dry dusts are usually easier to disperse than moist dusts (one exception can be heavily electrostatically charged dry plastic powders). Even small quantities of adsorbed moisture can, in some cases, increase the attraction forces between particles considerably. Adsorbed layers of up to 3 nm thickness can adhere firmly to the particle surface and make it more smooth. This can appreciably reduce the effective distance between two touching particles. Even for a spherical particle as small as 1 μm diameter, the volume of a 3 nm layer of liquid water constitutes only 2% of the particle volume. (The situation is different if the moisture is also absorbed by the interior of the particle rather than just on its surface.)

The next stage is reached when the moisture content in the powder has become so high that excess water starts to form liquid bridges between particles, as illustrated in Figure 3.1(a). If the moisture content increases further, a transition range is reached that is characterized by some of the space between particles being completely filled with water (Figure 3.1(b)). Figure 3.1(c) illustrates the capillary range where the capillary underpressure is the main source of the cohesion. If the water content is increased beyond this point, the system is transformed from a cohesive powder to a suspension of particles in a liquid (Figure 3.1(d)).

To assess the strength of liquid bridges between particles in a powder (Figure 3.1(a)), Schubert (1973) used the approximate relationship derived by Rumpf (1970) for the tensile strength σ_T of a bed of monosized spheres (see Section 3.4.1):

$$\sigma_T = \frac{1-\epsilon}{\epsilon} \bullet \frac{F(\epsilon)}{x^2} \qquad (3.8)$$

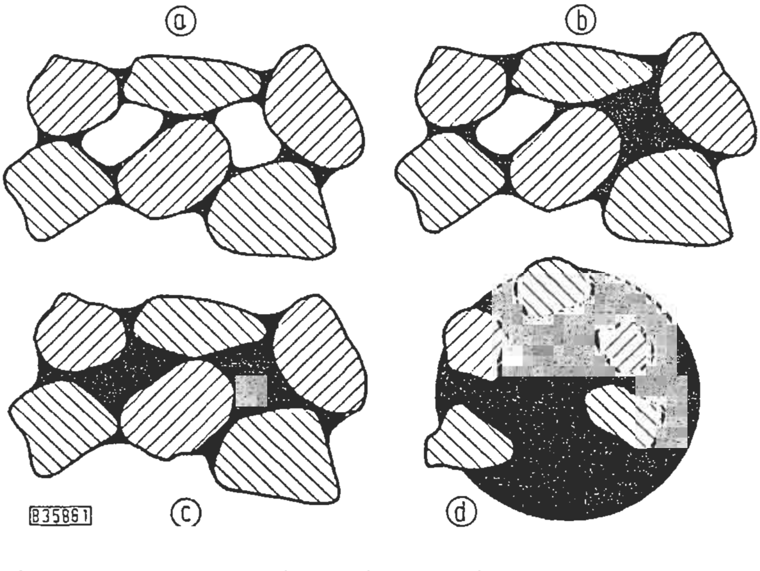

Figure 3.1 *Distribution of a liquid in a powder (From Schubert, 1973).*

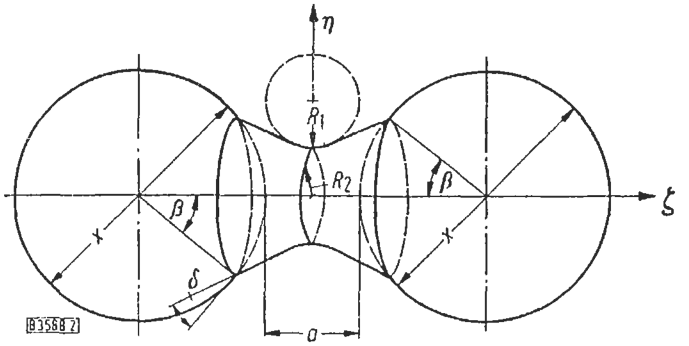

Figure 3.2 *Liquid bridge between two identical spherical particles (From Schubert, 1973).*

Here ϵ is the porosity of the bed, $F(\epsilon)$ the mean interparticle force (dependent on ϵ), and x is the particle diameter. Equation (3.8) is derived from equation (3.10) via the relationship $\epsilon \times k(\epsilon) \approx 3.1 \approx \pi$, found experimentally for spherical particles.

Schubert's equation for the tensile strength of a powder due to interparticle liquid bridges is as follows:

$$\sigma_T = \frac{\gamma}{x} \bullet \frac{1-\epsilon}{\epsilon} \bullet F_F\left(\epsilon,\ S,\ \delta,\ \frac{a}{x}\right) \tag{3.9}$$

Here γ is the surface tension of the liquid. $F_F(\epsilon, S, \delta, a/x)$ is the dimensionless liquid-bridge interparticle attraction force, where S is the fraction of the total pore volume between the particles that is filled with liquid, and a and δ are as shown in Figure 3.2. Equation (3.9) cannot be solved analytically, but Schubert (1973) arrived at a graphical solution.

The liquid bridge regime extends up to about $S = 0.25$ (Schubert's experiments with 70 μm limestone particles). This regime is the most relevant one with a view to transformation of dust deposits into explosible dust clouds. For a powder of specific density of 1 g/cm^3 packed to a porosity ϵ of 0.4, $S = 0.25$ represents a moisture content of 14% (neglecting moisture absorbed by the interior of the particles). The transition regime in which the liquid partly forms bridges between particles and partly fills the voids completely spans from $S = 0.25$ to $S = 0.8$. When the voids between the particles are just filled with liquid, the tensile strength of the bulk powder is determined solely by the internal underpressure caused by capillary forces. In practice, this is the case for $0.8 < S < 1.0$.

Figure 3.3 summarizes some of Schubert's (1973) experimental and theoretical results. He found that equation (3.9), using $a/x = 0.05$, yielded excellent agreement with the experiments in the liquid bridge regime, for which there is a strong increase of σ_T as S increases from 0 to 0.1.

For particles of density 1 g/cm^3 packed to a porosity of 0.4, $S = 0.1$ corresponds to a moisture content of 6.25%. It is therefore to be expected that the influence of the moisture content on the dispersibility of the powder is particularly strong in the range of a few percent of moisture. However, this does not apply if a significant fraction of the moisture is absorbed by the interior of the particles rather than adhering to the particle surfaces.

As S increases and moves into the capillary pressure region, the tensile strength of the powder bed increases further. As Figure 3.3 shows, the tensile strength of the powder

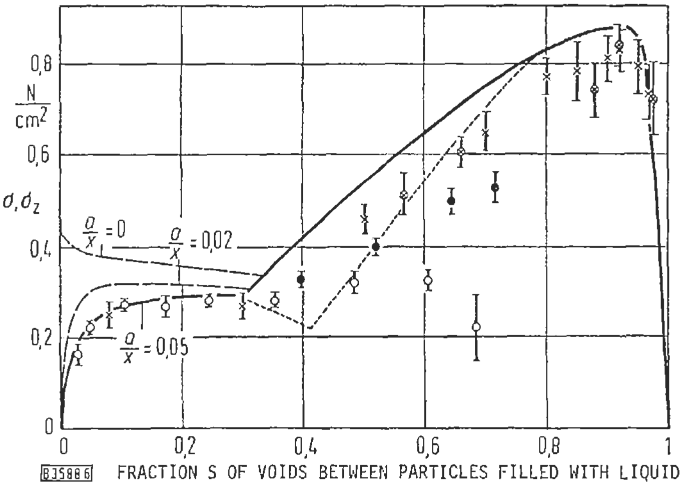

Figure 3.3 *Tensile strength σ_T of a powder bed as a function of the fractions of the voids between the particles that are filled with liquid. Experiments are with limestone of 70 μm particle diameter; $\epsilon = 0.415$; and ——, – – – and --- are theoretical calculations using different assumptions (From Schubert, 1973).*

bed in the region just before complete saturation is three times the maximum tensile strength in the liquid bridge region.

However, as pointed out by Enstad (1980), the tensile strength of the powder bed in the capillary underpressure regime can never exceed a pressure difference of 1 atmosphere. In the liquid bridge regime, there is no such limitation; and for small particle diameters $\ll 70$ μm, equation (3.9) can easily give tensile strengths corresponding to pressure differences of several atmospheres. In this range of particle sizes, the shape of the curve of $\sigma_T(S)$ differs from that in Figure 3.3 by having its maximum in the liquid bridge range of $S < 0.25$.

Adding liquids to dusts is sometimes used intentionally in industry for reducting dust dispersibility. One application of this method is addition of soy bean oil to grain to prevent the generation of grain dust clouds in grain storage plants. See Section 1.4.10 in Chapter 1.

3.4
RELATIONSHIP BETWEEN INTERPARTICLE ATTRACTION FORCES AND STRENGTH OF BULK POWDER

3.4.1
THEORIES

The question arises whether it would be possible to deduce some measure of the interparticle forces in powder deposits from measurement of bulk powder properties such as shear strength and tensile strength. As already mentioned, Rumpf (1970) developed the following equation for the relationship between the bulk strength σ of a powder bed of monosized particles and the mean interparticle force $F(\epsilon)$, the coordination number $k(\epsilon)$ (average number of neighboring particles with which a given particle is in contact), particle diameter x, and porosity of the powder bed ϵ:

$$\sigma = \frac{1-\epsilon}{\pi} k(\epsilon) \frac{F(\epsilon)}{x^2} \tag{3.10}$$

Equation (3.10) shows that, for geometrically similar powder beds, differing only in particle size x, and assuming that the mean attraction force per interparticle contact is independent of particle size, the strength of the bulk powder is inversally proportional to x^2; that is, the powder strength increases strongly as the particle size decreases.

Rumpf (1970) was able to show that equation (3.10) is valid not only for spherical particles, but also for irregular ones provided certain statistical conditions concerning the arrangement of the particles in the bed and the particle shape are fulfilled. By extending his treatment to beds containing a variety of particle sizes, he arrived at the equation

$$\sigma = \frac{1-\epsilon}{f_0 M_{30}} \int_{x=0}^{\infty} [k(x) F(x, n(x)) n(x)]\, dx \tag{3.11}$$

Here f_0 is a particle shape factor and M_{30} the "third moment" of the particle size distribution (distribution of particle volume).

For integration of equation (3.11), the coordination number $k(x)$ as a function of particle size and the interparticle force $F(x, n(x))$ as a function of particle size and particle size distribution must be known. The practical usefulness of equation (3.11) is therefore limited, but it establishes a formal logical link between the bulk strength of a powder and the mean microscopic interparticle attraction force.

Molerus (1978) also studied the link between interparticle forces and bulk powder strength. He used the following empirical relationship between the adhesive force F between a limestone particle and a plane metal surface and the external force N used initially for pressing the particle against the surface:

$$F = F_0 + \kappa N \tag{3.12}$$

F_0 is the attraction force for particles that are just touching the plate without having been pressed against it by an external force. On the basis of theoretical considerations of the interparticle forces in a cohesive bulk powder, Molerus developed a relationship of the same form as equation (3.12), where F_0 and κ were expressed in terms of the Hamaker constant, the plastic yield pressure of the particle material, a characteristic distance of adhesion (about 0.9 nm), and the size of the spot where the particles touch. An encouraging agreement with experiment was obtained for limestone. Molerus then developed a theoretical model for the connection between such interparticle forces and the cohesive properties of the bulk material by assuming that

1. Van der Waals forces and deformation of the contact areas where the particles touch each other are responsible for the interparticle adhesion.
2. The coordination number $k(\epsilon)$ is a unique function of the porosity of the particle bed.

3. Equation (3.10) is generally applicable for relating the macroscopic tensile and shear strength of the bulk powder to the corresponding microscopic interparticle forces.
4. Breakdown of interparticle adhesion occurs at a critical ratio between shear force and compressive force, defining the internal angle of friction of the powder bed.

The theory predicts yield loci (see Section 3.4.2.1) for a bulk powder, with the corresponding cohesion and tensile strength values as a function of the degree of compaction (or porosity ϵ). Encouraging agreement between experiments and theoretical prediction was found for a cohesive barite powder.

3.4.2
MEASUREMENT OF THE MECHANICAL STRENGTH OF COHESIVE BULK POWDERS AND DUSTS

3.4.2.1
Basic Concepts

If a sample of dry sand is subjected to a compressive force, the volume reduction, or reduction in the porosity ϵ, is very small. Furthermore, as soon as the compressive force is released, the sand flows freely again. Such behavior is characteristic of noncohesive powders, in which interparticle forces of the nature discussed in Section 3.3 play little or no role compared with gravity. If, however, a sample of finer dust or powder, such as an organic pigment, is subjected to compression, the powder sample shrinks and the porosity ϵ is reduced. Removal of the compressive force does not cause the powder sample to return to its original state of loose packing, rather it maintains a lower porosity and sticks together as a lump. The larger the compressive force is, the lower the resulting ϵ and the stronger the powder sample becomes.

The science of powder mechanics, which deals with these relationships in a systematic way, was established by the pioneering work of Jenike (1964). Jenike used Sokolovski's (1960) theory of the statics of soils as his starting point. Schwedes (1976) produced a concise summary of the basic concepts in Jenike's theory. The powder mechanical state of one specific cohesive powder sample of a given porosity ϵ is characterized by the so-called yield locus, as illustrated in Figure 3.4. The yield locus is an envelope curve for all the Mohr circles describing stress combinations causing yield

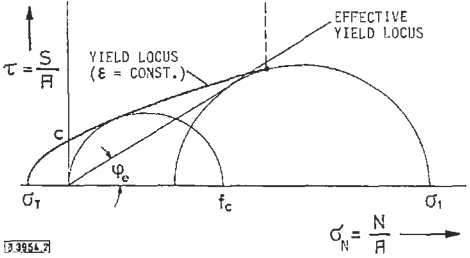

Figure 3.4 *Yield locus and effective yield locus of a given powder at a given porosity ϵ (From Schwedes, 1976).*

referred to a specific powder sample for which σ_1 is the maximum principal consolidation stress during preparation of the sample. The porosity (and bulk density) of the specific powder in question is a unique function of σ_1. S is the tensile force, N the normal force, and A is the area of the powder specimen in the shearing plane. The quantity f_c is the maximum principal stress at failure when the powder sample is in a situation where the minor principal stress is 0. Here, σ_T is the tensile strength of the powder sample and c is the cohesion, defined as the shear strength of the powder sample at zero normal load.

For a given type of cohesive powder, there exists a continuous range of yield loci, each locus characterized by a given porosity $\epsilon(\sigma_1)$. Further, f_c, the cohesion c, and the tensile strength σ_T increase systematically with decreasing ϵ or increasing σ_1. The straight line $\tau = \sigma_N \times \tan \varphi_e$ is called the *effective yield locus*. The angle φ_e is a measure of the internal friction in the powder during steady flow (plastic deformation).

For a noncohesive, free-flowing powder, the yield locus and the effective yield locus coincide and pass through the origin, and both σ_T and c are 0.

3.4.2.2
Shear Cells

Yield loci as illustrated in Figure 3.4 are determined by means of shear cells. A cross section of the well-known Jenike cell is shown in Figure 3.5.

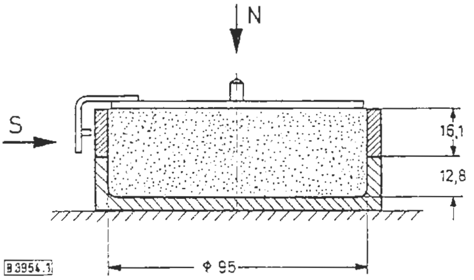

Figure 3.5 *Vertical cross section of the Jenike shear cell for measuring the mechanical strength of powders. All dimensions are in mm (From Schwedes, 1976).*

This cylindrical cell of 95 mm diameter is split, and the upper ring can be pushed horizontally in relation to the lower, fixed part. The test procedure for obtaining a point on a yield locus (Figure 3.4) consists of two steps. First, the powder is consolidated during plastic flow to a given porosity ϵ under the action of a major principal stress σ_1. In the second step, the sample is shear strained at a constant strain rate, while being compressed by a constant normal stress $\sigma_N = N/A$, where N is the normal force and A is the cross section of the cell (71 cm^2). The shear force S, which is recorded continuously during the process, increases with the strain to a maximum value, at which the powder sample fails and S drops suddenly. This maximum value of S defines the $\tau = S/A$ value that, together with the corresponding $\sigma_N = N/A$, gives a point on the yield locus. By shearing identical powder samples (the same $\epsilon(\sigma_1)$), at different σ_N, the entire yield locus is determined.

In the context of dust dispersibility, the mechanical "strength" of a given powder, consolidated to a given porosity ϵ by a major principal stress σ_1, can be characterized by $f_c(\epsilon)$, $c(\epsilon)$, or $\sigma_T(\epsilon)$ (Figure 3.4). The Jenike shear cell gives a measure of $f_c(\epsilon)$. The value of $c(\epsilon)$ can be estimated only by extrapolating Jenike cell failure loci to $\sigma_N = 0$, which may be uncertain, whereas $\sigma_T(\epsilon)$ cannot be determined by the Jenike shear cell. A detailed standardized procedure for conducting the Jenike shear cell tests has been worked out via international cooperation (EFCE Working Party on the Mechanics of Particulate Solids, 1989).

The validity of $f_c(\epsilon)$ from the Jenike shear cell in absolute terms has been questioned. Arthur, Dunstan, and Enstad (1985) developed a biaxial test apparatus that enables more-direct measurement of $f_c(\epsilon)$, right down to very low consolidation stresses, where $f_c \approx \sigma_1$.

3.4.2.3
Tensile Strength Testers

Figure 3.6 illustrates the traditional split-plate tilting-table tensile strength tester. Schubert and Wibowo (1970) also used a more sophisticated cell by which the capillary underpressure, during the tensile strain of powder saturated with liquid, could be measured.

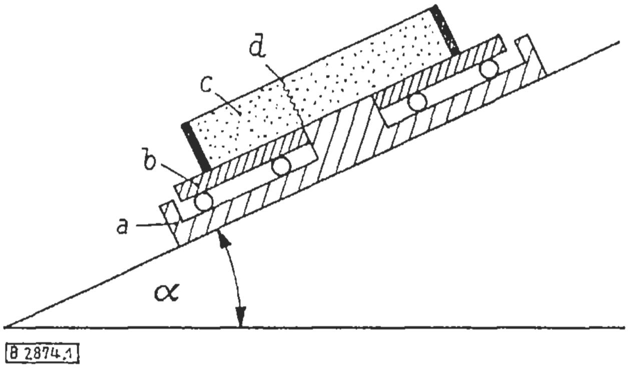

Figure 3.6 *Split-plate tilting-table tensile strength tester for powders: (a) base plate, (b) movable plate, (c) powder or dust sample, (d) rupture plate (From Schubert and Wibowo, 1970).*

By slowly increasing the tilting angle α shown in Figure 3.6, a point is reached where the powder sample ruptures. When the mass of the system that travels down the inclined plane after the rupture is known, the tensile force is also known, assuming that frictional losses can be neglected. This is a reasonable assumption when the cell is supported by steel balls as indicated in Figure 3.6.

The ratio of the estimated tensile force at the point of rupture and the cross-sectional area of the powder sample in the plane of rupture have traditionally been taken as a measure of the tensile strength of the powder. However, Schubert and Wibowo (1970) investigated the influence of the depth of the powder bed on the measured tensile strength. Although the maximum tensile force just before the rupture increased somewhat with the bed thickness, the ratio of the two decreased as the thickness increased. This is because it is impossible to apply the tensile force evenly over the entire rupture plane.

Instead, the tensile stress in the powder is concentrated in the region close to the bottom of the cell, where the movable and stagnant bottom plates separate. When rupture occurs, it propagates from the bottom, upward in the powder bed. Therefore, tensile strength values of powders determined from just one bed thickness are bound to be arbitrary numbers, although relative comparison of different powders may be possible. Schubert and Wibowo (1970) suggested that this problem can be overcome by determining the nominal tensile strength (tensile force just before the rupture divided by the rupture area) for various powder bed thicknesses, extrapolating to zero thickness. A typical set of results are given in Figure 3.7.

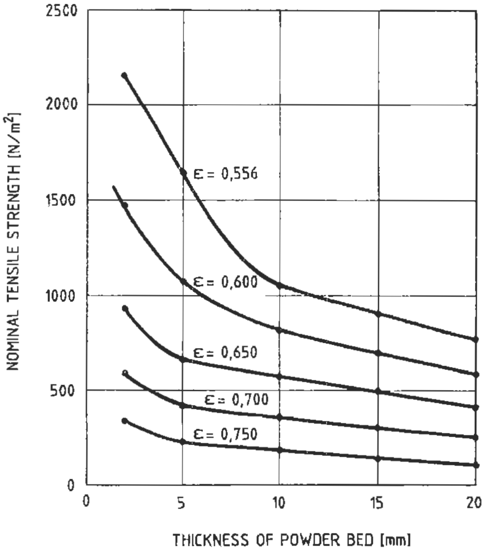

Figure 3.7 *Influence of powder bed thickness and powder porosity ϵ on nominal tensile strength of a fine limestone powder of mean particle diameter 3 μm (From Schubert and Wibowo, 1970).*

The question is now whether the tensile strength σ_T for a powder, determined by Schubert and Wibowo's extrapolation method, fits together with the yield loci from shear cell measurements, as would be expected from Figure 3.4. Eckhoff, Leversen, and Schubert (1978) investigated this using a fine SiC powder. The results from the tensile strength measurements are shown in Figure 3.8, and Figure 3.9 shows that the σ_T values from extrapolation for the various major principal stresses σ_1 (i.e., various porosities ϵ) could be joined to the yield loci by approximately straight lines, assuming isostatic conditions in the tensile tests. However, if uniaxial conditions are assumed, the deviations between the extrapolated yield loci and the experimental shear cell data in the low stress regime become pronounced.

The results indicate that the Jenike shear cell underestimates the shear strength at low normal stresses. When performing the necessary extrapolation of yield loci data for estimating f_c and c by the Jenike cell, results for $\sigma_N < 0.3\ \sigma_1$ should definitely be discarded. Even σ_N data in the range $0.3\ \sigma_1 < \sigma_N < 0.5\ \sigma_1$ should be treated with caution.

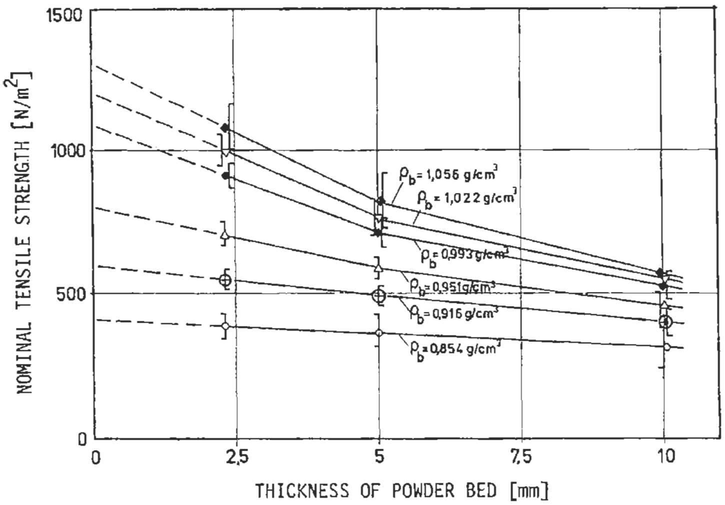

Figure 3.8 *Nominal tensile strength of a fine SiC powder as a function of the powder bed thickness and bulk density (or porosity ϵ) (From Eckhoff et al., 1978).*

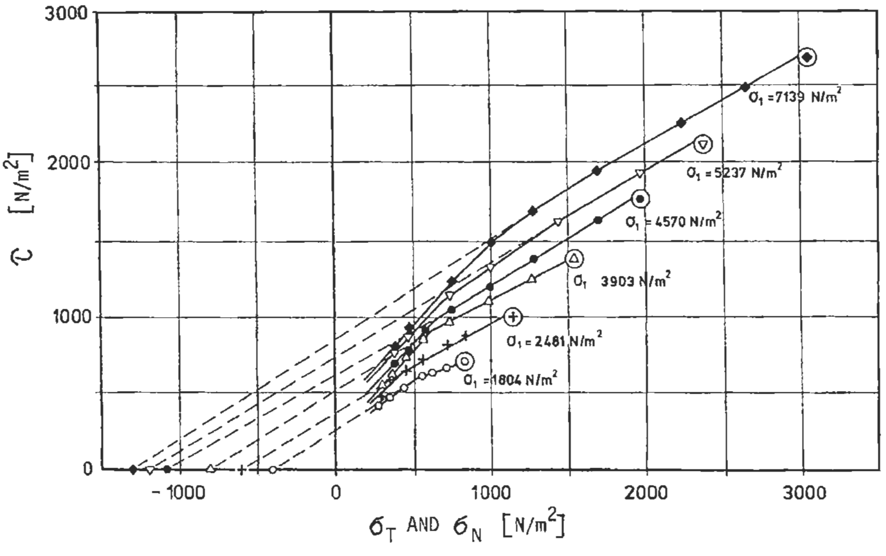

Figure 3.9 *Combination of shear test data assuming isostatic conditions in tensile tests (From Eckhoff et al., 1978).*

This emphasizes the need for improved methods for measuring basic properties of powders, as proposed by Arthur et al. (1985).

An interesting experimental study of the correlation between the tensile strength of a bulk powder and its dispersibility in a gas was performed by Yamamoto (1990).

3.5
DYNAMICS OF PARTICLES SUSPENDED IN A GAS

3.5.1
TERMINAL SETTLING VELOCITY OF A PARTICLE IN THE GRAVITATIONAL FIELD

Terminal settling velocities of particles in air have been determined experimentally in numerous investigations. An early example is the work of Zeleny and McKeehan (1910), who conducted careful measurements of the terminal velocities of spherical drops and particles of paraffin, black wax, and mercury in air at atmospheric pressure and room temperature. The measurements were in excellent agreement with Stokes' theory for the laminar flow regime.

Some pollens and spores were also included in this investigation, but for these particles, the experimental terminal settling velocities were generally somewhat lower than the theoretical Stokes' velocity. This also applied to lycopodium, the spore of club moss, which has been widely used all over the world in dust explosion research (Eckhoff, 1970). Lycopodium particles are close to monosized, with an arithmetic mean diameter of about 30 μm. The particle density is about 1.18 g/cm^3. According to Figure 3.10, this corresponds to a Stokes' terminal velocity of 0.035 m/s, whereas the experimental value was only 0.017 m/s. The difference by a factor of 2 was attributed to the formation of eddies in the wake of the spore and rotational settling, due to assymetric particle shape and a very rough surface texture (see Figures 3.11 and 3.12). If, on the other hand, a lower particle density based on the hydrodynamic envelope volume is used, agreement with Stokes' law might be found. Geldart (1986) gives a simple method for measurement of appropriate particle densities of porous particles.

Figure 3.10 gives the terminal settling velocity in air in the gravitational field for smooth spherical particles of various diameters and densities. The straight parts of the lines in Figure 3.10 essentially represent the Stokes' law regime for the terminal settling velocity, v_t, of smooth spherical solid particles in a quiescent gas:

$$v_t = \rho_p x^2 g / (18\,\mu) \tag{3.13}$$

As smooth, spherical particles get smaller than a few μm diameter, they attain somewhat higher terminal settling velocities than predicted by Stokes' law (Cunningham slip correction). For comparatively large particles, the viscous drag becomes greater than assumed in Stokes' law and the terminal settling velocities are lower than predicted. This is the reason for the curving of the lines in Figure 3.10 in the range of large particles.

The settling velocities indicated in Figure 3.10 apply even to particles in a dust cloud, provided the particle concentration is not too high and particle agglomeration can be neglected. For solids volume fractions below 0.001, the hindered settling effect causes less than 1% reduction of the settling velocities given in Figure 3.10 (Perry and Chilton, 1973). For a dust of particle density 1 g/cm^3, a volume fraction of 0.001 corresponds to a dust concentration of 1 kg/m^3, which would be in the upper part of the explosible range. Therefore, Figure 3.10 is also adequate for a rough evaluation of the gravitational settling velocities of particles in explosible dust clouds.

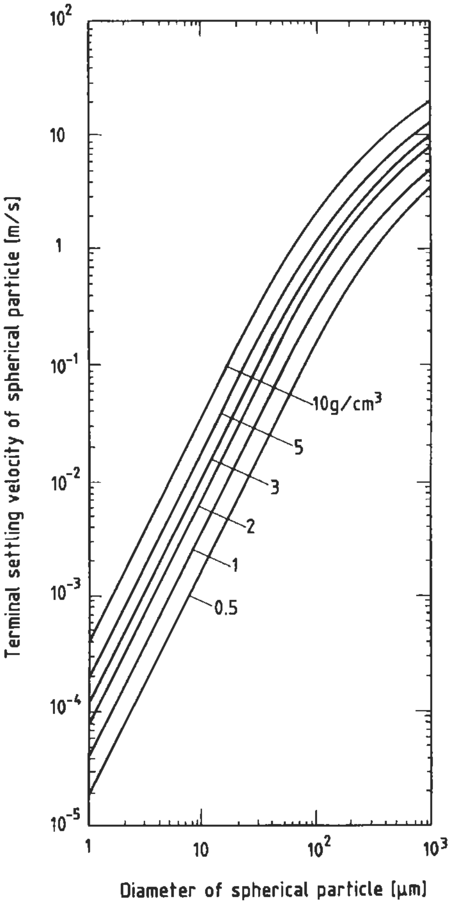

Figure 3.10 *Terminal settling velocities for spherical particles of various diameters and densities at atmospheric pressure and 20°C (From Perry and Chilton, 1973).*

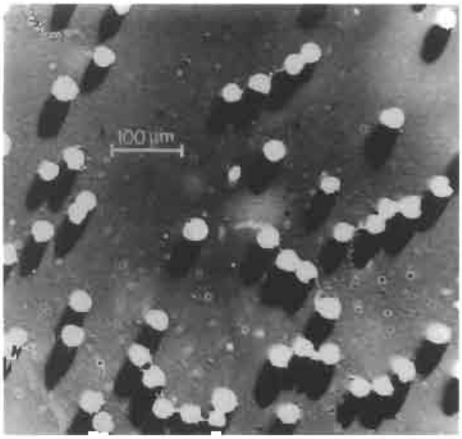

Figure 3.11 *Optical micrograph of a metal shadowed sample of lycopodium. The shadowing angle is 20°.*

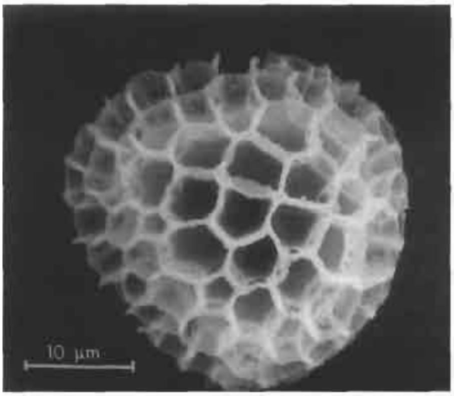

Figure 3.12 *Scanning electron micrograph single lycopodium particle showing the rough surface topography.*

3.5.2
DRAG ON A PARTICLE IN GENERAL

Figure 3.10 covers the terminal settling velocities of the particle sizes of primary interest in relation to dust explosion problems, and as shown, Stokes' laminar theory applies over most of the range. However, in many situations in industry and particularly during dust explosions, general inertia forces may dominate the gravity force, and other flow regimes may be of primary interest. The Reynolds number of the particle is an important indicator of the flow regime. The Reynolds number for a particle of diameter x traveling in a gas is defined as

$$Re = \frac{\rho_g v_{\mathrm{rel}} x}{\mu} \tag{3.14}$$

where ρ_g is the density of the gas, v_{rel} is the relative velocity between the particle and the gas, and μ is the viscosity of the gas. The drag coefficient C_D is another important parameter. It is the ratio between the drag force acting on the particle and the product of the cross-sectional area of the particle and the dynamic pressure acting on that area. For laminar flow conditions (Stokes' range),

$$C_D = \frac{24}{Re} \tag{3.15}$$

The change of the drag coefficient C_D as Reynolds number increases is shown in Figure 3.13 for three different particle shapes.

According to Haider and Levenspiel (1989) one can find more than 30 equations in the literature that relate the drag coefficient C_D to the Reynolds number for spherical particles falling at their terminal velocities. They also give more recent experimental data confirming that Figure 3.13 is adequate for isometric particles of sphericities Φ of 0.7–1.0, where Φ is defined as the ratio of the surface area of a sphere having the same volume as the particle to the actual surface area of the particle. For disks of lower Φ values, in the range 0.2–0.02, the C_D at a given Re are higher, by a factor on the order of 10, than that shown by the curve in Figure 3.13.

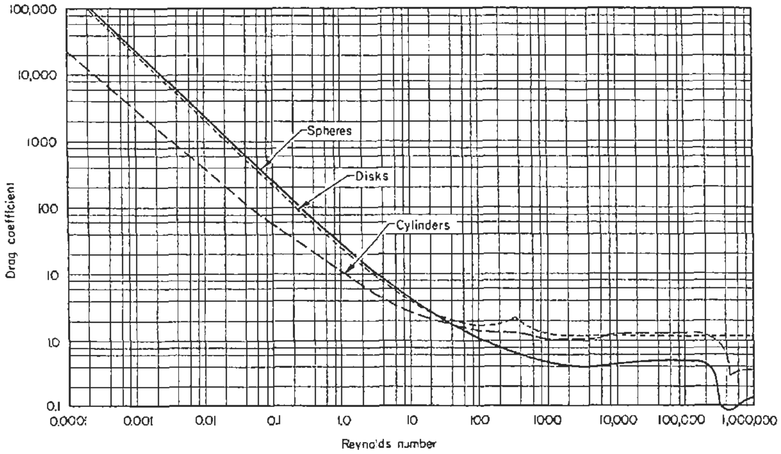

Figure 3.13 *Drag coefficient C_D for particles of various shapes, moving in a fluid at various Reynolds numbers (From Perry and Chilton, 1973).*

Haider and Levenspiel also presented a series of graphs, corresponding to Figure 3.10, for the terminal settling velocities of nonspherical particles of various sphericities Φ.

The general expression for the terminal gravitational settling velocity of a particle in a gas is

$$v_t = \left[\frac{V_p \rho_p 2g}{A \rho_g C_D} \right]^{1/2} \tag{3.16}$$

where V_p is the particle volume, A is the projected particle area in a plane perpendicular to the gas flow direction, and ρ_p is the particle density.

Rumpf's (1975) discussion of the various regimes of Re for smooth spherical particles is summarized in Table 3.1.

Table 3.1 Ranges of drag forces on smooth spherical particles moving in a quiescent, noncompressible viscous medium

$Re \leq 025$	Range of Stokes' drag (i.e., C_D equals $24/Re$).
$0.25 < Re < 10^3$	Significant deviation from perfect streamline flow around the particle and eddy formation in its wake starts at about $Re = 25$. The regime of eddy formation is fully developed at $Re = 10^3$. Navier-Stokes equations are applicable up to $Re = 100$.
$10^3 < Re < Re_c$ $(Re_c = 3 \cdot 10^5)$	The size of the eddy liberation zone in the wake of the particle remains approximately constant, and C_D is also approximately constant and equal to 0.4–0.5.
$Re = Re_c$	At this point, the laminar boundary layer around the upstream part of the particle breaks down, the boundary region becomes fully turbulent, and C_D suddenly drops to the order of 0.1.
$Re > Re_c$	In this supercritical range, C_D again starts to increase with the Re.

Source: Rumpf, 1975.

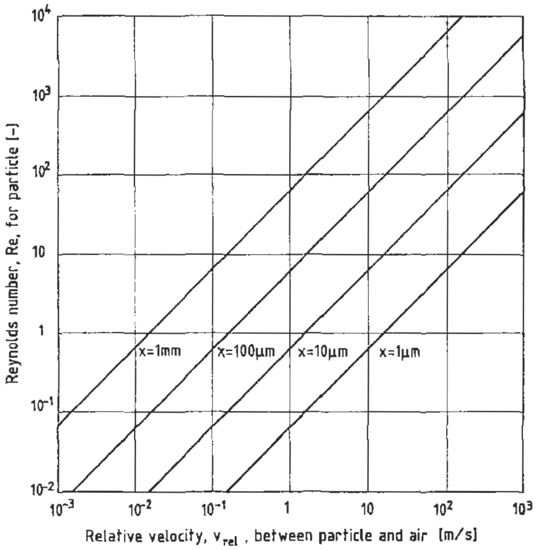

Figure 3.14 *The Reynolds number for a spherical particle of a diameter x moving relative to air of 20°C and atmospheric pressure, at velocity* v_{el}.

In the context of a dust particle in a gas, $Re = 10^5$ is an extremely high number. As an example, a 100 μm diameter particle in air at atmospheric pressure and room temperature has a relative velocity with respect to the gas of 17 km/s, which is far beyond even detonation front velocities.

Considerations based on assuming noncompressible conditions hold only at low Mach numbers (the Mach number is defined as the ratio between the relative velocity between the particle and the gas and the speed of sound in the gas). Figure 3.14 shows the variation of *Re* for the particle with the relative velocity for particles of various diameters, traveling in air at atmospheric pressure and 20°C. For transformations to higher gas temperatures, Sutherland's formula for the influence of temperature (absolute) on the viscosity of gases is useful (Forsythe, 1959):

$$\mu(T) = \mu_0\left(\frac{273+C}{T+C}\right)\left(\frac{T}{273}\right)^{3/2} \tag{3.17}$$

For air, μ_0 (the viscosity at 0°C) is 1.7×10^{-5} kg/sm, whereas the temperature constant C equals 118 K.

According to Rumpf (1975), the assumption of noncompressible conditions holds with reasonable accuracy up to Mach number 0.6, provided $Re > 100$. For smaller Re, the situation at such large Mach numbers becomes very complicated, because the gas can no longer be regarded as a continuum.

Figure 3.14 shows that, at $v_{rel} = 200$ m/s (i.e., a Mach number of 0.6), *Re* is 13 for a 1 μm particle, 130 for a 10 μm particle, and 1300 for a 100 μm particle. Therefore, the condition of Mach number < 0.6 and $Re > 100$ means that the particles must be larger than about 8 μm.

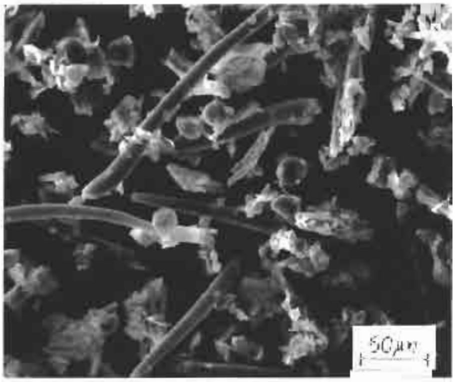

Figure 3.15 *Particles in sample of dust from Australian wheat grain. Elongated fibrous particles (hairs) are typical of wheat grain dusts.*

If the particle shape differs appreciably from sphericity, as illustrated in Figure 3.15, Stokes' law for the terminal velocity of a sphere cannot be applied unless some equivalent particle diameter is used, as indicated in Figure 3.13. This is often done by regarding an arbitrary particle as having a nominal "Stokes'" diameter equal to that of a sphere of the same density, which has the same terminal velocity as the arbitrary particle.

According to Herdan (1960), calculations have been made of the drag on ellipsoids and infinitely long cylinders, flat blades, and infinitely thin disks. The theoretical drag depends on the particle orientation with respect to the direction of motion. Therefore, the viscous drag for a disk moving edge on is equal to that on a sphere with a diameter $16/9\pi$ times that of the disk, compared with $24/9\pi$ times that when the disk is moving broadside. As a rough approximation, it has been suggested that the viscous drag on a particle of any shape, taking an averaged orientation, is equivalent to the drag on a sphere having the same surface area as the particle. Rumpf (1975) also discussed the influence of the particle shape on the drag acting on the particle.

The particle density may not be known in some cases, as discussed by Rudinger (1980). One may then define an "aerodynamic" or "kinetic" diameter as the diameter of a spherical particle of density 1 g/cm^3 that has the same terminal settling velocity as the particle.

3.5.3

MOVEMENT OF A PARTICLE IN AN ARBITRARY FLOW

In an arbitrary, nonsteady flow, the influence of gravity can be neglected whenever the drag force exerted on the particle by the motion of the gas is considerably greater than the weight of the particle. As an illustration, Rudinger (1980) discussed the case where a particle is introduced into a gas flow of velocity

$$v(t) = v_0 + bt \tag{3.18}$$

at time $t = 0$. The initial velocity of the particle is 0. The constant b can be either positive or negative. Then, the velocity $v_p(t)$ of the particle at time t equals

$$v_p(t) = v(t) - b\tau_v + v_0(b\tau_v / v_0 - 1)\exp(-t/\tau_v) \tag{3.19}$$

τ_v, called the *velocity relaxation time of the motion*, is a characteristic time constant for the particle to reach its terminal velocity.

Rudinger differentiated among three cases of equation (3.19). In the first case, the flow is stationary (i.e., b is 0), and $v_p(t)$ approaches v_0 asymptotically. If b has a finite, positive value, $v_p(t)$ approaches $v(t) - b\tau_v$ asymptotically. For a negative b, $v_p(t)$ catches up with and starts to exceed $v(t)$ at the time

$$\tilde{t} = \tau_v \ln(1 - v_0/b\tau_v) \tag{3.20}$$

after which it approaches $v(t) - b\tau_v$ asymptotically. The three different cases are illustrated in Figure 3.16.

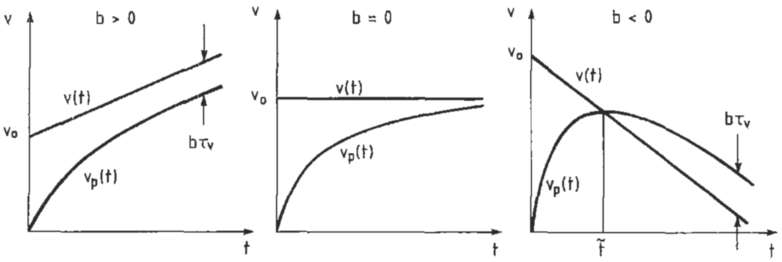

Figure 3.16 *Velocity $v_p(t)$ of a particle introduced in a gas flow of velocity $v_0 + b_t$ at $t = 0$ (From Rudinger, 1980).*

In a turbulent dust cloud, b varies with time and space. The flow changes continuously both in direction and magnitude, the particles move in all directions, and never attain the same velocity as the gas element in which it is at any instant. The fact that real particles not only are in translatory motion but also rotate adds to the complexity of the problem. The irregular movement of particles causes the local dust concentration to vary irregularly with time.

A number of experimental and theoretical studies have been published on various aspects of the interaction of dust particles and gas in turbulent flows. Some of these are discussed in Section 3.8.

3.5.4
SPEED OF SOUND IN A DUST CLOUD

The speed of sound plays an important role in all compressible flow phenomena, including dust explosions. Rudinger (1980) distinguished between two extreme cases. In the first case, the particles are considered in equilibrium with the gas at all times; that is, the particles follow the gas movement exactly and have the same temperature as the gas. Provided the volume fraction of the particles in the cloud is small, as it is in an explosible dust cloud, the equilibrium speed of sound, a_e, is given by the expression

$$\left(\frac{a_e}{a}\right)^2 = \frac{(1-\phi)(1-\phi+\delta\phi)}{(1-\phi+\gamma\delta\phi)} \tag{3.21}$$

where a is the sound speed in the particle free gas, ϕ is the mass fraction of particles in the dust cloud, δ is the ratio between the specific heat of the particle material and the specific heat at a constant pressure of the gas, and γ is the specific heat ratio c_p/c_v for the gas. Values for the specific heat of various solids as a function of temperature, partly based on interpolation, are given in Table 3.2.

Table 3.2 Specific heats of various solids (kJ/°C × kg)

	Temperature (°C)				
Material	**0**	**100**	**300**	**600**	**900**
Al	0.87	0.94	—	1.16	—
C (graphite)	0.45	0.80	—	—	1.90
Fe	0.44	0.48	0.58	—	—
Mg	0.97	1.08	1.17	1.30	—
Si	0.7	—	—	—	—
Wood	1.30	—	—	—	—
Polyethylene	2.3	—	—	—	—
Polymethyl methacrylate (PMMA)	1.5	—	—	—	—
Polypropylene	2.1	—	—	—	—
Epoxy resin	1.1–1.7	—	—	—	—
Phenolformaldehyde	1.5–1.7	—	—	—	—

Source: Hodgman, *Handbook of Chemistry and Physics*, 1963.

For air at atmospheric pressure and room temperature, the specific heat at constant pressure is 1.0 kJ/°C kg. Most of the values in Table 3.2 are within a factor of 2, upward and downward, of the air value. A variation spectrum of δ of 0.5–2 has only modest influence on a_e. For a dust cloud of $\varphi = 0.5$, which is in the rich or central part of the explosible dust concentration range, $\delta = 0.5$ gives $a_e = 0.66a$, whereas $\delta = 2.0$ gives $a_e = 0.63a$. For a cloud of $\varphi = 0.1$ (i.e., in the lean concentration range), $\delta = 0.5$ gives $a_e = 0.88a$, whereas $\delta = 2.0$ gives $a_e = 0.84a$. These examples also show that the "equilibrium" sound speed in explosible dust clouds may be lower than in the dust free gas, by a factor of down to 0.5–0.6.

The other extreme value of the sound speed in a dust cloud considered by Rudinger (1980) is the so-called frozen-flow speed of sound. In this case, it is assumed that the changes of the gas flow are so fast that the particles cannot respond and remain fixed in space. The "frozen" sound speed is somewhat higher than the sound speed, a, in dust-free gas. However, if the particle volume fraction is negligible, as in an explosible dust cloud, the frozen sound speed becomes practically identical to the sound speed in the particle-free gas.

In practice, the sound speed in a dust cloud has a value somewhere between the equilibrium and frozen values, depending on the frequency of the sound wave, which in the context of dust explosions is determined by the characteristic dimension of the enclosure in which the explosion takes place.

3.5.5
PROPAGATION OF LARGE-AMPLITUDE PRESSURE WAVES IN DUST CLOUDS

Rudinger (1980), also discussed the propagation of shock waves and large-amplitude waves of arbitrary form in dust clouds. Shock waves are of primary importance in the propagation of dust cloud detonations but are also generated in fast, high-turbulence dust cloud deflagrations. Because the volume fraction of the particles in an explosible dust cloud at atmospheric pressure is very small, it can be neglected in the theoretical treatment.

The speed of a shock wave is at least on the order of the speed of sound. This means that, even for a particle of only 0.1 μm diameter, the velocity and thermal relaxation times τ_v and τ_T are about 10^3 times longer than the period during which a shock passes the particle. Therefore, the dynamic and thermal conditions of particles are the same immediately after the shock front has passed as just before it passes, and particle movement can be omitted from the equations describing conservation of mass momentum and energy of the gas across the shock front itself.

However, immediately after a shock has passed, the dust cloud is in a state of non-equilibrium and the particles start to move in relation to the gas. The distance behind the shock required to reach velocity equilibrium between particles and gas is on the order of 0.5 m (0.3 m for 10 μm glass spheres in air at a particle mass fraction $\varphi = 0.17$ according to Rudinger, 1980). Temperature equilibrium is established at a similar distance behind the shock. However, these estimates are somewhat uncertain because they depend on a number of assumptions.

The theoretical analysis or arbitrary nonsteady, large-amplitude pressure waves through dust clouds is even more complicated than the shock wave analysis. As pointed out by Rudinger (1980), it is necessary to solve a complete set of partial differential equations, using the method of characteristics. An analysis of this kind was undertaken by Rudinger and Chang (1964).

3.6
DISLODGEMENT OF DUST PARTICLES FROM A DUST OR POWDER DEPOSIT BY INTERACTION WITH AN AIRFLOW

3.6.1
AIRFLOW PARALLEL TO A MONOLAYER OF PARTICLES ON A PLANE, SMOOTH SURFACE

A simple configuration for investigating particle dislodgement is a monolayer of particles adhering to a plane of smooth surface. This well-defined geometry enables systematic comparison between the drag force exerted on the particle by the gas and the adhesion force between the particle and the substrate. Corn and Stein (1965) carried out particle monolayer dislodgement studies in a small laboratory-scale wind tunnel of cross section only 1 mm × 25 mm. In such systems, the gas velocity profile is well defined and hence also the gas velocity past the particles, and the drag forces acting on them can be estimated fairly accurately. Figure 3.17 shows the velocity profile calculated by Corn and Stein (1965) for the airflow in their tiny 1 mm × 25 mm wind tunnel. The thickness of the laminar sublayer close to the substrate was calculated to be 40 μm, but in reality the transition between the laminar sublayer and the buffer layer is not sharp. Figure 3.18 shows some results from Corn and Stein's reentrainment experiments in one of their small high-velocity wind tunnels. Initially, 430 glass spheres were placed on the wall of the test chamber and exposed to airstreams with successively increasing mean velocities; the number and size distributions of the remaining particles after each run were determined by microscopy.

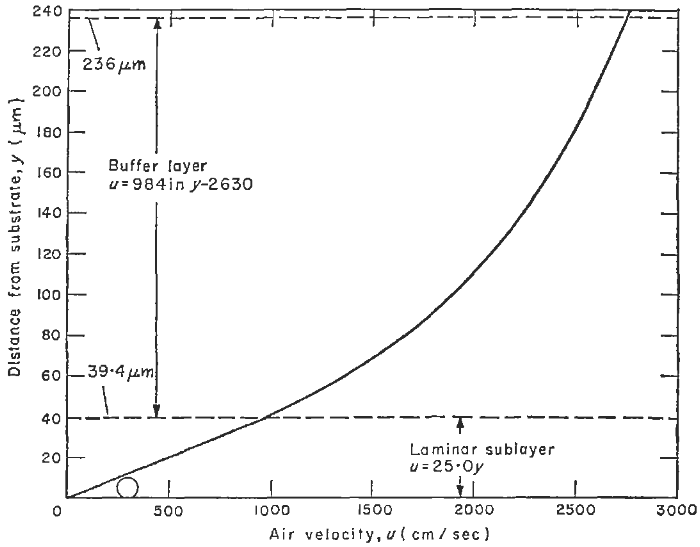

Figure 3.17 *Examples of calculated air velocity profile in the boundary layer near the wall in a shallow wind tunnel of 1 mm × 25 mm cross section (From Corn and Stein, 1965).*

As can be seen, the size distribution on a number basis was systematically shifted toward smaller particles with increasing air velocity, showing that in a given airstream and with particle diameters on the order of 1 to 10 μm, a small particle is more difficult to reentrain than a larger one. Comparison was also made between the force needed to separate a particle from a substrate by centrifugation and the calculated drag force required for separation in an airstream, and fair agreement, mostly within one order of magnitude, was found between theory and experiment.

Singer, Greninger and Grumer (1967) carried out experiments in a wind tunnel of somewhat larger cross section. Figure 3.19 shows the same effect as exhibited by Figure 3.18. As the average air velocity in the wind tunnel is increased, the particle size for which 75% entrainment is obtained, is shifted systematically toward smaller particles for all the three types of particles. Singer et al. (1967) compared their results with those of Corn and Stein (1965) and concluded that the two studies agreed within a factor of 5.

Figures 3.18 and 3.19 illustrate that, in the cohesive size range, small particles are more difficult to dislodge and entrain in an airflow than larger ones. This has important implications for the understanding of dispersion of cohesive powders and dusts in air in practical industrial situations.

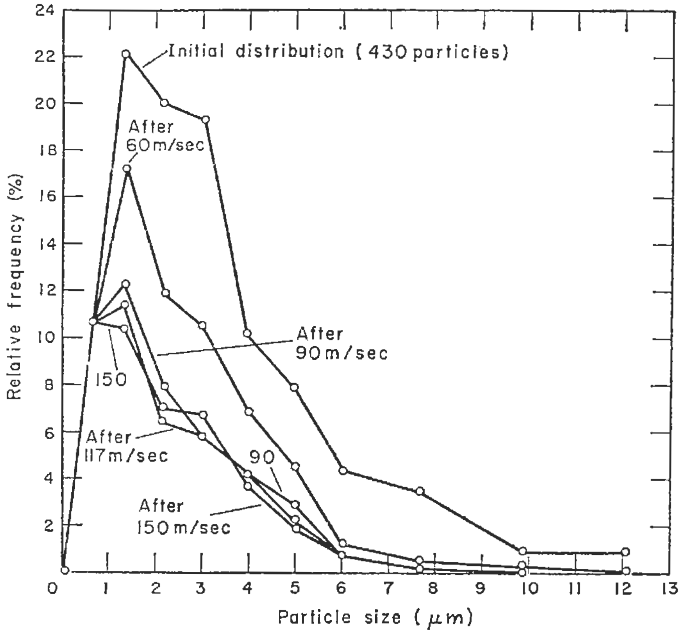

Figure 3.18 *Dislodgement of fly ash particles adhering to a glass substrate in high-velocity airflows in a 2 mm × 6.4 mm wind tunnel (From Corn and Stein, 1965).*

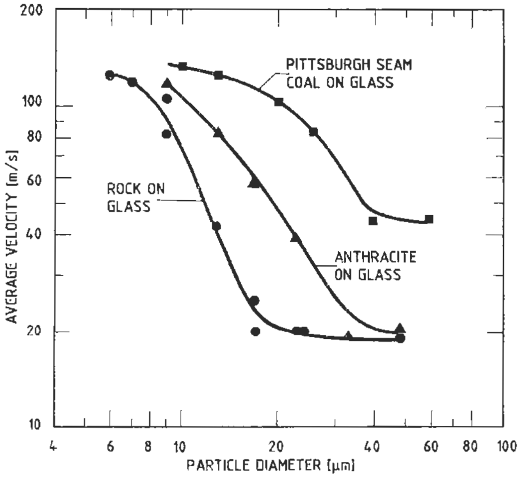

Figure 3.19 *Average air velocity for 75% dislodgement of different sizes of rock and coal particles from a smooth glass surface in a 51 mm × 76 mm wind tunnel (From Singer et al., 1967).*

3.6.2

AIRFLOW PARALLEL TO THE SURFACE OF A POWDER OR DUST DEPOSIT

Several investigations have also been carried out on the entrainment of particles from powder beds by a gas flowing past the bed. Under steady conditions of turbulent gas flow parallel with the surface of a powder bed of uniform roughness, the Prandtl-Karman relation for rough boundaries applies (Bagnold, 1960):

$$v = 5.75\left(\frac{\tau_0}{\rho}\right)^{1/2} \log_{10}\frac{30z}{x} \tag{3.22}$$

Here v is the mean gas velocity parallel with the powder surface, measured at a distance z from the surface, x is the characteristic surface roughness dimension (characteristic particle size), τ_0 is the shear stress at the interface between gas flow and powder surface, and ρ is the density of the gas. The term $(\tau_0/\rho)^{1/2} = v_*$, called the *drag velocity*, has the dimensions of a velocity. It characterizes a specific gas flow.

Bagnold (1960) suggested a two-stage mechanism for the reentrainment process. In the first stage, the horizontal gas flow fluidizes a relatively thin layer of the powder surface, whereby the interparticle bonds are broken. In the second stage, the detached particles are moved upward against gravity by eddies in the turbulent gas. This requires that at least some of the eddies have upward vertical gas velocities exceeding the gravitational settling velocity of the particle in the gas. Bagnold reported experiments showing that, in the case of deposits of particles of uniform size, the gas flow required to generate such conditions is much higher than that needed to produce the initial fluidization of the powder surface layer. His experimental values for v_* for initial fluidization of the surface of beds of monosized silica sand are shown in Figure 3.20. Bagnold suggested that the measured increase of v_* as the particle diameter becomes smaller in the range 80–40 μm is not primarily caused by interparticle adhesion but by the way in which the viscous gas interacts with the particle surface. (Interparticle forces, however, dominate when the particles become considerably smaller than 40 μm.)

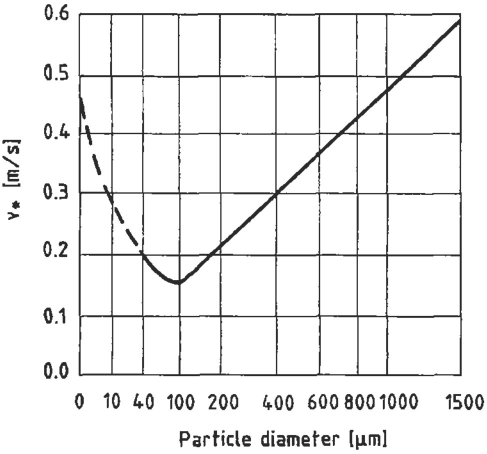

Figure 3.20 *Critical drag velocity v_* for initial fluidization of the surface of a bed of monosized silica sand as a function of particle size of the sand (From Bagnold, 1960).*

Even if the gas flow passing over the powder bed is turbulent, there is a thin laminar boundary layer of thickness on the order of $\mu/(\rho v_*)$, where μ is the viscosity of the gas and ρ is its density. If the particles are on the same order or smaller than the thickness of the laminar layer, they cannot be caught by the turbulent eddies and entrained in the gas flow. Furthermore, reducing the particle size also reduces the effect of the disturbance of one particle in the surface layer by the impact of others.

According to Gutterman and Ranz (1959), the thickness δ of the laminar boundary layer of gas in contact with a smooth powder surface is given by

$$\delta \frac{(\tau_0 \rho)^{1/2}}{\upsilon} \simeq 11.4 \tag{3.23}$$

where τ_0 is the shear stress at the interface between the flowing gas and the powder surface, υ is the kinematic viscosity of the gas, and ρ is the gas density. The total boundary layer is then the sum of the laminar sublayer and the buffer layer, as illustrated in Figure 3.17. The simple approximate expression (an alternative to the Prandtl-Karman equation (3.22)) for the gas velocity gradient in the laminar layer near the powder surface, adopted by Gutterman and Ranz (1959), is

$$v = \left(\frac{\tau_0}{\upsilon \rho}\right) z \tag{3.24}$$

For the experimental conditions employed by Gutterman and Ranz, δ was at least 250 μm. Therefore, in the case of a smooth dust surface, most particle sizes associated with dust explosions would be submerged in the boundary layer and subjected to velocities according to equation (3.24).

To estimate the aerodynamic force acting on a particle of diameter x in the powder layer surface, Gutterman and Ranz assumed spherical particles, no interparticle forces except gravity, the effective velocity of the laminar flow acting on the particle is given by equation (3.24) for $z = x/2$, the aerodynamic drag force on the particle is the same as if the particle had been suspended in an infinite gas volume, and the aerodynamic drag is resisted by the particles having to roll over neighboring particles against gravity.

Gutterman and Ranz then arrived at the following set of equations for the critical shear stress at the particle bed surface for initiation of particle movement

$$C_D Re^2 = 0.65 \bullet 10^{12} x^3 \rho_p \phi \tag{3.25}$$

$$\tau_0 = 5.9 \bullet 10^{-10} Re/x^2 \ [\mathrm{N/m^2}] \tag{3.26}$$

where C_D is the viscous drag coefficient as discussed in Section 3.5.2, Re is the Reynolds number, x is the particle diameter, ρ_p is the particle density, φ is the internal friction factor of the bulk powder ($0 < \varphi < 1$), and φ was measured in a shear box similar to the Jenike shear cell (Section 3.4.2). The powder was charged gently into the shear box by means of a funnel, after which the box was rapped sharply three times to obtain a standard degree of consolidation of the powder. The shear force required for causing powder samples prepared in this way to fail was measured as a function of the vertical force acting on the sample (similar to the determination of failure loci as discussed in Section 3.4.2). The plot of shear stress at failure versus vertical force usually gave an approximately straight line, and the tangent of the angle between this line and the vertical force axis was defined as the internal friction factor φ. When comparing this approach with the comprehensive approach described in Section 3.4.2, it seems that a measure of the degree of consolidation of the powder sample, either in terms of the porosity ϵ, the bulk density, or the major principal consolidation stress σ_1, was lacking in this early work of Gutterman and Ranz (1959).

To determine τ_0 from equation (3.26), $C_D \times Re^2$ was first calculated from equation (3.25), after that Re was found by trial and error from the universal $C_D(Re)$ graph (Figure 3.13).

Gutterman and Ranz also conducted wind tunnel experiments with different powder types, and found reasonable agreement between the critical experimental τ_0 for the onset of particle movement on the powder surface and the theoretical values from equations (3.25) and (3.26). Reasonable agreement was also found between the corresponding theoretical and experimental critical gas velocities for initial particle movement. Initial bulk movement (fluidization) of the powder surface was the result of a cascade process, starting with a particle upstream being lifted into the airflow. When this particle impinged on the bed surface, one or more new particles were ejected from the bed, and their return to the bed surface ejected further particles, and so on.

Bagnold (1960) largely limited his studies to silica sand in the noncohesive range of particle diameters >40 μm. He was fully aware of the strong influence of cohesion on the range of smaller particles but found that the knowledge of the nature of interparticle forces was insufficient to allow him to conduct any systematic studies. He nevertheless carried out an entrainment experiment with a smooth layer of fine, uncompressed cement in a wind tunnel. Even at a wind speed of 36 m/s, measured 10 cm above the powder layer, there was no continuing disruption of the powder surface. However, as also implied by Bagnold, deposits of fine, cohesive powders can be easily disrupted if the characteristic surface roughness is considerably larger than the particle size and the laminar boundary layer. This is particularly so if the surface topography of the bed is characterized by sharp edges rather than rounded contours.

Figure 3.21 illustrates how agglomerates of fine cohesive particles can be entrained by and carried along with the airflow as apparent single "particles." As long as the agglomerate is not exposed to shear or tensile stresses that exceed its cohesive strength, it will not be broken down further.

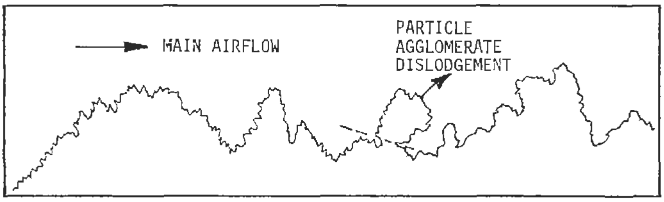

Figure 3.21 *Rough surface topography of a deposit of fine, cohesive particles.*

In the case of powders having very wide particle size distributions, the entrainment of the large particles can include mechanical disturbance of the fine ones and facilitate their deagglomeration (breaking of cohesive interparticle bonds) and entrainment. This process is called *saltation*.

Fairchild, Tillery, and Wheat (1985) studied the reentrainment of fine, cohesive aluminum particles of <10 μm diameter in a wind tunnel, without and with large saltation particles in the airflow sweeping over a fine-particle bed. The saltation particles were monosized spheres of 100, 240, and 500 μm diameter, and they were introduced into the airstream upstream of the bed of fine particles after stationary flow conditions had been established. Measurement of dust concentration as a function of distance above the bed surface was conducted between 10 and 150 mm. It was concluded that, within the experimental range, resuspension of particles from a bed of loosely packed aluminum particles increased monotonically with increasing gas velocity and size of saltation particles.

Singer et al. (1967) studied the entrainment of coal and rock dust in an airstream passing over a loosely packed dust ridge placed on the floor of a laboratory scale wind tunnel, as illustrated in Figure 3.22. The properties of the three dusts tested are given in Table 3.3

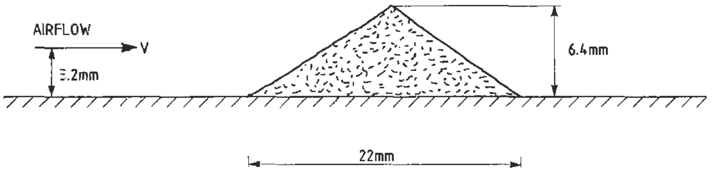

Figure 3.22 *Cross section of typical dust ridge used in wind tunnel dust entrainment experiments. The length of the ridge is 25 mm (From Singer et al., 1967).*

Table 3.3 Properties of dust used in dust ridge entrainment experiments

Dust type	Pittsburgh coal	Anthracite	Rock
Bulk density (g/cm^3)	0.56	0.47	1.20
Solid density (g/cm^3)	1.37	1.61	2.76
Porosity (ϵ)	0.59	0.71	0.57
Median particle size (μm)	34	10	27

Source: Singer et al., 1967.

Photographic studizes disclosed various mechanisms of dust dispersion. These included erosion from a dust surface and denudation from a dust surface under the influence of a pulsating airstream. In erosion, the dust is dispersed particle by particle from the deposit surface. In denudation, the entire dust layer leaves the surface suddenly without the particles being separated at the instant of lifting. Denudation was considerably faster than erosion for similar deposit geometries.

Even at air velocities only slightly higher than the minimum air velocity for particle entrainment, the ridge dispersion was relatively rapid, having a characteristic time constant of less than 0.1 s. Minimum air velocities for dust dispersion at half ridge height above the wind tunnel floor were calculated to be 10–20 m/s, using classical boundary layer theory. There was no clear difference between the minimum velocities for Pittsburgh coal and the finer anthracite. However, as Table 3.3 shows, the finer anthracite had a considerably higher porosity than the coal; and this probably compensated for finer particles being more difficult to entrain than larger ones at the same bed porosity. As would be expected, the bulk density of the dust ridge had a significant influence on the minimum air velocity for dispersion of the ridge. It was further suggested that the tensile strength, σ_T, of the powder deposit (Section 3.4.2) was a significant factor.

Based on resolution of velocity vectors, Singer et al. (1967) proposed a simple empirical model for estimation of lift and drag coefficients on particles in deposits exposed to airflow. The model neglected the pressure difference between both the windward and the leeward sides of the dust ridge and the surface roughness. It took the following form:

$$\begin{aligned} C_D &= k(Re)^m \cos\beta \\ C_L &= k(Re)^m \sin\beta \end{aligned} \tag{3.27}$$

where C_D and C_L are the drag and lift coefficients; Re is a special Reynolds number based on the upstream air velocity at midheight of the dust ridge, the ridge height, and the density and viscosity of air; β is the angle between the base and the windward side of the ridge; and m and k are empirical constants.

Singer et al. (1967) also found that large-amplitude airstream pulsations, of up to 33 Hz, superimposed on the main airflow by a rotating vane in a vent duct, broke dust ridges into lumps. The lumps were lifted almost vertically into the turbulent pulsating airstream, where they were eventually dispersed as individual particles into the turbulent core.

Iversen (1985) determined reentrainment rates of fine powders of Al, Cu, Mo, and W of average particle size 5 μm in a wind tunnel of width 0.50 m and height 0.71 m. The length of the powder layer was 1.8 m and its width 0.14 m. The bed was prepared by dispersing dust via air guns and allowing the dispersed dust to settle under gravity and form the bed.

The data for particle mass collected as a function of height above the surface, wind speed, and particle density were analyzed using the following solution of the equations for diffusion from a two-dimensional source oriented laterally to the mean wind direction:

$$C = C_0 \exp(-B(z/z_1)^{(n+1)/n}) \tag{3.28}$$

Here C is the dust concentration at height z above the powder bed surface, and n is a velocity profile exponent defined by

$$v = v_1(z/z_1)^{1/n} \tag{3.29}$$

and

$$B = v_1 z_1[n/(n+1)^2]\lambda y \tag{3.30}$$

where λ is a diffusion coefficient and y is the coordinate in the wind direction.

Equation (3.28) was used for calculating the average vertical flux, q_v, of particles from the bed surface (equal to horizontal flux divided by the area of the powder bed) for molybdenum particles. The following empirical equation was found to fit the experimental data for all four powders:

$$q_v = 2.3 \cdot 10^4 \rho_p v_* (v_*/v_{*,\min} - 1) \tag{3.31}$$

where ρ_p is the particle density, v_* is the actual "drag velocity" of the air (see the paragraph following equation (3.22)), and $v_{*,\min}$ is the minimum "drag velocity" for entrainment of particles (Figure 3.20). The $v_{*,\min}$ values for the four powders were 20, 23, 24, and 27 m/s, in order of increasing particle density.

Akiyama and Tanijiri (1989) used a wind tunnel of 3.6 m length and a rectangular cross section of 30 mm width and 150 mm height in their study of reentrainment of dust particles from a powder bed having its plane surface flush with the wind tunnel floor. The particles studied included glass beads, talc, alumina, and fly ash of volume-surface diameters ranging from 15 to 80 μm, solid densities in the range from 2.3 to 4.0 g/cm^3, and bulk porosities in the uncompressed state from 0.47 to 0.77.

The bed of particles to be tested in the wind tunnel was conditioned in a humidistat of relative humidity H for more than 6 hours before being exposed to the reentrainment experiment. The humidity of the air in the wind tunnel was not controlled, but it was assumed that the short test period of about 60 s did not significantly influence the humidity inside the bed. To obtain $H = 0$, the particle bed was kept at 177°C for more than 10 hours.

With a powder bed of 220 mm length and 30 mm width and an average air velocity of 15 m/s in the wind tunnel, the entrained particle mass per unit time was independent of relative humidity up to 65%. For higher humidities, there was a drop of the entrainment rate with increasing humidity, increasing with decreasing particle size. However, at the given conditions, some of the particle systems tested could not be entrained at all, even at low air humidity. It should be pointed out that the particles investigated were non-hygroscopic, in the sense that moisture did not penetrate into the bulk of the individual particles but accumulated only on the particle surface. For some natural organic materials, the influence of the relative humidity may therefore be more complex.

Akiyama and Tanijiri then investigated the relationships between the entrainment rate and the four powder mechanical properties: angle of repose, angle of spatula, compressibility, and cohesiveness or cohesion. All these parameters are somewhat arbitrary and not easy to relate to the more fundamental powder mechanical properties described in Section 3.4. They are determined in a set of somewhat arbitrary tests, specified in terms of apparatuses and procedures. An overall dimensionless flowability coefficient F was defined as a function of the four measured parameters, and the rates of reentrainment measured in the wind tunnel were correlated with F for the various powders. Reasonable monotonic correlations comprising all seven powders were obtained for the three overall wind tunnel velocities 8, 12, and 15 m/s investigated.

Ural (1989a, 1989b) postulated that the dispersibility of dusts can be characterized by two parameters: the minimum aerodynamic shear stress required for dust entrainment from a horizontal surface and the settling velocity distribution of a dust cloud. This is an interesting approach, which will be discussed in greater detail in Chapter 7, treating various test methods related to the dust explosion hazard.

It should finally be noted that Bagnold (1960) briefly mentioned the reentrainment of a powder layer by a sudden blast of gas rather than a steady flow. This clearly is an important case in the context of dust explosions. Even if the Mach number is considerably smaller than unity and the static pressure gradient in the direction of air movement is negligible, the dynamic pressure gradient (gas velocity gradient) can be considerable. Section 9.2.2.4 in Chapter 9 gives further references to works on generation of dust clouds by dispersion of dust layers and deposits.

3.6.3
ENTRAINMENT OF PARTICLES BY AN UPWARD AIRFLOW THROUGH A PARTICLE BED

Entrainment of particles of equal shape in a fluidized bed configuration, illustrated in Figure 3.23, was studied by Schofield, Sutton, and Waters (1979).

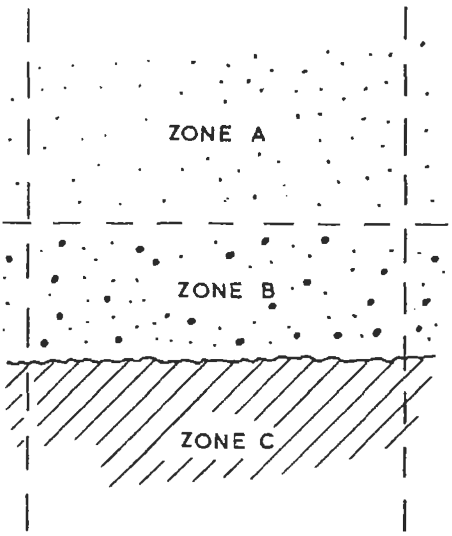

Figure 3.23 *The emission of dust from a fluidized bed (From Schofield et al., 1979).*

Let v_n be the minimum local air velocity inside zone C needed to lift a particle of aerodynamic cross section a_n from zone C into zone B, and v_m be the average vertical air velocity in zones B and A corresponding to v_n in zone C. Often, v_m is denoted the "superficial" gas velocity through a fluidized bed. Because the effective cross section for vertical airflow in zone C is smaller than in zones A and B, $v_m < v_n$. Therefore, the largest particles injected from zone C to zone B drop back into zone C. Only particles of aerodynamic cross sections smaller than a maximum value a_m are lifted further into zone A. At a given v_m, all the particles in zone C of smaller aerodynamic cross section than a_m eventually are extracted from zone C and pass through zone B into zone A. Therefore, the concentration of these particles in zone C can be regarded as only approximately constant during the initial phase of the fluidization process. This was accounted for in the investigation by Schofield et al. (1979), who used a fluidized bed of 46 cm^2 cross section in their experiments. All experimental data were acquired during the initial fluidization phase. Grade emission curves, illustrated in Figure 3.24, were determined for a chalk powder exposed to various values of v_m.

The grade emission curve expresses the mass per unit time at which particles smaller than a given size are emitted from the bed under a given set of experimental conditions. For example, with reference to Figure 3.24 and 0.205 m/s air velocity, particles smaller than 10 μm are emitted at a rate of 20 mg/min, whereas particles smaller than 2 μm are emitted at 4.5 mg/min. This means that particles between 10 and 2 μm are emitted at 15.5 mg/min.

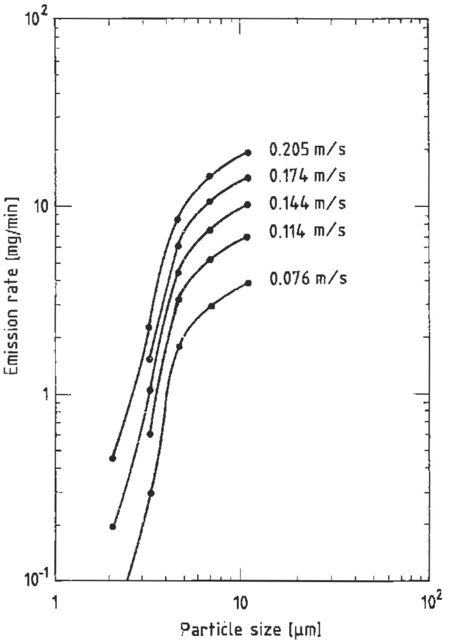

Figure 3.24 *Grade emission curves for a chalk powder at various fluidization velocities (From Schofield et al., 1979).*

The grade emission curve represents a useful empirical concept, which permits relative comparisons of the "dustability" of various powders and dusts. Schofield et al. (1979) give results illustrating the effect on the grade emission curve of dust moisture content and particle size distribution of the initial dust bed.

In the fluidized bed studies of cohesive powders by Geldart and Wong (1984), the expansion of the entire powder bed due to airflow through the bed was used as an indication of the strength of the interparticle forces, or the cohesive strength of the powder. The data were analyzed using the Richardson-Zaki equation:

$$v_{m,\epsilon} = v_{m,\epsilon=1}\,\epsilon^{n} \tag{3.32}$$

where $v_{m,\epsilon}$ is the superficial gas velocity through the bed, and $v_{m,\epsilon=1}$ is the minimum superficial velocity needed for dispersing the entire bed; ϵ is the porosity of the bed and a direct measure of the bed expansion; and n is an empirical constant. For laminar liquid/solid systems, n has been found to equal 4.65. For gas/solid systems, n is generally higher than 4.65 and therefore $n/4.65 > 1$. Geldart and Wong (1984) correlated the ratio $n/4.65$ with the ratio between the tapped and loose bulk density of a range of cohesive powders and found

$$\frac{n}{4.65} = 0.65\left(\frac{\rho_{\text{tapped}}}{\rho_{\text{loose}}}\right)^{4.16} \tag{3.33}$$

Both the loose and the tapped densities are sensitive to the methods of sample preparation, and Geldart and Wong (1984) specify detailed experimental procedures for determining the two densities.

Geldart and Wong (1984) also found a correlation similar to equation (3.33) using the superficial gas velocity v_m:

$$\frac{n}{4.65} = 1.65\left(\frac{v_{m,\epsilon=1}}{v_{m,\epsilon}}\right)^{0.132} \tag{3.34}$$

Expansion of beds of cohesive powders is caused by proliferation and enlargement of horizontal and inclined cracks. Powders become more cohesive as the particle size is reduced. For any given superficial air velocity, Geldart and Wong (1984) found that the bed expansion ratio (or ratio of ϵ after and before expansion) increased with decreasing mean particle size down to about 12 μm. However, a further decrease of the particle size caused the bed expansion ratio to drop markedly. This was attributed to the generation of vertical cracks and channels in very cohesive powders. (See also Section 9.2.2.4.)

3.7

DISPERSION OF AGGLOMERATES OF COHESIVE PARTICLES SUSPENDED IN A GAS BY FLOW THROUGH A NARROW NOZZLE

The effective "particles" in clouds of very fine, cohesive dusts often are large agglomerates of primary particles rather than the small primary particles themselves. Depending on the actual degree of dispersion, or deagglomeration, the effective particle size distribution in the dust cloud can differ considerably for the same cohesive powder. This results in corresponding differences in both ignition sensitivity and explosibility of the dust cloud, because an agglomerate behaves as a single particle of the agglomerate size.

Bryant (1973) studied the degree of agglomeration of fine boron carbide particles of diameters 1 μm or less, dispersed as a cloud in a gas. He generated the cloud by blowing dust through a narrow nozzle and measured the mean effective "particle" size (agglomerates) as a function of the injection pressure (injection velocity). At a pressure of 3.5 bar(g), the mean diameter of the particles in the cloud was 6.2 μm; whereas at 7 bar(g), it had been reduced to 3.5 μm.

This important phenomenon was investigated in greater detail by Yamamoto and Suganuma (1984), and their findings are significant to both the actual industrial dust explosion hazard and the design of experimental methods to assess ignitability and explosibility of clouds of cohesive dusts. Figure 3.25 shows the dispersing nozzle used in the investigation by Yamamoto and Suganuma (1984).

The dust was first dispersed in the upstream airflow by simply feeding it into the 26 mm diameter air supply pipe from a vibration feeder via a funnel. For cohesive powders, this gave comparatively poor dispersion and large effective particle size. The primary dust cloud was then forced through the narrow nozzle, where the agglomerates were dispersed to varying extents, depending on the flow conditions in the nozzle. A sample of the secondary, dispersed dust cloud was sucked through a five- or six-stage cascade impactor, from which the effective, aerodynamic in-situ size distribution in the secondary dust cloud was obtained. (Cascade impactors, sedimentation balances, and other methods for determining particle size distributions are described by Herdan, 1960; Green and Lane, 1964; Allen, 1981; Kaye, 1981; and Bunville, 1984.) Figure 3.26 gives a set of typical results.

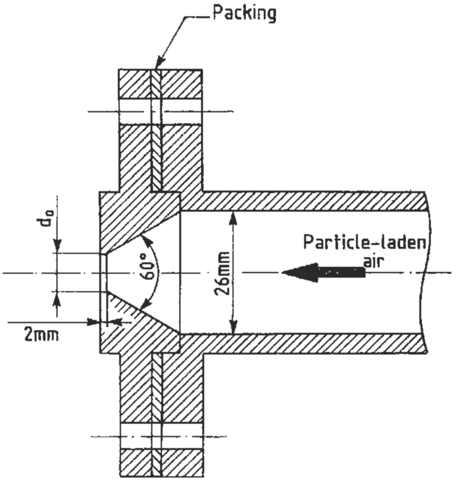

Figure 3.25 *The nozzle for dispersing agglomerates of cohesive dust particles (Yamamoto and Suganuma, 1984).*

The distribution of effective particle sizes is shifted systematically toward smaller particles as the dispersion process in the nozzle gets more effective, that is, as the average air velocity through the nozzle increases.

The effect is quite dramatic. For an air velocity in the nozzle of 10.5 m/s, the median effective particle size is somewhat larger than 10 μm; whereas for velocities in the range 100–150 m/s, it is only 1 μm. For the primary dust cloud, which was generated in a way that would be typical in industry, the median particle size would probably be considerably larger than 10 μm. It can be observed from Figure 3.26 that, at the highest air velocities in the nozzle, the distribution of the sizes of "effective" particles in the secondary dust cloud approached the size distribution found in a sedimentation balance after having dispersed the powder in a liquid in a way that would be expected to produce close to perfect dispersion.

Yamamoto and Suganuma arrived at the following empirical relationship for the efficiency of the nozzle dispersion process:

$$\frac{x_a}{x_s} = 31.3 \bullet h^{-0.2} \tag{3.35}$$

where x_a is the effective in-situ median particle diameter determined by the cascade impactor for the actual secondary dust cloud, and x_s is the ultimate median particle size determined by the sedimentation balance. The parameter h is defined by

$$h = 0.4 \bullet \Delta p_o \bar{v} / d_o \quad [\mathrm{J/m^3\,s}] \tag{3.36}$$

where Δp_o is the pressure drop across the dispersing nozzle, $\bar{v}$ is the mean air velocity through the nozzle, and d_o is the orifice diameter.

It is interesting to compare the results in Figure 3.26 with those of Corn and Stein (1965), in Figure 3.18, from particle dislodgement experiments in a narrow wind tunnel of cross section comparable with those of the smallest nozzles in Figure 3.26. The order of air velocities required to dislodge particles in the size range 1–10 μm in Corn and Stein's experiments is the same as required to break up agglomerates of 1–10 μm in the Yamamoto and Suganuma's nozzle dispersion experiments. This indicates that the adhesive forces between particles in an agglomerate, a particle, and a plane substrate are of the same nature

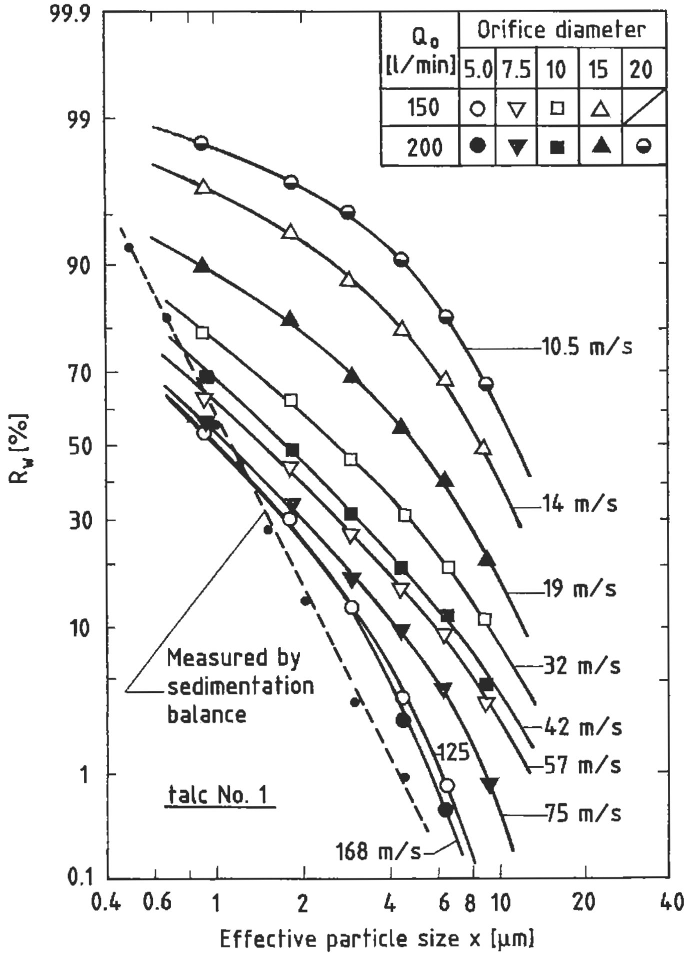

Figure 3.26 *Effective particle size distributions of airborne talc dust after dispersal by different orifices and air velocities, where R_w is the percentage of the effective "particles" larger than size x (From Yanamoto and Suganuma, 1984).*

(probably mostly van der Waal forces) and that viscous drag forces are dominant dislodging forces in both cases.

3.8
DIFFUSION OF DUST PARTICLES IN A TURBULENT GAS FLOW

Gutterman and Ranz (1959) determined the dust concentration gradient in turbulent airflow, following the injection of a given quantity of dust in a closed-loop laboratory-scale wind tunnel system. The average solid volume concentration of dust was about 200 cm^3 per 1 m^3 of air, that is, in the explosible concentration range for most combustible dusts. Typical experimental dust concentration profiles are shown in Figure 3.27.

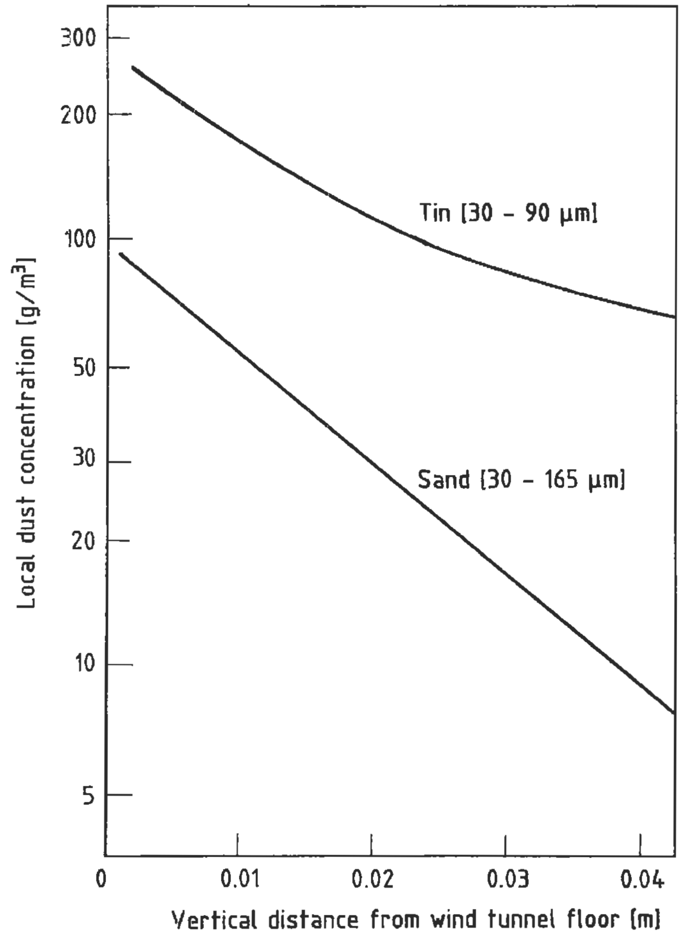

Figure 3.27 *Dust concentration gradients in horizontal turbulent airflow in a wind tunnel (From Gutterman and Ranz, 1959).*

According to Gutterman and Ranz (1959), the general differential equation for the distribution of dust concentration in a dust cloud moving in a two-dimensional flow can be written as

$$\frac{\partial c}{\partial t} + v_y \frac{\partial c}{\partial y} + v_z \frac{\partial c}{\partial z} + v_{\text{term}} \frac{\partial c}{\partial z} = D_{\text{eff}} \left(\frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \tag{3.37}$$

Here, c is dust concentration, t is time, v_y is the average gas velocity in the horizontal flow direction y, v_z is the average gas velocity in the vertical direction z, v_{term} is the terminal particle settling velocity in the gravitational field, and D_{eff} is the effective diffusion coefficient for the particles. D_{eff} is a function of both y and z. The system studied by Gutterman and Ranz was stationary in both time and y direction, and the average vertical gas velocity v_z was 0. Therefore,

$$v_{\text{term}}\, c = D_{\text{eff}} \frac{\partial c}{\partial z} \tag{3.38}$$

Here, c is a function of z only, $\partial c/\partial z$ could be determined from experimental $c(z)$ correlations (Figure 3.27), v_{term} can be calculated, and therefore an "experimental" diffusion coefficient, D_{exp} could be found. This was compared with the theoretical turbulent diffusion coefficient D_{turb} (related to the turbulent eddy viscosity) for the gas and for particles so small that they follow the turbulent gas motion. Some results are shown in the middle column of Table 3.4.

Table 3.4 Average ratios between experimentally determined diffusion coefficients for various particle types and theoretical turbulent diffusion coefficients for the gas

Particles	$D_{\text{exp}}/D_{\text{turb}}$	$D_{\text{exp}}/D_{\text{bounce}}$
Glass 3–40 μm 2.50 g/cm^3	1.1	—
Sand 30–165 μm 2.65 g/cm^3	5.6	1.8
Tin 30–90 μm 7.3 g/cm^3	4.3	—

Source: Gutterman and Ranz, 1959.

Because of the small size of the glass beads, D_{exp} was very close to D_{turb}; that is, the glass beads followed the gas motion fairly well, whereas the coarser sand particles and the high-density tin particles had considerably higher diffusion coefficients than the gas.

According to Gutterman and Ranz, the turbulent gas diffusion behavior of particles can be expected if the Weiss-Longwell criterion for diffusion of solid particles in an oscillatory gas velocity field

$$\frac{D_{\text{eff}}}{D_{\text{turb}}} = \frac{(18\,\mu/\rho_g x^2)^2}{\omega^2 + (18\,\mu/\rho_g x^2)^2} \tag{3.39}$$

is close to unity. This is the case for small particle diameters x, for which $\omega^2 \ll 18\,\mu/\rho_g x^2$, ω being the average rotational frequency (radians per second) of the gas eddies.

Gutterman and Ranz also compared their experimental diffusion coefficients based on measured dust concentration gradients with coefficients derived theoretically by assuming the governing diffusion mechanism was back-mixing of particles into the gas flow by irregular statistical bouncing when the particles hit the bottom and roof of the wind tunnel. The third column of Table 3.4 gives the result for angular sand particles. This shows that, for coarse particles in a narrow boundary zone of a few cm from the wall of the wind tunnel, the theory of back-mixing by bouncing against the wall finds better agreement with experiments than the theory of turbulent gas diffusion.

Hwang, Singer and Hartz (1974) performed theoretical studies of the dispersion of dust in a turbulent gas flow in a duct, following the initial entrainment of the dust deposits from the duct wall. In particular, they studied the entrainment of deposited dust by the nonstationary turbulent air blast ahead of a self-sustained dust explosion sweeping through a long duct. The objective was to predict the dust concentration in the gas flow as a function of time and location in the duct.

The dust flux leaving the duct walls was treated as originating from single or multiple stationary or moving sources. Formulas and sample computations for various types of dust sources in circular and rectangular channels were derived based on experimental dust entrainment rates. The theoretical results appeared to agree with the physical characteristics of explosion-driven dust dispersion in a 0.6 m diameter and 50 m long explosion tunnel.

In the theoretical analysis, the process of turbulent mixing was treated as a diffusion process, using diffusion-type equations that had been successfully applied to the dispersion of dusts in pipes, open channels, and semi-infinite systems. The generalized form of the diffusion equation used was

$$\frac{\partial c}{\partial t} + \bar{v} \bullet \text{grad } c = \text{div } (k \text{ grad } c) \tag{3.40}$$

where c is the dust concentration, k is the diffusion coefficient (assumed to be 25–100 cm^2/s), and $\bar{v}$ is the velocity with which the dust particles were convected, in addition to being diffused, $\bar{v}$ differs from the gas velocity because of the inertia of the dust particles in the flow. It was assumed that the effect of gravity could be neglected during the initial period of the dispersion process and that equation (3.40), employing an appropriate value of k, determined the gross behavior of the dust cloud.

Figure 3.28 shows an example of the computational results obtained. Dust concentrations that would be in the middle of the explosible range for combustible dusts have developed at 2.5 m downstream of the dust source. However, at 3.5 m downstream, the concentrations are below the typical minimum explosible limit range.

Hinze (1975) discussed the Tchen theory of diffusion of discrete solid particles in a fluid of homogeneous turbulence. This theory makes the following assumptions:

1. The turbulence of the fluid is homogeneous and steady.
2. The domain of turbulence is infinite in extent.
3. The particle is spherical and so small that its motion relative to the ambient fluid follows Stokes' law of resistance.
4. The particle is small compared with the smallest structure present in the turbulence.
5. The particle is embedded in the same fluid element during the motion.
6. Any external force acting on the particle originates from a potential field, such as the field of gravity.

All assumptions, except number 5, may in reality actually be satisfied. However, the mechanism of a real turbulence is such that it is hardly possible for assumption 5 to be satisfied. If the element of fluid containing a small discrete particle could be considered nondeformable, it might satisfy this assumption, provided its size was larger than the amplitude of the motion of the discrete particle relative to the fluid (no overshooting). However, in turbulent motion, the fluid elements are distorted and stretched into long, thin ribbons and it seems; unreasonable that the fluid element should continue to contain the same discrete particles during this stretching process.

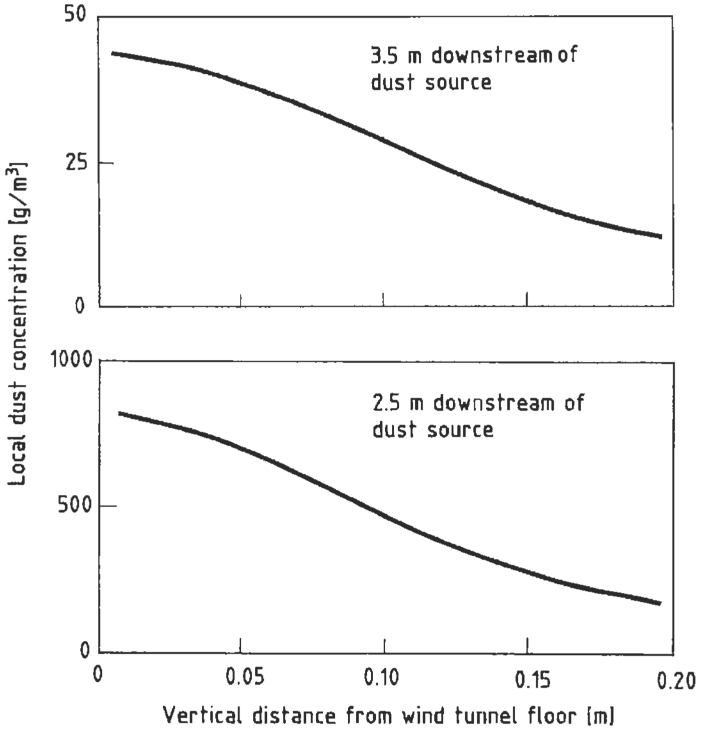

Figure 3.28 *Computed two-dimensional dust concentration distributions at two locations in a wind tunnel of square cross section 0.53 m × 0.53 m at 1.0 s after onset of dust dispersion. Dust source is 140 g of rock dust distributed as a 0.2 m long, even layer over the entire channel width. The average wind velocity is 5 m/s and the dust diffusion coefficient $k = 50$ cm²/s (From Hwang et al., 1974).*

As part of an account on the use of laser-doppler anemometry to characterize turbulence, Durst, Melling, and Whitelaw (1981) also discussed various theories for the movement of small particles in a turbulent flow.

During the 1980s, a number of further experimental and theoretical studies on the interaction of dust particles and a gas in turbulent flows were published. Some central papers are those by Alquier, Gruat, and Valentian (1979); Tomita et al. (1980); Genchev and Karpuzov (1980); Tadmor and Zur (1981); Ebert (1983); Elghobashi and Rizk (1983); Chen and Wood (1983); Beer, Chomiak, and Smoot (1984); Lee (1984); Krol and Ebert (1985); Picart, Berlemont, and Gouesbet (1986); Bachalo, Rudoff, and Houser (1987); Johansen (1987); Shrayber (1988); and Lee (1989). These and other similar investigations are important to the development of comprehensive computer codes for numerical simulation of combustion and explosion of dust clouds (see Chapter 4).

A number of different methods are now available for experimental investigation of the turbulence in gases and dust clouds. Some of those discussed by Smolyakov and Tkachenko (1983) are

- Hot-wire and hot-film anemometer.
- Laser-doppler anemometer.
- Flow visualization by means of small particles (<1 μm) as "markers."
- Flow analysis by thermal markers (rapid heating of a small gas volume by hot wires:

the movement of the heated gas volumes is followed by another set of hot wires; poor spatial resolution).

- Acoustic anemometer (poor spatial resolution).
- Electric discharge anemometer (corona and glow discharge).
- Cold-wire anemometer (for measurement of temperature fluctuations).

Durst et al. (1981) presented an in-depth discussion of one of the most versatile methods, the laser-doppler anemometer.

Beer et al. (1984) discussed the application of such methods in the study of turbulence effects in burning dust clouds. Laser anemometers may be used for local particle velocity measurements, particle sizing, and concentration fluctuation measurements. Very accurate measurements of both mean and fluctuating particle temperatures are possible by other optical methods. As long as the flow is optically thin, which means low dust concentrations, flow visualization is no more difficult in dust clouds than in gas flows. Some techniques, like direct high-speed photography, are even simpler for two-phase combustion than for gas flames, due to the strong radiation of the flames. However, the investigations are extremely time consuming and difficult. Multipoint, conditionally sampled measurements have to be performed for flame structure studies. Advanced data-reduction techniques must be applied to evaluate and interpret and to extract information about individual events. The development of controlled excitation studies provides the possibility of investigating the details of the coherent structures through phase lock on the induced perturbation.

Hatta et al. (1989) extended the theoretical equations for flow of dust/gas mixtures through nozzles to the complicated case of polysized particle systems. The equations covered both subsonic and supersonic gas flow. Some numerical solutions were discussed.

Fan Jiaren, Zhao Hua, and Cen Kefa (1989) studied the flow of polysized particles/gas mixtures in a coaxial jet system, both theoretically and experimentally. Advanced instrumentation was used to experimentally determine particle movement. Numerical computations gave results in good agreement with the experiments.

Lockwood and Papadopoulos (1989) described a powerful method to calculate dispersion (not deagglomeration) of solid particles in a turbulent flow. An equation, which correctly accounts for particle momentum conservation, was derived for the evolution of the probability of particle velocity and position. The method enabled determination of the position and velocity probability density functions for all cells within the computational domain at a fraction the cost of conventional stochastic computations.

3.9

METHODS FOR GENERATING EXPERIMENTAL DUST CLOUDS FOR DUST EXPLOSION RESEARCH

3.9.1

BACKGROUND

Over half a century ago Hartmann, Nagy, and Brown (1943) found it necessary, when discussing research in the field of dust explosions, to make the following statement:

> Over the past 30 years, various investigators have worked on means of producing uniform dust clouds; comparison of results indicated that none of them has been wholly successful. The mechanisms to produce such a cloud, of sufficient volume to be usable for test work, remain to be perfected.

Although a substantial amount of work has been carried out during the years since the statement of Hartmann et al. to overcome this basic problem in dust explosion research, their words are still valid.

It appears, however, that the problem does not merely arise from experimental difficulties. The basic question is, perhaps, not how to produce the "perfect" experimental dust cloud but rather whether a realistic definition of such a dust cloud can be given at all. The ideal static, fully dispersed, and uniform dust cloud is impossible to realize in practice, whether in the laboratory or real life. In any realistic dust cloud, the particles and supporting gas are in motion, the dust concentration is only to some extent uniform, and the dispersion of agglomerates may not be complete.

Sophisticated means of overcoming the problems have been attempted. These include the use of free-falling explosion chambers by which the influence of gravity is eliminated (Ballal, 1983; Gieras et al., 1986) and steady-state suspension of the dust cloud in a strong electrostatic field (Gardiner, Caird, and Bardon, 1988). However, while such methods may provide useful insight into basic details of ignition and combustion of dust particles and clouds, they do not represent practical industrial conditions. Disregarding such highly sophisticated techniques, the methods used for the formation of experimental dust clouds for dust explosion research may be classified in the three main groups, illustrated in Figure 3.29.

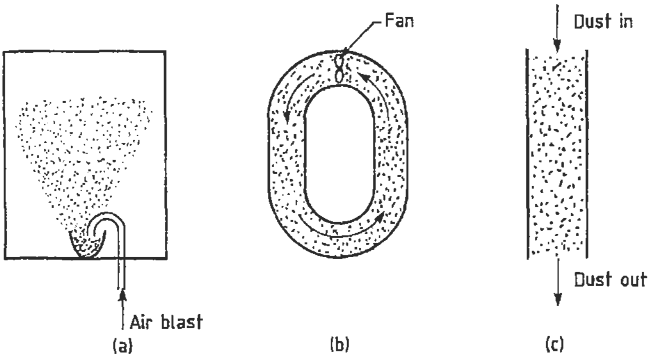

Figure 3.29 *Three basic principles used for generating dust clouds for dust explosion research: (a) transient clouds generated by dispersing a given quantity of dust by a short blast of air, (b) stationary circulation of a given quantity of dispersed dust in a closed system, and (c) stationary formation of a dust cloud in an open system.*

3.9.2
TRANSIENT DUST CLOUDS GENERATED BY A SHORT AIR BLAST

Due to the relatively simple equipment and minimal dust quantities needed, the transient dust cloud method has been adopted in the major part of published investigations, both in small and large scale.

According to Brown and James (1962), the transient air blast method was probably first introduced by Holtzwart and von Meyer (1891). Their very simple explosion apparatus consisted of a glass tube of 50 cm^3 capacity, fitted with a pair of platinum electrodes, across which an induction spark was passed. The dust was placed in a piece of a narrower tube attached to one end of the explosion tube, and the dust cloud was formed in the region of the spark by means of a short blast of compressed air. Engler (1907) used glass flasks of 250 to 500 cm^3 capacity as explosion vessels (see Figure 1.57). In the spherical explosion bomb of 1.4 liter capacity used by Trostel and Frevert (1924), the dust was placed in a small cup near the bottom of the bomb, and the dispersing blast of air was introduced through a glass tube, entering the bomb through the bottom and, having a bend of 180°, facing the opening downward toward the dust heap in the dispersion cup. In their explosion vessels of 1 liter capacity, Boyle and Llewellyn (1950) and Eckhoff (1970) used arrangements practically identical to that introduced by Trostel and Frevert.

The well-known Hartmann apparatus, which was first described by Hartmann et al. (1943), consists of a vertical cylinder having a volume of about 1.2 liter, supported by a metal bottom part shaped like a cup, in which the powder is placed (see Chapter 7). The dispersing air blast is introduced axially from below and deflected downward toward the dust heap by means of a small conical "hat" or "mushroom." As discussed by Dorsett et al. (1960), this apparatus, in the form of either an open tube or a closed bomb, has been used to determine the numerous values of minimum ignition energy, minimum explosible dust concentration, rates of pressure rise, maximum explosion pressure, and so forth that have, through the years, been published by the U.S. Bureau of Mines.

Carpenter (1957) used a slightly modified form of the Hartmann apparatus, the main features, however, being identical. In a subsequent work, Carpenter and Davies (1958) used a smaller, detached dust dispersion cup of 2 cm diameter fitted in the lower part of a cylindrical 275 cm^3 combustion chamber. Meek and Dallavalle (1954) employed a rather large explosion chamber of about 60 liters. The dust was dispersed from a polished funnel-shaped cup, fitted with a special dispersing cone.

Various versions of the transient air blast method have been used in a number of other investigations. Nagy et al. (1971) adapted this technique over a wide range of explosion vessel volumes, ranging from 1 liter to 14 m^3. Moore (1979) employed the method in three different vessels of volumes from 1 to 43 liters; and Enright (1984) used it in three vessels of volumes from 1 to 20 liters.

The simplest version of the transient air blast method, based on just directing a blast of air towards a dust heap, was found to give a rather poor dispersion of very fine, cohesive dusts. To improve dust dispersion, more refined versions of the air blast method were developed, based on forcing the dust/air suspension through narrow nozzles (see Section 3.7).

This was done, for example, by Helwig (1965), who generated his dust clouds from the 100 cm^3 cylindrical "whirling"chamber shown in Figure 3.30. The chamber was placed inside the 43 liter explosion bomb. By means of a blast of compressed air admitted through the bottom of the whirling chamber, the dust was fluidized and the fluidized suspension forced through a number of holes in the chamber lid at the top. There is little doubt that the nozzle dispersion mechanism discussed in Section 3.7 played an essential role in this process.

In his 1 m^3 explosion vessel, Bartknecht (1971) used a dust dispersion system by which the dust was forced at high velocity by high pressure air through a number of 4–6 mm diameter holes in a U-shaped tube of 19 mm internal diameter. Bartknecht's 1 m^3 vessel and dust dispersion system has later been adopted as an ISO standard (International Standards Organization, 1985). From what has been said in Section 3.7, it is quite clear that this standard test method produces a high degree of dispersion, even for very cohesive dusts.

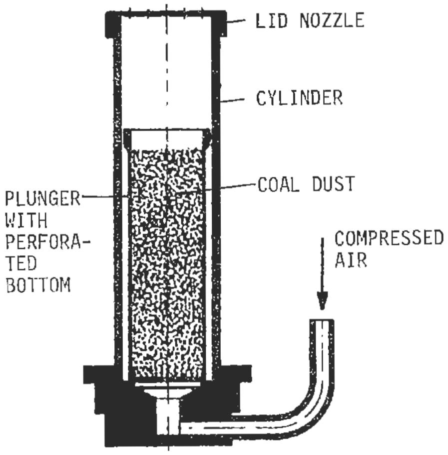

Figure 3.30 *"Whirling" chamber for fluidizing the dust sample and subsequently forcing the dense dust/air suspension through a series of parallel nozzle holes (From Helwig, 1965).*

Siwek (1977) developed a smaller spherical apparatus capable of yielding approximately the same degree of dust dispersion and turbulence as the 1 m^3 ISO vessel. However, obtaining an acceptable correlation with the 1 m^3 ISO vessel required a large experimental effort, starting with a bomb of volume 5 liter, continuing with one of volume 10 liter, and ultimately finishing up with the final bomb of 20 liter. In particular, it was necessary to investigate a range of different dispersion nozzle systems before finally arriving at one that produced turbulence and dust dispersion levels in acceptable agreement with those generated in the 1 m^3 standard chamber. It is not surprising that the dispersion system finally arrived at was very similar to the perforated U-tube system of the 1 m^3 vessel.

However, Siwek (1988) introduced a quite different dispersal nozzle for the 20 liter sphere, based on the high-velocity impact of agglomerates on target plates. This system was claimed to produce degrees of dust dispersion comparable to those generated by the original nozzle (see Figure 7.58).

Following the development of the 20 liter vessel by Siwek, an alternative 20 liter vessel was proposed by Cashdollar and Hertzberg (1985). They mention the interesting possibility of inserting interchangeable dust dispersion units at the bottom of their vessel. This makes it possible to work with the intensity of dust dispersion relevant for the problem to be investigated.

The Institute of Iron and Steel in Kiev, USSR, developed a dust dispersion unit particularly suitable for dispersing cohesive metal powders. The unit, which was mounted at the upper end of a 4 liter vertical cylindrical explosion vessel of internal diameter 110 mm, is shown in Figure 3.31. The basic philosophy behind this design is the same as for several of the methods already discussed. The dust cloud, after having been initially dispersed by the air blast in the conventional way, is forced through a system of narrow nozzles at high speed, causing further breakup of particle agglomerates before the cloud is admitted to the explosion vessel (see Section 3.7). The concentration distribution of the resulting transient dust cloud in the vessel, as a function of time and position in space, was investigated by means of a special gravimetric concentration sampling probe. The dust clouds were also studied by means of high-speed photography by replacing the explosion vessel with a glass container. Generally, a reasonably homogeneous

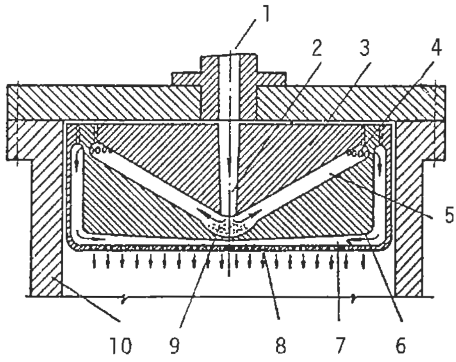

Figure 3.31 *Cross section of dust dispersion system developed at the Institute of Iron and Steel in Kiev, USSR (From Eckhoff, 1977):*

1. *Entrance for dispersing air blast.*
2. *Nozzle directing air toward dust heap.*
3. *Internal body of dispersion unit.*
4. *Narrow peripheral nozzles for agglomerate breakup.*
5. *Slot for flow of primary dust cloud to the narrow peripheral nozzles.*
6. *Intermediate body of dispersion unit.*
7. *Slot for flow of dispersed dust toward perforated bottom. Tapering ensures even distribution of dust concentration over explosion vessel cross section.*
8. *External body of dispersion unit, having the entire bottom penetrated by narrow nozzles for distribution of dispersed dust in the explosion vessel underneath.*
9. *Initial dust sample.*
10. *Wall of explosion vessel.*

cloud, filling the entire vessel volume, was obtained at some stage during the dispersion process.

Nedin et al. (1975) compared the transient dust concentration distributions generated by the U.S. Bureau of Mines Hartmann tube dispersion system (see Chapter 7) with two systems used in the USSR to generate experimental laboratory-scale clouds for dust explosion testing and research.

In spite of its extensive use, the transient air blast method has its clear limitations. The method inevitably yields both time- and space-dependent dust concentration. Schläpfer (1951) found that powders of different density, particles size, and surface properties were dispersed in different ways when exposed to the same air blast conditions.

Consequently, it is difficult to make meaningful comparison of results obtained with different powders. Schläpfer concluded rather pessimistically that the best that could be expected from experiments based on the transient air blast technique is relative data for dusts of one material.

It should finally be mentioned that Proust and Veyssiere (1988) generated laminar transient dust clouds by gently fluidizing a given quantity of maize starch (6% moisture content) from a bed of about 600 g of starch, initially resting on a porous bed at the bottom of a vertical column of 0.2 m × 0.2 m cross section. The average velocity of the fluidizing air was on the order of 0.1 m/s. This setup enabled the study of genuinely laminar flame propagation, but the method is probably limited to powders that are comparatively easy to disperse and have relatively narrow size distributions (see also Chapter 4).

3.9.3
STATIONARY DUST CLOUD IN A CLOSED CIRCULATION SYSTEM

Several workers tried to experiment with systems in which a given quantity of dust, suspended in a given volume of air, circulates in a closed loop. An early attempt was made by Bauer (1918), who simply used a fan located near the bottom of the vertical cylindrical explosion chamber, rotating at 90° with respect to the axis of the chamber, to keep the dust in suspension. However, the assumption that this arrangement could produce a uniform dust concentration was not, according to Selle (1957), justified, because the dust could not be completely raised from the bottom of the vessel.

Eckhoff (1970) attempted to adopt a similar system as that used by Bauer, by using a coaxial fan at the bottom of the cylindrical 1 liter bomb and a "beater" rotating at 90° to the cylinder axis. However, it was impossible to generate a stationary dust cloud. The dust initially introduced in the bomb was raised into suspension, but the dust concentration decreased systematically and comparatively fast with time due to the inevitable deposit of dust on parts of the vessel wall and such.

Brown and Woodhead (1953) arrived at the same conclusion for another version of the closed circuit apparatus. These workers studied the dust cloud formed in a closed loop of 7.5 cm diameter glass tubing, through which the dust dispersion was circulated at various rates of flow. They concluded that it was impossible to obtain a uniform cloud, and very high circulation velocities were required to prevent dust from depositing at the bends of the loop. Furthermore, at these high circulation speeds, it was noted that significant comminution of the particles could take place.

A special version of the method based on the circulation of a constant quantity of dispersed powder in a closed apparatus was developed by Gliwitzky (1936). To keep the dust dispersed, two propellers, rotating at different speeds and in opposite directions, were situated coaxially inside a horizontal cylinder with open ends, which was placed inside the 43 liter explosion chamber. The closed circuit thus consisted of the inside of the internal cylinder and the annulus between this cylinder and the wall of the explosion chamber. However, this system was not found to be satisfactory, since even with easily dispersed aluminum flakes, the dust dispersion was incomplete.

It therefore appears to be justified to conclude that none of the various versions of the closed circuit system developed for the formation of experimental dust clouds has proven to offer an acceptable solution to the problem.

3.9.4
STATIONARY DUST CLOUD IN AN OPEN-CIRCUIT SYSTEM

Because of the limitations and shortcomings of the two other categories of methods, open-circuit dust cloud generators have been used by a number of workers, despite the comparatively large dust quantities and more-complicated apparatus required.

A simple version of the open-circuit principle for dust dispersion was in fact described by Weber (1878) more than a century ago as part of a comprehensive investigation of causes of dust explosions and fires in flour mills. The flour was placed on a 100 mm diameter sieve of a suitable mesh size, and by vibrating the sieve, a controlled column of falling dust was created in the region below the sieve. By means of an annulus, placed at the bottom of the sieve, the diameter of the dust column could be controlled. The measurement of the dust concentration in the column was carried out simply by inserting two parallel plates, separated by a fixed distance, into the falling dust column, the plates being perpendicular to the axis of the column. Since the diameter of the column could be measured and the distance between the plates was known, the volume of the dust cylinder trapped between the plates was known; consequently, the dust concentration was given by the amount of flour that settled on to the lower plate, divided by the volume of the dust cylinder initially trapped between the plates.

Seventy years later, Weber's idea was adopted by Jones and White (1948), who by sieving the dust into a vertical cylinder, avoided the gradual distortion of the falling dust column, which in Weber's case occurred as the dust traveled away from the sieve. The sieving method for dispersing dust was also adopted by Craven and Foster (1967) as part of a more refined experimental setup and, on a comparatively large scale, by Palmer and Tonkin (1968).

Schläpfer (1951) used a conveyor screw to supply the powder at a constant rate at the bottom of the vertical dust explosion tube, in which air was flowing upward at a constant rate. The bottom part of the tube, where the dust was introduced, was narrow to ensure high turbulence during dispersion of the powder in the airstream. The upper part of the tube was considerably wider, and hence more laminarlike flow of the dust cloud could be obtained.

A similar arrangement was used by Cassel (1964). In this apparatus, to obtain a constant flow rate and dust concentration, the dust was dispersed by a jet of gas from a hypodermic needle directed vertically downward toward a horizontal rotating dust layer of constant thickness. The arrangement also incorporated an electromagnetic vibrator, the purpose of which was to prevent the powder from depositing on the inner walls of the apparatus.

Line, Clark, and Rahman (1957) used an apparatus where a turbulent dust cloud was initially formed by means of jets of oxidizer gas passing through a bed of the dust. This cloud was then directed downward through a vertical cylindrical tube, under laminar conditions. The combustion chamber, having a considerably larger diameter, was attached to the tube; consequently, on leaving the tube, the dust cloud formed a continuous wall-free column traveling downward through the combustion chamber.

To investigate the burning velocity of laminar flames of lycopodium, Kaesche-Krischer and Zehr (1958) fed lycopodium into the lower end of a vertical 2 cm diameter tube, where it was dispersed into a stationary dust cloud by an upward-moving stream of air. This arrangement made it possible to obtain stable flames in the concentration range of dust between 200 and 500 g/m^3. Mason and Wilson (1967), who also studied the burning velocity of stationary flames of lycopodium, described a dispersing arrangement where the lycopodium was elutriated from a fluidized bed. These workers could obtain stable dust flames in the concentration range 125–190 g/m^3.

Ballal (1983) also supplied the dust to be dispersed to a worm conveyor, from which it was fed at the desired rate at the top of the apparatus into the controlled downward airflow. In very fine powders, particle clusters or agglomerates tended to form at the output of the worm conveyor. The problem could be somewhat reduced by modifying the design of the screw and optimizing its speed of rotation. However, to ensure proper dust dispersion, the dust output from the worm conveyor was fed into a swirl chamber driven by a controlled airflow. A high level of turbulence shear created within this chamber by the colliding whirling jets produced cluster-free, uniform dust dispersion. For high dust concentrations and especially for coal dust, a secondary dust dispersion source in the form of a high-speed rotary disk was incorporated within the settling chamber. Thus, a uniform and finely dispersed dust cloud could be produced. This was gently drawn into the explosion chamber by a small suction pump.

3.9.5
CONCLUSION

Provided the relatively large amounts of powder required and the relatively complicated experimental apparatus can be justified, the open-circuit principle is the most satisfactory alternative for dust dispersion. However, as for the transient cloud systems, it is essential that the dust dispersion system be designed carefully, to ensure that the degree of agglomeration of the particles in the cloud and the cloud turbulence corresponds with the state actually wanted. Quite often, it is desirable or even necessary to keep the consumption of dust or powder at a minimum. In such cases, the transient air blast technique may, provided the limitations of the technique are borne in mind, offer the best solution.

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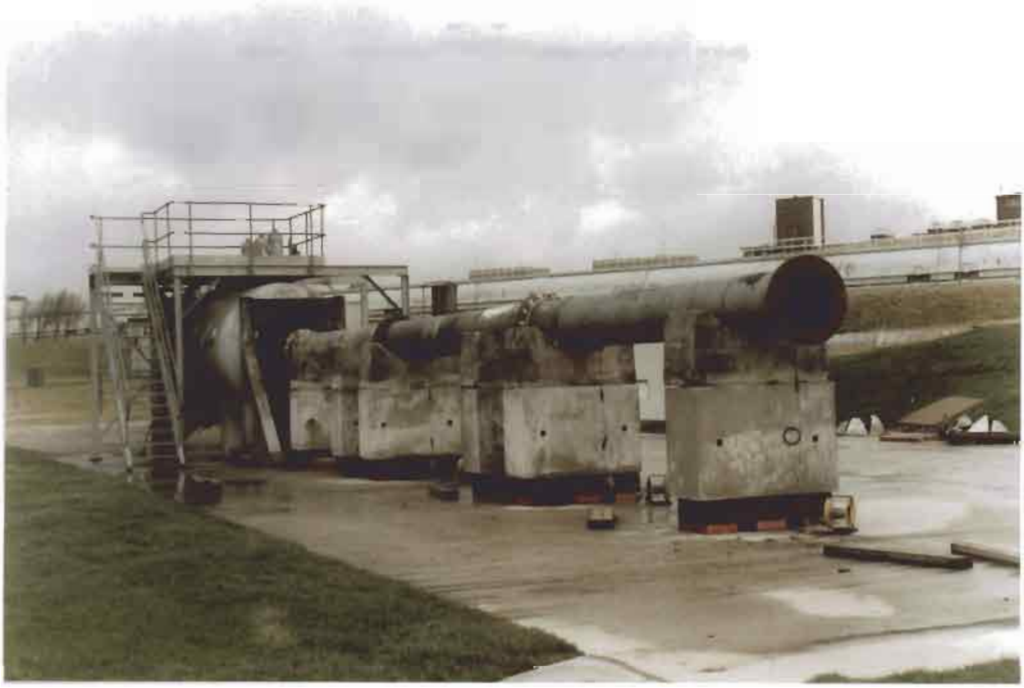


Plate 1 *18.5 m³ vented explosion vessel connected to a straight vent duct (Courtesy of Health and Safety Executive, United Kingdom).*

Plate 2 *Coal dust explosion in 18.5 m³ vessel vented through a duct with a 90° bend at the end (Courtesy of Health and Safety Executive, United Kingdom).*

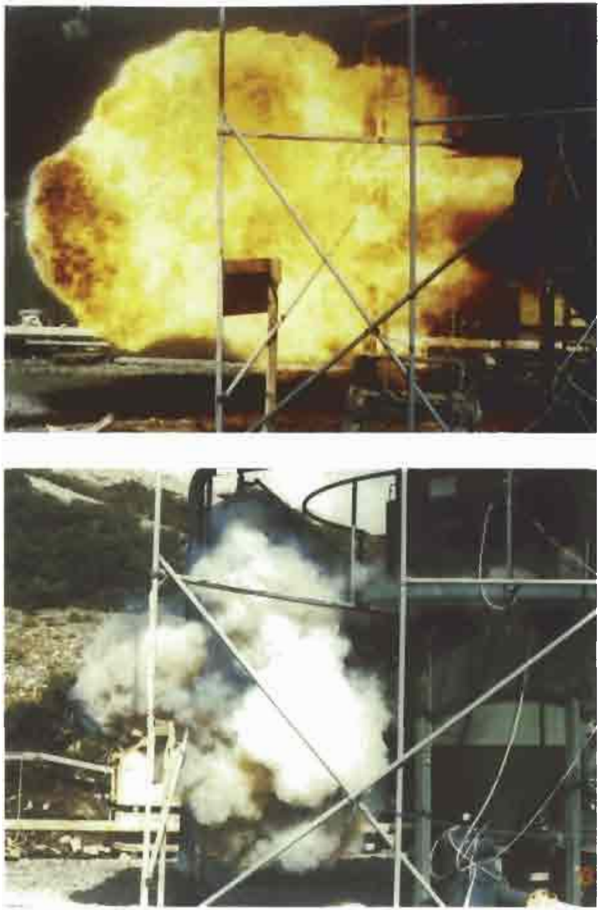


Plate 3 *Venting of a polypropylene/air explosion in a 5.8 m*^{3} *bag filter unit without (top) and with (bottom) quenching tube (Courtesy of F. Alfert and K. Fuhre, Chr. Michelsen Institute, Bergen, Norway).*

Plate 4 *Application of automatic dust explosion suppression to bucket elevators (Courtesy of T. Pinkwasser, Bühler, Switzerland).*

Chapter 4

Propagation of Flames in Dust Clouds

4.1
IGNITION AND COMBUSTION OF SINGLE PARTICLES

4.1.1
ALUMINUM

Friedman and Macek (1962, 1963) studied the ignition and combustion of aluminum particles in hot gases of varying oxygen content. They concluded that ignition occurred only after melting of the oxide layer (melting point 2300 K) that coats the particle. The process of ignition did not appear to be affected by the moisture content of the hot ambient gas and was only slightly influenced by the oxygen content. At an oxygen content of only 2–3 mole percent (mol%), ignition occurred at 2300 K, whereas at 35 mol% oxygen, it occurred at 2200 K. On the other hand, the concentrations of oxygen and water vapor had significant influence on the combustion of the metal. Oxygen promoted vigorous combustion and, if its concentration was sufficiently high, fragmentation of particles. In the absence of moisture, diffusion and combustion took place freely in the gas phase, whereas in the presence of moisture, the process was impeded and confined to a small region, because the reactants had to diffuse through a condensed oxide layer on the surface of the molten particle.

Cassel (1964) injected single 60 μm diameter aluminum particles into the center of a laminar aluminum dust flame of known spatial temperature distribution. Ignition of the particles occurred at 2570 K, but this was probably higher than the minimum temperature required for ignition, because the residence time of the particle in the hot environment was no more than 2 ms. This is shorter than the induction period required for self-heating of the particle from its minimum ignition temperature to the minimum temperature for self-sustained oxidation.

Cassel further observed that, within 2 ms after ignition, a concentric burning zone, of diameter about nine times the original particle diameter, developed around the particle. After 3 ms, a detached envelope appeared, which at first surrounded the particle concentrically but then became elongated and gradually developed into a cylinder of length more than 10 times its diameter. This expanding oxide envelope, being in the liquid state, followed the relative motion of the ambient atmosphere.

Burning times of 60 μm aluminum particles located between the lobes of the aluminum-dust flame were found to be on the order of 10.5 ms (about 4.5 times longer than for magnesium particles burning under the same conditions). Cassel attributed this to the greater oxygen requirement for the oxidation of aluminum.

Prentice (1970) studied the ignition and combustion of single 300–500 μm aluminum particles in dry air, following initial heating and melting by a light flash from either a pulsed Nd-glass laser or a xenon-flash discharge lamp. In air (as opposed to in Ar/O_2), oxide accumulated on the burning aluminum droplet. Because of this, the combustion process was terminated by fragmentation of the droplet (as shown by Nelson, 1965, for zirconium). The very fast flash-heating method generated fully developed metal droplets with practically no oxide on the surface. This presented initial conditions for studying the subsequent ignition and combustion processes, when the virgin droplets interacted with the surrounding air. Detailed SEM studies of the oxide layer buildup revealed a porous structure with a great number of fumaroles. Over the experimental range, the burning time to fragmentation increased linearly with the particle diameter from about 200 ms at 300 μm to 600 ms at 500 μm. Prentice studied the combustion of aluminum droplets in dry air over a range of pressures up to 4.5 bar (abs). The particles were found to fragment in dry air at pressures up to about 2.4 bar (abs). Fragmentation became quite weak and sporadic at this pressure and finally ceased as the pressure was raised to approximately 4.0 bar (abs). The time to fragmentation was found to be inversely proportional to the air pressure, that is, to the oxygen concentration.

Prentice also found that the nitrogen in the air played an active role in the combustion process, causing the oxide generated to adhere to the droplet surface and form an asymmetrical, spin-generating oxide layer that appeared to be a precondition for fragmentation. The driving gas causing particle fragmentation is in part aluminum vapor, but for combustion in air, the major constituent is nitrogen from nitride.

Frolov, Pokhil, and Logachev (1972) studied ignition and combustion of single aluminum particles in high-temperature oxidizing gases, as a function of particle size and state of the gas. Various theories were reviewed.

Grigorev and Grigoreva (1976) modified the theory of aluminum particle ignition by Khaikin, Bloshenko, and Merzhanov (1970), by including a fractional oxidation law accounting for possible changes of the structure of the oxide film during the preflame heating period. Experiments had revealed that the minimum ignition temperature of aluminum particles was independent of particle size, and Grigorev and Grigoreva attributed this to the oxidation rate depending very little on the thickness of the oxide layer.

Razdobreev, Skorik, and Frolov (1976) studied the ignition and combustion of individual 230–680 μm diameter aluminum particles in air, following exposure to stationary laser light fluxes. At incident fluxes approaching 150 W/cm^2, the particle melted, but ignition occurred only at fluxes higher than 250 W/cm^2. Coefficients of reflection were not measured but assumed to be in the range 96–50%, which means that less than half the incident light flux was absorbed by the particle. The time from onset of radiant heating to ignition increased with particle diameter from 100 ms for 230 μm, through 270 ms for 400 μm, to 330 ms for 680 μm.

Ermakov et al. (1982) measured the surface temperature of 400–1200 μm diameter aluminum particles at the moment of ignition. The heating was performed by a continuous laser of wavelength 10.6 μm at a constant flux incident on the particle in the range 1500–4500 W/cm^2, that is, much higher than the experimental range of Razdobreev et al. (1976). The particle temperature was measured by a tungsten-rhenium thermocouple, whose junction of thickness 18–20 μm was located at the center of the particle. Microscopic high-speed film records were made synchronously with recording the particle temperature at a rate up to 4500 frames/s. The simultaneous recording permitted detailed simultaneous comparison of the temperature of the particle with physical phenomena observed on the particle surface. The appearance of a flame in the form of a tongue on a limited section of the surface was noted at a particle temperature of 2070 ± 50 K. With further heating to 2170 K, the flame tongue propagated to the entire particle surface, and the particle temperature remained constant at 2170 K during the subsequent burning. This temperature is slightly lower than the melting point of the oxide, and Ermakov et al. challenged the oxide melting point hypothesis. They concluded that the ignition temperature obtained in their experiments showed that ignition is not caused by melting the oxide film but the destruction of the integrity of the film due to thermomechanical stresses arising during the heating process. This was indicated by photographs of the particle surface at the time that the flame tongue appeared. No influence of the incident heating flux density on the stationary combustion temperature of the particle was detected. See Section 9.2.3.2 in Chapter 9 for further works on aluminum particles.

4.1.2
MAGNESIUM

Cassel and Liebman (1959) found that ignition temperatures of magnesium particles in air did not differ from those in pure oxygen. Therefore, they excluded oxygen diffusion as the reaction rate controlling mechanism in the ignition process and proposed a theory based on a simple chemical control Arrhenius term for describing the rate of heat generation per unit of particle surface area. An average value of the activation energy of 160 ± 13 J/mole was derived from the available experimental data.

Cassel and Liebman (1963) measured the ignition temperatures of single magnesium particles of 20–120 μm diameter by dropping the particles into a furnace containing hot air of known temperature. They found that the minimum air temperature for ignition decreased systematically with increasing particle size, being 1015 K for a 20 μm diameter particle, 950 K for 50 μm, and 910 K for 120 μm.

Cassel (1964) proposed a physical model for the combustion of individual magnesium particles, as illustrated in Figure 4.1. After ignition, the oxide layer that coats the particle prior to ignition, is preserved, growing only slightly in thickness. During combustion, the oxide shell encloses the evaporating metal drop, while superheated metal vapor diffuses through the semi-permeable shell to the outside and reacts with oxygen that diffuses toward the particle from the ambient atmosphere. The rate of burning of the

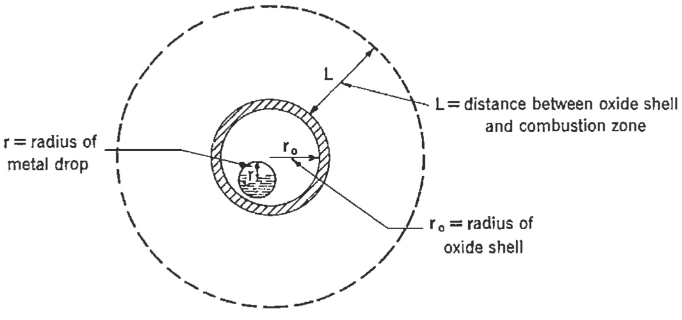


Figure 4.1 *Model of burning magnesium particle (From Cassel, 1964).*

particle is therefore governed by the rate of oxygen diffusion toward the reaction zone. In the initial stage of combustion, the site of reaction is close to the outer surface of the oxide layer. However, owing to depletion of oxygen, this zone is detached from the oxide surface and shifted to a distance, *L*, from the particle shell. The rate of oxygen diffusion and the rate of combustion are determined by the gradient of oxygen partial pressure at $r_0 + L$. This gradient remains approximately constant over the lifetime of the burning particle, except for the final stage, when the reaction zone withdraws to the oxide shell.

Cassel (1964) also suggested a theoretical model for the combustion of a magnesium particle. On the assumption that the location of the liquid drop inside the oxide shell is unimportant and the rate of oxygen diffusion is always slower than the rate of the chemical reaction, the burning rate of a magnesium particle is given by the quasistationary balance of the oxygen diffusion rate,

$$\overline{W}_{O2} = 4\pi(r_0 + L)\frac{Dp}{RT}\ln\frac{p - p_L}{p - p_\infty} \tag{4.1}$$

and the rate of metal vaporization,

$$\overline{W}_{\text{Mg}} = -\frac{4\pi\rho r^2}{M\epsilon}\frac{dr}{dt} \tag{4.2}$$

Here *D* is the average oxygen diffusion coefficient at average temperature *T*, *M* is the mole weight of magnesium, ρ is density of magnesium, ϵ is oxygen equivalent (=2 for oxidation of magnesium), *p* is the absolute total pressure at distance r_0 (just outside of the oxide shell), and p_L and p_∞ are the partial pressures of oxygen at distances *L* and infinity.

The time τ required for complete combustion of a particle is obtained by combining equations (4.1) and (4.2) and integrating from the initial drop radius r_0 to 0. The resulting equation is

$$\tau = \frac{\rho RT}{M\epsilon Dp}\frac{r_0^3}{3(r_0 + L)}\bigg/\ln\left(\frac{p - p_L}{p - p_\infty}\right) \tag{4.3}$$

Equation (4.3) was used to derive values of (*D*/*T*) from observed τ values. Note that ρ, p_∞, and *D* refer to different temperatures; namely, the boiling point of the metal, the ambient gas temperature, and the temperature in the diffusion zone near the reaction front, *T*. The estimates of *D*, assuming molecular diffusion, gave an unrealistically high *T* value of 4860 K for a magnesium particle burning in air. Cassel suggested, therefore, that the combustion of magnesium particles is governed predominantly by diffusion of atomic oxygen. He also suggested that the same must be true in any dust flame burning at 3000 K or more.

Liebman, Corry, and Perlee (1972) studied experimentally the ignition of individual 28–120 μm diameter magnesium particles suspended in cold air, by an approximately square laser light pulse of 1.06 or 0.69 μm wavelength and 0.9 ms duration. The results suggest that, during the heating of a magnesium particle by a short flash of thermal radiation, the particle temperature first rises rapidly to the boiling point. Vaporized metal then expands rapidly from the particle surface, and vapor-phase ignition may occur near the end of the radiant pulse. In accordance with the model proposed by Cassel (Figure 4.1), ignition is assumed to occur at some distance from the particle surface, where conditions (magnesium and oxygen concentrations and temperature) are optimal. The onset of ignition was characterized by the rapid appearance of a large luminous zone. Radiant intensities required to ignite the particles were found to increase with particle size and the thermal conductivity of the ambient gas environment. In accordance with the results from hot gas ignition, little change in the radiant intensities were required for ignition when replacing air by pure oxygen.

Florko et al. (1982) investigated the structure of the combustion zone of individual magnesium particles using various techniques of spectral analysis. They claimed that their results confirmed the assumption that the oxide, after having been generated in the gas phase in the reaction zone, condenses between this zone and the surface of the burning particle. This observation is an interesting supplement to the observation made and the physical model proposed by Cassel (1964).

Florko et al. (1986) estimated the temperature in the reaction zone of burning magnesium particles as a function of the pressure of the ambient gas, by analyzing the spectrum of the unresolved electron-vibration bands of the MgO molecules in the reaction zone. For large particles of 1.5–3 mm diameter, the reaction zone temperature was practically independent of the gas pressure and equal to 2700–2800 K in the range 0.3 to 1 bar (abs). When the pressure was reduced to 0.05 bar (abs) the reaction zone temperature dropped only slightly, to about 2600 K. The burning time of 1.5–3 mm diameter particles was proportional to the square of the particle diameter. For a 2 mm diameter particle at atmosphere pressure, the burning time was about 6 s. Extrapolation to 60 μm particle diameter yields a burning time of 5.4 ms, which is quite close to the times of a few ms found by Cassel (1964) for Mg particles of this size. When the pressure was reduced to 0.2 bar (abs), Florko et al. (1986) found a slight reduction, by about 10%, of the burning time. See Section 9.2.3.2 in Chapter 9 for further works on Mg particles.

4.1.3
ZIRCONIUM

Nelson and Richardson (1964) and Nelson (1965) introduced the flash light heating technique for melting small square pieces of freely falling metal flakes to spherical droplets. They applied this method for generating droplets of zirconium, which were subsequently studied during free fall in mixtures of oxygen/nitrogen and oxygen/argon. The duration of the light flash was only on the order of a few ms. A characteristic feature was the sparking or explosive fragmentation of the drop after some time of free fall. This was supposed to be due to forcing out the solution of nitrogen, hydrogen, and carbon monoxide that had been chemically combined with the metal earlier in the combustion process. The experimental results for air at atmospheric pressure showed, as a first-order approximation, that the time from droplet formation to explosive fragmentation was proportional to the initial particle diameter. The relative humidity of the air had only a marginal influence on this time. The heat initially received by a given particle by the flash was not specified.

4.1.4
CARBON AND COAL

Research on the explosibility of coal dust has a long tradition. According to Essenhigh (1961), the possible role of coal dust in coal mine explosions was suggested as early as in 1630 by Edward Lloyd, when commenting on information received from Anthony Thomas concerning an explosion in England in about 1580. The role of coal dust in such explosions was certainly clear to Faraday and Lyell (1845), discussing the disastrous explosion in the Haswell collieries the year before. More systematic investigations into the ignitability and explosibility of coal dusts started at the end of the 19th and the beginning of the 20th centuries.

However, the combustion of coal dust particles is not only related to the explosion problem, the increasing use of pulverized coal in burners for energy production has become an important area of research and development, and much information on the combustion of coal particles directly applicable to the coal dust explosion problem has been generated in that context. Furthermore, this use of pulverized coal in industry as well as the public sector has caused coal dust explosions to become a potential hazard, not only in mines but also in power generating plants utilizing powdered coal.

Coal normally contains both solid carbon and combustible volatiles. In addition, there is usually some ash and some moisture. The simplest system to study is the combustion of pure carbon or char. Nusselt (1924) proposed that the oxidation of pure carbon was essentially a direct conversion of solid carbon to CO_2 at the particle surface. However, later investigations disclosed a more complex picture even for oxidation of pure carbon, as illustrated in Figure 4.2.

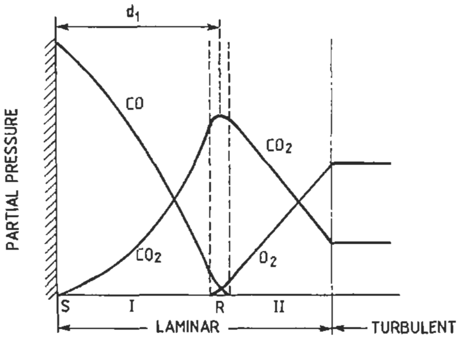


Figure 4.2 *Composition of laminar gas layer during combustion of solid carbon according to the theory of Held (1961) for surface temperatures >1400 K. Nitrogen is not considered, S = carbon surface; R = reaction zone (From Graaf, 1965).*

In zone I, the concentration of O_2 is 0; whereas in Zone II, the CO concentration is 0. At the carbon surface, S, CO_2 reacts with the solid carbon according to the endothermic scheme $CO_2 + C \rightarrow 2CO$. The required heat is supplied from the oxidation zone, R, where the temperature is at maximum and the exothermic reaction $CO + {}^1\!/_2O_2 \rightarrow CO_2$ takes place. Using the theory of Held (1961), Graaf (1965) found that the temperature in the oxidation zone R was about 2500 K for a coal surface temperature of 1800 K.

For low carbon surface temperatures of <1400 K, a significant concentration of O_2 may exist right at the surface; and at very low surface temperatures of <800 K, direct oxidation by oxygen according to the consecutive scheme $2C + O_2 \rightarrow 2CO$ and $2CO + O_2 \rightarrow 2CO_2$ takes place close to the surface. Graaf carried out experiments that supported van der Held's theory.

However, conclusions from experiments with burning of comparatively large samples of carbon may not necessarily apply to the burning of very small particles. Ubhayakar and Williams (1976) studied the burning and extinction of single 50–200 μm diameter carbon particles in quiescent mixtures of oxygen and nitrogen, ignited by a light flash from a pulsed ruby laser. An initial objective of their study was to investigate whether a gas phase burning mechanism or a surface burning mechanism, possibly accompanied by pore diffusion, governs the combustion of submillimeter carbon particles. An additional objective was to obtain burning duration data for such small particles. The lowest mass fraction of oxygen used in the oxidizer gas was 0.5, which is considerably larger than in air. They concluded that, in the temperature range 2000–3500 K, the kinetics of the carbon oxidation could be represented by a surface reaction producing CO and having an activation energy of 75 kJ/mole. As expected, the maximum temperature at the particle surface increased with increasing oxygen fraction in the oxidizer gas. At atmospheric pressure, it was about 3000 K in pure oxygen and about 2200 K at an oxygen mass fraction of 0.6. Typical particle burning durations at atmospheric pressure were 60 ms for 100 μm diameter particles and 25 ms for 60 μm particles. For low oxygen mass fractions, extinction occurred before the particles had burned away, and this explained why burning times for a given particle size were shorter in atmospheres of lower oxygen mass fractions than in pure oxygen.

In a purely theoretical investigation, Matalon (1982) considered the quasi-steady burning of a carbon particle that undergoes gasification at its surface by chemical reaction, followed by a homogeneous reaction in the gas phase. The burning rate M was determined as a function of the gas phase Damköhler number D_g (ratio of chemical and diffusion controlled reaction rates) for the whole range $0 < D_g < \infty$. The monotonic $M(D_g)$ curve, obtained for comparatively hot or cool particles, described the gradual transition from frozen flow to equilibrium. For moderate particle temperatures, the transition was abrupt and the $M(D_g)$ curve was either S-shaped or Z-shaped, depending on the relative importance of the two competitive surface reactions $2C + O_2 \rightarrow 2CO$ and $C + CO_2 \rightarrow 2CO$.

Specht and Jeschar (1987) also investigated the governing mechanisms for the combustion of solid carbon particles of various diameters. The chemical reactions considered were the same as discussed previously, but it was found that their relative importance depends on particle size via its influence on the Damköhler number D_g.

On the basis of idealized considerations, Fernandez-Pello (1982) derived theoretical expressions for the instantaneous local mass burning rate and the overall regression rate (rate of reduction of the particle radius) for the combustion of a spherical condensed fuel (e.g., carbon) particle in a forced convective oxidizing gas flow. The model is illustrated schematically in Figure 4.3.

The equations derived are of the form

$$\frac{dm}{dt} = -\frac{\lambda}{rC}(Re)^{1/2} f_1(B, G, \sigma) \tag{4.4}$$

$$\frac{dr^2}{dt} = -\frac{\lambda}{\rho C}(Re)^{1/2} f_2(B, G, \sigma) \tag{4.5}$$

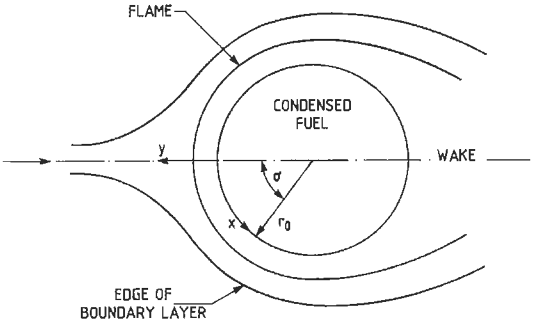


Figure 4.3 *Combustion of a condensed fuel particle in a forced convective oxidizing gas flow, the theoretical model and coordinate system (From Fernandez-Pello, 1982).*

where

m is the remaining particle mass at time t;
r is the particle radius at time t;
λ is the thermal conductivity of the oxidizing gas;
C is the mean specific heat of the reaction products;
ρ is the density of the particle;
Re is the particle Reynolds number, referred to the velocity and viscosity of the oxidizing gas upstream of the particle;
f_1 and f_2 are functions of a mass transfer number B, a normalized energy species function G, and the angular coordinate σ.

The predicted dependence of the overall particle regression rate, or the Nusselt number, on the Reynolds and mass transfer numbers was in qualitative agreement with semi-empirical correlations based on experiments with polymethyl methacrylate particles burning in mixtures of oxygen and nitrogen. Quantitative comparison between theory and experiments was difficult because of different definitions of the mass transfer number B and difference between theoretical and experimental environment conditions. However, it appeared that the theoretical analysis predicts higher (by a factor of approximately 2) mass burning rates than those observed experimentally. The choice of the thermophysical properties of the fuel and oxidizer used in the theory and the idealized assumptions implicit in the theoretical analysis could explain the quantitative disagreement with the experiments. The predicted variation of the particle radius with time is of the form $r_0^{3/2} - r^{3/2} \sim t$.

Unless the total specific surface area (N_2 adsorption) of the particles exceeds about 100 m^2/g, clouds of pure carbon dust, such as graphite, in air at atmospheric pressure are unlikely to represent a significant explosion hazard in practice. Therefore, coals containing volatiles are of greater practical interest. However, the volatiles complicate the ignition and combustion mechanisms, and the picture is less clear than for pure carbon combustion.

Gomez and Vastola (1985) compared the ignition and combustion of single coal and char particles in an isothermal flow reactor, by measuring the concentrations of CO and CO_2 in the downstream gas flow as functions of time. A subbituminous coal containing 22% moisture, 4.6% ash, 33.8% volatiles, and 39.6% fixed carbon was used in the study.

For each run, a single particle from a 850–1000 μm sieve fraction was injected into a reaction furnace swept with air. Experiments were performed at five temperatures: 928 K, 980 K, 1076 K, 1118 K, and 1273 K. At each temperature, two types of run were performed, coal combustion and char combustion. The char particles were prepared by injecting a coal particle into the reactor with a flowing nitrogen gas stream at the desired temperature. After pyrolysis was completed, the char was ignited by switching the carrier gas from nitrogen to air.

The main conclusion drawn by Gomez and Vastola from their experiment was that two chemical reactions compete for the oxygen surrounding the coal particle. The two reactions are quite different in nature, one involving the carbon surface (heterogeneous) and the other involving the volatiles (homogeneous). The gas concentration curves obtained for the heterogeneously oxidized char particles were considered typical for the heterogeneous reaction involving the carbon surface. Oxidation of coal particles could be heterogeneous, depending on the temperature. The gas concentration curves obtained for heterogeneous oxidation were similar to the curves for char combustion, except for an initial peak of carbon monoxide attributed to the combustion of volatiles on the surface or within the particle at low oxygen concentrations. However, when the coal particles ignited homogeneously, an initial pronounced peak of carbon dioxide was detected, which was attributed to the gas phase combustion of the volatile matter at conditions of sufficient oxygen for burning most of the carbon in the volatiles to carbon dioxide. The initial peaks of carbon monoxide for heterogeneous coal ignition and carbon dioxide for homogeneous ignition can be used to measure the pyrolysis time during combustion.

Gomez and Vastola suggested that all the carbon in the volatiles is oxidized to carbon monoxide or carbon dioxide. This is because methane, the most difficult hydrocarbon to oxidize, which was detected in the volatiles of coal particles after pyrolysis in nitrogen, was not traced in the products from combustion in air.

If the particle burns under external diffusion control, the reaction proceeds on the external surface of the particle at a very low oxygen concentration. The particle diameter then reduces as the combustion advances, but the density of the remaining particle mass m at time t is the same as of the initial particle mass m_0. Integration of the reaction rate equation for this case, assuming spherical geometry, results in

$$(m/m_0)^{2/3} = kt \tag{4.6}$$

where the global constant k embraces a number of constants and parameters. If this relationship describes the mechanism controlling the combustion process, a plot of the power two-thirds of the reduced mass m of the particle against time, determined experimentally, should result in a straight line. For char particles, Gomez and Vastola's experiments gave straight lines at gas temperatures >1100 K; whereas for coal particles, straight lines were found for gas temperatures >980 K.

The total combustion times, determined by both the method just described and independent light intensity measurements, varied from 5–10 s at a gas temperature of 1300 K to 20 s at 930 K. These times are very long in the context of dust explosions and due mainly to the large particle diameter of about 1 mm and partly to the comparatively low oxidizing gas temperatures in Gomez and Vastola's experiments.

Howard and Essenhigh (1965, 1966, 1967), discussing the results of their extensive research on coal particle combustion, first indicated that ignition of a bituminous coal particle generally occurs on the solid surface of the particle rather than in the volatile pyrolysis products. However, in their final conclusion (Howard and Essenhigh, 1966), they differentiated among various mechanisms on the basis of particle size. The classical view, of ignition taking place in the volatiles, still seemed valid for particle diameters larger than 65 μm. Smaller particles would, however, not be able to generate a sufficiently concentrated envelope of volatiles to prevent oxygen from diffusing to the solid carbon surface. For particle diameters smaller than 15 μm, the ignition reaction is more or less entirely heterogeneous oxidation at the particle surface.

The essential point in Howard and Essenhigh's argument is the assumption that, for particles of diameters smaller than 100 μm, the total devolatilization time is independent of particle size. This implies that the average flow of volatiles per unit of particle surface area increases with the particle size. For very small particles, the volatile flux is insufficient to maintain a volatile flame envelope round the particle.

In a more recent investigation of the devolatilization process by Johnson, Murdoch, and Williams (1988), Howard and Essenhigh's assumption of negligible influence of particle size on devolatilization rates (or total devolatilization times) was maintained for the range of particle sizes typical of most pulverized fuels and explosible dusts. These workers studied the devolatilization of monolayers of coal particles in an inert atmosphere, at heating rates from 100 to 1500 K/s. The results also indicated that, for 10–1000 μm diameter particles of bituminous coal resting on an electrically heated filament, the heating rate had little influence on the devolatilization yield, which rather was determined by the peak temperature. The maximum rate of devolatilization and maximum hydrocarbon yield occurred at peak temperatures between 700 and 1000 K.

Froelich et al. (1987) studied the combustion in air at 1400 K of single 80–100 μm diameter coal particles containing 30% volatile matter. They used the experimentally determined relationship between particle temperature (two-color pyrometer) and time in a furnace of known temperature to calculate the rate of gasification of the solid carbon of a coal particle. After about 5 ms in the furnace, the particle temperature reached a sharp peak of 2200 K, which was attributed to the devolatilization and ignition of the volatiles. A second, less-sharp temperature rise, which started at about 10 ms and terminated at about 60 ms, had a peak value of about 1800 K and was associated with the gasification of the solid carbon.

In their theoretical analysis, Froelich et al. assumed that

- The particle was a perfect and homogeneous sphere.
- The temperature of the particle was uniform.
- Either the diameter or the density of the particle remained constant (devolatilization or combustion of solid carbon).
- The furnace and the particle were black and gray bodies, respectively.
- The particle was in permanent thermal equilibrium with the gas and walls of the furnace.

The following equation was proposed:

$$\frac{xC_p\rho_c}{6}\frac{dT_p}{dt} = H_r + H_c + H_q \tag{4.7}$$

where

H_r is the radiative heat flux received by the particle per unit time;
H_c is the convective heat flux received by the particle per unit time;
H_q is the heat of reaction per unit time;
C_p is the specific heat capacity of the particle;
T_p is the temperature of the particle;
ρ_c is the density of the particle;
x is the diameter of the particle.

H_r was determined from the Stefan-Boltzmann law by assuming that the particle is in radiative equilibrium with the furnace wall:

$$H_r = E\tau(T_f^4 - T_p^4) \tag{4.8}$$

where

E is the total emissivity of the coal;
τ is the Stefan-Boltzmann constant;
T_f is the furnace wall temperature.

The convective heat flux H_c was taken as

$$H_c = h_c(T_g - T_p) \tag{4.9}$$

where T_g is the temperature of the gas around the particle and h_c is the convective heat transfer coefficient between the particle and the gas determined from the Nusselt number, assuming laminar flow around a spherical particle.

The heat of reaction per unit time H_q was taken as

$$H_q = AW\frac{\pi}{4}x^2 \tag{4.10}$$

where W is the rate of devolatilization per unit of particle surface area and A is a constant.

W, as a function of time, was calculated from the experimentally determined particle temperature as a function of time, by inserting equations (4.8), (4.9), and (4.10) in (4.7) and applying an iterative numerical method of solution. W was found to have a peak of 4×10^{-2} kg/m^2 s at about 17 ms and remain fairly constant at $3 \times 10^{-2} - 2 \times 10^{-2}$ kg/m^2 s from 20–40 ms to about 55 ms, after which it dropped rapidly to 0.

In their study of ignition and combustion of single coal particles, Gieras et al. (1985, 1986) eliminated the influence of gravity by performing the experiment during 1.4 s of free fall of the test chamber. In this way, gravity-driven convective heat transfer was avoided and the exclusive roles of conductive and radiative heat transfer could be studied. The experiment was performed with one or more coal particles glued onto thin quartz needles. The smallest particle size that could be used without the needle and glue significantly influencing the particle ignition and combustion was about 300 μm. Therefore, the most interesting particle sizes from a dust explosion point of view (diameters <100 μm) could not be studied. The observed trends are nevertheless of interest.

In one series of experiments, pairs of equal-size particles separated by a fixed center-to-center distance D were studied after a particle had been ignited by the flame from a burning 1 mm diameter drop of n-octane. For 700 μm diameter particles, the maximum

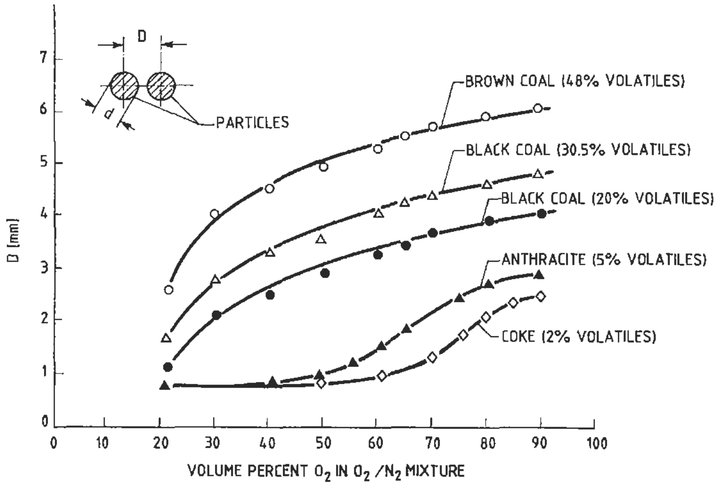


Figure 4.4 *Influence of volatile content in coal and oxygen concentration in gas on the maximum center-to-center distance between particles for the ignition of a 700 μm diameter coal particle by a burning neighbor particle of the same size, at zero gravity (From Gieras, Klemens, and Wojcicki, 1985).*

distance $D_{\max}$ for the second particle to become ignited by the first one increased systematically with the volatile content of the coal and the oxygen content of the gas, as shown in Figure 4.4. It was also found that $D_{\max}$ was proportional to the particle diameter in the range 300–1200 μm investigated. For anthracite and coke in air, ignition of the second particle did not take place unless the particles were nearly touching, whereas particles of the coal of the highest volatile content in air could be separated by up to about two to three particle diameters.

In Figure 4.5, the relative flame radius, R_f, as observed on 48 fr/s movie photos, has been plotted as a function of time. R_f is defined as the ratio between the radius of the apparent flame around the particle and that of the original particle. Figure 4.5 shows that the time required to reach the maximum flame radius decreased and the maximum flame

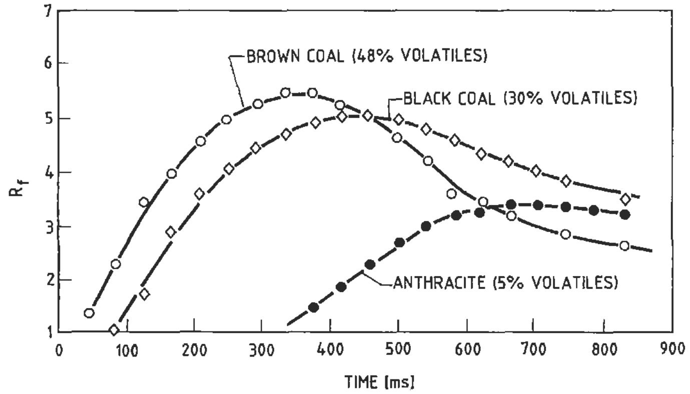


Figure 4.5 *Change of relative flame radius R_f with time during combustion of a 700 μm diameter coal particle at zero gravity (From Gieras et al., 1985).*

radius increased with increasing volatile content. This trend was interpreted in terms of the volatiles burning more rapidly than the char, in agreement with the general understanding of the combustion of coal particles.

In a further series of experiments, Gieras et al. (1985) studied the propagation of combustion through static linear chains of consecutive coal particles separated by a given optimal center-to-center distance D_{opt} depending on the volatile content. It was confirmed that the velocity of the "one-dimensional" flame propagation increased (approximately proportionally) with the volatile content of the coal.

When similar interparticle flame transfer experiments were conducted at normal gravity conditions, buoyancy played an important role (Gieras et al., 1986). The maximum interparticle distance for upward flame transfer was then significantly larger than for horizontal transfer. This has important implications in dust explosions, such as in the definition of the concept of minimum explosible dust concentration. Under gravity conditions, the limiting dust concentration for flame propagation depends on whether the propagation occurs upward, downward, or horizontally (see Section 4.2.6.2).

Wagner et al. (1987) studied the ignition and combustion of single coke and coal particles of diameters 63–125 μm in a vertical reactor containing hot oxidizing gas, through which the particles settled for predetermined periods (distances) before being captured and cooled rapidly. The initial volatile content for the materials investigated varied from 4.5% to 37%. The experimental data were compared with predictions by a numerical computer model, based on the earlier work by Field (1969) and Smith (1971). The model also treated the devolatilization process, by considering it as a single-stage reaction of activation energy 228.5 kJ/mole. The combustion was considered controlled partly chemically and partly by diffusion processes. Both convective and radiative heat transfer were considered.

Figure 4.6 shows a set of experimental results for particles burning in air at atmospheric pressure and the corresponding predictions by the computer model. For all three coals

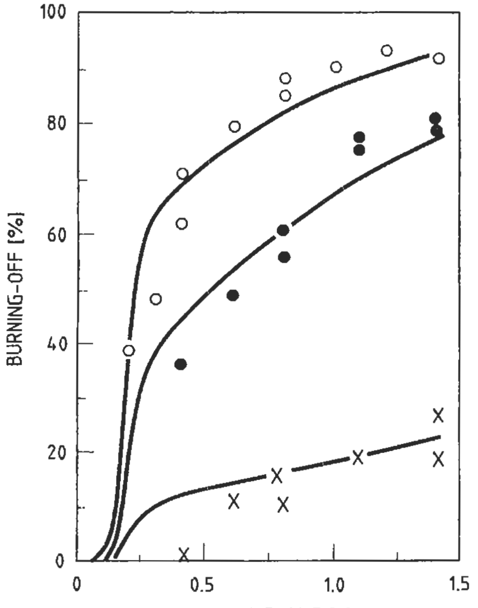


Figure 4.6 *Burning-off of 63–125 μm coal particles of various volatile contents as functions of residence time in hot gas (1170 K) in a vertical reactor:*

○ = 37.1% volatiles
● = 20.7% volatiles
x = 7.3% volatiles
– = computer model predictions
(From Wagner et al., 1987).

and a gas temperature of 1170 K, devolatilization and combustion of volatiles is completed within about 0.5 s, whereas the burning-off time of the char increases markedly with decreasing content of volatiles.

Levendis, Flagan, and Gavals (1989) studied mechanisms and rates of oxidation of char particles in the size range from a few μm to several tens of μm. The specific surface area of the char particles varied with the origin of the char (polymers with pore-forming additives). When heated in an inert atmosphere, the char particles maintained their amorphous nature up to 1600 K. However, when oxidized at 1600 K, the carbon matrix underwent partial graphitization.

Vareide and Sönju (1987) developed approximate computer models for predicting burn-off of char particles. Two alternative assumptions concerning the particle size and density were adopted, constant density/decreasing diameter and constant diameter/decreasing density. The total burn-off time decreased with initial particle diameter. In the shrinking particle model, the total burn-off time at 15 vol% O_2 and 1500 K was about 1 s for a 100 μm particle and 0.1 s for a 10 μm particle. The corresponding burn-off times predicted by the constant particle-diameter model were about 0.3 s and 0.04 s.

Essenhigh, Misra, and Shaw (1989) provided a comprehensive survey of the status on coal particle ignition in the light of the historical development over the previous two decades. The possibility of extending the single-particle results to dust clouds was examined. Theories are available, but experimental verification is incomplete. The boundary between conditions that produce heterogeneous ignition and those producing homogeneous ignition is not fully identified.

4.1.5
WOOD

Malte and Dorri (1981) developed a complete theory for the life of a single wood particle, of diameter from 100 μm upward, in a wood waste furnace of the grate type. The particle was followed from the moment of injection via drying and pyrolysis to completion of combustion. A main objective was to study the extent to which small particles were entrained by the upward airflow before combustion was completed.

Equation (3.16) in Chapter 3 was used to calculate the gravitational terminal settling velocity v_t of the particle. The drag coefficient C_D was determined experimentally for various particle sizes and shapes. One problem is that v_t depends on particle drying and devolatilization, because these processes reduce the particle density.

The homogeneous particle temperature was calculated by integrating the following equations, (4.11)–(4.15). The drying process was described by

$$\frac{\dot{Q}}{m_{\mathrm{DW}}} = (C + MC_l)\frac{dT}{dt} - h_v \frac{dM}{dt} \tag{4.11}$$

$$-\frac{dM}{dt} = \frac{\dot{Q}}{h_v m_{\mathrm{DW}}}(1 - e^{-M/b}) \tag{4.12}$$

where

$\dot{Q}$ is the rate of heat transfer to particle;
C is the specific heat of dry wood;
C_l is the specific heat of liquid water;
m_{DW} is the dry mass of wood particle;
T is the homogeneous particle temperature;
h_v is the latent heat of vaporization, including differential heat of wetting;
M is the fractional moisture content: mass H_2O/dry mass; parameter b (empirical correlation) equals

$$b = \frac{1.08\dot{Q}}{h_v m_{\mathrm{DW}}} + 0.14 \tag{4.13}$$

The pyrolysis process, neglecting particle swelling, was described by

$$\frac{\dot{Q}}{V_p} = \rho C \frac{dT}{dt} - [C_v(T - T_0) - q]\frac{d\rho}{dt} \tag{4.14}$$

$$-\frac{d\rho}{dt} = (\rho - \rho_F)k \tag{4.15}$$

where

ρ is the particle density at time t;
ρ_F is the final particle density;
V_p is the particle volume;
C_v is the specific heat of volatiles;
T_0 is the reference temperature;
q is the exothermic heat of pyrolysis at reference temperature;
k is the Arrhenius rate constant equal to $A \exp(-E/RT)$.

The value of k varies with temperature, activation energy, and the constant A. A and E in turn vary with the details of the composition of the wood, the rate of heating, and so forth. This aspect was investigated in some detail by Malte and Dorri (1981).

A computer model was used to simulate trajectories of wood particles of various sizes and shapes, in the waste furnace. It could be shown that particles of diameters smaller than 500 μm had a significant tendency to become entrained by the upward air in the furnace and escape ignition and combustion at the hot grate in the furnace bottom.

4.2
LAMINAR DUST FLAMES

4.2.1
LAMINAR FLAME PROPAGATION IN PREMIXED, QUIESCENT GASES

The basic concepts of flame propagation in dust clouds are adopted from premixed gas propagation theory. It is appropriate, therefore, to briefly introduce some central aspects of the latter.

The linear rate at which a laminar combustion wave or reaction zone propagates relative to the unburned gas of a flammable mixture is called the *fundamental* or *laminar burning velocity*, commonly denoted S_u. As pointed out by Kuchta (1985), this velocity is a fundamental property of the mixture and depends primarily on the thermal diffusivity $\lambda/\rho C_p$ of the unburned gas, where λ is the thermal conductivity, ρ is the density, and C_p is the specific heat at constant pressure of the unburned gas, and on the chemical reaction rate and heat of combustion of the gas. The reaction zone in a premixed gas is normally quite thin, on the order of 1 mm. According to the classical Mallard-le Chatelier (1883) theory, the fundamental laminar burning velocity of a homogeneous gas mixture equals

$$S_u = \frac{\lambda(T_b - T_i)}{\rho C_p L(T_i - T_u)} \tag{4.16}$$

where T_i is the ignition temperature of the gas mixture and L is the thickness of the reaction zone. One problem with this theory is that a relevant value of T_i is normally not known for a given gas mixture. The fundamental limitation of the theory is that it does not relate S_u to the heat release rate. Therefore, more refined theories have been developed, as are mentioned here.

Of great practical interest is the flame speed S_f; that is, the speed of the flame front relative to an observer or fixed geometries. It may be defined as

$$S_f = S_u + S_g \tag{4.17}$$

where S_g is the gas velocity component caused by the expansion and buoyancy of the combustion product gases. Figure 4.7 illustrates the experimental relationship among S_u, S_f, and S_g for spherical flame propagation in CH_4 air as a function of equivalence ratio (fraction of stoichiometric fuel concentration). The maximum S_f and S_u values occur on the rich side of stoichiometric composition and the ratio S_f/S_u is about 6. Under ideal adiabatic conditions, the maximum S_f/S_u ratio is about 7.5, which is typical of the combustion product expansion ratio E for most organic fuels. The plane, one-dimensional flame

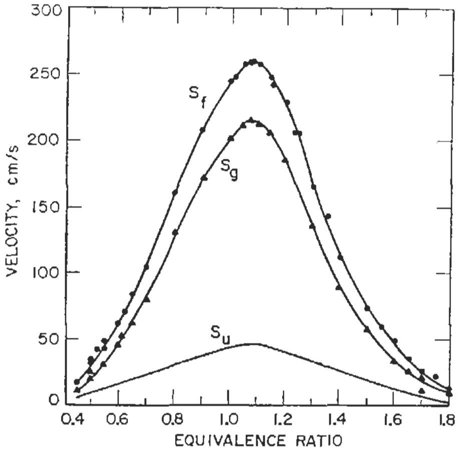


Figure 4.7 *Flame speed S_f, gas velocity S_g, and burning velocity S_u versus equivalence ratio for spherical methane/air flame propagation and atmospheric pressure (From Kuchta, 1985; originally from Andrews and Bradley, 1972).*

speed may be calculated from the following expressions:

$$S_f = S_u E = S_u \rho_u / \rho_b \tag{4.18}$$

$$S_u \rho_u / \rho_b = S_u \frac{M_u T_b p_u}{M_b T_u p_b} \tag{4.19}$$

where M is the molecular weight, T is the temperature (K), p is the pressure (absolute), ρ is the gas density, and the u and b subscripts refer to the unburned and burned states, respectively. In the case of spherical flame propagation, the radial flame speed is given by equations (4.18) and (4.19) if the flame thickness is negligible compared with the radius of the spherical flame surface. For finite flame thicknesses, methods for correcting for flame stretch have been developed, as shown by Kawakami, Okajima, and Tinuma (1988).

The burning velocity in air generally increases consistently with increasing initial temperature, whereas for many fuels, it decreases somewhat with increasing pressure. When the ratio of O_2/N_2 in the oxidizing gas is either smaller or larger than in air, the burning velocity decreases or increases correspondingly. In pure oxygen, burning velocities are considerably higher than in air because of increased reaction rates and heats, particularly at stoichiometric fuel concentrations, which are much higher in oxygen than in air at the same total pressure. Table 4.1 summarizes maximum S_u values for some gases mixed homogeneously with air, at atmospheric pressure and normal room temperature.

Table 4.1 Maximum fundamental burning velocities S_u for homogeneous mixtures of air and various combustible gases, at atmospheric pressure and normal room temperature

Fuel gas	**S_u [m/s]**
Hydrogen	3.25
Acetylene	1.60
Ethylene	0.80
Methane to n-heptane	0.42–0.47

Source: Data from Freytag, 1965; Zabetakis, 1965; and Kuchta, 1985.

In his book on combustion phenomena, Glassman (1977) reviewed various theories for the laminar burning velocity of gases. He showed the historical development from thermal diffusion theories via "particle" diffusion theories to comprehensive theories. The classical Mallard-le Chatelier theory (1883) [equation (4.16)] is a purely thermal diffusion theory, assuming the existence of a specific "ignition" temperature for the combustible mixture. This theory was later improved by Zeldovich and Frank-Kamenetzkii, who included the diffusion of molecules. Their theoretical derivation was presented in detail by Semenov (1951) and Glassman (1977). Diffusion of free radicals and atoms was included at a later stage. Tanford and Pease (1947) suggested that the flame propagation process in a gas mixture is governed essentially by the diffusion of free radicals and not by the temperature gradient, as assumed in thermal diffusion theories.

Glassman (1977) showed, however, that both a modified form of the Mallard-le Chatelier equation (4.16) and the equation resulting from the more complex approach by Zeldovich, Frank-Kamenetzkii and Semenov can be expressed as

$$S_u \sim (\alpha G)^{1/2} \tag{4.20}$$

where α is the thermal diffusivity and G is the chemical reaction rate.

4.2.2

DIFFERENCES BETWEEN FLAMES IN PREMIXED GAS AND IN DUST CLOUDS

Leuschke (1965) pointed out some characteristic differences between a laminar, premixed gas flame and a laminar dust flame. One important difference is that the reaction zone in the dust cloud is considerably thicker than in the gas, irrespective of the type of dust, and on the order of at least 10–100 mm. When discussing this feature of the dust flame, Cassel (1964) distinguished between two types of flames. The first, the Nusselt type, is controlled by diffusion of oxygen to the surface of individual, solid particles, where the heterogeneous chemical reaction takes place. In the second type, the volatile flame, the rate of gasification, pyrolysis, or devolatilization is the controlling process and the chemical reaction takes place mainly in the homogeneous gas phase. In Nusselt-type flames, the greater thickness of the combustion zone, compared with that of premixed gas flames, results from the slower rate of molecular diffusion, compared to diffusion in premixed, homogeneous gases. In the volatile flame type, the greater flame thickness is due to the preheating zone, where volatiles or pyrolysis gases are driven out of the particles ahead of the flame. When mixed with air, these gases and vapors burn almost as a premixed gas. The combustion of the remaining solid char particles occurs subsequently at a slower rate in the tail of the flame, and therefore the volatile flame in clouds of coals and organic dusts is also in fact coupled to a Nusselt-type flame.

In metals, low melting-point materials may oxidize in the vapor phase, but due to the oxide film around each particle, this does not result in a homogeneous metal vapor/air flame. Because of the large heat of combustion per mole of O_2 for example, of aluminum and magnesium dust compared with organic dusts, the temperature of the burning particles is very high and thermal radiation plays a central role in the transfer of heat in the combustion wave. Radiative heat transfer is also supposed to play a role in coal dust flames. However, because the thermal radiation is proportional to the fourth power of the temperature, the role of thermal radiation in coal dust flames is less important than in, for example, aluminum and magnesium dust flames. Radiative heat transfer in dust flames is a complex process, and it is of interest to note that Elsner, Köneke, and Weinspach (1988) investigated the solid particle emissivity in dust clouds as a function of dust cloud thickness, specific surface area of the particles, dust concentration, and absorption and scatter coefficients. Experiments were conducted with fluidized bed ash and quartz sand. Good agreement was found between the experiments and a theoretical equation.

Leuschke (1965) conducted an illustrative series of experiments demonstrating the importance of radiative heat transfer in metal dust flames, using the experimental setup illustrated in Figure 4.8. Two transient dust clouds were generated simultaneously on the two sides of a double-glass window, one being ignited immediately by a gas flame. It was then observed whether the radiation from the burning cloud was able to ignite the other cloud.

Table 4.2, summarizing the results, shows that only the flames of Zr, Ti, Al, and Mg produced sufficient radiation to ignite the other cloud. Ignition of graphite was not accomplished at all, in agreement with the inability of graphite dust clouds to propagate a self-sustained flame in air at normal temperature and pressure. The reason why the gas

Table 4.2 Ignition of various dust clouds by radiation from various dust flames, experiments according to Figure 4.8

Radiating cloud / Cloud to be ignited by radiation	Zirconium	Titanium	Aluminum (pyro)	Aluminum (greased)	Magnesium	Carbonyl iron	Iron	Graphite	Gas-flame coal	Brown coal
Zirconium	+	+	+	+	+	–	–		–	–
Titanium	+	+	+	–	+					
Aluminum (pyro)	+	+	+	+	–					
Aluminum (greased)	+	+	+	–	+					
Magnesium	+	+	–	–	–					
Carbonyl iron	+	+	+	+	+	–				
Iron	+	+	–	–	–		–			
Graphite	–	–	–	–	–			–		
Gas flame coal	+	+	–	–	–				–	
Brown coal	–	–	–	–	–					–

+ = ignition, – = no ignition.
Source: Leuschke, 1965.

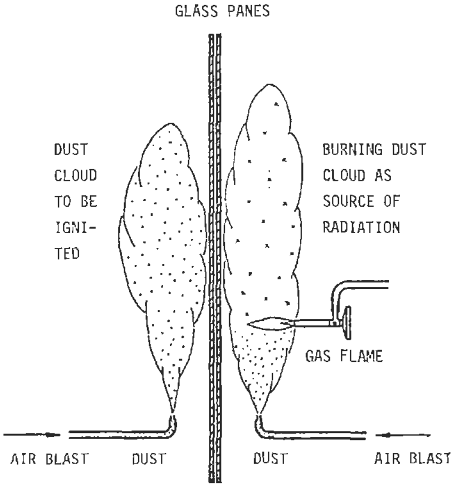


Figure 4.8 *Experiment demonstrating the ignition of a cloud of metal dust in air by radiation from a burning cloud of the same dust, through a double-glass window (From Leuschke, 1965).*

flame coal could be ignited by the radiation from zirconium and titanium clouds, whereas the brown coal did not ignite, is not clear. Leuschke (1965) pointed out that clouds in air of iron and zinc powder, wood and cork dust, and lycopodium ignited easily when exposed to light flashes of the type used for illumination in photography. As far as self-sustained flame propagation in dust clouds is concerned, Table 4.2 confirms that radiative heat transfer is much more important in high-temperature metal flames than in flames of organic materials and coal.

With respect to the role of radiative heat transfer in dust flames, Cassel (1964) reasoned that losses from the heat generated in the combustion zone necessarily make the maximum temperatures actually attained considerably lower than the temperatures predicted thermodynamically for adiabatic conditions. However, in the interior of sufficiently large dust clouds, temperatures undoubtedly approach theoretical values. Therefore, as heat losses by radiation decrease with decreasing surface-to-volume ratio of the burning cloud, dust flames should show a positive correlation between flame size and burning velocity not encountered in combustible gas mixtures. Therefore, in the absence of other scale effects, larger high-temperature dust flames may be expected to burn faster than smaller ones.

Another difference between flame propagation in a premixed gas and dust clouds has been elucidated by Goral, Klemens, and Wolanski (1988). They studied upward propagation of flames in a lean methane/air mixture to which had been added inert particles (sand). It was found that the upward flame velocity increased with increasing sand grain size, from 0.33 m/s for the 5.1 vol% methane/air with no sand particles, via 0.4 m/s for 40 μm particles, 0.65 m/s for 180 μm particles to 0.75 m/s for 360 μm particles. The effect was attributed mainly to the enhanced combustion due to the microturbulence generated in the wake of the falling particles. However, thermal radiation effects were also assumed to play a role.

4.2.3

EXPERIMENTAL BURNING VELOCITIES, FLAME THICKNESSES, QUENCHING DISTANCES, AND TEMPERATURES OF LAMINAR DUST FLAMES

In the case of premixed gases, the properties of laminar flames can be investigated in detail in special stationary burners. The same technique has been adopted in the study of laminar dust flames. However, as Lee (1987, 1988) pointed out, laminar dust flames are difficult to stabilize without causing significant cooling of the flame. Therefore, such stabilized flames are nonadiabatic, and average burning velocities are lower than for an adiabatic flame. In addition, the flame is not uniform over its cross section, and burning velocities and flame thicknesses are not always easy to define. Nevertheless, much valuable information on the nature of laminar dust flames has been obtained from stationary burner flame studies. Section 9.2.4.2 in Chapter 9 gives references to further works on laminar flame propagation in dust clouds.

4.2.3.1

Metal Dusts

Cassel (1964) developed a special burner for studying stationary propagation of flat "laminar" graphite and metal dust flames. Circular Mache-Hebra nozzles were used to ensure a reasonably uniform distribution of the upward velocity of the dust cloud into the flame region. Once ignited, the flat dust flame floated approximately 20–30 mm above the burner port. The flame was stabilized by an enveloping divergent gas stream without using a pilot flame. Burning velocities were determined photographically both

Table 4.3 Burning velocities and brightness temperatures for flat, laminar flames of 6 μm aluminum particles in various oxidizer gases at atmospheric pressure

Gas mixture	Dust concentration (g/m^3)	Nozzle diameter (cm)	Flame area (cm^2)	S_u (m/s)	Brightness temperature (K)
Air	200	0.95	1.13	0.21	1790
	250	0.95	1.33	0.30	1910
	300	0.95	1.54	0.35	2060
$O_2 + 4$ Ar	200	0.45	0.21	0.21	1850
	250	0.45	0.26	0.28	1910
	300	0.45	0.31	0.32	1960
$O_2 + 4$ Ar	200	0.95	0.87	0.23	1980
	250	0.95	1.08	0.32	2080
	300	0.95	1.17	0.38	2140
$O_2 + 4$ Ar	200	1.30	1.30	0.27	2070
	250	1.30	1.42	0.36	2230
	300	1.30	1.48	0.41	2320
$O_2 + 4$ He	200	0.95	0.87	0.70	2090
	250	0.95	1.08	1.00	2320
	300	0.95	1.23	1.15	2430

Source: Cassel, 1964.

by measuring the minimum upward vertical particle velocity in the preheating zone below the flame and the particle velocity in the cold dust cloud further down.

Some results for dust clouds of 6 μm aluminum particles are given in Table 4.3. The results for argon/air mixtures show that both the burning velocity and the brightness temperature increase somewhat with nozzle diameter or flame area. This indicates that the values in Table 4.3 are minimum values in the dust explosion context. The brightness temperatures were measured by optical pyrometry. Because the burning dust cloud is not a black body, the true flame temperatures are higher than the brightness temperatures. Cassel, using the particle track method of Fristrom et al. (1954), estimated the true temperature of a 240 g/m^3 cloud of 6–7 μm diameter aluminum particles, burning in a mixture of 20 vol% O_2 and 80 vol% Ar at atmospheric pressure, to about 2850 K. If Ar is replaced by He, the temperature estimate rises to 3250 K. In both cases, the ratio of the estimated true flame temperature and the brightness temperature is about 1.4.

If this factor is applied to the brightness temperatures in Table 4.3 of the flames in air, the flame temperature estimates are 2500 K for 200 g/m^3, 2670 K for 250 g/m^3, and 2900 K for 300 g/m^3. Closed-bomb experiments with aluminum dust clouds in air give the highest peak pressures, with dust concentrations above the stoichiometric, typically in the range of 500 g/m^3. This could indicate that the temperature of a flame of 500 g/m^3 fine aluminum particles in air at atmospheric pressure would exceed 3000 K.

In the discussion published with Friedman and Macek's (1963) paper, Glassman asserted that the temperature of aluminum particle diffusion flames does not depend on the concentration of oxygen in the atmosphere, except at very low concentrations. The flame temperature equals the boiling point of the oxide, 3800 K.

Cassel (1964) has a photograph of a flat, laminar flame of 230 g/m^3 6 μm diameter aluminum particles in air at atmospheric pressure, which suggests a flame thickness on the order of 10 mm; that is, at least 10 times the characteristic flame thickness of laminar premixed gas flames. The burning velocity for the 6 μm aluminum particles in air varied, as seen from Table 4.3, with the dust concentration, being 0.21 m/s for 200 g/m^3 and 0.35 m/s for 300 g/m^3.

Other experiments by Cassel (1964) showed that the burning velocity of aluminum/air clouds also increased with decreasing particle size. At 200 g/m^3, it was roughly 0.2 m/s for a "<30 μm" atomized aluminum powder and 0.4 m/s for "<10 μm" quality. The latter value agrees favorably with the maximum value of 0.42 m/s determined by Ballal (1983) for aluminum of a volume surface mean diameter (D_{32}) of 10 μm. The maximum flame speed occurred close to the stoichiometric concentration 310 g/m^3. Ballal (1983) conducted his sophisticated experiments in a special vertical explosion tube during free fall (zero gravity conditions), and it is interesting to observe that, for particle sizes of about 10 μm, gravitational effects did not seem to play a dominating role in the laminar flame propagation through aluminum dust clouds.

Gardiner, Caird, and Bardon (1988) studied flame propagation in comparatively small, electrostatically suspended clouds of 20 μm volume surface mean diameter aluminum particles in air in a small semi-closed cylindrical vessel and found maximum flame speeds in excess of 2.0 m/s.

Alekseev and Sudakova (1983) measured radial flame speeds of spherical flames in essentially unconfined clouds of five different metal powders. The experimental dust clouds were generated by dispersing a given quantity of dust by means of a special atomizer during a period of 0.4 s. A glowing resistance wire coil or a pyrotechnical charge was used to ignite the dust cloud of about 10 liter volume at its center. Flame propagation was recorded by high-speed photography. Dust concentration was assessed both from the volume of the dust cloud just prior to ignition and by sampling the cloud at various locations using a fast-response probe. Figure 4.9 gives some results for the five powders specified in Table 4.4. Particle size clearly plays a key role and explains, for example, why the magnesium powder (median particle size of about 45 μm) gave a considerably lower flame speed than the aluminum powder (median particle size of about 9 μm). As seen from Figure 4.9, the radial flame speed for the aluminum powder at 300 g/m^3 was about 1.5 m/s.

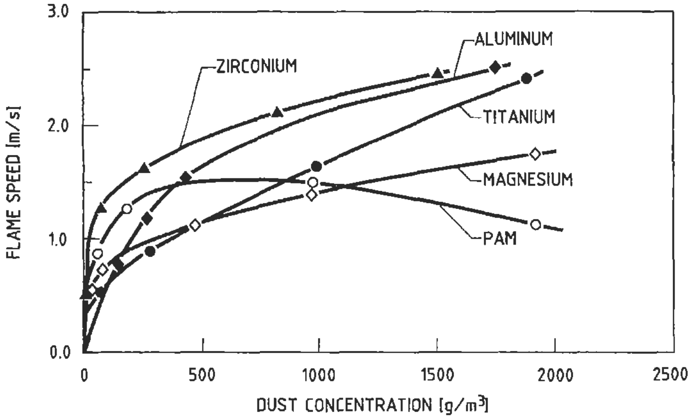


Figure 4.9 *Flame speed as a function of dust concentration in unconfined clouds of metal dusts, special flame propagation (From Alekseev and Sudakova, 1983).*

Table 4.4 Size distributions of five metal powders used in flame propagation experiments

Powder type	Cumulative mass fraction (%) finer than stated particle size					
	6 μm	10 μm	16 μm	25 μm	40 μm	50 μm
Zirconium	6	14	23	39	92	100
Aluminum	21	58	88	97	99	100
Titanium	1	1	4	8	22	100
Magnesium	2	5	10	20	75	100
PAM*	2	3	6	29	74	100

*Aluminum/magnesium alloy.
Source: Alekseev and Sudakova, 1983.

Experiments in closed bombs give pressure rise ratios up to 12.5 for explosions of aluminum dust in air (BIA/BVS/IES, 1987). For ideal adiabatic expansion and assuming a specific heat ratio of 1.4, this gives expansion ratios of up to 6.1, and according to equation (4.18), the radial flame speed is then 6.1 times the radial burning velocity. The burning velocity corresponding to a flame speed of 2.5 m/s is then about 0.4 m/s; that is, close to the value found in laminar burner experiments for aluminum flames.

Jarosinski et al. (1987) determined the quenching distance for laminar flames in air of aluminum flakes of thickness 0.1 μm and average diameter 15 μm and atomized aluminum particles of average diameter 8 μm. The smallest quenching distance found for both dusts was 10 mm. This occurred in the dust concentration range 700–1000 g/m^3.

4.2.3.2
Coal Dusts

In a comprehensive survey of a number of investigations on the propagation of laminar pulverized coal dust/air flames, Smoot and Horton (1977) discussed factors influencing experimentally determined burning velocities, flame temperatures, and flame thicknesses. Most experiments are performed by stabilizing dust flames in burners of various kinds. Due to heat losses by radiation from the hot dust particles and conduction, typical stabilized burner flames have temperatures lower than the adiabatic flame temperature. In principle, heat losses can be avoided by using burners of very large diameters or equipped with walls having temperature and emissivity profiles matching those of the flame. However, according to Smoot and Horton, the use of such devices had not been reported up to the time of their survey (1977).

Smoot and Horton found large differences in burning velocities observed by various investigators that could not be explained in terms of variations in dust properties or dust concentration. They considered incomplete dispersion of fine cohesive dusts as the main source of error (see Chapter 3). Figure 4.10 illustrates how improved dispersion of a fine coal dust increases burning velocity by 50% and even more. Some main conclusions from the survey of Smoot and Horton are given in Table 4.5.

Horton, Goodson, and Smoot (1977), investigating flat, laminar coal dust flames, found that the peak burning velocities for a 9 μm (mass average particle size) Pittsburgh coal dust in air was about 0.33 m/s, whereas a coarser fraction of the same coal (33 μm mass average fraction) gave peak velocities of about 0.22 m/s. A similar influence of particle size was found for a Pocahontas coal.

Table 4.5 Summary of some experimental observations for laminar coal dust flames in air at atmospheric pressure

1. Observed flame velocities depend on the burner used.
2. Peak burning velocities range mostly from 0.05 to 0.35 m/s, depending on burner design, coal type, and particle size. An exception was the high value of 0.86 m/s measured by Ghosh, Basu, and Roy (1957), which was attributed to the use of a furnace with preheated walls.
3. Peak burning velocities occur at higher fuel concentration than the stoichiometric, somewhere in the neighborhood of the stoichiometric concentration for combustion of the volatile matter. The peak flame velocity increases with the specific surface area of the coal dust.
4. The rich flammability limit occurs at higher fuel concentrations than that giving the peak burning velocities, as compared to gaseous flames.
5. Decreasing coal-dust particle size increases burning velocity on the lean side of the peak but may decrease it on the rich side. Also, smaller particles shift the peak and rich flammability limit to a leaner concentration.
6. Increasing volatiles content increases the burning velocity and slightly shifts the peak to a leaner concentration.
7. Oxygen enrichment beyond the 21 vol% in air increases burning velocity, as does the addition of methane.
8. Thicknesses of steady, laminar, coal dust flames are usually on the order of 5 mm, but larger thicknesses have been observed, especially for larger particles at high coal dust concentrations.
9. Measured peak flame temperatures range from 1000 to 1500 K and may be correlated with coal dust concentration. These measured temperatures may be lower than the real temperatures due to inadequate measurement techniques.
10. In the flame front, liberated volatile matter burns rapidly in the gas phase, while there is very little heterogeneous combustion of the char.
11. In traversing the flame front, the irregularly shaped solid particles soften and become rounded and filled with blow holes but remain about the same size.
12. A considerable amount of volatile matter remains in the char leaving the flame front, the amount being a strong function of coal dust concentration.
13. The extent of coal devolatilization is related especially to coal dust concentration.
14. The volatile material liberated during rapid pyrolysis in this type of flame has a higher C/H ratio than the volatile matter liberated during proximate analysis.
15. Only small amounts of H_2 or CH_4 are observed in the flame.

Source: Smoot and Horton, 1977.

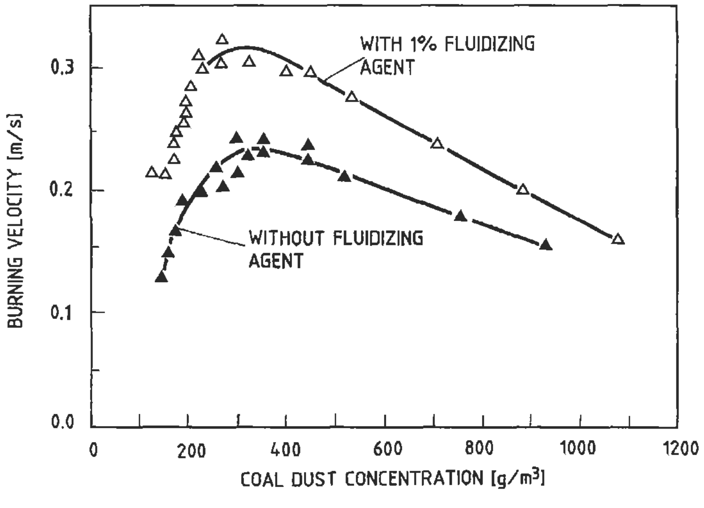


Figure 4.10 *Effect of very fine SiO2 fluidizing agent (Acrosil) on the burning velocity of an air suspension of 10 µm, 28% volatile content Sewell coal dust (From Smoot and Horton, 1977).*

The question of what are the true laminar burning velocities for coal dust clouds to some extent remains unanswered. The true peak values are probably somewhat higher than 0.35 m/s but certainly lower than the exceptional value of 0.86 m/s measured by Ghosh, Basu, and Roy (1957) (see Table 4.5, observation 2).

In a comprehensive investigation comprising several types of dusts, Ballal (1983) determined the laminar burning velocity in clouds of coal dust in air under zero gravity conditions, using a free-fall explosion tube. For a coal dust of 8 μm surface-volume diameter (D_{32}) and 13.8% volatile matter, the maximum burning velocity of 0.11 m/s was found for dust concentrations close to the stoichiometric, that is, 210 g/m^3. For coals of higher volatile contents, the maximum values were about 0.25 m/s (40% volatiles and $D_{32} =$ 12 μm), 0.17 m/s (27% volatiles and $D_{32} = 11$ μm), and 0.12 m/s (37% volatiles and $D_{32} =$ 47 μm). The experimental concentration range did not extend beyond the stoichiometric concentration for which the maximum values were obtained. However, the trend of the experimental burning velocity-versus-dust concentration curves indicated that even higher burning velocities would have been found for dust concentrations somewhat higher than the stoichiometric. It is interesting to note that the burning velocities measured by Ballal for coal/air under zero gravity conditions are close to those found under normal gravity conditions by Smoot and Horton (1977) and Horton et al. (1977).

Hertzberg, Zlochower, and Cashdollar (1986) analyzed experimental data from explosions of Pittsburgh seam bituminous coal dust in a closed bomb. When assuming that all the volatiles participated in the combustion reaction and treating the char as an inert substance, they found that the theoretical adiabatic maximum explosion pressures and maximum flame temperatures were considerably higher than the experimental values. Maximum theoretical adiabatic flame temperatures were 2500 K for constant volume and 2200 K for constant pressure combustion. The experimental maximum value for constant volume was 1850 K. Details of the experimental method used for measuring coal dust flame temperatures were given by Cashdollar and Hertzberg (1983). Hertzberg et al. (1986) attributed the discrepancy between idealized theory and experiment to incomplete devolatilization. They found that the effective fraction β of volatiles that can take part in the combustion is a function of the intrinsic devolatilization rate constant, the effective heating flux of the approaching flame, the decomposition chemistry, and the time available for devolatilization. The experimental data for maximum constant-volume explosion pressures could be readily interpreted in terms of estimated β factors. Figure 4.11 shows how the

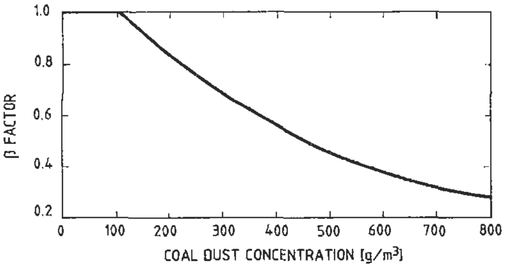


Figure 4.11 *Fraction of coal volatiles, β, assumed to contribute to flame propagation to obtain agreement between measured explosion pressures and calculated pressures for constant volume combustion (From Hertzberg et al., 1986).*

fraction of volatiles assumed to take part in the combustion of Pittsburgh seam bituminous coal dust decreases with increasing dust concentration.

In a subsequent paper, Hertzberg et al. (1987) formulated a three-stage model for coal dust flame propagation:

1. Heating and devolatilization of dust particles.
2. Mixing of emitted volatiles with air in the space between the particles.
3. Gas phase combustion of premixed volatile/air.

Each stage is characterized by a time constant. For small particles and low dust concentrations, the combustion process is controlled by stage 3, whereas for large particles and high dust concentrations, stage 1 controls the combustion rate. When discussing the influence of particle size on devolatilization in coal dust flames, Hertzberg et al. (1987) suggested that, for particles smaller than 50–100 μm diameter, devolatilization is complete and not rate limiting for the combustion reaction; that is, β in Figure 4.11 is equal to unity. On the basis of measurement of pyrolysis rates of single particles and microscopic studies of particle morphology, they concluded that the pyrolysis wave preceding a coal dust flame is nonisothermal, with a velocity proportional to the net absorbed heat flux intensity and inversely proportional to the overall enthalpy change of the combustion reaction.

In view of Hertzberg et al.'s suggestion of a limiting particle diameter of 50–100 μm, it is interesting to consider the influence of particle size on maximum explosion pressure and maximum rate of pressure rise of lignite dust in air in a 1 m^3 vessel, as measured by Scholl (1981). As shown in Figure 4.12, there was no further systematic increase of the two parameters with decreasing particle size below 60–80 μm diameter, in accordance with what would be expected on the basis of the hypothesis of Hertzberg et al.

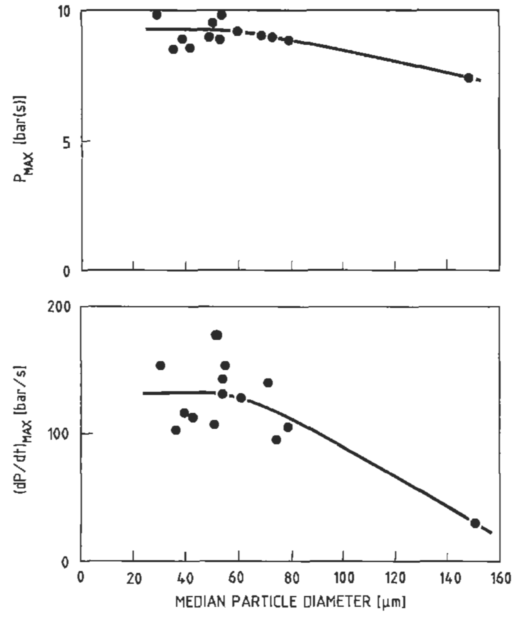


Figure 4.12 *Explosion characteristics of lignite dusts in a 1 m^3 closed vessel as a function of median particle size (From Scholl, 1981).*

Bradley, Habik, and Swithenbank (1986) simulated the combustion of rapidly devolatilizing coal dusts by generating stabilized laminar flames of mixtures of <10 μm diameter graphite dust and methane in air. The laminar burning velocities measured agreed well with the theory of coal dust flame propagation, assuming rapid devolatilization and subsequent gas phase mixing and no heat sink influence by the graphite particles. Apart from radiative losses from the particles, which were also accounted for in theory, the flames were in fact close to adiabatic. The theoretical prediction also agreed well with experimental burning velocities for coal dusts as long as the particle diameter did not exceed 10 μm and the volatile content of the coal was greater than about 25%.

In a subsequent study Bradley, Dixon-Lewis, and Habik (1989) investigated the burning velocities of CH_4/air/graphite dust flames near the minimum explosible concentration at subatmospheric pressure of 0.14 bar(abs). On the basis of an indicated experimental peak flame temperature of 1550 K at the limit concentration for flame propagation, a theory was developed that enabled computation of chemical species concentration profiles, gas temperatures, and heat release rates for flames at atmospheric pressure. As an example, it was found that the laminar burning velocity for a fuel concentration corresponding to an equivalence ratio of 0.72 decreased from 0.18 m/s for methane as the only fuel to 0.06 m/s for a fuel mass ratio of CH_4/graphite of 0.2. The relevance of assuming that CH_4/graphite mixtures can be used for simulating coal dust mass was investigated theoretically.

The lower experimentally determined limit of volatile content of the coal for a cloud of coal dust to be able to propagate a self-sustained flame at normal atmospheric conditions is about 13% according to Cybulski (1975) and Ballal (1983) and 8–10% according to Scholl (1981).

It should be mentioned that Helwig (1965), who used a 43 liter closed bomb, found that the rate of explosions of coal dust containing 10–50% volatiles, did not increase monotonically with decreasing particle size. Instead, the explosion rate for the finest fraction, of 0–10 μm particle diameter, was systematically lower than for the most explosible size range 20–30 μm. It is not clear whether incomplete dispersion of the finest particle fraction contributed to this effect.

Jarosinski et al. (1987) measured the quenching distance for flames in air of a <74 μm bituminous coal dust of 32% volatile matter and the same dust ground to <5 μm particle diameter. The quenching distances were 190 mm for the <74 μm dust and 25 mm for the <5 μm one. The reason for these unexpectedly high values is not clear.

4.2.3.3
Organic Materials

Laminar 20 mm diameter flames of lycopodium/air and polyvinyl alcohol/air were studied by Kaesche-Krischer and Zehr (1958) and Kaesche-Krischer (1959). The burning velocity, defined as the ratio of airflow to flame cone area, was determined photographically from the height of the flame cone. Some results are given in Figure 4.13. Lycopodium/air flames of dust concentrations lower than 180 g/m^3 and higher than 500 g/m^3 were difficult to stabilize (stoichiometric concentration ≈ 125 g/m^3). The appearance of a stabilized lycopodium/air flame was very similar to that of a rich hydrocarbon/air flame, that is, a blue flame front followed by a more or less luminous soot edge. Approximate thermocouple measurements of flame temperatures showed about 1800 K

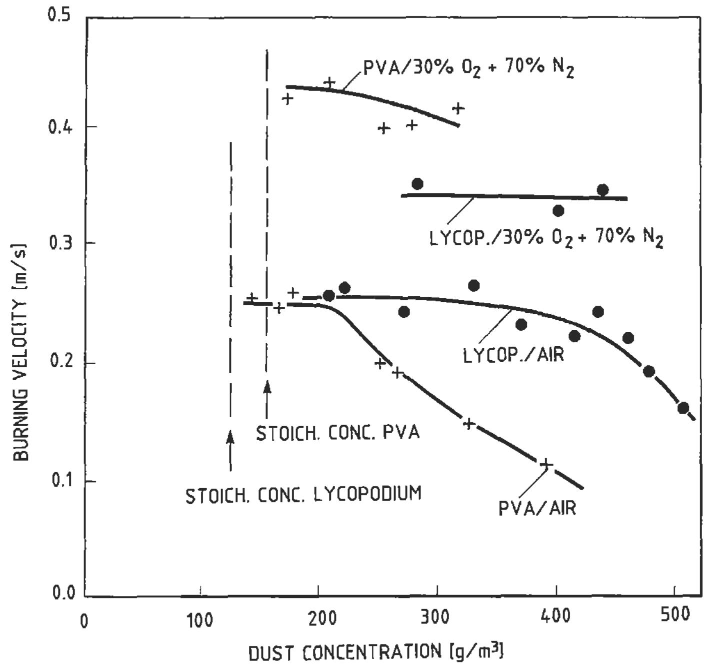


Figure 4.13 *Burning velocities of flame of lycopodium and polyvinyl alcohol dust (<60 μm particle diameter) flames as functions of dust concentration. The dotted stoichiometric concentration lines refer to dust in air only (Data from Kaesche-Krischer and Zehr, 1958, and Kaesche-Krischer, 1959).*

for a 180 g/m^3 flame and 1100 K for a 500 g/m^3 flame. Figure 4.13 shows the measured burning velocities as a function of the dust concentration. In the range 180–300 g/m^3, the burning velocity of lycopodium flames has a maximum value of about 0.25 m/s. The corresponding concentration range for the PVA dust was 140–220 g/m^3. Figure 4.13 also shows that an increase of the oxygen percentage in the gas from 21 for air to 30, caused a significant increase of the measured burning velocities for both dusts, in accordance with expectations. The photographs provided by Kaesche-Krischer and Zehr (1958) indicate typical thicknesses of lycopodium flames of a few mm.

Kaesche-Krischer implied that the differences in the concentration ranges giving the highest burning velocities for the two dusts were due to a higher volatile content in the PVA than in lycopodium, assuming that the flame essentially propagates through a homogenous mixture of volatiles and air. This is in accordance with the findings of Hertzberg et al. (1986) for coal dust and polyethylene.

Mason and Wilson (1967) investigated laminar flames of lycopodium in air in the dust concentration range 125 to 190 g/m^3. When accounting for wall cooling effects in their experiments, they arrived at maximum burning velocities similar to those found by Kaesche-Krischer and Zehr (1958), about 0.25 m/s. Mason and Wilson also measured some temperatures in a 140 g/m^3 flame using a 25 μm thermocouple. At 2 mm below the flame front, the temperature was 330–350 K; whereas 1.5 mm above the flame front, it was about 1800 K. The latter figure is in complete agreement with the temperature measured by Kaesche-Krischer and Zehr (1958) in a 180 g/m^3 lycopodium/air flame.

These measurements showed that the preheating zone was about 2 mm thick and on the same order as for gases of similar burning velocities and that the total thickness of a laminar lycopodium/air flame is on the order of a few mm.

More recently Proust and Veyssiere (1988) studied the propagation of genuinely laminar dust flames in clouds of maize starch of 6% moisture content in air. They used the comparatively large apparatus illustrated in Figure 4.14. Dust clouds were generated in

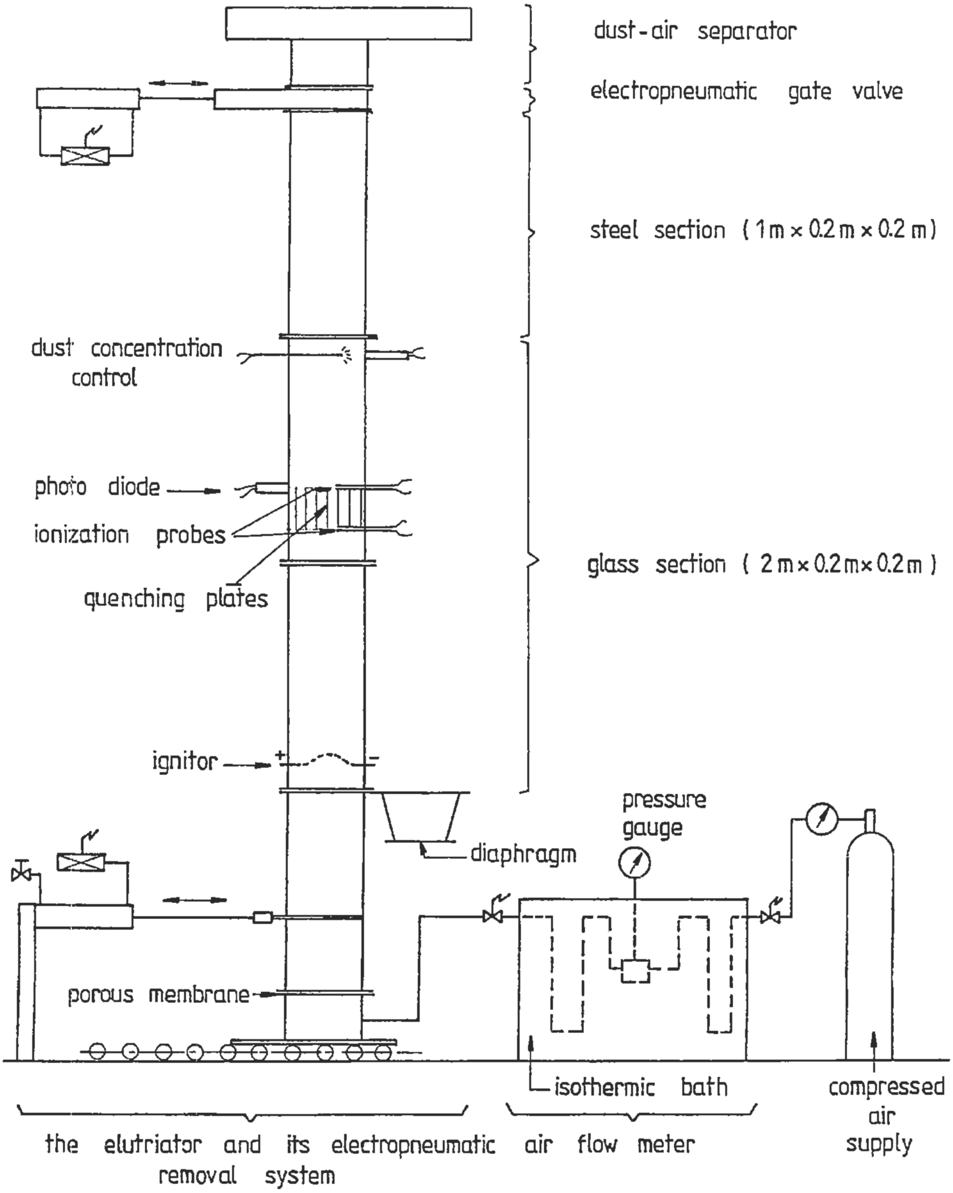


Figure 4.14 *Large vertical duct for studying flame propagation in dust clouds (From Proust and Veyssiere, 1988).*

the vertical experimental glass duct of 0.2 m × 0.2 m cross section and 2 m height by low-velocity elutriation from a fluidized bed of 600 g of starch resting on a porous membrane at the bottom of the system. The average vertical air velocity was on the order of 0.1 m/s. A battery of parallel vertical steel plates 0.5 mm thick was inserted across the whole cross section of the duct when quenching distances were measured. Average dust concentrations were determined from the dust mass lost from the fluidized bed as a function of time and the airflow through the system. A laser tomography system was used to control the homogeneity of the dust cloud.

Laminar burning velocities were determined from the measured flame speeds and photographically estimated flame surface areas, as in the case of Kaesche-Krischer (1959), but the applicability of this method to flame propagation in tubes is not obvious. (See specific comment in Section 9.2.4.2 in Chapter 9.) To obtain proper laminar flame propagation, it is necessary to avoid the buildup of fundamental-mode standing acoustic wave motion in the duct. Such waves are easily generated by the gas expansion following the initial flame and can subsequently interfere with the flame propagation. Proust and Veyssiere solved this problem by fitting a special damping diaphragm at the open bottom end of the duct (see Guenoche, 1964).

A series of photographs of the propagating laminar maize starch flame is shown in Figure 4.15. Figure 4.16 shows the upwards laminar flame front velocity (duct closed at the upper end) as a function of the dust concentration. The velocity was measured by means of ionization probes. The maximum value of 0.63 m/s occurred close to the stoichiometric dust concentration 235 g/m^3. A corresponding laminar burning velocity of 0.27 m/s was deduced by assuming that its value normal to the flame surface was uniform across the entire flame hemisphere. However, this assumption is not necessarily justified.

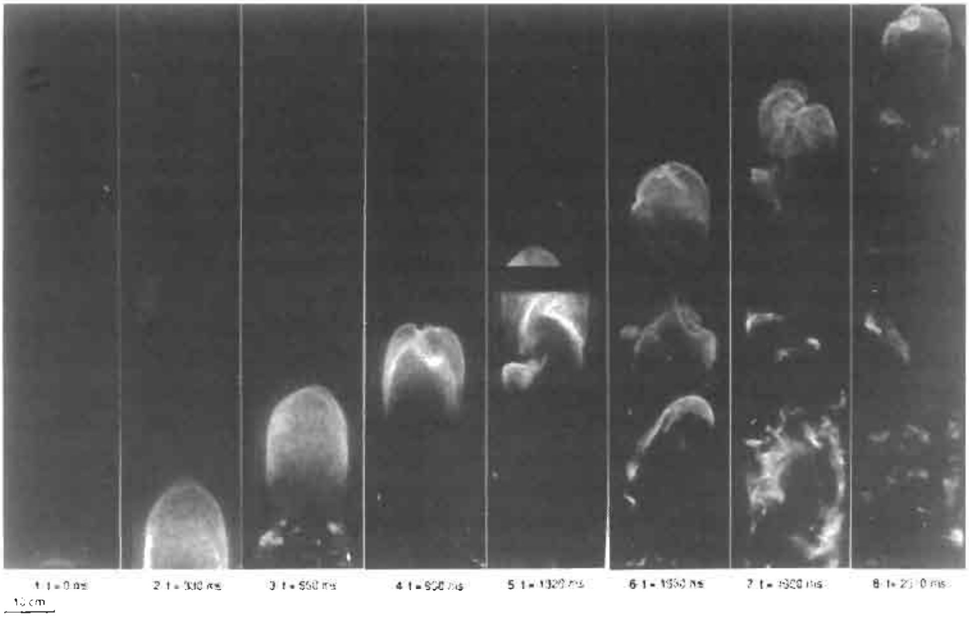


Figure 4.15 *Photographic records of an upward propagating laminar flame in a 120 g/m^3 cloud of maize starch in air (From Proust and Veyssiere, 1988).*

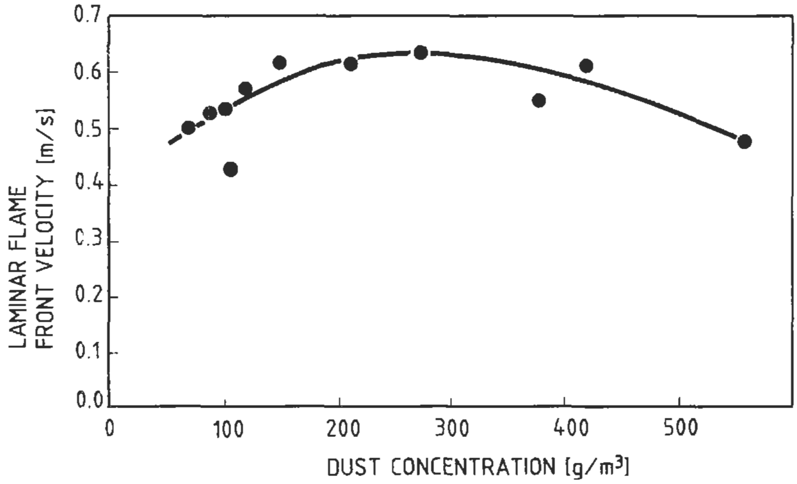


Figure 4.16 *Upward laminar flame front velocity through a cloud of maize starch in air as a function of dust concentration (From Proust and Veyssiere, 1988).*

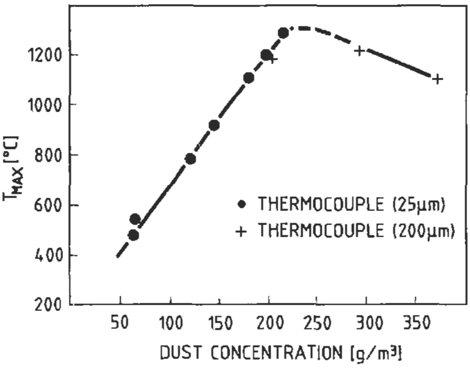


Figure 4.17 *Variation of the maximum temperature of maize starch flames with dust concentration (From Proust and Veyssiere, 1988).*

The flame temperature was measured by means of thermocouples of either 25 μm or 200 μm junction diameter. The results are shown in Figure 4.17.

The maximum value of about 1600 K was obtained close to the stoichiometric dust concentration of 235 g/m^3. This maximum is somewhat lower than the maximum temperatures of about 1800 K measured in laminar burner flames of lycopodium and polyvinyl alcohol.

The results from measurement of quenching distances for laminar flames of maize starch in air are shown in Figure 4.18.

The quenching distance was defined as the maximum distance between the vertical parallel plates that prevented laminar flame propagation through the plate battery and further upward in the test duct. As Figure 4.18 shows, the quenching distance depends on the dust concentration. Below about 80 g/m^3, flame propagation is impossible even with an interplate distance of 30 mm, and this therefore also is the minimum explosible concentration for upward laminar flame propagation. With increasing dust concentration, the quenching distance decreases systematically and reaches about 7 mm at about the

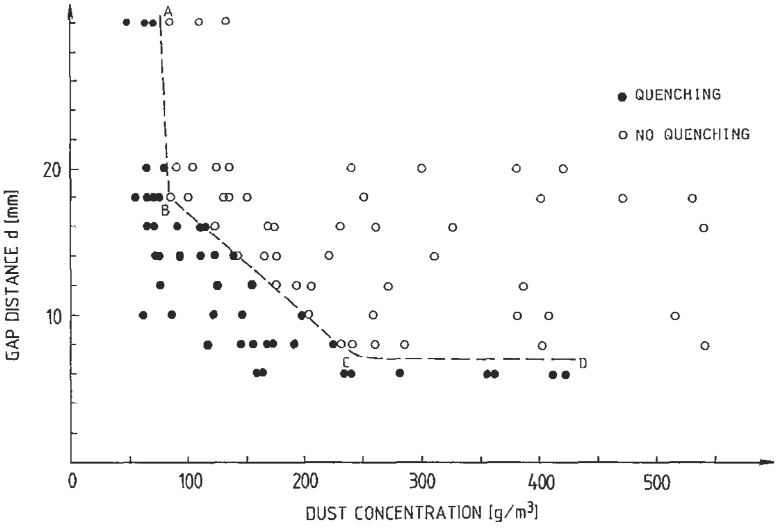


Figure 4.18 *The quenching distance of laminar flames of maize starch/air mixtures as a function of the dust concentration (From Proust and Veyssiere, 1988).*

stoichiometric concentration of 235 g/m^3. For higher dust concentrations, up to 550 g/m^3, the quenching distance remains unchanged at the minimum value of 7 mm.

The lowest value of about 7 mm for the quenching distance for maize starch/air mixture is in close agreement with the lowest value of about 6 mm found by Jarosinski et al. (1987) in a similar experimental configuration. However, these workers found their lowest value in the concentration range 500–1100 g/m^3, whereas the values in the range <500 g/m^3 increased with decreasing concentration, being about 10 mm at 400 g/m^3.

Proust and Veyssiere (1988) also determined the thickness of the laminar starch dust/air flame, using the criterion for laminar gas flames proposed by Jarosinski (1984).

$$\text{Flame thickness} = 2(T_b - T_u)/(dT/dx)_{\max} \tag{4.21}$$

In spite of some experimental difficulties, they were able to identify a flame thickness of 3–4 mm at stoichiometric dust concentration. According to Jarosinski (1984), there is a factor of 2 between the quenching distance and the thickness of a laminar gas flame, which was also the result obtained by Proust and Veyssiere for their laminar flame of maize starch/air.

Comparing with properties of methane/air flames, Proust and Veyssiere summarized their results for 6% moisture content maize starch as shown in Table 4.6.

Table 4.6 Comparison of characteristic experimental parameters of laminar flames in air of maize starch (6% moisture) and methane at stoichiometric fuel concentrations

Fuel	Maize starch	Methane
Laminar burning velocity (m/s)	0.27	0.45
Quenching distance (mm)	7	2
Flame thickness (mm)	3–4	1

Source: Proust and Veyssiere, 1988.

4.2.3.4
Miscellaneous Dust/Gas Mixtures

Characteristics of laminar flames of graphite in O_2/N_2 mixtures richer in O_2 than air have been determined by Cassel (1964), Chamberlain and Gray (1967), Bryant (1971), and Ballal (1983). Cassel (1964) and Ballal (1983) also give data for magnesium dust flames. For a given particle size, the burning velocities of magnesium dust clouds in air are somewhat higher than for aluminum dust clouds. Ballal (1983) further investigated the influence of a higher oxygen concentration than in air and the addition of hydrogen and methane to the gas phase (hybrid mixtures).

4.2.4
THEORIES OF ONE-DIMENSIONAL LAMINAR FLAME PROPAGATION IN DUST CLOUDS

See also Section 9.2.4.2 in Chapter 9.

4.2.4.1
Theory by Cassel, Das Gupta, and Guruswamy

To obtain an approximate equation for laminar burning in dust clouds, Cassel, Das Gupta, and Guruswamy (1949) modified the Mallard-le Chatelier (1883) theory for premixed gases by incorporating a term for thermal radiation effects due to the particles in a dust cloud. Their equation was

$$S_u = \frac{\mu(T_b - T_i)/b + bw\sigma\alpha F(T_b^4 - T_u^4)/\rho_d r}{(c_p\rho + c_d w)(T_i - T_u)} \tag{4.22}$$

Here, S_u is the burning velocity and μ is the heat conductivity; T_u, T_b, and T_i are the temperatures of the unburned and burned masses and of ignition; σ is the emissivity of the particle surfaces and α is a correction factor, larger than 1, that accounts for the radiation of glowing combustion products (solids and gas); F is a geometrical view factor; b is the thickness of the burning zone; c_p is the specific heat of the gas, ρ its density, whereas c_d is the specific heat of the dust, ρ_d its density and w its concentration; and r is the average particle radius.

Cassel et al. pointed out that the factor b, which is assumed to have the same value in both the conduction and the radiation terms, depends on r, w, and F. By introducing the burning time of a single particle, τ, and equation (4.18), the factor b can be replaced by $\tau S_u\rho_u/\rho_b$.

Equation (4.22) then takes the form

$$S_u^2 = \frac{K\rho_b}{\tau\rho_u}\,\frac{(T_b - T_i)}{\left(T_i - T_u - \dfrac{\tau w\sigma\alpha F\rho_u(T_b^4 - T_u^4)}{\rho_d\rho_b r(c_p\rho + c_d w)}\right)} \tag{4.23}$$

where K is the thermal diffusivity and equals $\mu/(c_p\rho + c_d w)$.

Assuming that oxygen diffusion governs the burning of individual particles, an upper limit for the burning velocity is obtained if τ is expressed in terms of the diffusion rate of oxygen:

$$\tau = \rho_d r^2 R T_u^{3/2} / (2MDpT_a^{1/2}) \tag{4.24}$$

Here, D is the diffusion coefficient at temperature T_u, R is the gas constant, T_a is the average ambient gas temperature around a particle as it passes through the reaction zone, p is the average partial pressure of oxygen, M is the oxygen equivalent of the fuel, expressed in grams of fuel per mol. of oxygen. Equation (4.23) therefore takes the form

$$S_u^2 = \frac{KD_p}{r^2 k} \frac{(T_b - T_i)}{\left(T_i - T_u - \dfrac{rwkF\sigma\,\alpha(T_b^4 - T_u^4}{\rho_d Dp(c_p \rho + c_d w)} \right)} \tag{4.25}$$

where $k = \rho_d \rho_u R T_u^{3/2} / (2M\rho_b T_a^{1/2})$

Cassel et al. illustrated the implications of equation (4.25) by first estimating the burning time of a representative dust particle from equation (4.24). For instance, for a 25 μm diameter aluminum particle, a time τ of about 0.01 s is obtained. Assuming a value of $S_u(\rho_u/\rho_b)$ on the order of 2.5 m/s from experimental data for S_u, the thickness of the burning zone in an aluminum dust flame is calculated to be on the order of 25 mm. This is 25–100 times greater than typical values for flames of premixed gases. This comparatively great thickness of the burning zone is a characteristic feature of laminar aluminum dust flames, as confirmed by experiments (see Section 4.2.3.1).

4.2.4.2
Ballal's Theory for Zero Gravity Conditions

Ballal (1983) postulated that the necessary and sufficient condition for the self-propagation of a laminar flame through a dust cloud is

$$t_q = t_e + t_c \tag{4.26}$$

where t_q is the quenching time; t_e is the evaporation, pyrolysis, or devolatilization time; and t_c is the chemical reaction time. The criterion simply says that a flame can propagate steadily only if the quenching time just equals the sum of the time required to generate an explosible gas mixture and the time required for completion of the chemical gas phase reaction. Ballal claimed this approach to be universally applicable to dust clouds of any combustible material, from metals to organic materials and even liquid sprays. In pure carbon in O_2/N_2, he considered the reaction $2C + O_2 \rightarrow 2CO$ as the "evaporation" stage associated with t_e.

Evidence from flame propagation experiments under zero gravity conditions (Ballal, 1983) suggested that the laminar burning velocity of dust clouds in air is influenced by particle size, dust concentration, volatile matter content (for coal), heat loss by radiation from burning dust particles, and a mass transfer number B of the particles. B has the dimensions of dust concentration and equals the stoichiometric dust concentration for particles that react directly with oxygen in the solid state. If the main chemical oxidation reaction takes place in the gaseous phase, B is a complex function of boiling point, gas temperature, surface temperature, heat of combustion, and the like.

By considering the theoretical influence of these variables, Ballal (1983) arrived at the following expressions for t_q, t_e, and t_c in Equation (4.26):

$$t_q = [\alpha_g/\delta_r^2 + (9q/c_{p,g}\rho_f)(C_1^2/C_3^3)(fD_{32})^{-1}\epsilon\sigma T_p^4/\Delta T_r]^{-1} \tag{4.27}$$

$$t_e = \frac{C_3^3 \rho_f D_{32}^2}{8C_1(k/c_p)_g \ln(1+B)} \quad \text{(truly evaporating particles)} \tag{4.28}$$

$$t_e = \frac{C_3^3 \rho_f D_{32}^2}{8f^2 C_1(k/c_p)_g \phi \ln(1+B)} \quad \text{(carbon, coal)} \tag{4.29}$$

$$t_c = \delta_r / S_u \tag{4.30}$$

where the thickness of the reaction zone, δ_r, is defined as

$$\delta_r = \frac{k_g}{c_{p,g}\rho_u S_u}\frac{\Delta T_r}{\Delta T_{pr}} \tag{4.31}$$

The notation for equations (4.27)–(4.31) is as follows:

B is the mass transfer number (–);
C_1 is the ratio of mean particle diameters D_{20}/D_{32} (–);
C_3 is the ratio of mean particle diameters D_{30}/D_{32} (–);
T_p is the particle temperature (K);
T_{pr} is the preheat zone temperature (K);
T_r is the reaction zone temperature (K);
S_u is the laminar burning velocity (m/s);
q is the dust concentration (g/m^3);
k is the thermal conductivity (J/msK);
φ is the equivalence ratio (=1 for stoichiometric concentration);
δ_r is the thickness of reaction zone (m);
c_p is the specific heat of gas at constant pressure (J/kgK);
g is the subscript for gas;
ρ_u is the density of unburned gas (kg/m^3);
ρ_f is the density of particle (kg/m^3);
f is the swelling factor for particle (–);
ϵ is the emissivity of fuel particles (–);
σ is the Stefan-Boltzmann constant ($= 5.66 \bullet 10^{-8}$ J/sm^{2}K^4);
α is the thermal diffusivity $k/c_p\rho$ (m^2/s).

By substituting equations (4.27), (4.28), or (4.29) and (4.30) and (4.31) into equation (4.26), a complex expression for the flame thickness δ_r results. The equation is composed of three main terms: a diffusion term, a chemical kinetics term, and a radiative

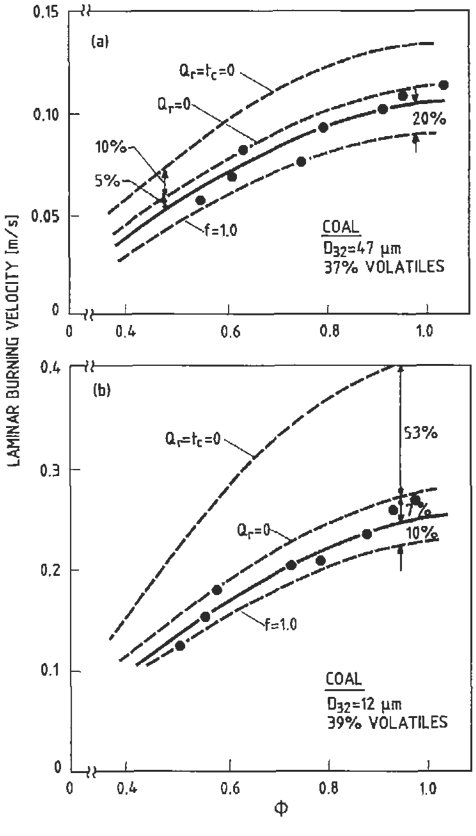


Figure 4.19 *Burning velocities of clouds of two coal dusts in air at zero gravity as functions of equivalence ratio (=1 for stoichiometric mixtures). The data points are experimental values. The solid line is a comprehensive theory. The dotted lines are a simplified theory neglecting either radiative losses only, radiative losses and chemical reaction time, or particle swelling. Percentages indicate the roles of the respective factors (From Ballal, 1983).*

heat loss term. Once δ_r has been calculated, the corresponding S_u can be obtained from equation (4.31).

Figure 4.19 shows that the theoretical prediction of S_u (solid lines) agrees well with the experimental data. Figure 4.19 also shows the predicted relative influence of the factors t_c, Q_r (radiative loss from particles), and f.

Figure 4.20 gives the theoretically predicted dimensionless flame thickness (the real flame thickness divided by average surface/volume particle diameter D_{32}) as functions of the equivalence ratio (dimensionless dust concentration).

The 37% volatiles coal in Figure 4.19(a) has a burning velocity of about 0.11 m/s at stoichiometric concentration. According to Figure 4.20, the corresponding δ_r/D_{32} value is about 25, which for $D_{32} = 0.047$ mm gives $\delta_r = 1.18$ mm. This is somewhat smaller than the experimental values in Section 4.2.3.2 and illustrates the limitations of the theory. Ballal (1983) pointed out that his theory is not applicable if

1. The equivalence ratio $\varphi >> 1$; in which case, radiation contributes positively to flame propagation.
2. Radiative heat transfer from shielding walls or pilot flames is significant.
3. The combustion is or becomes turbulent.
4. Gravitational effects play a significant role (particle diameter >5 μm).

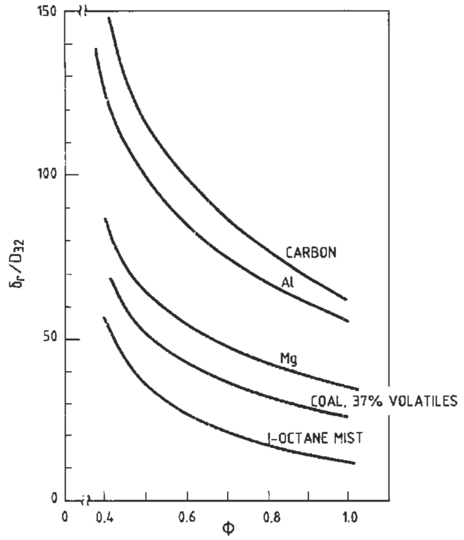


Figure 4.20 *Computed values of the flame thickness for dust clouds and isooctane mist in air at atmospheric pressure, 290 K, and zero gravity, as functions of the equivalence ratio (From Ballal, 1983).*

4.2.4.3
Theory by Ogle, Beddow, and Vetter

Ogle, Beddow, and Vetter (1984) presented a simplified thermal diffusion theory for plane, laminar flames in dust clouds, neglecting the velocity slip and temperature lag between the particle and gas phases. They first developed a model considering radiation, convection, and conduction (RCC). The governing equations were the continuity and thermal energy equations for the steady, one-dimensional laminar flow of a compressible, gray absorbing fluid of arbitrary optical thickness and constant physical properties:

$$G = \rho V = \rho_0 V_0 = \text{ constant} \tag{4.32}$$

$$\rho c_p V \frac{dT}{dx} = k \frac{d^2T}{dx^2} + 2\sigma a T_f^4 E_2(ax) \tag{4.33}$$

In these equations, ρ is the density, V is the velocity, x is the coordinate in the direction of flame propagation, G is the mass flux, c_p is the specific heat at constant pressure, k is the thermal conductivity, σ is the Stefan-Boltzmann constant, a is the absorption coefficient, T is the temperature, the subscript f denotes the flame position, and E_2 is the exponential integral of order 2. The exponential integral term represents the radiative absorption of energy emitted from the flame sheet at temperature T_f. The subscript 0 denotes the initial ambient conditions.

The boundary conditions were

$$\begin{aligned} &T(x=0) = T_0 \\ &\frac{dT}{dx}(x \to \infty) = 0 \\ &T(x \to \infty) = T_f \end{aligned} \tag{4.34}$$

The first two boundary conditions allow determination of the temperature profile, and the third one specifies the burning velocity. By making certain assumptions, equations (4.32)–(4.34) were solved to yield the temperature profile and the burning velocity:

$$(T - T_0) / T_f - T_0) = 1 - e^{-1.5ax} \tag{4.35}$$

$$S_u = \frac{1}{\rho_0 c_p (T_f - T_0)} \left[\sigma T_f^4 - \frac{3}{2} ka (T_f - T_0) \right] \tag{4.36}$$

This is the RCC model. To evaluate the relative importance of conduction, the thermal conductivity can be set equal to 0, yielding the radiation and convection model (RC). This results in the same temperature profile but a different expression for the burning velocity:

$$S_u = \rho T_f^4 / [\rho_0 c_p (T_f - T_0)] \tag{4.37}$$

It was found that the difference between burning velocities predicted by the RCC and RC models was negligible. Hence, conduction was negligible compared to convection and radiation. The predicted burning velocity was 0.27 m/s for a flame temperature of 1750 K and increased almost linearly with flame temperature to 0.37 m/s for the adiabatic flame temperature 1950 K. Predicted burning velocities in the range 0.27–0.37 m/s for flame temperatures in the range 1750–1950 K are in reasonable agreement with experimental values.

Weber (1989) proposed a modification of the approach by Ogle et al. He used the mathematical condition for an inflection point (second derivative equal to 0) to obtain the burning velocity S_u as an eigenvalue from the two-point boundary value problem for a linear, second-order differential equation with arbitrary forcing. The flame was divided into a preheating zone from T_0 to T_i, where T_i was the inflection point of the temperature-versus-distance profile, and a reaction zone from T_i to T_f. The application to dust flames, with thermal radiation, was considered.

4.2.4.4
Theory by Nomura and Tanaka for Monosized Particles

In the theory for plane flames developed by Nomura and Tanaka (1978) for monosized particles, it is assumed that the particles are initially arranged in a cubical pattern with center-to-center distance L in all three main directions. The relationship between L and the dust concentration C_d is given by

$$L = \left[\frac{\pi}{6} D_p^3 \rho_p / C_d \right]^{1/3} \tag{4.38}$$

where D_p is the particle diameter and ρ_p is the particle density. The flame propagation is assumed to occur as a one-dimensional wave composed of identical parallel elements of cross-sectional area L^2, starting from a plane wall, as indicated in Figure 4.21.

Each particle is assumed to be located at the center of a cubical air element of volume L^3, indicated by the dotted lines in Figure 4.21. When particle number 1 burns, the surrounding gas element is heated adiabatically at constant pressure and expands in the x

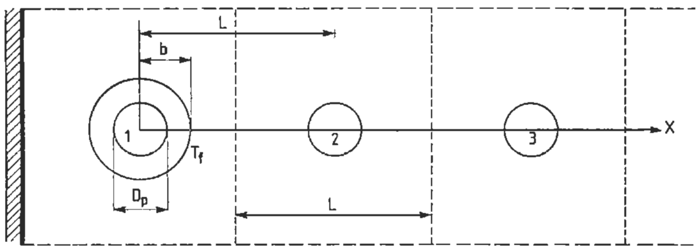


Figure 4.21 *Physical model forming the basis of the one-dimensional Nomura and Tanaka (1978) theory for laminar flame propagation through dust clouds of monosized particles.*

direction, while the cross section L^2 normal to the x axis is maintained constant. During this plug flow expansion, the whole chain of subsequent gas elements are pushed to the right along the x axis. The unburned particles are assumed to follow their respective gas elements completely during this process.

When calculating the temperature profile due to combustion of particle no. 1, a one-dimensional model is used, corresponding to the particle being a plane of size L^2, normal to the x axis rather than a sphere. The corresponding thermal diffusion equation is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{4.39}$$

where T is the gas temperature at distance x at time t and α is the thermal diffusivity. If the boundary condition at $x = 0$ is $T = T_f$, that is, a constant flame temperature, and $T = T_0$ at $x = \infty$, the solution of equation (4.39) is

$$T(x, t) = (T_f - T_0)\, erf\left(\frac{x}{\sqrt{\alpha t}}\right) + T_0 \tag{4.40}$$

A dynamic heat balance for each particle is obtained by considering the heat transfer from the burning particle no. n, to the unburned particle no. $(n + 1)$ as given in equation (4.41):

$$\frac{\pi}{6} D_p^3 \rho_p c_p \frac{dT_{dL}}{dt} = h\pi D_p^2 (T_{gL} - T_{dL}) + \frac{\pi D_p^2}{2}(a_p \epsilon_f F \sigma T_f^4 + a_p \epsilon_G \sigma T_G^4) - \pi D_p^2 \epsilon_p \sigma T_{dL}^4 \tag{4.41}$$

The notation not already explained is as follows:

c_p is the specific heat of particle (J/gK);
T_{dL} is the temperature of particle no. $(n + 1)$ (K);
T_{gL} is the temperature of gas surrounding particle no. $(n + 1)$ (K);
T_G is the temperature of hot gas sphere surrounding particle after burning (K);
h is the heat transfer coefficient (J/(cm^{2}sK));
a_p is the absorptivity of particle (–);
ϵ_f is the emissivity of flame (–);
ϵ_G is the emissivity of hot gas surrounding particle after burning (–);
ϵ_p is the emissivity of the particle (–);
F is the particle shape factor (–);
σ is the Stefan-Boltzmann constant ($= 5.66 \cdot 10^{-8}$ J/(sm^{2}K^4)).

The left-hand side of equation (4.41) is the net heat input to particle no. $(n + 1)$, whereas the three terms on the right-hand side are the convective heat flow to particle no. $(n + 1)$ from the surrounding gas, the radiative heat flows to this particle from the flame front and the hot gas sphere around the burned particle no. n, and the radiative heat loss from particle no. $(n + 1)$.

Nomura and Tanaka analyzed the various parameters in equation (4.41) in detail and concluded that the radiative heat loss from particle no. $(n + 1)$ was only about 10% of the radiative heat input to this particle from particle and gas element no. n. A simplified equation (4.41), deleting the last term on the right-hand side, was then integrated from $t = 0$ to $t = \tau$, the total burning time of a particle, to identify the unknown time Δt_i when particle n reached its ignition temperature T_{ig}. T_{ig} was assumed to be known from experiments or other theory. The calculations started with $n = 1$ and were repeated for $n = 2, 3, \ldots$, up to $n = 500$. The time Δt_n for ignition of particle no. $(n + 1)$ decreases with increasing I if the burning time τ is considerably larger than ΔI. This is because more particles burn simultaneously and produce a greater heat flow to the next unburned particle than if only one particle burns. In the examples shown by Nomura and Tanaka, Δt_n reached a constant value Δt_∞ for $n > 100$.

Nomura and Tanaka introduced the following expression for the burning time of a particle:

$$\tau = K_D D_p^2 \tag{4.42}$$

The burning constant K_D was assumed to be on the order of 1000 s/cm^2 for solid particles in general and about 2000 s/cm^2 for coal particles specifically.

By using the corresponding τ from equation (4.42), Δt_∞ was calculated, and the laminar burning velocity is then given by the simple relationship

$$S_u = L / \Delta t_\infty \tag{4.43}$$

Calculated S_u values for coal dust in air at a dust concentration of 600 g/m^3 are 0.70 m/s for 20 μm diameter particles and 0.36 m/s for 40 μm diameter particles.

By requiring an experimental "ignition temperature" of a particle, the Nomura-Tanaka theory suffers from the same basic weakness as the classical Mallard-le Chatelier (1883) theory for gases: The "ignition temperature" is not a true physical property of the particle but depends on the actual circumstances under which the particle is ignited.

4.2.4.5

Specific Theories for Coal Dust in Air

Smoot and Horton (1977) have a comprehensive review of the theoretical work on laminar coal dust/air flames up to the time of their paper, starting with the pioneering contributions on carbon/air flames by Nusselt (1924) and concluding with the unified theory for coal/air by Krazinski, Buckius, and Krier (1977). The last theory did not consider the devolatilization process and assumed that the particles had the same velocity as the surrounding gas. However, both thermal radiation and conduction were accounted for, as well as char oxidation. The treatment of thermal radiation also included scattering effects. However, the theory is limited to low-volatile coals and was not confirmed by experiments. The predicted influence of particle size on the burning velocity was small.

In another paper, Smoot, Horton, and Williams (1977) presented their own, improved theory for laminar coal/air flame propagation, assuming particle/gas dynamic equilibrium and constant pressure. The general transformation method for computerized calculations of laminar burning velocities developed by Spalding, Stephenson, and Taylor (1971) was adopted. The effects of gaseous diffusion, coal pyrolysis, char oxidation, and gaseous reaction were considered; whereas the effects of gravity, viscous dissipation, forced diffusion, thermal diffusion, and temperature gradients within particles were neglected. The unsteady state equations were solved numerically using finite difference techniques. The theory suggested that, in a laminar coal-dust flame, gas phase diffusion and conduction, gas particle conduction, and coal pyrolysis are important rate-determining steps, while hydrocarbon and char oxidation may not be rate limiting. The importance of gas phase diffusion processes in such flames was suggested.

The theory comprised six basic, one-dimensional differential equations for

1. Conservation of gas species.
2. Conservation of particle species.
3. Particle mass consumption rate.
4. Gas phase thermal energy balance.
5. Particle thermal energy balance including radiation.
6. Particle number balance.

Computed laminar burning velocities for coal dust in air, neglecting radiative effects, generally differed from experimental values by less than 25%.

Although not directly related to the theory of laminar flames, it should be mentioned that Wolanski (1977) developed a comparatively simple, one-dimensional theoretical model of coal dust combustion in a constant-pressure combustion chamber with recirculation of some of the exhaust gases. The model comprised five basic differential equations for

1. Energy balance for the gas, including heat conduction and convection.
2. Energy balance for the solid residue, including conduction and radiation.
3. Mass balance for the released volatiles.
4. Mass balance for the solid residue.
5. Mass balance for oxygen.

The set of equations is similar to that used by Smoot et al. (1977).

Wolanski calculated gas and particle temperature-versus-time profiles, with and without recirculation and for various particle sizes and dust concentrations. For a coal of 35% volatiles, primary and secondary air temperatures of 360 and 600 K and a wall temperature of 650 K, the calculated peak temperatures were about 1500 K for the gas and 3600 K and 2300 K for 10 μm and 80 μm diameter particles, respectively.

The laminar burning of clouds of graphite dust in methane/air and coal dust in air was investigated theoretically by Bradley et al. (1986). They calculated laminar burning velocities from the profile of net heat release rate Q versus dimensionless gas temperature τ, using Spalding's (1957) analytical approach. Their equation was

$$Q = f_1(\tau) f_2(\tau) h \tag{4.44}$$

Here, $f_1(\tau)$ is the ratio between the thermal gas conductivities at actual and unburned gas temperatures, expressed as a function of gas temperature; $f_2(\tau)$ is the volumetric reaction rate, expressed as a function of gas temperature; and h is the heat of reaction. This equation implies the calculation of the eigenvalue using the centroid of area expression given by Spalding (1957).

Bradley et al. (1986) assumed that the fuel was essentially premixed gas generated by rapid devolatilization of the coal particles and subsequent rapid mixing of the volatiles with the air. Furthermore, they assumed that the methane was the essential component of the volatiles and the presence of the char particles in the gas phase did not change the gas composition or chemical kinetics. The radiative loss from the char particles as they moved through the flame was computed. For a chemical heat release rate q per unit surface area of a smooth spherical particle, the total energy equation for a particle was taken as

$$\alpha(T_p - T_g) = q - \epsilon\sigma T_p^4 - \frac{1}{3r^2}\frac{\partial r^3 \rho_p h}{\partial t} \tag{4.45}$$

Here, α is the convective heat transfer coefficient; T_p and T_g are the particle and gas temperatures; ϵ is the particle emissivity, assumed equal to unity throughout; σ is the Stefan-Boltzmann constant; r, ρ_p, and h are the particle radius, density, and enthalpy; and t is the time. The equation neglects radiative absorption from the walls, gas, and other particles.

The net heat-release-rate-versus-gas-temperature profile was calculated using the comprehensive chemical kinetic model for methane/air combustion developed by Dixon-Lewis and Islam (1982), correcting for the rate of net energy supply from the particles due to their heating by oxidation of the char or graphite. The correction, which was generally found to be small compared with the heat release rate from the gas combustion, is given by

$$H = 4\pi r^2 \alpha n (T_p - T_g) \tag{4.46}$$

where n is the number density of particles in the cloud, and the other notations as for equation (4.45).

Figure 4.22 shows a comparison of burning velocities predicted theoretically by Bradley et al. and experimental data from Smoot et al. In general, Bradley et al. found that their theory agreed well with experiments as long as devolatilization and gas phase mixing were sufficiently fast and the char did not create a significant heat sink. This was found to be satisfied if the particle diameter was <10 μm and the volatile content >25%.

The basic approach suggested by Hertzberg et al. (1982, 1987) is similar to that of Ballal (1983). It was assumed that three sequential processes are involved in the propagation of flame through a dust/air mixture:

1. Heating and devolatilization of dust particles.
2. Mixing of the volatiles with air.
3. Gas phase combustion of the premixed volatiles.

The characteristic time constants for the three consecutive processes are τ_{dv}, τ_{mx}, and τ_{pm}. It was realized that the process of particle heating and devolatilization is a complex combination of conductive, convective, and radiative heat exchange between the burned products and the unburned reactants. However, the problem was simplified by handling those processes implicitly in the laminar burning velocity, S_u, which characterizes the overall rate of flame propagation. A laminar flame propagating at S_u has an overall reaction

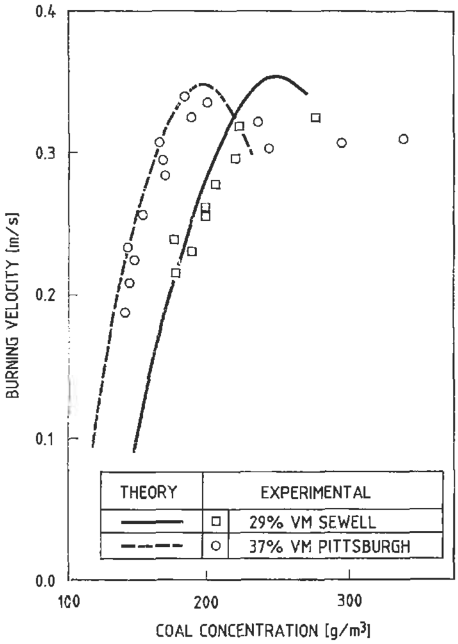


Figure 4.22 *Curves of theoretical burning velocities for clouds in air of coal dusts of 29 and 37% volatile matter and particle diameter 10 μm; the experimental points are from Smoot et al. (1977) (From Bradley et al., 1986).*

zone thickness of $\delta = \alpha/S_u$, where α is the effective diffusivity across the flame front. The overall reaction time for species passing through the reaction zone is $\tau = \delta/S_u$; therefore,

$$S_u = (\alpha/\tau)^{1/2} \tag{4.47}$$

and, by definition,

$$\tau = \tau_{dv} + \tau_{mx} + \tau_{pm} \tag{4.48}$$

According to Hertzberg et al. (1982), the mixing process is normally comparatively rapid and τ_{mx} is shorter than both τ_{dv} and τ_{pm}. Furthermore, for small particles $\tau_{dv} \ll \tau_{pm}$, and the process essentially is controlled by premixed gas combustion. For larger particles, it was assumed that the fraction of a particle devolatilized at a time t after the particle has entered the reaction zone equals

$$\beta = 1 - (1 - 2\dot{x}_0 t/D_0)^3 \tag{4.49}$$

where $\dot{x}$ is the constant rate with which the pyrolysis or devolatilization wave progresses into the spherical particle of initial diameter D_0. It is further assumed that

$$\dot{x}_0 = kS_u c\rho(T_b - T_u) \tag{4.50}$$

where k is the rate constant for the pyrolysis or devolatilization process, c is the heat capacity, ρ is the density of the unburned mixture, and T_b and T_u are the gas temperatures of the burned and unburned mixture. As the dust particles become coarser and the dust concentration higher, the heating and devolatilization processes begin to control the combustion rate; that is, $\tau_{dv} > \tau_{pm}$. At conditions that give the highest burning velocities, approaching 0.40 m/s, the overall time constant τ is on the order of only 1 ms.

Hertzberg et al. (1987) suggested that, for such rapidly propagating dust flames, only the surface regions of the dust particles can contribute volatiles to the flame. The flame "rides the crest" of a near-stoichiometric concentration of volatiles regardless of the dust concentration. This was considered the reason why Hertzberg et al. were unable to detect a sharp upper explosible concentration limit for dusts.

Although excess volatiles may continue to be emitted in the burned gases at high dust concentrations, they are emitted too late to dilute the flame front with excess fuel vapor. Krazinski, Buckius, and Krier (1978) developed a theory for flame propagation in mixtures of monosized particles of low volatile coal dust and air, neglecting the role of the volatiles but accounting for radiative heat transfer from the burning to the unburned particles. For a stoichiometric mixture of air and 30 μm particles, an adiabatic burning velocity of 0.72 m/s was predicted. The flame thickness was on the order of several m, and this may in part explain why clouds of pure carbon in air are unable to propagate a flame in laboratory-scale apparatus.

Greenberg and Goldman (1989) developed a simplified theory for coal dust/air combustion for investigating the characteristics of a counterflow pulverized coal combustor. The model should be applicable even to laminar flames. It is related to the microscopic behavior of the coal particles only, whereas the velocity, temperature, and composition of the gas has to be obtained independently from experiments or other theories. The model includes drag between particle and gas, particle devolatilization and combustion, and heat transfer to and from the particles due to convection, radiation, and chemical reactions.

4.2.5
THEORIES OF LAMINAR FLAME PROPAGATION IN CLOSED VESSELS

See also Section 9.2.4.5 in Chapter 9.

4.2.5.1
Theories by Nagy, Conn, and Verakis

Sections 4.2.3 and 4.2.4 show that both experiment and theory confirms that the concept of laminar burning is applicable to combustible dust clouds as well as to combustible premixed gases. Therefore, the characteristic features of laminar dust explosions in closed vessels should be similar to those of laminar gas explosions in closed vessels. The explosion development in a closed spherical vessel was studied theoretically by Nagy, Conn, and Verakis (1969). This treatment is also included in the book by Nagy and Verakis (1983). The following simplifying assumptions were made:

1. The equation of state for ideal gases is applicable.
2. Point ignition is at the sphere center by a negligible energy supply.
3. Viscosity and heat capacities are constant.
4. Burning velocity is low compared to the velocity of sound; that is, the pressure is spatially uniform throughout the vessel at any instant.
5. The thickness of the propagating reaction zone is negligible compared to the vessel radius.

The overall flame speed S_f with reference to the vessel was considered as the sum of three additive velocities: the laminar burning velocity S_u, the gas expansion or contraction velocity S_n due to the chemical change of number of molecules, and the gas expansion velocity S_e due to the heating of the gas.

The dependence of S_u on pressure P and temperature T_u in the unburned mixture was taken as

$$S_u = S_{u,r}(T_u/T_r)^2(P_r/P)^{\beta} \tag{4.51}$$

where the index r refers to the reference state of 300 K and atmospheric pressure; β is an empirical constant that equals 0.5 or less for gases.

The problem was first simplified by treating the flame propagation as an "isothermal" process, considering T_u as a constant equal to the mixture temperature T_0 before ignition, and T_b in the combustion products as a constant equal to the overall temperature T_m when all the mixture has burnt and the flame reaches the vessel wall.

The resulting analytical equation for the rate of pressure rise was

$$\frac{dP}{dt} = \frac{3S_{u,r}T_0^2P_r^{\beta}P_m^{2/3}}{RT_r^2P_0}(P_m - P_0)^{1/3}\left(1 - \frac{P_0}{P}\right)^{2/3}P^{(1-\beta)} \tag{4.52}$$

where R is the vessel radius and P_m is the pressure when the flame reaches the vessel wall. This equation can be integrated analytically for $\beta = 0$. If $T_0 = T_r$, $P_0 = P_r$, $S_{u,0} = S_{u,r}$, and $\beta = 0$, the equation reduces to

$$\frac{dP}{dt} = \frac{3S_{u,0}}{R}(P_m - P_0)^{1/3}P_m^{2/3}\left(1 - \frac{P_0}{P}\right)^{2/3}\left(\frac{P}{P_0}\right) \tag{4.53}$$

The maximum $(dP/dt)_{\max}$ occurs when $P = P_m$; that is,

$$(dP/dt)_{\max} = \frac{3S_{u,0}}{R}(P_m - P_0)(P_m/P_0) \tag{4.54}$$

Equation (4.54) shows that this idealized isothermal treatment predicts that $(dP/dt)_{\max}$ is inversely proportional to R, that is, to the cube root of the vessel volume, in agreement with the frequently quoted "cube root law." However, this treatment also shows the strict conditions under which the cube root law is valid. These conditions were explicitly pointed out by Eckhoff (1984/1985 and 1987) in a simplified analysis. First, the thickness of the reaction zone or flame must be negligible compared to R. Second, $S_u(T_u, P)$ must be independent of R. Under conditions of significant and unspecified turbulence, which are typical of dust explosion experiments in closed vessels, neither of these requirements is fulfilled (see Section 4.4.3.3 for further discussion).

Nagy et al. (1969) extended the isothermal treatment to the more realistic adiabatic conditions for which T_u and T_b are not constants but given by

$$T_u = T_0\left(\frac{P}{P_0}\right)^{\frac{\gamma_u - 1}{\gamma_u}} \tag{4.55}$$

$$T_b = T_m\left(\frac{P}{P_m}\right)^{\frac{\gamma_b - 1}{\gamma_b}} \tag{4.56}$$

Here, γ_u and γ_b are the specific heat ratios for the unburned and burned mixture. Nagy et al. simplified the calculation by assuming an average value for γ, neglecting the difference between γ_u and γ_b. The resulting equation (4.57) for (dP/dt), assuming that the initial conditions $S_{u,0}$, T_0, and P_0 equals the reference conditions $S_{u,r}$, T_r, and P_r, is similar to equation (4.53) but contains γ as a complicating parameter and must be integrated numerically:

$$\frac{dP}{dt} = \frac{3S_{u,0}}{R} \bullet \frac{\gamma P_m^{2/3\gamma}}{P_0^{(2-1/\gamma-\beta)}} \bullet (P_m^{1/\gamma} - P_0^{1/\gamma})^{1/3} \left[1 - \left(\frac{P_0}{P}\right)^{1/\gamma}\right]^{2/3} P^{(3-2/\gamma-\beta)} \tag{4.57}$$

Values of both β and $S_{u,0}$ can be determined from equation (4.57) and experimental data for $P(t)$, by plotting the experimental $(dP/dt)/[1-(P_0/P)^{1/\gamma}]^{2/3}$ as a function of P in a double logarithmic diagram. Then, β is determined from the slope and $S_{u,0}$ from the intercept with the ordinate axis ($\log P = 0$). This theoretical treatment yielded a reasonable burning velocity for 7.7 vol% acetylene in air, $S_{u,0} = 1.1$ m/s, which is close to values from direct measurements.

However, when applying this approach to data from corn starch explosions in a 3 m^3 rectilinear closed vessel, β was found to be 0.36, which appears reasonable, but $S_{u,0}$ was found to be 3.15 m/s, which is about 10 times the experimental laminar burning velocities for corn starch in air. Nagy et al. pointed out that this high apparent value was most probably due to the turbulent conditions in the explosion. It is therefore necessary, when trying to determine laminar burning velocities from closed-bomb dust explosion experiments, to correct for the inevitable initial turbulence in such experiments. Nagy and Verakis (1983) attempted to do this and derived laminar burning velocities for clouds in air of various dusts by applying a modified form of equation (4.53) to experimental dust explosion data from the elongated 1.2 liter Hartmann bomb. Corrections were made for the increase in the initial pressure due to the dispersing air. The first modification made in equation (4.53) was that the ratio $3/R$ for a spherical vessel was replaced by the general ratio A/V for any arbitrary vessel shape, where A is the internal surface area of the vessel and V is the vessel volume. Second, the initial laminar burning velocity, $S_{u,0}$, at atmospheric pressure and 300 K, was replaced by the corresponding turbulent burning velocity $S_{u,0}\alpha$, where α is a turbulence enhancement factor, >1. Furthermore, β was taken as equal to 0. The generalization of the theory to nonspherical vessels was justified by referring to the work on premixed gases by Ellis (1928) and Ellis and Wheeler (1928), and later work at the U.S. Bureau of Mines. These investigations indicated that, in nonspherical vessels, the initially spherical flame front gradually assumes the vessel shape.

The modified version of equation (4.53) suggests that a straight line should result if (dP/dt) is plotted as a function of $[1-(P_0/P)]^{2/3}(P/P_0)$. The slope of this line determines the apparent turbulent burning velocity $S_{u,0}\alpha$. It was then simply assumed that $\alpha = 3.0$ could be used as a representative average value for all the Hartmann bomb experiments. The resulting $S_{u,0}$ values are given in Table 4.7. No information on particle size is given explicitly; therefore, the possibilities of detailed interpretation are limited. The values are generally on the same order as laminar burning velocities determined by other methods, but it is clearly unsatisfactory to have to rely on somewhat arbitrary estimates of the factor α.

Table 4.7 Laminar burning velocities at atmospheric pressure and 300 K for combustible dust/air clouds estimated from experiments in the closed 1.2 liter Hartmann bomb at a dust concentration of 500 g/m^3

Dust	Maximum pressure, P_m (bar(g))	Maximum rate of pressure rise, $(dP/dt)_{max}$ (bar/s)	Estimated burning velocity, $S_{u,0}$ at atmospheric pressure and 300 K (m/s)
Alfalfa	4.55	76	0.20
Aluminum, atomized	6.20	480	0.75
Aluminum, flaked	6.50	690	0.95
Antimony	0.55	7	0.49
Cellulose acetate	5.40	152	0.29
Cellulose acetate	5.85	248	0.43
Cellulose acetate	6.85	414	0.52
Chromium	3.50	255	1.08
Cinnamon	7.85	270	0.26
Citrus peel	3.50	76	0.33
Corn (maize) starch	7.95	620	0.59
Cotton linters	3.30	10	0.06
Gilsonite	6.15	262	0.43
Hemp hurd	7.10	690	0.82
Hydroxyethyl cellulose	7.30	180	0.20
Hydroxypropyl cellulose	5.80	200	0.33
Lignite, brown	5.70	172	0.30
Magnesium	6.75	760	0.98
Onion	1.25	7	0.16
Pittsburgh coal	5.70	160	0.26
Polyethylene	5.70	172	0.30
Polypropylene	4.75	193	0.46
Shellac	5.05	248	0.56
Sorbic acid	5.50	345	0.66
Stearic acid	6.00	290	0.46
Sulfur, 100% 44 μm	3.85	213	0.75
Titanium	6.20	760	1.15

Source: Nagy and Verakis, 1983.

4.2.5.2

Three-Zone Model by Bradley and Mitcheson

Bradley and Mitcheson (1976) carried the theoretical analysis further by first giving further support to the useful relation

$$\frac{P-P_0}{P_m-P_0}=\frac{m_b}{m_0}=n \tag{4.58}$$

suggested by Lewis and von Elbe (1961). Equation (4.58) simply says that the fractional pressure rise equals the fractional mass burned and rests on a number of assumptions of chemical and physical nature. Simplified analytical solutions of pressure versus time obtained by using this equation agreed fairly well with comprehensive computer solutions. Equation (4.58) replaces assumptions concerning the density and specific heat ratio of the burned fraction. Bradley and Mitcheson further emphasized the importance of knowing the dependence of S_u on pressure and temperature, and they referred to a number of suggested relationships, including equation (4.51) proposed by Nagy et al. (1969).

In the complete three-zone computer model of Bradley and Mitcheson (1976), equation (4.58) was superfluous, because most basic relationships were accounted for directly. Flame propagation was considered as consumption of unburned combustible mixture in small mass decrements dm_u. However, in reality, this mass does not burn instantaneously but passes through a reaction zone of finite thickness, and this was accounted for. The overall model, therefore, comprises three zones, the volumes of unburned, reacting, and burned mixture, the sum of which equals the known vessel volume. The inclusion of a finite reaction zone is of particular interest in the context of dust explosions, where reaction zone thicknesses are generally much larger than in laminar premixed gases.

The flame was, in turn, considered to consist of two zones: a preheat zone, extending from unburned mixture temperature T_u to its ignition temperature T_{ig}, and a reaction zone, in which the temperature increased from T_{ig} to the ideal equilibrium temperature T_f. This picture is in agreement with the classical model by Mallard and le Chatelier (1883). T_{ig} is not a fundamental constant for a given mixture but depends on the method of determination.

The unburned gas was assumed isotropic, but each burned gas element arising from each mass decrement dm_u was treated independently to estimate its temperature after isotropic compression. Any energy exchange between mixture elements by conduction, convection, or radiation was neglected.

The comprehensive computer model gave good agreement with experimental data for pressure versus time in laminar closed-bomb explosions of methane/air mixtures. However, no comparisons with dust explosions were made.

4.2.5.3
Theory by Nomura and Tanaka

Nomura and Tanaka (1980) extended their theory for plane laminar burning of dust clouds at constant pressure (Nomura and Tanaka, 1978) to laminar burning in closed vessels. By making certain assumptions, they derived the general equation

$$\frac{P^{1/\gamma} - P_0^{1/\gamma}}{P_m^{1/\gamma} - P_0^{1/\gamma}} = \frac{m_b}{m_0} \tag{4.59}$$

which is slightly different from equation (4.58) by having all three pressures raised to the power of $1/\gamma$, where γ is the average specific heat ratio for the burned and unburned mixture.

As before (Nomura and Tanaka, 1978), it was assumed that the dust cloud consisted of monosized particles arranged in a regular, static pattern. However, in this case, ignition occurred at a point, as opposed to an infinite plane, and the flame propagation was spherical, as opposed to the plane, one-dimensional propagation considered earlier. Consequently, the particle centers were considered as located at concentric spherical shells, rather than in the regular cubical grid structure applicable to plane flames. In the spherical geometry, the relationship between the average interparticle distance L, the particle density ρ_p, the particle diameter D_p, and the dust concentration C_d was defined as

$$L = \left(\frac{\rho_p}{C_d}\right)^{1/3} D_p \tag{4.60}$$

which differs from equation (4.38) by the factor $(\pi/6)^{1/3}$.

Equation (4.41) was used in a simplified form by neglecting all thermal radiation except that from the flame front to the next particle shell. The resulting equation for the maximum rate of pressure rise in a spherical vessel with central point ignition was

$$(dP/dt)_{\max} = \frac{3\gamma D_p}{R\Delta t}\left(\frac{\rho_p}{a}\right)^{1/3} P_m\left[1-\left(\frac{P_0}{P_m}\right)^{1/\gamma}\right] \tag{4.61}$$

which conforms with the "cube root law" as long as all constants at the right-hand side are independent of the vessel radius R. It is implicitly assumed, during the derivation of this equation, that the thickness of the flame zone is negligible compared to the vessel radius R. The constant a in equation (4.61) has the dimensions of mass per unit volume and equals the effective dust concentration that can burn completely consuming the oxygen available. For dust concentrations C_d up to stoichiometric the parameter $a = C_d$, whereas for higher concentrations, it maintains the stoichiometric value.

The Δt is the time required for the flame to propagate from the $(n - 1)$th to the nth particle shell. For starch dusts of $D_p < 50$ μm, Δt was found to be independent of n for $n > 30$. Therefore, the burning velocity equals $S_u = L/\Delta t_\infty$, as defined by equation (4.43). Nomura and Tanaka derived Δt_∞ as a complex function of particle and combustion properties.

Nomura and Tanaka (1980) also extended their theoretical treatment to nonspherical vessel shapes. This was done by maintaining spherical flame propagation for any part of the flame that had not reached the vessel wall. As soon as a part of the flame reached the wall, flame propagation stopped for that part. Heat loss to the vessel wall was not considered. Under these conditions the theoretical analysis showed that the "cube root" relationship was valid even for elongated, cylindrical vessels, as long as they were geometrically similar.

Figure 4.23 illustrates the theoretical development of pressure with time in an elongated cylinder. At time t_1, the spherical flame reached the cylinder wall, and at time t_0, the entire dust cloud has burned.

Nomura and Tanaka tried to correlate their theoretical results for laminar flame propagation with experimental data from dust explosions in closed vessels. However, inevitable and unknown turbulence in the experimental dust clouds could not be accounted for, and the value of the correlation therefore seems limited.

4.2.5.4
Simplified Theory by Ogle, Beddow, and Vetter

Ogle, Beddow, and Vetter (1983) proposed a simplified three-element theory for the development of a dust explosion in a closed vessel. The first element was a model for

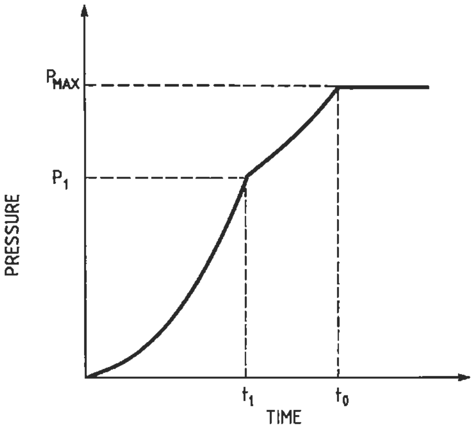


Figure 4.23 *Theoretical relation between pressure and time in dust explosions in a closed, elongated cylindrical vessel (From Nomura and Tanaka, 1980).*

the burning time τ of a particle:

$$\tau = \frac{r_0}{k_c Y_{O_2}} \tag{4.62}$$

where r_0 is the characteristic size of the particle (m) obtained from morphological Fourier analysis, k_c is a first-order rate constant (m/s) and Y_{O_2} is the initial mass fraction of oxygen in the gas phase.

The second element was a model for the laminar burning velocity of the dust cloud, based essentially on the classical Mallard-le Chatelier (1883) model for premixed gases, with an additional term for thermal radiation. The resulting equation for the burning velocity is

$$S_u = B + (B^2 + A)^{1/2} \tag{4.63}$$

where

$$B = 1/2\left(\frac{\epsilon\sigma}{\rho_u c_p}\right)\left(\frac{T_f^4 - T_0^4}{T_i - T_0}\right)$$

$$A = \frac{\lambda}{\rho_u c_p \tau}\left(\frac{T_f - T_i}{T_i - T_0}\right)$$

Here

ρ is the initial density of the gas phase (kg/m^3);
σ is the Stefan-Boltzmann constant (= 5.66 10^{-8} J/s m^{2}K^4);
ϵ is the emissivity (–);
c_p is the heat capacity of gas at constant pressure (J/kg K);
T_f is the flame temperature (K);
T_i is the ignition temperature (K);
T_0 is the initial temperature (K);
λ is the thermal conductivity (J/s m K);
τ is the burning time of a dust particle (s).

Equation (4.63) differs somewhat from equation (4.22) derived by Cassel et al. (1949) but rests on a similar basic philosophy.

The third model element was the equation for the rate of pressure rise:

$$(dP/dt)_{\max} = \frac{3\gamma r^2 P}{R^3 - r^3}\left(\frac{\rho_u}{\rho_b} - 1\right)S_u \tag{4.64}$$

where γ is the specific heat ratio, r is the radius of the spherical flame, and ρ_u and ρ_b are the densities of the unburned gas and the combustion gases. Equation (4.64) is based on the approximation $dr/dt = (\rho_u/\rho_b)S_u$.

Estimates for S_u for aluminum dust clouds, using the theory by Ogle et al., gave considerably higher burning velocities, by a factor of 4, than experimental values from laminar burners.

4.2.5.5
Computer Model by Continillo

The laminar flame propagation through a coal dust/air suspension in a spherical enclosure was studied by Continillo (1988a) by means of a one-dimensional, spherically symmetric mathematical model. An Eulerian formulation was adopted for the gas phase mass continuity, species, and energy balance equations, while a Lagrangian formulation was employed for the mass, energy, and momentum balance equations for the particles.

For the "gas phase," the following assumptions were made: The flow is laminar and spherically symmetric. The viscous dissipation rate is negligible and the pressure is uniform in space (low Mach number) but varies in time. The gas mixture is thermally perfect. Binary diffusion coefficients for each pair of species are taken to be equal, thermal mass diffusion is neglected. Mass diffusion and heat conduction are governed by Fick's and Fourier's laws, respectively. The diffusion coefficient varies with temperature and pressure. The Lewis number is unity. Radiative heat transfer is neglected. The combustion chemistry is described by means of a single-step, irreversible reaction of the volatiles with the oxygen, and Arrhenius-type kinetics with nonunity exponents for fuel and oxygen concentrations apply. The equations also include coupling terms accounting for mass, momentum, and energy exchanges between the gas phase and particle phase.

In the simplified treatment of the "particle phase," a coal particle was represented by a sphere containing ash, fixed carbon, and volatiles in specified initial fractions. The particle was considered to remain spherical and conserve its volume. The temperature was considered uniform in the particle, including its surface. The transport processes in the gas film next to the particle were assumed to be quasi-steady, and the thermophysical properties of the air/fuel vapor mixture were assumed uniform and evaluated at a conveniently averaged value of the temperature in the gas film. The fuel vapor production rate was assumed to depend on the particle temperature and global composition only. During the particle heat-up, the volatiles were assumed to be released according to a simple one-step Arrhenius pyrolysis reaction. Due to the highly transient character of the particle history in this kind of phenomena, surface oxidation reactions were not considered. This eliminated the need to consider the mass transfer processes in the film. All the volatiles released by the particle were immediately available in the gas phase. The model accounted for the effects of the convective transport caused by the gas/particle relative motion by means of correction factors to the spherically symmetric stagnant film situation.

Ignition was induced by introducing a heat source of a given intensity in the energy equation for a limited time. The model then predicted the particle heat-up, devolatilization, and ignition of the volatiles and the subsequent flame propagation through the spherical volume.

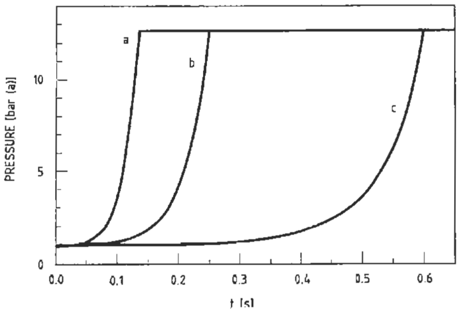


Figure 4.24 *Computed pressure-versus-time patterns for spherical explosions of coal dust of various particle diameters in air in a vessel of 0.10 μm diameter: (a) 30 μm, (b) 50 μm, (c) 100 μm (From Continillo, 1988).*

Figure 4.24 shows an example of computations for laminar explosions of coal dusts of various diameters in air, in a spherical vessel of 0.10 m diameter.

The predicted final pressure of about 12.5 bar(abs) is close to the maximum theoretical adiabatic pressure. This is much higher than maximum pressures found in experiments. The reasons are that the model accounts for neither heat losses nor endothermic dissociation in the burned mixture.

Continillo (1988b) expressed some important view points concerning the use of computer models for simulating dust explosions. A space resolution on the order of a few μm is necessary for a detailed description of particle-scale phenomena. On the other hand, the typical thickness of a real dust flame is on the order of 10 mm or more, whereas the physical dimensions of process units in which dust explosions take place is on the order of 1–10 m. This means that the ratio of the various length scales involved covers up to 7 orders of magnitude. Therefore, detailed comprehensive modeling considering all the relevant mechanisms across all 7n orders of magnitude is not really feasible, even by means of extensive numerical computing. In addition, such a model would require information about a number of microscopic characteristics of the dust particles and their interaction with heat and gas flows, which can be acquired only by complex, extensive experimentation. Furthermore, as discussed in Chapter 3, the mechanics of generation of dust clouds is very complex, and very small particles on the order of 1 μm diameter may not become dispersed into individual primary particles but appear as considerably larger agglomerates constituting the effective particles in the dust cloud.

The optimal simulation model should include the minimum level of detail necessary to reproduce the significant features of the explosion development with sufficient accuracy. The specific interpretation of this statement may vary with the objective of the simulation. From an industrial safety point of view, the upper range of the length scale is most important, whereas for studies of the combustion process as such, for example, for predicting chemical conversion, the smaller scales may be of greater interest.

No matter what the objective, it is beyond doubt that computer simulation is the future tool for predicting dust explosion development in industrial practice. However, it is then necessary to include some other important factors in addition to those considered by Continello (1988), in particular turbulence and aspects of entrainment and dispersion of dust particles, as discussed in Chapter 3 (see also Section 4.4.8).

4.2.6
MINIMUM AND MAXIMUM EXPLOSIBLE DUST CONCENTRATIONS

See also Section 9.2.4.3 in Chapter 9.

4.2.6.1
The Problem

The existence of well-defined minimum and maximum explosible concentrations of fuel in air is well established for various gases and vapors. At the outset, it would be reasonable to expect that such limits of explosible fuel concentrations also exist for combustible dusts. However, as shown by Makris and Lee (1988), who considered the minimum explosible concentration, there is substantial disagreement among experimental data for a given dust. For example, reported values for corn starch in air range from 8 g/m^3 to 400 g/m^3. The disagreement arises from considerable differences in apparatus and interpretation of data. Because of the extremely energetic pyrotechnical igniter used, it is not surprising that the exceptionally low value of 8 g/m^3 was determined by Siwek (1977) using a 20 liter spherical bomb. On the other hand, it cannot be excluded that there were some real differences among the dusts used. Although the primary grains of corn starch have a fairly uniform size of 10–15 μm diameter, commercial corn starch qualities often contain considerable fractions of stable agglomerates that behave as large single particles, as shown by Eckhoff and Mathisen (1977/1978). Furthermore, the moisture contents of the corn starches investigated were often not reported and may have varied.

One basic problem in all experimental determination of explosibility limits is the definition of an *explosion*. It has been customary to relate this definition to either direct observation of a self-sustained flame through the dust cloud, at constant pressure, or to the increase in pressure that results if flame propagation occurs at constant volume in a closed vessel. If the dust concentrations are in the middle of the explosible range, the observation of explosion is simple, irrespective of the criterion chosen. Both extensive flame propagation and extensive pressure buildup result. Problems arise when the dust concentration approaches the lower or upper explosibility limits, and flame propagation and pressure rise become marginal. Because of the inherent inhomogeneity of real dust clouds and the corresponding comparatively poor reproducibility of repeated, apparently identical experiments, it is necessary to choose some arbitrary criterion of a minimal explosion, either in terms of a minimal extent of flame propagation or a minimal magnitude of pressure rise. Unfortunately, there seems to be no really basic scientific criterion that specifies the "right" choice.

In their analysis, Makris and Lee (1988) concluded that any meaningful criterion of a minimum explosible dust concentration must be related to a distinct flame propagation in the dust/air mixture at constant pressure. They claimed that it is not possible to decide whether or not such flame propagation occurs in constant volume experiments, and they therefore did not consider that results from closed bombs had any fundamental significance.

This argument may not be fully justified, but it is necessary to account for the fact that, in any closed-bomb experiment, the unburned mixture starts to become compressed right from the onset of flame propagation.

4.2.6.2
Experimental Determination of Minimum Explosible Dust Concentration

Selle and Zehr (1957) described a closed-bomb method that utilized the flame propagation criterion of explosion. A spherical glass bomb of volume 1.4 liters was used, in which a given quantity of dust, placed in a small hemispherical cup, was dispersed into a cloud by means of a blast of compressed air and exposed to an ignition source at the sphere center. The concentration of dust was gradually lowered in a series of consecutive experiments until the flame no longer propagated throughout the entire volume of the bomb. This means that Selle and Zehr had chosen the requirement of a fully developed flame within the bomb as their criterion of explosion. The size of the flame was recorded on photographic film, and this facilitated an objective decision of whether the flame had actually filled the entire volume of the bomb. Nevertheless, the explosion criterion itself was the result of a subjective choice.

Selle and Zehr observed that flames that occupied only part of the bomb volume were not necessarily located in the vicinity of the ignition source. Due to inhomogeneities in the dust concentration throughout the volume of the explosion bomb, flame propagation could be restricted to local, almost detached "pockets" in the dust cloud.

This kind of nonhomogeneous structure is an inherent feature of real dust flames in general, which clearly complicates the interpretation of marginal flame propagation in small-scale apparatus in terms of minimum explosible concentration in large, industrial-scale systems. Therefore, experiments have also been conducted in fairly large industrial-scale equipment. The work of Palmer and Tonkin (1971) is a good example. Figure 4.25 shows their apparatus.

The dust was introduced at the top of the tube by a screw feeder and dropped into a vibrating 20 cm diameter and 15 cm high dispersing cylinder hanging immediately underneath the screw exit. After having passed the perforated bottom of the cylinder, the dispersed dust settled freely under gravity through the entire length of the tube until finally collected in a bin at the bottom end. Dust concentration and flame propagation could not be measured in the same test but had to be determined in separate tests at nominally identical dust cloud generation conditions, that is, rotating speed of the feeding screw conveyor and vibration mode of the dust disperser. The dust concentration was measured gravimetrically. A manually operated sliding tray was inserted into the tube like a gate valve about 3.5 m from the tube top. By simultaneously closing the tube at the top with a conventional sliding gate valve, the volume of dust cloud was trapped between the top valve and the tray. By dividing the amount of dust finally settled out on the tray by the volume 0.182 m^3 between the tray and the top valve, the average dust concentration in this section of the tube was obtained.

Immediately before performing an explosion test, the dust feed was stopped and the bottom end of the tube closed by a gate valve located just below the ignition zone. The ignition source was a propane flame generated by injecting a small pocket of a propane/air mixture into the bottom region of the explosion tube and igniting by means of an electric spark located at the tube axis.

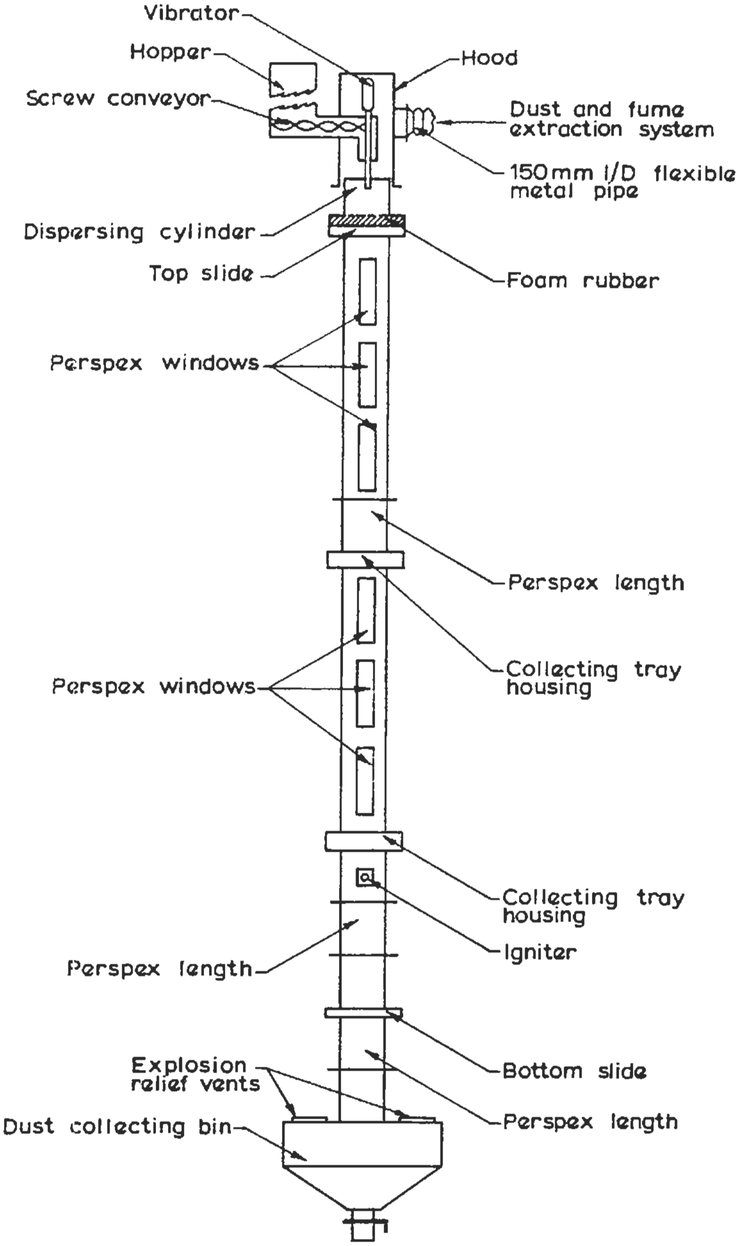


Figure 4.25 *Vertical large-scale explosion tube facility for flame propagation studies. The internal tube diameter is 0.25 m. The total tube length is 5.2 m. The ignition point is 1.5 m above the bottom (From Palmer and Tonkin, 1971).*

This facility was made available to Eckhoff and Fuhre (1975) to determine the minimum explosible concentration of a wheat grain dust of 10% moisture content, taken from a dust extraction filter in a grain silo plant. Due to poor flow properties of the dust, a constant rotation speed of the dust feeding screw did not always result in a constant dust feed. For this reason, several dust concentration measurements had to be performed during a test series at a given screw rotation speed, and some scatter had to be accepted. Only flame propagation lengths of more than about 0.5 m upward in the tube were considered significant. Propagation lengths of about 0.5–1.0 m were classified as "marginal."

The results of eight test series are summarized in Figure 4.26. Each series, run at a given set of nominal dust cloud generation conditions, comprised three to six consecutive experiments for measurement of dust concentration or flame propagation. Figure 4.26 gives the actual average dust concentration values determined in individual experiments in each series and the corresponding flame propagation results.

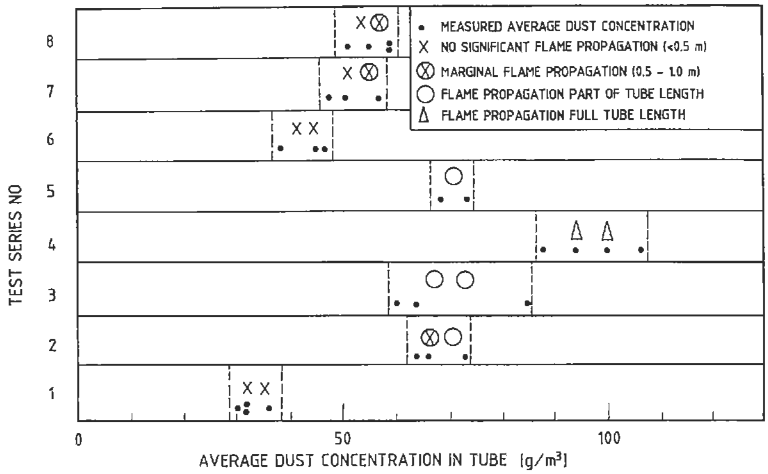


Figure 4.26 *Results from determination of the minimum explosible concentration in air of a wheat grain dust from a grain silo plant, containing 10% moisture, using the vertical large-scale dust explosion tube of diameter 0.25 m and height 5.2 m developed by Palmer and Tonkin (1971) (From Eckhoff and Fuhre, 1975).*

For dust concentrations below 50 g/m^3 no significant flame propagation was observed, whereas marginal propagation was observed in the range 50–60 g/m^3. From 60–80 g/m^3, flame propagated over part of the tube length, whereas full tube length propagation required dust concentration of at least 90–100 g/m^3.

This gradual increase of the extent of flame propagation with dust concentration over a considerable range was also observed by Palmer and Tonkin (1971) and was typical for the facility. This illustrates that realistic dust clouds are never perfectly homogeneous and a sharp minimum explosible concentration value is therefore nonexistent. However, some numerical value may be required in practice; and in the present case, a conservative figure would be 50 g/m^3.

The absence of a sharp minimum explosible concentration seems to be common also for experiments in a smaller scale. Therefore, the specification of a given value of the minimum explosible concentration for a given dust inevitably implies the use of some arbitrary criterion of explosion, as a finite minimum pressure rise at constant volume or a minimum finite extent of flame propagation at constant pressure. A transition range representing a factor of 2 of average dust concentrations, from the first sign of self-sustained flame to extensive flame propagation, is probably typical of many experiments.

Another aspect that needs consideration is the influence of the settling of particles due to gravity on the minimum explosible dust concentration. Burgoyne (1963), discussing the minimum explosible concentration of clouds of liquid droplets, distinguished between "static" and "kinetic" minimum explosible concentrations C_s and C_k. If the drops are sufficiently large for their gravitational sedimentation velocities v_t to be significant and S_u is the upward burning velocity in the drop cloud, then C_s and C_k differ according to

$$C_k = \left(\frac{S_u + v_t}{S_u} \right) C_s \tag{4.65}$$

This equation should also be applicable to solid particles that volatilize or pyrolyze in the preheating zone of the flame front, that is, organic materials and coals.

Figure 3.10 in Chapter 3 shows that, for a density of 1 g/cm^3, a particle diameter of 10 μm gives $v_t = 0.004$ m/s, which means that, for a limit value of S_u of about 0.1 m/s, C_k and C_s differ by only 4%. However, for particle diameters of 50 and 100 μm, $v_t = 0.09$ and 0.3 m/s, which for $S_u = 0.1$ m/s gives $C_k = 1.9\ C_s$ and 4.0 C_s, respectively. This indicates that, due to gravitational settling, flame propagation through clouds in air of volatilizing or pyrolyzing particles on the order of 50–100 μm diameter can take place at considerably lower "static" concentrations C_s than for particles of negligible v_t. Burgoyne converted independent experimental data for C_s and C_k for mists and sprays of organic liquids to the corresponding C_k and C_s values, using equation (4.65) and a limit value of S_u of 0.46 m/s for negligible v_t estimated by assuming that S_u and C_k are the same for upward and downward flame propagation. The results, shown in Figure 4.27, indicate that equation (4.65) is in accordance with reality.

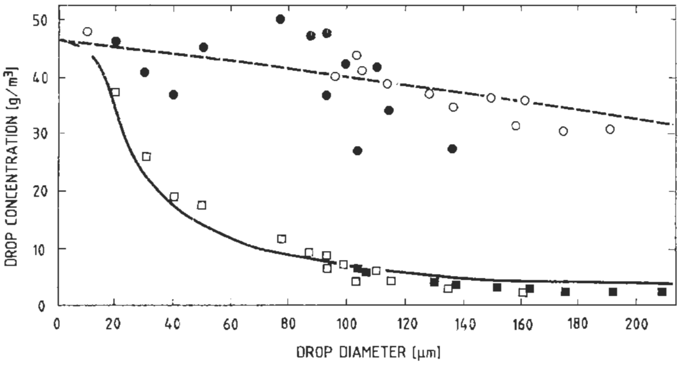


Figure 4.27 *Correlation of "static" and "kinetic" concentrations at the lower limit of flammability of tetralin/air suspensions with varying drop diameter:*

□ = C_s *experimental* ■ = C_s *calculated*
○ = C_k *experimental* ● = C_k *calculated*

(From Burgoyne, 1963).

As pointed out by Burgoyne (1963), equation (4.65) also applies to downward flame propagation, but then v_t, being numerically the same as for upward propagation, becomes negative. As a consequence, C_s for downward propagation becomes larger than C_k, and

$$C_{s,\mathrm{upwards}} < C_k < C_{s,\mathrm{downwards}} \tag{4.66}$$

Hartmann and Nagy (1944) introduced an arbitrary pressure criterion when determining the minimum explosible dust concentration using the 1.2 liter Hartmann tube. The top of the tube was closed by a paper membrane of bursting strength about 0.2 bar(g). The smallest quantity of dispersed dust that generated at least this pressure rise, divided by the volume of the tube, was taken as the minimum explosible dust concentration.

The continued use of this criterion in the extensive later investigations by the U.S. Bureau of Mines (USBM), was confirmed by Dorsett et al. (1960). However, Cashdollar and Hertzberg (1985) reconsidered the original USBM method and suggested their new 20 liter closed explosion vessel test as an alternative. The explosion criterion chosen was $P_m/P_0 \geq 2$, where P_m is the maximum absolute explosion pressure in the experiment and P_0 is the initial pressure, both corrected for the pressure rise due to the 2.5–5 kJ chemical ignitors used. By adopting this method, Cashdollar, Hertzberg, and Zlochower (1989) identified the minimum explosible concentration of Pittsburgh coal to about 90 g/m^3, in contrast to the earlier value of 135 g/m^3 found in an 8 liter bomb and reported by Hertzberg, Cashdollar, and Opferman (1979). Cashdollar et al. (1988) correlated minimum explosible dust concentrations of coal dusts measured in the USBM 20 liter bomb with values from large-scale mine experiments and found good agreement.

Hertzberg et al. (1987) postulated that flames in low-concentration clouds of organic dusts and coal dusts of small particle sizes are essentially premixed gas flames. This is because the burning velocity close to the minimum explosible concentration is so low that each particle becomes completely devolatilized and the volatiles mixed with air in the preheating zone of the flame front before combustion gets under way.

Following this line of thought, Cashdollar et al. (1989) determined the minimum explosible concentrations for various coals and mixtures of graphite and polyethylene dust as a function of the content of volatiles. Figure 4.28 shows the resulting correlation. It is worth noting that the value of 33 g/m^3 for polyethylene, which devolatilizes completely, is close to the minimum explosible concentration of methane in air.

This is further in good agreement with the results of Eckhoff and Pedersen (1988) for polyester and epoxy dusts, using a method reported by Nordtest (1989). Their results are given in Figure 4.29.

The straight line through the square points is approximately horizontal, indicating that the minimum explosible concentration of combustible material is, in fact, almost constant and independent of pigment content. The chemical composition of the combustible substance does not seem to influence its minimum explosible concentration. It is interesting to observe the close agreement between this value of 31–35 g/m^3 and the value 33 g/m^3 found for polyethylene by Cashdollar et al. (1989). It is also of interest to compare the value of 31–35 g/m^3 with published explosibility limits for gaseous hydrocarbon in air mixtures. For methane in air and propane in air, the limits are approximately 5.0 vol% and 2.0 vol%, respectively. Converted to mass concentrations, these equal 33 g/m^3 and 36 g/m^3, respectively (at 25°C), which is close to the measured minimum explosible concentrations of combustible material for the polyester and epoxy powders. This supports the view that the flame propagation through the dust clouds at the limiting

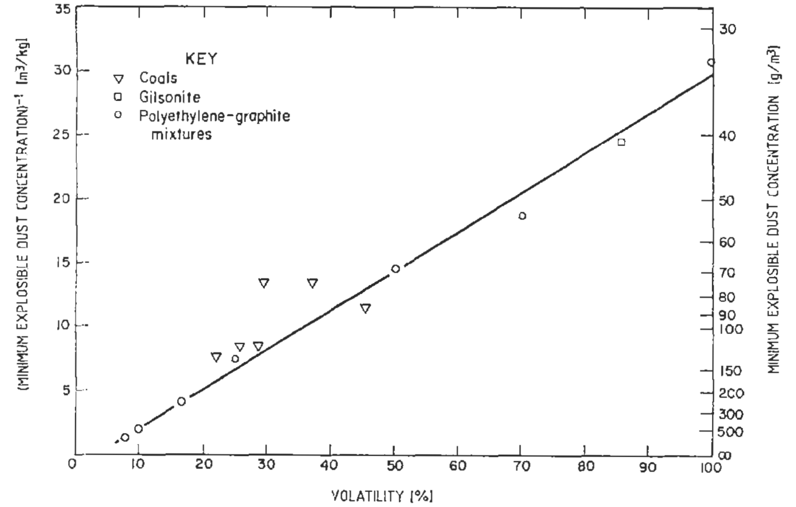


Figure 4.28 *Inverse and minimum explosible dust concentration versus content of volatiles for various dusts (From Cashdollar, Hertzberg, and Zlochower, 1988).*

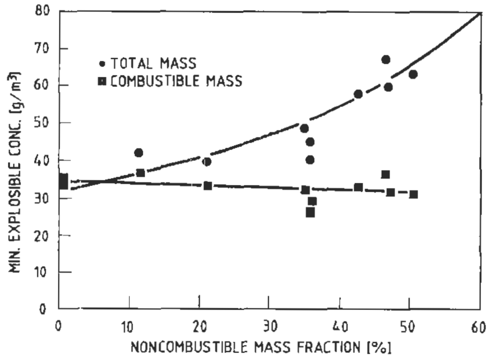


Figure 4.29 *Minimum explosible dust concentration versus non-combustible mass fraction for polyester and epoxy resins. (From Eckhoff, Pedersen, and Arvidsson, 1988).*

concentration is similar to that through a premixed gas; that is, flame propagation takes place in the combustible gas evolved from the particles in the preheating zone just ahead of the flame. In accordance with this model, p being the mass fraction of noncombustibles in percent, the minimum explosible dust concentration (MEC) of this category of dusts is

$$\text{MEC} = 32\ \text{g/m}^3\ [100/(100-p)] \qquad (4.67)$$

This relationship gives the curved line in Figure 4.29, and it is seen that the agreement with the experimental points is reasonable. Approximate estimates of MEC for various contents of noncombustible material can be obtained by this relationship. However, undue extrapolation beyond the experimental points give physically meaningless results because MEC $\rightarrow \infty$ when $p \rightarrow 100$.

Buksowicz and Wolanski (1983) studied flame propagation near the minimum explosible dust concentration, in a 5.5 liter vertical cylinder of 150 mm diameter. By choosing a minimum relative pressure rise P_m/P_0 of 1.5 as their explosion criterion, they obtained minimum explosible dust concentrations in close agreement with those based on self-sustained flame propagation in a long tube of 100 mm diameter. Buksowicz and Wolanski demonstrated by direct photography that, near the minimum explosible dust concentration, the dust flame is fragmented into detached zones of burning particle clusters. They also emphasized the need for using a sufficiently energetic ignition source, when studying propagation of lean limit flames.

Schläpfer (1951) measured minimum explosible concentrations of various dusts in air in a laboratory-scale vertical tube of diameter 30 mm and with a vertical distance of 0.6 m from the ignition source to the open top end of the tube. Dust suspensions of known concentration were conveyed upward in the tube at a laminar velocity of 0.6 m/s. Propagation of dust flame at least three-fourths of the distance of 0.6 m from the ignition source to the tube top was used as the explosion criterion. The ignition source was an electrically ignited 0.2 mm thick and 7 mm long aluminum wire. The results in Table 4.8 were obtained.

Table 4.8 Minimum explosible dust concentrations measured at laminar flow conditions in a 30 mm diameter vertical tube

Dust type	Minimum explosible concentration (g/m³)
Aluminum flakes, mean flake thickness 0.5 μm	90
Lignin, 100% finer than 120 μm	48
Phenol resin, brown, 100% finer than 120 μm*	45
Phenol resin, gray, 100% finer than 120 μm*	36

*The chemical difference between the two resins was not given but is probably primarily due to different coloring additives.
Source: Schläpfer, 1951.

Hertzberg et al. (1987) found that the minimum explosible dust concentration for polymethylmethacrylate was about 80 g/m^3 and independent of the particle diameter up to 100 μm. For Pittsburgh seam bituminous coal, the value of about 90 g/m^3 was found to apply from 2 μm to 60 μm particle diameter. However, when the particle diameter increased toward 200 μm, a substantial increase in the minimum explosible concentrations was found for both dusts. This influence of particle size agrees with the earlier results of Ishihama (1961) for various particle size fractions of coals of volatile matter contents in the range 46–49%. This worker also found that the minimum explosible dust concentration decreased with decreasing mean particle diameter down to about 60 μm. For a finer fraction, of mean size 29 μm, the minimum explosible concentration was only slightly lower than for the 60 μm fraction.

However, the actual minimum explosible concentration values found by Ishihama were only half those found by Hertzberg et al. (1987). This can in part be explained by the higher content of volatiles in the coals used by Ishihama, but the major factor is probably the different experimental methods and explosion criteria used.

Minimum explosible dust concentrations were determined in a comparative test series among four laboratories in different countries. Three methods were used: the 20 liter sphere method developed by Siwek (1977; see also ASTM, 1988), the 1 m^3 method specified by the International Standards Organization (1985), and the Nordtest (1989) Fire 011 method. The results are shown in Table 4.9.

Table 4.9 Minimum explosible dust concentration (g/m^3) determined by three methods in four laboratories

	Test method						
	20 liter sphere					1 m^3	Nordtest Fire 011
Dust	**Lab. 1**	**Lab. 2**	**Lab. 3**	**Lab. 4**	**Arithm. mean**	**Lab. 1**	**Lab. 3**
Lycopodium	30 (0.5)	20 (0.2)	15 (0.1)	40 (0.5)	26	30 (0.4)	35 ± 6*
Maize starch (11–12% moisture)	60 (0.5)	50 (0.3)	90 (0.2)	90 (0.2)	73	80 (0.3)	130 ± 14* [76 ± 4]
Light-protecting agent "Tinuvin"	30 (1.3)	10 (0.2)	20 (0.2)	20 (0.1)	20	40 (0.3)	27 ± 3*
Spanish coal (36% volatiles)	40 (0.6)	30 (0.4)	25 (0.3)	30 (0.1)	31	70 (0.2)	98 ± 20* [73 ± 5]
Zinc	600 (0.9)	600 (0.3)	400 (0.3)	400 (0.1)	500	650 (0.8)	565 ± 65*

*Standard deviation.

Note: Figures in parentheses ( ) indicate measured maximum explosion pressure in bar(g) minus that due to the ignitor (assumed to be 1.3 bar(g) for the 20 liter sphere). Figures in brackets [] are from more-recent data.

Source: Eckhoff, 1988.

The 20 liter Siwek test was based on a rather weak and vaguely defined pressure rise criterion. In addition, the very strong 10 kJ pyrotechnical ignitor may cause combustion of dust even if the dust concentration is below that required for self-sustained flame propagation at constant pressure. Therefore, it is not unexpected that the 20 liter minimum explosible dust concentrations were generally lower than for the two other methods. The work of Continillo et al. (1986) with the 20 liter Siwek sphere indicates significant pressure rise for coal dust/air clouds even at dust concentrations as low as 50 g/m^3, in accordance with the low minimum explosible concentration for coal dust for this apparatus in Table 4.9. Furthermore, the real, local dust concentration in the region of the ignition source was not known. The problem of generating nonhomogeneous distributions of dust concentration in small-scale experiments has been emphasized by Eggleston and Pryor (1967).

The 1 m^3 method also involves a 10 kJ ignition source and a pressure rise criterion, but because of the large size of the vessel, the net influence of the 10 kJ ignitor on the pressure rise is small. However, the distribution of dust concentration is not known.

The Nordtest Fire 011 is essentially a constant pressure method, because the top of the 15 liter vessel is covered only by a weak paper diaphragm. The explosion criterion is independent, upward flame propagation through the experimental dust cloud to an extent that the flame, as observed visually, is clearly detached from the ignition source. A special feature of this method is that the actual local dust concentration in the region of the ignition source is measured directly gravimetrically. Most of the Nordtest data in Table 4.9 are based on an earlier, quite restrictive criterion of explosion, requiring fairly extensive flame propagation. More recent data, based on the present criterion of any flame propagation clearly detached from the ignition source, are given in brackets.

Lovachev (1976) discussed some unrealistically low values for the minimum explosible concentration of some dusts reported in USSR, and he emphasized the necessity of observing self-sustained flame propagation through the dust cloud, beyond the influence of the ignition source (see also Section 7.13).

4.2.6.3
Experimental Determination of Maximum Explosible Dust Concentration

The results of Palmer and Tonkin (1971) from the large-scale apparatus shown in Figure 4.25 give an indication of the maximum explosible concentration of a coal dust containing 36.4% volatiles on a dry, ash-free basis. Extrapolation from their data for mixtures of coal and sodium chloride to zero content of the latter indicates a value of 2000–3000 g/m^3. This is on the same order as the value indicated by extrapolating the data from stabilized burner experiments with a similar coal dust (Pittsburgh) in air, presented by Smoot et al. (1977). These workers measured laminar burning velocities of more than 0.15 m/s even at 1800 g/m^3.

Slezak, Buckius, and Krier (1986), using a tumbling horizontal explosion cylinder of 0.3 m diameter and 4.5 m length, estimated the maximum explosible concentration of Pittsburgh coal dust in air to be about 1500 g/m^3.

However, Cashdollar et al. (1988), using their closed 20 liter explosion vessel, were unable to detect any maximum explosive dust concentration for Pittsburgh coal up to 4000 g/m^3. They refer to other laboratory and large-scale experiments that confirm this result.

On the other hand, Ishihama, Enomoto, and Sekimoto (1982) could determine maximum explosible concentrations of different noncohesive coal dust fractions using a rotating drum apparatus in which the dust cloud was generated continually by being lifted along the drum wall, subsequently falling freely under gravity. For the particle size fraction 35–50 μm, the maximum explosible concentration in air was 2700 g/m^3 for a 45% volatiles coal, 2200 g/m^3 for 33% volatiles, and 1400 g/m^3 for 22% volatiles. The maximum explosible concentration decreased with increasing particle size, and for the 45% volatiles coal, it was 2400 g/m^3 for 50–75 μm and 1800 g/m^3 for 100–150 μm.

Ishihama et al. also investigated potato starch of mean particle size 50 μm and found a very high maximum explosible concentration of about 8000 g/m^3. It seems probable that the cohesive potato starch, as opposed to the free-flowing coal dust fractions, only dispersed partly in the rotating drum apparatus, yielding a lower real concentration of dispersed dust than the nominal value.

Other data on maximum explosible dust concentration, from more-direct experimental determination than these rather scattered and partly contradictory results, have not been traced. It is therefore of interest to consider the more indirect determinations by Zehr (1959). He made the first-order assumption that the conditions for flame propagation in a dust/air mixture depends only on the mass ratio of dust to air and is independent of air pressure and mean distance between particles. He then constructed the cylindrical combustion bomb illustrated in Figure 4.30 to determine the maximum explosible concentration of dusts.

The central 25 cm long glass tube of about 1 cm^2 cross section and one end closed is first filled completely with the dust to be tested, loosely packed. The glass tube is then inserted into the combustion bomb and the air pressure raised to the desired level. Because the bulk densities of loosely packed organic dusts are typically on the order of 500 kg/m^3 and maximum explosible concentrations on the order of 1 kg/m^3, air pressures up to the order of 500 bar were required to obtain the same dust/air mass ratio in Zehr's combustion tube as in a dust cloud at the maximum explosible concentration at atmospheric pressure. At these high pressures, the equation of state has to be corrected for nonideal gas behavior. Zehr (1959) gives a detailed description of the computational

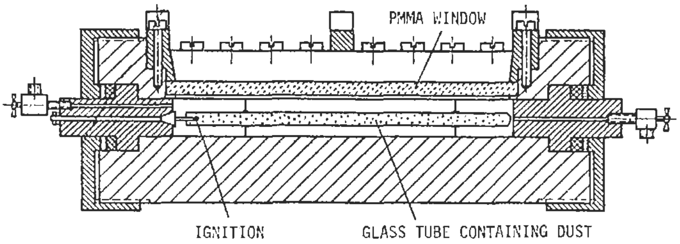


Figure 4.30 *Apparatus for indirect experimental determination of the maximum explosible concentration of dusts in air (From Zehr, 1959).*

procedure used to convert the actual high-pressure conditions to atmospheric pressure conditions. After achieving the desired initial conditions, the dust was ignited at the open end of the glass tube and observed, through a narrow uncovered slit of the Perspex window, whether combustion propagated along the tube toward its closed end. Some of Zehr's results are summarized in Table 4.10.

Table 4.10 Maximum explosible concentrations of dusts in air determined by an indirect experimental method of Zehr (1959)

Dust	Maximum explosible dust concentration (g/m^3)
Coal, <10 μm particle size, high content of volatiles	>800*
Wheat and rice flour	>1000*
Peat, dried	2600
Cotton	1800–2400
Cork	1400–1500
Cork	2000–2500**
Polyurethane	1000
Polyvinyl alcohol	2000–2300
Polyvinyl alcohol	>750–900*
Sulfur	>900*

* Value obtained with 50% kieselguhr mixed into dust.
** Standard glass tube replaced by one of two times larger diameter.

The experiments with kieselguhr mixed into the combustible dust were performed only when the propagation of the combustion in the combustible dust could not be clearly identified. However, although the kieselguhr facilitated distinction between propagation and no propagation, the maximum explosible dust concentrations estimated from the experiments with kieselguhr were much lower than would be expected in the combustible dust alone, as illustrated by the data for polyvinyl alcohol in Table 4.10.

Zehr's method might be improved by increasing the glass tube diameter and using thermocouples at various locations in the tube to detect propagation of combustion, rather than rely on visual observation. However, due to the very high temperatures to be expected, the method may not be suitable for metal dusts such as silicon, aluminum, and magnesium.

4.2.6.4
Theories of Minimum and Maximum Explosible Dust Concentrations

The first attempt to predict the minimum and maximum explosible concentrations for dust clouds theoretically was probably made by Jaeckel (1924), who considered the one-dimensional heat transfer from a plane flame front to the adjacent unburned layer of dust cloud.

The minimum explosible concentration, according to Jaeckel, is the minimum amount of dust, per unit volume of dust cloud, that by complete combustion liberates enough energy to heat the next unit volume of dust cloud to the ignition temperature. This means that the assumption of the existence of such a temperature is as basic in Jaeckel's theory as the classical flame propagation theory of Mallard-le Chatelier (1883).

According to Jaeckel, the maximum explosible concentration arises from the fact that the air contains a limited amount of oxygen, which is totally consumed by the complete combustion of a given amount of dust, the stoichiometric concentration C_s. A further increase in the dust concentration therefore merely has the effect that more energy is required for heating the next volume to the ignition temperature, since the excess dust acts only as a coolant or heat sink.

Jaeckel (1924) formulated the condition for self-sustained flame propagation through the dust cloud of concentration $C < C_s$ at constant volume as

$$CQ \geq L + (T_i - T_0)(Cc_d + d_g c_v) \tag{4.68}$$

where

c_v is the specific heat at a constant volume of the gas;
d_g is the density of the gas;
Q is the heat of combustion of the dust;
c_d is the specific heat of the dust particles;
T_0 is the initial temperature of the dust cloud;
T_i is the ignition temperature of the dust cloud;
L is the heat losses by radiation and conduction.

By equating the two sides and rearranging, one obtains the expression for the minimum explosible concentration C_1:

$$C_1 = \frac{L}{[Q - c_d(T_i - T_0)]} + \frac{(T_i - T_0)d_g c_v}{[Q - c_d(T_i - T_0)]} \tag{4.69}$$

For dust concentrations above the stoichiometric concentration the heat production is constant and equal to $Q \times C_s$, whereas the heat consumption increases with the dust concentration. In this case, the condition for self-sustained flame propagation is

$$C_s Q \geq L + (T_i - T_0)(Cc_d + d_g c_v) \tag{4.70}$$

By rearranging, Jaeckel's theoretical upper explosible limit becomes equal to

$$C_u = \frac{C_s Q - L}{(T_i - T_0)c_d} - \frac{d_g c_v}{c_d} \tag{4.71}$$

Jaeckel considered a constant volume explosion. In a typical real case, a dust explosion is probably neither a pure constant pressure nor a pure constant volume process, since pressure gradually builds up in the unburned cloud, although the flame may not be fully confined in volume.

As can be seen from equations (4.69) and (4.71), a substitution of c_v by c_p increases C_1 and decreases C_u. The loss L is difficult to estimate, and Jaeckel suggested, as a first approximation, that the loss factor L be neglected. If this is done and c_v is replaced by c_p, equations (4.69) and (4.71) can be written

$$C_1 = \frac{(T_i - T_0)d_g c_p}{Q - c_d(T_i - T_0)} \tag{4.72}$$

$$C_u = \frac{C_s Q}{(T_i - T_0)c_d} - \frac{d_g c_p}{c_d} \tag{4.73}$$

If the left-hand sides of equations (4.68) and (4.70), representing the heat production, are denoted H_p, it is seen that for $0 < C < C_s$, H_p is a linear function of C; and for $C > C_s$, it is constant and independent of dust concentration.

If the ignition temperature is considered independent of dust concentration and the loss L is neglected, and the right-hand sides of equations (4.68) and (4.70), representing the heat consumption, are denoted H_c, H_c becomes a linear function of the dust concentration. According to Jaeckel's simple model, the condition of self-sustained flame propagation is

$$H_p \geq H_c \tag{4.74}$$

Zehr (1957) suggested that Jaeckel's theory be modified by replacing the assumption of an ignition temperature of finite value by the assumption that the dust flames of concentrations near the minimum explosible limit have a temperature of 1000 K above the ambient temperature. Zehr further assumed that the combustion is adiabatic and runs completely to products of the highest degree of oxidation and the dust particles are so small that the dust cloud can be treated as a premixed gas. The resulting equations for the minimum explosible concentration in air are

$$C_1 = \frac{1000\,M}{107\,m + 2.966[Q_m - \sum \Delta I]} \quad (\text{g/m}^3) \tag{4.75}$$

for constant pressure, and

$$C_1 = \frac{1000\,M}{107\,m + 4.024[Q_m - \sum \Delta U]} \quad (\text{g/m}^3) \tag{4.76}$$

for constant volume. Here M is the mole weight of the dust material and m is the number of moles of O_2 required for complete oxidation of 1 mole of dust; Q_m is the molar heat of combustion of the dust; $\sum \Delta I$ is the enthalpy increase of the combustion products; and $\sum \Delta U$ is the energy increase of the combustion products.

Schönewald (1971) derived a simplified empirical version of equation (4.75) that also applies to dusts containing a mass fraction $(1 - \alpha)$ of inert substance, α being the mass fraction of combustible dust:

$$C_1^* = \frac{C_1 / \alpha}{1 - 2.966(1-\alpha)c_p C_1 / \alpha} \tag{4.77}$$

where the minimum explosible dust concentration without inert dust is $C_1 = -1.032 + 1.207 \bullet 10^6/Q_0$, Q_0 being the heat of combustion per unit mass (in J/g), as determined in a bomb calorimeter. As can be seen from Freytag (1965), equations (4.75) and (4.76) were used in the Federal Republic of Germany for estimating minimum explosible dust concentrations, but later, this method was replaced by experimental determination.

Table 4.11 gives examples of minimum explosible dust concentrations calculated from equations (4.75) and (4.76), as well as some experimental results for comparison. The calculated and experimental results for the organic dusts polyethylene, phenol resin, and starch are in good agreement. This would be expected from the assumptions made in Zehr's theory. However, the result for graphite clearly demonstrates that Zehr's assumption of complete combustion of any fuel as long as oxygen is available is inadequate

Table 4.11 Minimum explosible dust concentrations (g/m³) calculated by the theory of Zehr (1957)

Dust type	Calculated minimum explosible dust concentrations (g/m³)		Experimental minimum explosible dust concentration (g/m³)
	Constant volume	Constant pressure	
Aluminum	37	50	90, constant pressure (Schläpfer, 1951)
Graphite	36	45	Flame propagation in graphite/air at normal conditions not observed
Magnesium	44	59	
Sulfur	120	160	
Zinc	212	284	500–600, constant pressure, constant volume (Eckhoff, 1988)
Zirconium	92	123	
Polyethylene	26	35	33, constant volume (Cashdollar, Hertzberg, and Zlochower, 1988)
Polypropylene	25	35	
Polyvinyl alcohol	42	55	
Polyvinyl chloride	63	86	
Phenol resin	36	49	36–45, constant pressure (Schläpfer, 1951)
Corn starch	90	120	70, constant pressure (Proust and Veyssiere, 1988)
Dextrin	71	99	
Cork	44	59	50, constant pressure (Essenhigh and Woodhead, 1958)
Lignite	49	68	
Bituminous coal	35	48	70–130, constant volume (Cashdollar, Hertzberg, and Zlochower, 1988)

Source: Most data from Freytag (1965); comparison with experimental data.

for other types of fuel. The results for bituminous coal and the metals also reflect this deficiency.

Buksowicz and Wolanski (1983) postulated that, at the minimum explosible concentration, flames of organic dusts have the same temperature as lower limit flames of premixed hydrocarbon gas/air. They then proposed the following simple, semi-empirical correlation between the heat of combustion (calorific value) Q (kJ/kg) of the dust, and the minimum explosible concentration C_1 (g/m^3) in air at normal pressure and temperature:

$$C_1 = 1.55 \bullet 10^7 Q^{-1.21} \tag{4.78}$$

The assumptions implied confine the applicability of this equation to the same dusts to which Zehr's equations (4.75) and (4.76) apply. For starch, equation (4.78) gives C_1 = 114 g/m^3, which is somewhat higher than the value of 70 g/m^3 found experimentally by Proust and Veyssiere (1988) but close to that calculated by Zehr for constant pressure. For polyethylene, equation (4.78) gives 36 g/m^3, in close agreement with both experiments and Zehr's calculations.

Lunn (1988) also investigated this group of materials and obtained further support for the hypothesis that the minimum explosible concentration of organic dusts that burn more or less completely in the propagating flame is primarily a function of the heat of combustion of the dust.

Shevchuk et al. (1979), being concerned primarily with metal dusts, advocated the view that a discrete approach, considering the behavior and interaction of individual particles, is necessary for producing an adequate theory for the minimum explosible dust concentration. They analyzed the distribution of a heat wave in a dilute suspension of monosized solid fuel particles in a gas, assuming no relative movement between particles and gas, no radiative heat transfer, and that the rate of heat production q_p during combustion of a single particle of mass m_p was constant during the entire burning lifetime t_b of the particle and equal to $q_p = Qm_p/t_p$, where Q is the heat of combustion of the particle material. The resulting equation for the minimum explosible dust concentration, assuming that the average flame temperature equals the ignition temperature T_i of the dust cloud as determined in a heated-wall furnace, is

$$C_1 = (T_i - T_0) c_g \rho_g / [FQ - c_d (T_i - T_0)] \tag{4.79}$$

Here, T_0 is the ambient temperature, c_g and c_d are the heat capacities of gas and dust material, ρ_g is the gas density, and F is a special particle distribution factor resulting from this particular analysis; and the last term causes equation (4.79) to differ from Jaeckel's equation (4.72). Using T_i data from Jacobson, Cooper, and Nagy (1964), Shevchuk et al. compared equations (4.72) and (4.79), as shown in Table 4.12.

Table 4.12 Minimum explosible concentrations of metal powders in air

Powder type	Ti (K)	Eq. (4.72) (g/m³)	Eq. (4.79) (g/m³)
Aluminum	920	25	51
Magnesium	890	29	62
Titanium	600	21	44
Iron	590	52	107
Manganese	730	62	129

Source: Shevchuk et al., 1979.

Reliable experimental data for metal dusts are scarce. However, Schläpfer (1951) found a value of 90 g/m^3 for fine aluminum flakes, which indicates that both equations underestimate the minimum explosible concentration considerably, equation (4.72) by a factor of nearly 4 and (4.79) by a factor of nearly 2. A main reason for this is probably the use of the ignition temperature T_i as a key parameter.

Mitsui and Tanaka (1973) derived a theory for the minimum explosible concentration using the same basic discrete microscopic approach as adopted later by Nomura and Tanaka (1978) to model laminar flame propagation in dust clouds, and discussed in Section 4.2.4.4. Working with spherical flame propagation, they defined the minimum explosible dust concentration in terms of the time needed from the moment of ignition of one particle shell to the moment when the air surrounding the particles in the next shell has been heated to the ignition temperature of the particles. If this time exceeds the total burning time of a particle, the next shell never reaches the ignition temperature. Because this heat transfer time increases with the mean interparticle distance, it increases with decreasing dust concentration. By using some empirical constants, the theory reproduced the trend of experimental data for the increase of the minimum explosible dust concentration of some synthetic organic materials with mean particle size in the coarse size range from 100–500 μm particle diameter.

Nomura, Torimoto, and Tanaka (1984) used a similar discrete theoretical approach to predict the maximum explosible dust concentration. They defined this upper limit as the dust concentration that just consumed all available oxygen during combustion, assuming that a finite limited quantity of oxygen, much less than required for complete combustion, was allocated for partial combustion of each particle. Assuming that oxygen diffusion was the rate-controlling factor, they calculated the total burning time of a particle in terms of the time taken for all the oxygen allocated to the particle to diffuse to the particle surface. For the flame to be transmitted to the next particle shell, the particle burning time has to exceed the heat transfer time for heating the gas surrounding the next particle shell to the ignition temperature. Equating these two times defines the maximum explosible dust concentration. Two calculated values were given, 1400 g/m^3 for terephthalic acid of 40 μm particle diameter and 4300 g/m^3 for aluminum of 30 μm particle diameter. The ignition temperatures for the two particle types were taken as 950 K and 1000 K, respectively.

Bradley et al. (1989) proposed a chemical kinetic theoretical model for propagation of flames of fine coal dust near the minimum explosible dust concentration. It was assumed that the combustion occurred in premixed volatiles (essentially methane) and oxidizing gas, the char particles being essentially chemically passive. The predicted minimum explosive concentrations were in good agreement with experimental values (about 100 g/m^3 for 40% volatile coal, and 500 g/m^3 for 10–15% volatiles).

4.3

NONLAMINAR DUST FLAME PROPAGATION PHENOMENA IN VERTICAL DUCTS

This section treats some transitional phenomena observed under conditions where laminar flames could be expected. This does not include fully turbulent combustion, which is discussed in Section 4.4.

Buksowicz, Klemens, and Wolanski (1982) and Klemens and Wolanski (1986) describe experiments with a lignite dust of 52% volatiles, 6% ash, and <75 μm particle size, in a 1.2 m long vertical duct of rectangular cross section of width 88 mm and depth 35 mm. The duct was closed at the top and open at the bottom. Dust was fed at the top by a calibrated vibratory feeder yielding the desired dust concentration. The ignition source (an electric spark of a few J energy or a gas burner flame) was located near the open bottom end. Flame propagation and flame structure were recorded through a pair of opposite 80 mm × 80 mm glass windows. Diagnostic methods included Mach-Zehnder interferometry, high-speed framing photography, and high-frequency response electrical resistance thermometry. Figure 4.31 shows a compensation photograph of a lignite dust/air flame propagating upward in the rectangular duct. The heterogeneous structure of the flame, which is typical for dust flames in general, is a striking feature. This is reflected by the

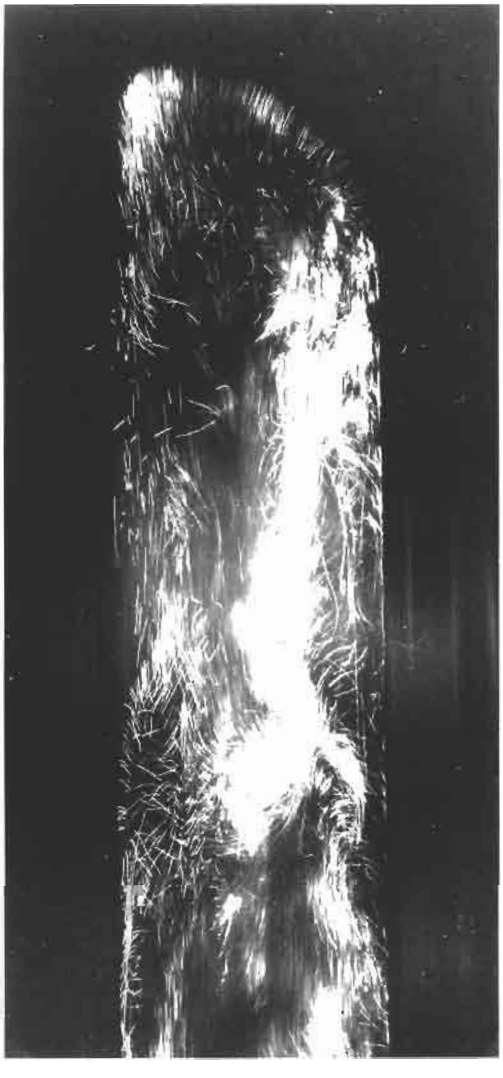


Figure 4.31 *Compensation photograph of a 80 g/m^3 lignite dust/air flame in a vertical rectangular duct of width 88 mm (From Buksowicz et al., 1982).*

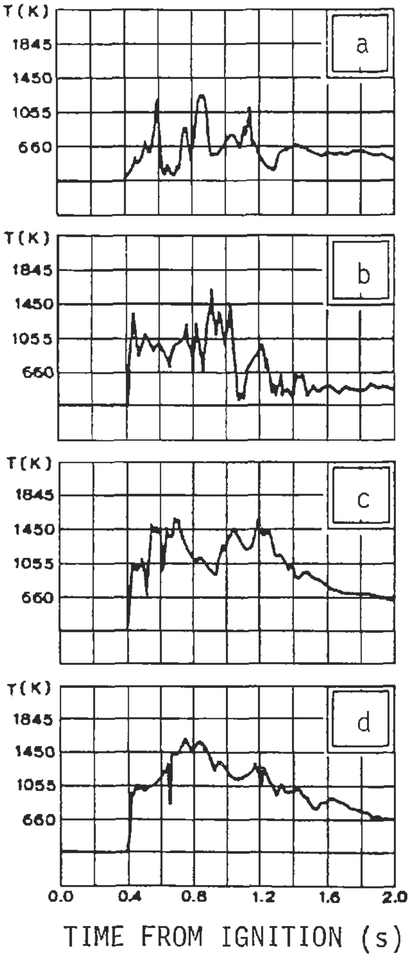


Figure 4.32 *Temperature variation with time at four fixed locations in a 103 g/m^3 lignite/air dust flame propagating in a vertical duct of 88 mm × 35 mm rectangular cross section. Temperature probe locations: (a) 2 mm from duct wall, (b) 6 mm from duct wall, (c) 26 mm from duct wall, and (d) 44 mm from duct wall (= duct center) (From Klemens and Wolanski, 1986).*

marked temperature fluctuations recorded at fixed points in the flame during this kind of experiments, as shown in Figure 4.32.

The amplitudes of the temperature oscillation with time are substantial, up to 1000 K. The very low temperature of almost ambient level at about 1.1 s in Figure 4.32(b) shows that, at this location and moment, there was probably a pocket of cool air or a very dilute, noncombustible dust cloud. Klemens and Wolanski (1986) were concerned mainly with quite low dust concentrations. From a quantitative analysis of their data, they concluded that the thickness of the flame front was 11–12 mm, whereas the total flame thickness could reach 0.5 m due to the long burning time (and high settling velocities) of the larger particles and particle agglomerates. The flame velocities relative to the unburned mixture of 0.5–0.6 m/s were generally about twice the velocity for lean methane/air mixtures in the same apparatus. This was attributed to the larger flame front area for the dust/air mixture and the intensification of the heat and mass exchange processes in the dust/air flame. Even for Reynolds numbers of less than 2000 (calculated as proposed by Zeldovich et al., 1980) eddies, generated by the nonuniform spatial heat generation rate caused by the nonuniform dust cloud, could be observed in the flame front.

Gmurczyk and Klemens (1988) conducted an experimental and theoretical study of the influence of the nonuniformity of the particle size distribution on the aerodynamics of the combustion of clouds of coal dust in air. It was suggested that the nonhomogeneous particle size, amplified by imperfect dust dispersion, produces a nonhomogeneous heat release process and leads to the formation of vortices.

Xufan et al. (1987) and Dehong (1986) studied upward flame propagation in airborne clouds of Ca-Si dust and coal dust in a vertical cylindrical tube of internal diameter 150 mm and length 2 m. The tube was open at the bottom end and closed at the top. The Ca-Si dust contained 58% Si, 28% Ca, and 14% Fe, Al, C, and the like and had a mean particle diameter of about 10 μm. The Chinese coal dust from Funsun contained 39% volatiles and 14% ash and had a median particle diameter by mass of 13 μm. The dust clouds were generated by vibrating a 300 μm aperture sieve, mounted at the top of the combustion tube and charged with the required amount of dust, in such a way that a stationary falling dust cloud of constant concentration existed in the tube for the required period of time. The dust concentration was measured by trapping a given volume of the dust cloud in the tube between two parallel horizontal plates, inserted simultaneously, and weighing the trapped dust. Ignition was accomplished by means of a glowing resistance wire coil at the tube bottom, after 10–20 s of vibration of the sieve. Upward flame velocities and flame thicknesses were determined by two photodetectors positioned along the tube. For the Ca-Si dust, the flame velocities were in the range 1.3–1.8 m/s, and the total thickness of the luminous flame extended over almost the total 2 m length of the tube. The net thickness of the reaction zone was not determined. Figure 4.33 shows a photograph of a Ca-Si dust flame propagating upwards in the 150 mm diameter vertical tube. Figure 4.34 gives the average upwards flame velocities in clouds of various concentrations of the Chinese coal dust in air.

On average, these flame velocities for coal/air are about half those found for the Ca-Si under similar conditions. The data in Figure 4.34 indicate a maximum flame velocity at about 500 g/m^3. If conversion of these flame velocities to burning velocities is made by assuming some smooth convex flame front shape, the resulting estimates are considerably higher than the expected laminar values. This agrees with the conclusion of Klemens and Wolanski (1986) that this kind of dust flames in vertical tubes easily becomes nonlaminar due to nonhomogeneous dust distribution over the tube volume.

In the initial phase of the experiments of Proust and Veyssiere (1988) in the vertical tube of 0.2 m × 0.2 m square cross section, nonlaminar cellular flames, as shown in Figure 4.35, were observed. In these experiments, the height of the explosion tube was limited to 2 m. Over the propagation distance explored, the mean flame front velocity was about 0.5 m/s, as for the proper laminar flame, but careful analysis revealed a pulsating flame movement of about 60 Hz. A corresponding 60 Hz pressure oscillation, equal to the fundamental standing wave frequency for the one-end-open 2 m long duct, was also recorded inside the tube. Further, a characteristic sound could be heard during the propagation of the cellular flames. Proust and Veyssiere, referring to Markstein's discussion of cellular gas flames, suggested that the observed cellular flame structure is closely linked with the 60 Hz acoustic oscillation. However, there seemed to be no straightforward relationship between the cell size and the frequency of oscillation.

It is of interest to relate Proust and Veyssiere's discussion of the role of acoustic waves to the corn starch explosion experiments of Eckhoff, Fuhre, and Pedersen (1987) in a 22 m

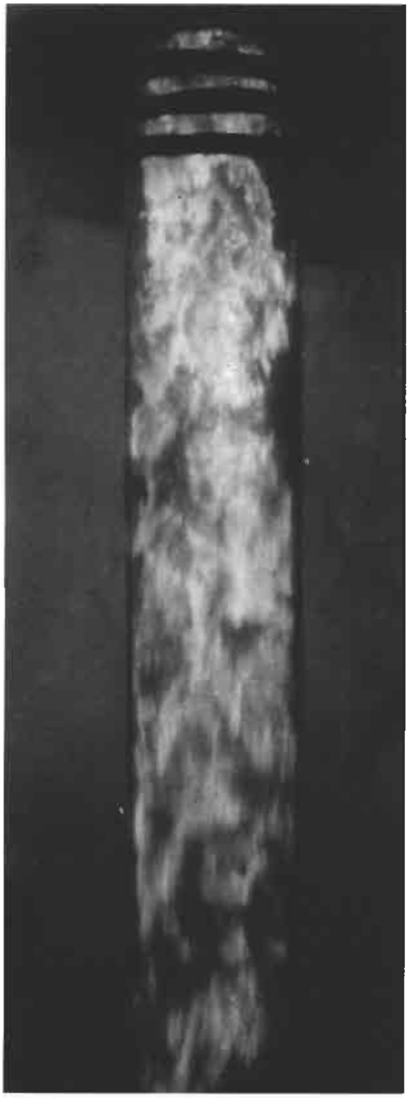


Figure 4.33 *Upward flame propagation in a Ca-Si dust cloud in a 150 mm, that is, vertical combustion, tube (From Deng et al., 1987).*

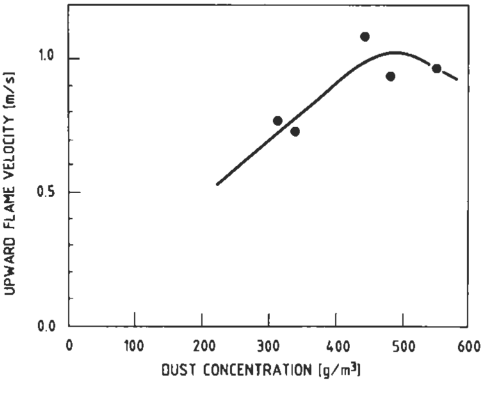


Figure 4.34 *Upward flame velocity versus concentration of dry coal dust in air in a vertical tube of internal diameter 150 mm, open at bottom, and closed at top. Coal dust from Funsun, Peoples Republic of China: 39% volatiles and 14% ash, median particle diameter by mass 13 µm, and particle density 2.0–2.5 g/cm³ (Data from Kong, 1986).*

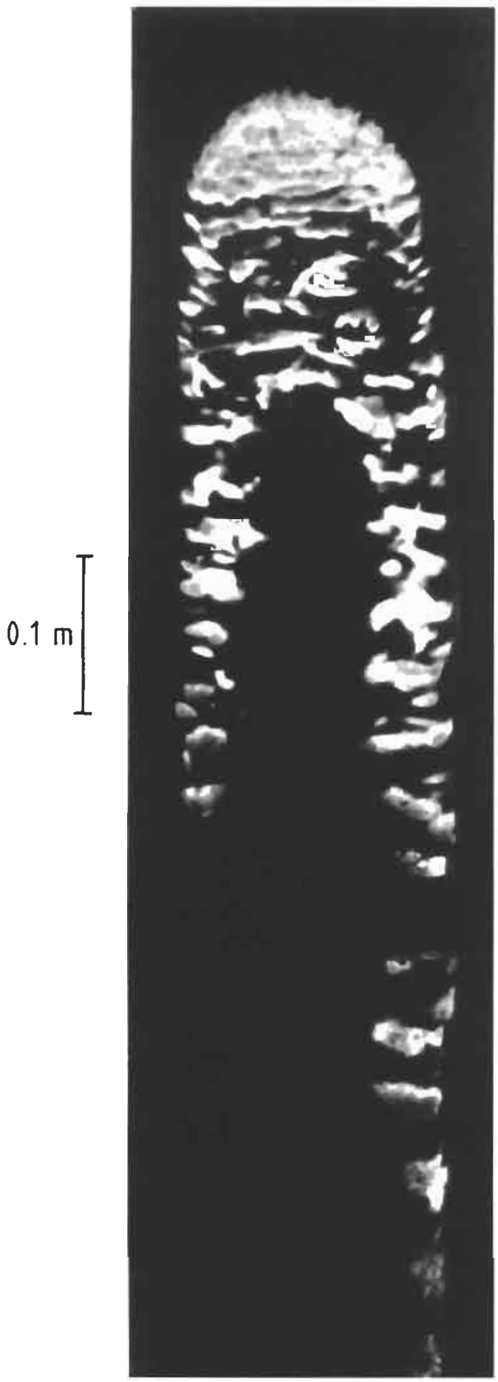


Figure 4.35 *A typical cellular flame in 150 g/m^3 corn starch in air, at 1.52 g/m^3 above the ignition point. The upward propagating flame is in a vertical duct of 0.2 m × 0.2 m cross section (From Proust and Veyssiere, 1988).*

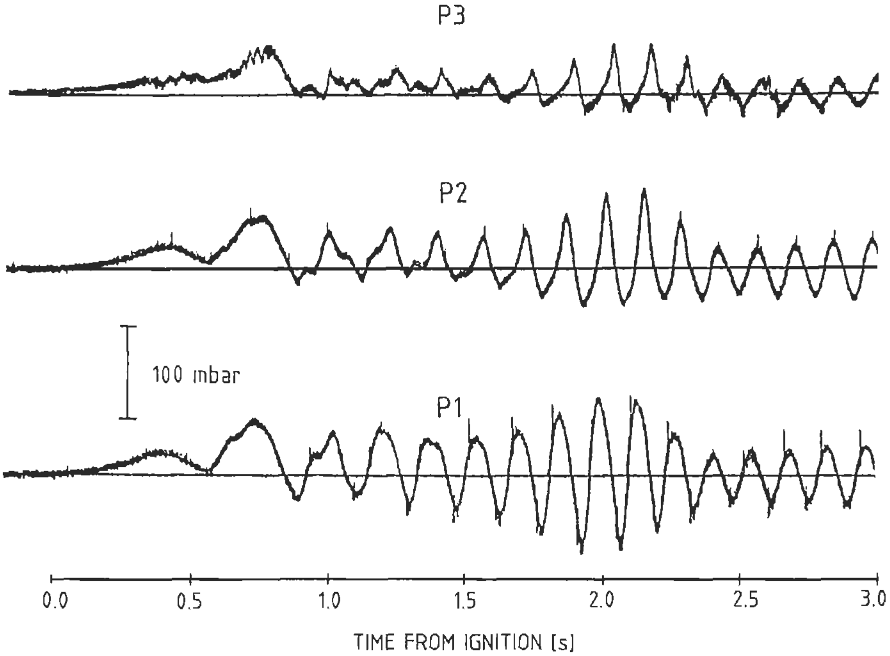


Figure 4.36 *Corn starch/air explosion in a vertical cylindrical silo of height 22 m and diameter 3.7 m with an open 5.7 m^2 vent in the roof. Oscillatory pressure development resulted from ignition in the upper half of the silo (13.5 m above bottom). Oscillations persisted for about 5 s. Dust concentration was 400–600 g/m^3. P_1, P_2, and P_3 were located at 3, 9, and 19.5 m above the silo bottom, respectively (From Eckhoff et al., 1987).*

long vertical cylindrical steel silo of diameter 3.7 m, vented at the top. Figure 4.36 shows a set of pressure-versus-time traces resulting from igniting the starch/air cloud in the silo at 13.5 m above the silo bottom, that is, somewhat higher up than halfway.

This kind of exaggerated oscillatory pressure development occurred only when the ignition point was in this region. The characteristic frequency of 4–7 Hz agrees with the theoretical first harmonic standing wave frequency in a 22 m long one-end-open pipe (22 m = $^1/_4$ wavelength). The increase in frequency with time reflects the increase in the average gas temperature as combustion proceeds. It is interesting to note that the peak amplitude occurs at about 2 s after ignition. The pulsating flow probably gradually distorts the flame front and increases the combustion rate. The oscillatory nature of this type of explosion could be clearly seen on video recordings. "Packets" of flames were ejected at a frequency matching exactly that of the pressure trace. Similar oscillations were also generated in experiments in the 236 m^3 silo when the vent was moved from the silo roof to the cylindrical silo wall, just below the roof (Eckhoff et al., 1988).

Artingstall and Corlett (1965) analyzed the interaction between a flame propagating outward in a one-end-open duct and reflected shock waves, making the simplifying assumptions that

- The initial shock wave and the flame are formed immediately when the ignition takes place and have immediate constant velocities.

- The burning velocity, that is, the speed of flame relative to the unburned reactants, is constant.
- Friction can be neglected.
- The effect of having to disperse the dust can be neglected.

They realized that the three first assumptions are not in accordance with reality in long ducts, where extensive flame acceleration is observed, but they indicated that their theoretical analysis can be extended to accelerating flames by using numerical computer models. It is nevertheless interesting to note that the simplified calculations predict the kind of oscillation shown in Figure 4.36. The calculations, in fact, showed that, before the flame reached the open end, the air velocity at the open end could become negative; that is, the air would flow inward. Further reflections cause the flow to reverse again. Artingstall and Corlett suggested that this theoretical result could help explain the pulsating flow observed in some actual dust explosions in experimental coal mine galleries.

It is of interest to mention in this context that Samsonov (1984) studied the development of a propagating gas flame in an impulsive acceleration field generated by a free-falling explosion chamber being suddenly stopped by a rubber shock absorber. He observed the flame-folding phenomena typical of those resulting from Taylor instabilities. These phenomena were also similar to those resulting from passage of a weak shock wave through a flame.

Essenhigh and Woodhead (1958) used an apparatus similar to that used by Schläpfer (1951), but of a large scale, to investigate flame propagation in clouds of cork dust in air in a one-end-open vertical duct. The duct was 5 m long and of diameter either 760 or 510 mm. They studied both upward- and downward-propagating flames and ignition at the closed as well as the open end. With ignition at the open end and upward flame propagation, constant flame velocities of 0.4–1.0 m/s were measured. For upward propagation and the top end open, the maximum flame speeds were about 20 m/s. Some of this difference was due to the expansion ratio burned/unburned material, but some was also attributed to increased burning rate.

Photographs of the flames were similar to Figures 4.31 and 4.33. The total flame thicknesses were in the range 0.2–1.2 m. The minimum explosible concentration of cork dust in air was found to be 50 ± 10 g/m^3 independent of median particle size by mass in the range 150–250 μm.

Phenomena of the kind just discussed are important to explain the moderate deviations from ideal laminar conditions. However, the substantial deviations giving rise to the very violent explosions that can occur in industry and coal mines are due to another mechanism, combustion enhancement due to flow-generated turbulence. (See also Section 9.2.4.6 in Chapter 9.)

4.4
TURBULENT FLAME PROPAGATION

4.4.1
TURBULENCE AND TURBULENCE MODELS

Before discussing the combustion of turbulent dust clouds, it is appropriate to include a few introductory paragraphs to briefly define and explain the concept of turbulence. A classical source of information is the analysis by Hinze (1975). His basic theoretical definition of *turbulent fluid flow* is "an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned." Turbulence can be generated by friction forces at fixed walls (flow through conduits, flow past bodies) or by the flow of layers of fluids with different velocities past or over one another. There is a distinct difference between the kinds of turbulence generated in the two ways. Therefore, it is convenient to classify turbulence generated and continuously affected by fixed walls as "wall turbulence" and turbulence in the absence of walls as "free turbulence."

In the case of real viscous fluids, viscosity effects result in the kinetic energy of flow being converted into heat. If there is no continual external source of energy to maintain the turbulent motion, the motion decays. Other effects of viscosity are to make the turbulence more homogeneous and less dependent on direction. Turbulence is called *isotropic* if its statistical features have no preference for any direction, so that perfect disorder exists. In this case, which is seldom encountered in practice, no average shear stress can occur and, consequently, no gradient of the mean velocity. The mean velocity, if any, is constant throughout the field.

In all other cases, where the mean velocity shows a gradient, the turbulence is nonisotropic (or anisotropic). Since this gradient in mean velocity is associated with the occurrence of an average shear stress, the expression *shear-flow turbulence* is often used to designate this class of flow. Most real turbulent flows, such as wall turbulence and anisotropic free turbulence, fall into this class.

If one compares different turbulent flows, each having its distinct "pattern," one may observe differences, for instance, in the size of the patterns. Therefore, to describe a turbulent motion quantitatively, it is necessary to introduce the concept of scale of turbulence. There is a certain scale in time and a certain scale in space. The magnitude of these scales are determined by the geometry of the environment in which the flow occurs and the flow velocities. For example, for turbulent flow in a pipe, one may expect a time scale on the order of the ratio between pipe diameter and average flow velocity, that is, the average time required for a flow to move the length of one pipe diameter, and a space scale on the order of magnitude of the diameter of the pipe.

However, it is insufficient to characterize a turbulent motion by its scales alone, because neither the scales nor the average velocity tell anything about the violence of the motion. The motion violence is related to the fluctuation of the momentary velocity, not to its average value. If the momentary velocity is

$$V = \overline{V} + v \tag{4.80}$$

where $\overline{V}$ is the average velocity and v the momentary deviation. $\overline{v}$ is zero by definition. However, $\overline{v^2}$ is positive and it is customary to define the violence of the turbulent motion, often called the *intensity of the turbulence* by

$$v' = (\overline{v^2})^{1/2} \tag{4.81}$$

The relative turbulence intensity is then defined by the ratio $v'/\overline{V}$.

As discussed by Beer, Chomiak, and Smoot (1984) in the context of pulverized coal combustion, it is customary to distinguish among three main domains of turbulence:

large scale, intermediate scale, and small scale. Large-scale turbulence is closely linked to the geometry of the structure in which the flow exists. It is characterized by strong coherence and high degree of organization of the turbulence structures, reflecting the geometry of the structure. For plane flow, the coherent large-scale structures are essentially two-dimensional vortices with their axes parallel to the boundary walls. For flow in axisymmetric systems, concentric large-scale vortex rings are formed. The theoretical description of the three-dimensional, large-scale vortex structures encountered in practice presents a real challenge. Also, experimental investigation of such structures is very difficult. According to Beer et al., the lack of research in this area is the most serious obstacle to further advances in turbulent combustion theory.

On all scale levels, turbulence has to be considered a collection of long-lasting vortex structures, tangled and folded in the fluid. This picture is quite different from the idealized hypothetical stochastic fluctuation model of isotropic turbulence. Beer et al. argue against the common idea that the small-scale structures are randomly distributed "little whirls." According to these authors, it is known that the fine-scale structures of high Reynolds number turbulence become less and less space filling as the scale size decreases and the Reynolds number increases.

According to Hinze (1975), Kolmogoroff postulated that, if the Reynolds number is infinitely large, the energy spectrum of the small-scale turbulence is independent of the viscosity and dependent on only the rate of dissipation of kinetic energy into heat, per mass unit of fluid, ϵ. For this range, Kolmogoroff arrived at his well-known energy spectrum law for high Reynolds numbers:

$$E(\alpha, t) = A\epsilon^{2/3}\alpha^{-5/3} \tag{4.82}$$

$E(\alpha, t)$ is called the *three-dimensional energy spectrum function of turbulence*; α is the wave number $2\pi n/\bar{V}$, where n is the frequency of the turbulent fluctuation of the velocity, and $\bar{V}$ is the mean global flow velocity; A is a constant; and ϵ is the rate of dissipation of turbulent kinetic energy into heat per unit mass of fluid.

Figure 4.37 illustrates the entire three-dimensional energy spectrum of turbulence, from the largest, primary eddies via those containing most of the kinetic energy to the low-energy range of very high wave numbers (or very high frequencies). Figure 4.37 includes the Kolmogoroff law for the universal equilibrium range.

In the range of low Reynolds numbers, other theoretical descriptions than Kolmogoroff's law are required. In principle, the kinetic energy of turbulence is identical to the integral of the energy spectrum curve $E(\alpha, t)$ in Figure 4.37 over all wave numbers.

A formally exact equation for ϵ may be derived from the Navier-Stokes equations. However, the unknown statistical turbulence correlations must be approximated by known or calculable quantities. Fully comprehensive calculation requires extensive computational capacity, and it is not yet a realistic approach for solving practical problems. Therefore, simpler and more approximate approaches are needed. One widely used approximate theory, assuming isotropic turbulence, is the k-ϵ model by Jones and Launder (1972, 1973), where k is the kinetic energy of turbulence, and ϵ the rate of dissipation of the kinetic energy of turbulence into heat. The k-ϵ model contains Equation (4.82) as

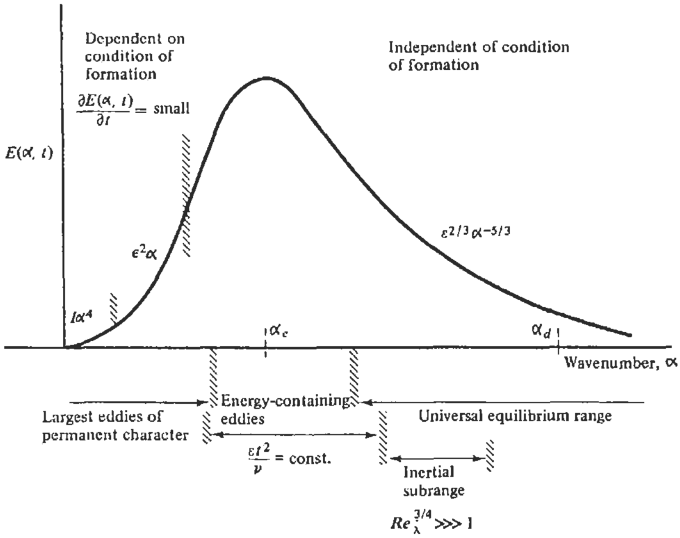


Figure 4.37 The three-dimensional energy spectrum $E(\alpha, t)$ in various waves number ranges: I is Loitsianskii's integral, ε is eddy viscosity, ϵ is dissipation of turbulent energy in heat per unit time and mass, and υ is kinematic viscosity; Re_λ is defined as $v'\lambda_g/\upsilon$, where v' is the turbulence intensity as defined by equation (4.81); and λ_g is the lateral spatial dissipation scale of turbulence (Taylor microscale) (From Hinze, 1975).

an implicit assumption. The approximate equations for k and ϵ proposed by Jones and Launder were

$$\rho u\frac{\partial k}{\partial x}+\rho v\frac{\partial k}{\partial y}=\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial y}\right]+\mu_T\left(\frac{\partial u}{\partial y}\right)^2-\rho\epsilon-2\mu\left(\frac{\partial k^{1/2}}{\partial y}\right)^2 \tag{4.83}$$

$$\rho u\frac{\partial \epsilon}{\partial x}+\rho v\frac{\partial \epsilon}{\partial y}=\frac{\partial}{\partial y}\left[\left(\mu+\frac{\mu_T}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial y}\right]+c_1\frac{\epsilon}{k}\mu_T\left(\frac{\partial u}{\partial y}\right)^2-\frac{c_2\rho\epsilon^2}{k}+2\frac{\mu\mu_T}{\rho}\left(\frac{\partial^2 u}{\partial y^2}\right)^2$$

Here ρ is the fluid density; u and v are the mean fluid velocities in streamwise and cross-stream directions, respectively; μ is the molecular viscosity and μ_T is turbulent viscosity; σ_k and σ_ϵ are turbulent Prandtl numbers for k and ϵ, respectively; and c_1 and c_2 are empirical constants or functions of the Reynolds number. Both equations are based on the assumption that the diffusional transport rate is proportional to the product of the turbulent viscosity and the gradients of the diffusing quantity. Jones and Launder (1973) emphasized that the last terms of the two equations were included on an empirical basis to bring theoretical predictions in reasonable accordance with experiments in the range of lower Reynolds numbers, where equation (4.82) is not valid. The k-ϵ model has been used for simulating turbulent combustion of gases and turbulent gas explosions. Later, as is discussed in Section 4.4.8, it was also adopted for simulating turbulent dust explosions.

While the k-ϵ theory has wide popularity, it should be pointed out that it is only one of several theoretical approaches. Launder and Spalding (1972) gave a classical review of the mathematical modeling of turbulence, including stress transport models, which is still relevant.

When the structure of turbulent dust clouds is to be described, further problems have to be addressed. Some of these were discussed in Chapter 3. Beer et al. (1984) pointed out that there are two aspects of the turbulence/particle interaction problem. The first is the influence of turbulence on the particles, the second is the influence of particles on the turbulence. With regard to the influence of turbulence on the particles in a burning dust cloud, two effects are important, mechanical interactions associated with particle diffusion, deposition, coagulation, and acceleration and convective interactions associated with heat and mass transfer between gas and particles, which influence the particle combustion rate. Beer et al. (1984) discussed available theory for the various regimes of Reynolds numbers (see Chapter 3) for the particle motion in the fluid. They emphasized that turbulence is a rotational phenomenon, and therefore the motion of the particles also includes a rotational component. Consequently, one can define a relaxation time for the particle rotation τ_{pr} as well as one for the translatory particle motion, τ_p. Both relaxation times are proportional to the square of the particle diameter and, hence, decrease markedly as the particles get smaller.

When $\tau_p \gg \tau_L$, where τ_L is the characteristic Lagrangian time of the turbulent motion, the particle is not convected by the turbulent fluctuations and its motion is fully determined by the mean flow. However, when $\tau_p \ll \tau_L$, the particle adjusts to the instantaneous gas velocity. If the particle follows the turbulent fluctuations, its turbulent diffusivity is equal to the gas diffusivity. If the particle does not follow the turbulence, its diffusivity is practically equal to 0. An interesting but most complicated case occurs when the characteristic relaxation times and turbulence times are on the same order. In this case, the particle only partially follows the fluid and its motion depends partially on Lagrangian interaction with the fluid and partially on Eulerian interaction over the distance it travels outside the originally surrounding fluid.

The effects of particles on the turbulence structure are complex. The simplest effect is the introduction of additional viscouslike dissipation of turbulent energy caused by the slip between the two phases. This effect is substantial in the range of explosible dust concentrations. Even small changes in dissipation can have a strong influence on the turbulence level. This is because turbulence energy is the result of competition between two large, almost equal sources of production and dissipation.

Beer et al. (1984) state that the change in turbulence intensity and structure caused by the increased dissipation affects the mean flow parameters and, in turn, the turbulence production terms, so that the outcome of the chain of changes is difficult to predict, even when the most advanced techniques are used. The difficulties are enhanced by a lack of reliable experimental data. For example, some experiments demonstrate dramatic effects of even minute admixtures of particles on turbulent jet behavior. Others demonstrate smaller effects even for high dust concentrations (see Section 3.8 in Chapter 3).

4.4.2
TURBULENT DUST FLAMES: AN INTRODUCTORY OVERVIEW

The literature on turbulent dust flames and explosions is substantial. This is because it has long been realized that turbulence plays a primary role in deciding the rate with which a given dust cloud will burn, and this role is not easy to evaluate either experimentally or theoretically. There are close similarities with turbulent combustion of premixed gases, as shown by Bradley, Chen, and Swithenbank (1988), although the two-phase nature of dust clouds adds to the complexity of the problem. Hayes, Napier, and Roopchand (1983) mentioned two predominant groups of theories of turbulent burning of a premixed fluid system of a fuel and an oxidizer:

1. The laminar flame continues to be the basic element of flame propagation. The essential role of turbulence is to increase the area of the flame surface that burns simultaneously.
2. Turbulence alters the nature of the basic element of flame propagation by increasing rates of heat and mass transport down to the scale of the "elementary flame front," which is no longer identical with the laminar flame.

In their comprehensive survey Andrews, Bradley, and Lwakamba (1975) emphasized the importance of the turbulent Reynolds number $R_\lambda = v'\lambda/\nu$ for the turbulent flame propagation, where v' is the turbulence intensity defined by equation (4.81), λ is the Taylor microscale, and ν is the kinematic viscosity. They suggested that, for $R_\lambda > 100$, a wrinkled laminar flame structure is unlikely and turbulent flame propagation is then associated with small dissipative eddies. A supplementary formulation is that laminar flamelets can exist in a turbulent flow only if the laminar flame thickness is smaller than the Kolmogoroff microscale of the turbulence. Bray (1980) gave a comprehensive discussion of the two physical conceptions and pointed out that the Kolmogoroff microscales and laminar flame thicknesses are difficult to resolve experimentally in a turbulent flame. Because of the experimental difficulties, the real nature of the fine structure of premixed flames in intense turbulence is still largely unknown.

Abdel-Gayed, Bradley, and Lung (1989) proposed a modified Borghi diagram for classifying various combustion regimes in turbulent premixed flames, using the original Borghi parameters L/δ_l and u'/u_l as abscissa and ordinate. Here L is the integral length scale, δ_l is the thickness of the laminar flame, u' is the root mean square turbulent velocity, and u_l is the laminar burning velocity. The diagram identifies regimes of flame propagation and quenching, and the corresponding values of the Karlovitz stretch factor, the turbulent Reynolds number, and the ratio of turbulent to laminar burning velocity.

Spalding (1982) discussed an overall model that contains elements of both of the physical conceptions 1 and 2 of a turbulent flame defined previously, see Figure 4.38. Eddies of hot, burned fluid and cold unburned fluid interact with the consequences that both fluids become mutually entrained.

Entrainment of burned fluid into unburned and vice versa is the rate-controlling factor as long as the chemistry is fast enough to consume the hot reactants as they appear. In other words, the instantaneous combustion rate per unit volume of mixture of burned and unburned increases with the total instantaneous interface area between burned and unburned per unit volume of the mixture. Spalding introduced the length l as a characteristic mean dimension of the entrained "particles" of either burned or unburned fluid,

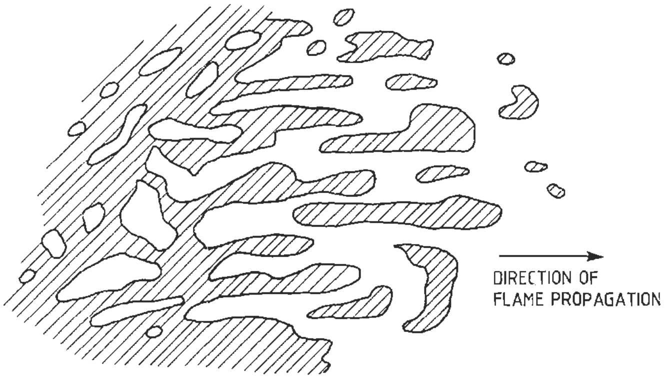


Figure 4.38 *Postulated microstructure of burning turbulent fluid. The shaded areas represent burned fluid, unshaded are unburned (From Spalding, 1982).*

and l^{-1} as a measure of the corresponding specific interface surface area. He then assumed a differential equation of the form

$$\frac{d(l^{-1})}{dt} = M + B + A \tag{4.84}$$

where M represents the influence of mechanical processes such as stretching, breakage, impact, and coalescence; B represents the influence of the burning; and A represents influences of other processes, such as wrinkling, smoothing, and simple interdiffusion. Spalding indicated tentative equations for M, B, and A, but emphasized that the identification of expressions and associated constants that correspond to physical reality over wide ranges, "is a task for the future."

It is nevertheless clear that the strong enhancing effect of turbulence on the combustion rate of dust clouds and premixed gases is due primarily to the increase of the specific interface area between burned and unburned fluid by turbulence, induced by mutual entrainment of the two phases. The circumstances under which the interface itself is a laminar flame or some thinner, elementary flame front remains to be clarified.

When discussing the specific influence of turbulence on particle combustion mechanisms, Beer et al. (1984) distinguished between microscale effects and macroscale effects. On the microscale, turbulence directly affects the heat and mass transfer and therefore the particle combustion rate. They discussed the detailed implications of this for coal particle combustion, assuming that CO is the only primary product of heterogeneous coal oxidation. On the macroscale, there is a competition between the devolatilization process and turbulent mixing. Concerning modeling of turbulent combustion of dust clouds, these authors stressed that three-dimensional microscopic models are too detailed to allow computer simulation without use of excessive computer capacity and computing time. They therefore suggested alternative methods based on theories like the k-ϵ model, adopting the Lagrangian Escimo approach proposed by Spalding and coworkers (Ma, Spalding, and Sun, 1983) or alternative methods developed to account for the primary coherent large-scale turbulence structures (Ghoniem, Chorin, and Oppenheim, 1981).

Lee (1987) suggested that the length scale that characterizes the reaction zone of a turbulent dust flame is at least an order of magnitude greater than that of a premixed gas flame.

For this reason, dust flame propagation should be studied in large-scale apparatus. It should be emphasized, however, that from a practical standpoint, *large* or *full scale* is not an unambiguous term. For example, a dust extraction duct of diameter 150 mm is full industrial scale and, at the same time, the scale of laboratory equipment. On the other hand, the important features of an explosion in a large grain silo cell of diameter 9 m and height 70 m are unlikely to be reproduced in a laboratory silo model of 150 mm diameter.

It should be mentioned here that Abdel-Gayed, Bradley, and Lawes (1987) identified generally applicable correlations in terms of dimensionless groups, enabling prediction of acceleration of flames in turbulent premixed gases. A similar approach might, in some cases, offer a means of scaling even dust explosions. The role of radiative heat transfer in dust flames then needs to be discussed, as done by Lee (1987). His conclusion was that conductive and convective heat transfer are probably more important than radiative transfer. This may be valid for coal and organic dusts but probably not for metal dusts like silicon and aluminum.

Amyotte, Chippett, and Pegg (1989) reviewed more than a hundred publications on various effects of turbulence on ignition and propagation of dust explosions. They considered the influence of both initial and explosion-induced turbulence on flame propagation in both vented and fully confined explosions. They suggested two possible approaches toward an improved understanding: concurrent investigations of dust and gas explosions and direct measurement of turbulent scales and intensities in real experiments as well as in industrial plants. See also Sections 9.2.4.4 and 9.2.4.7 in Chapter 9.

4.4.3
EXPERIMENTAL STUDIES OF TURBULENT DUST FLAMES IN CLOSED VESSELS

4.4.3.1
Common Features of Experiments

The majority of the published experimental studies of turbulent dust explosions in closed vessels have been conducted in apparatus of the type illustrated in Figure 4.39.

The closed explosion vessel of volume V_1 and initial pressure P_1 is equipped with a dust dispersion system, a pressure sensor, and an ignition source. In most equipment, the dust

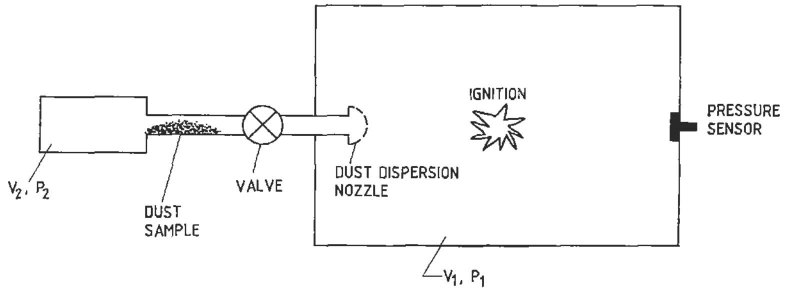


Figure 4.39 *The type of apparatus commonly used in closed-vessel turbulent dust explosion experiments.*

dispersion system consists of a compressed-air reservoir of volume $V_2 \ll V_1$, at an initial pressure $P_2 \gg P_1$. In some apparatuses, the dust is initially placed on the high-pressure side of the dispersion air valve, as indicated in Figure 4.39; whereas in other apparatus, it is placed downstream of the valve. Normally, the mass of dispersion air is not negligible compared with the initial mass of air in the main vessel. This causes a significant rise of the pressure in the main vessel once the dispersion air has been discharged into the main vessel. In some investigations, this is compensated for by partial evacuation of the main vessel prior to dispersion, so that the final pressure after dispersion completion, just prior to ignition, is atmospheric. This is important if absolute data are required, because the maximum explosion pressure for a given dust at a given concentration is approximately proportional to the initial absolute air pressure. Both the absolute sizes of V_1 and V_2 and the ratio between them vary substantially from apparatus to apparatus. The smallest V_1 used are on the order of 1 liter, whereas the largest that has been traced is 250 m^3. The design of the dust dispersion system varies considerably from apparatus to apparatus. A number of different nozzle types have been developed, with the aim to break up agglomerates and ensure homogeneous distribution of the dust in the main vessel. The ignition source has also been a factor of considerable variation. In some of the earlier investigations, continuous sources like electric arcs or trains of electric sparks and glowing resistance wire coils were used, but it has become common to use short-duration sources initiated at a given time interval after opening of the dust dispersion valve. These sources vary from electric sparks via exploding wires to various forms of electrically triggered chemical ignitors.

An important inherent feature of all apparatus of the type illustrated in Figure 4.39 is that the dispersion of the dust inevitably induces turbulence in the main vessel. The level of turbulence is maximum during the main phase of dust dispersion. After the flow of dispersion air into the main vessel has terminated, the turbulence decays at a rate that decreases with increasing V_1. (Compare the time scales of Figures 4.41 and 4.42.)

In view of this, it is clear that both the strength of the dispersion air blast and the delay between opening of the dust dispersion value and ignition have a strong influence on the state of turbulence in the dust cloud at the moment of ignition and, consequently, also on the violence of the explosion. The situation is illustrated in Figure 4.40.

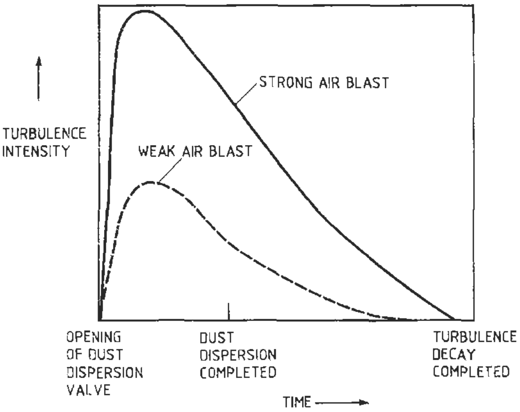


Figure 4.40 *Generation and decay of turbulence during and after dispersion of dust in an apparatus of the type illustrated in Figure 4.39. Note: A common way of quantifying turbulence intensity is the root mean square of turbulent velocity.*

4.4.3.2
Experimental Investigations

The data from Eckhoff (1977), given in Figure 4.41, illustrate the influence of the ignition delay on the explosion development in a cloud of lycopodium in air in a 1.2 liter Hartmann bomb. As can be seen, there is little difference between the maximum explosion pressure obtained with a delay of 40 ms and 200 ms, whereas the maximum rate of pressure rise is drastically reduced, from 430 bar/s to 50 bar/s, that is, by a factor of almost 10. There is little doubt that this is due to the reduced initial turbulence in the dust cloud at the large ignition delays. With ignition delay increasing beyond 200 ms, the maximum explosion pressure is also reduced as the dust starts to settle out of suspension before the ignition source is activated.

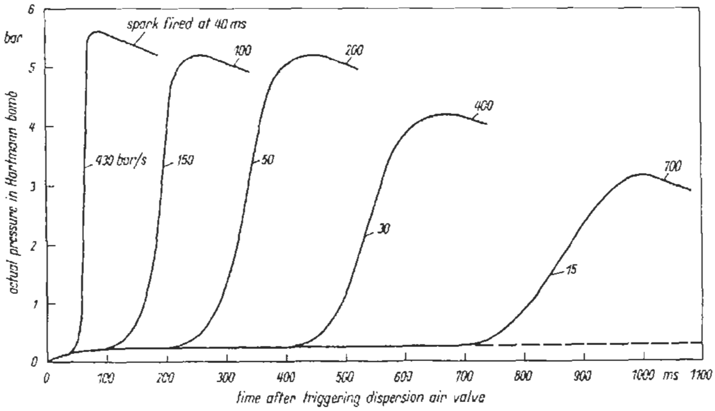


Figure 4.41 *Influence of ignition delay on development of lycopodium/air explosion in a 1.2 liter Hartmann's bomb. The ignition source is a 4 J electric spark of discharge time 2–3 ms. Dust concentration is 420 g/m^3. Initial pressure in 60 cm^3 dispersion air reservoir is 8 bar(g) (From Eckhoff, 1977).*

As would be expected, the same kind of influence of ignition delay as shown in Figure 4.41 is found in all experiments of the type illustrated in Figure 4.39. One of the first researchers to observe this effect was Bartknecht (1971). Some of his results for a 1 m^3 explosion vessel are given in Figure 4.42. As the ignition delay is increased from the lowest value of about 0.3 s to about 1 s, there is marked decrease of $(dP/dt)_{\max}$, whereas $P_{\max}$ is comparatively independent of the ignition delay for both dusts. If the ignition delay is increased further, however, there is a marked decrease even in $P_{\max}$ for the coal. The 1 m^3 apparatus used by Bartknecht in 1971 is in fact the prototype of the standard test apparatus specified by the International Standards Organization (1985).

In this standard, an ignition delay of 0.6 s is prescribed. As Figure 4.42 shows, this is not the worst case, because a significantly higher level of initial turbulence and resulting rates of pressure rise exist at shorter ignition delays, down to 0.3 s. The delay of 0.6 s was chosen as a standard because, at approximately this moment, the dust dispersion was completed; that is, the pressure equilibrium between V_1 and V_2 in Figure 4.39 was established. In view of this, there is no logical argument for claiming that an ignition delay of 0.6 s corresponds to the "worst case." One can easily envisage situations in industry where dust injection into the explosion space is continued after ignition.

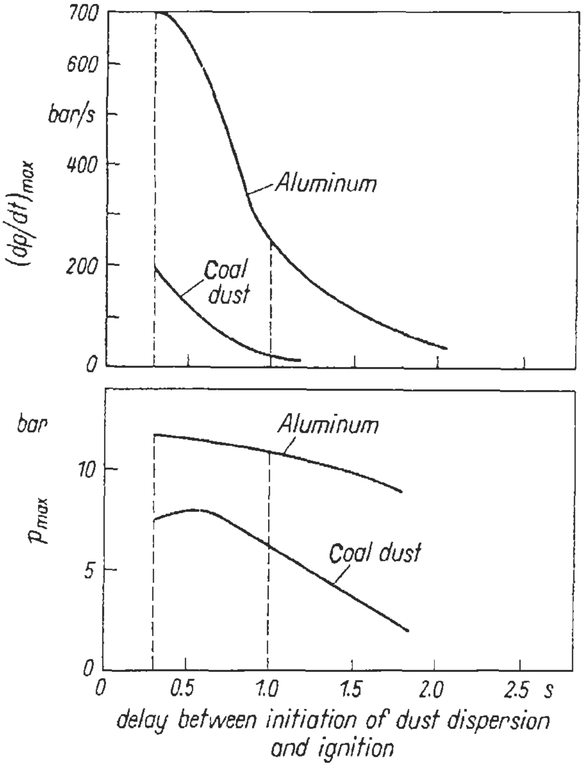


Figure 4.42 *Results from explosions of aluminum/air and coal dust/air in a closed 1 m^3 vessel. The ignition source is a chemical ignitor at vessel center (Data from Bartknecht, 1971).*

As shown by Eckhoff (1976), the data from experiments of Nagy et al. (1971) in closed bombs of various volumes confirm the arbitrary nature of $(dP/dt)_{max}$ values from closed-bomb tests. This was reemphasized by Moore (1979), who conducted further comparative tests in vessels of different volumes and shapes.

Dahn (1991) studied the influence of the speed of a stirring propeller on the rate of pressure rise, or the derived burning velocity, during lycopodium/air explosions in a 20 liter closed vessel. The purpose of the propeller was to induce turbulence in addition to that generated by the dust dispersion air blast. Typically, $(dP/dt)_{max}$ increased by a factor of 2–2.5 when the propeller speed increased from 0 to 10,000 rpm.

The implication of the effects illustrated by Figures 4.40–4.42 for predicting explosion violence in practical situations in industry was neglected for some time. The strong influence of turbulence on the rate of combustion of a dust cloud is also indeed of significance in practical explosion situations in industry (see Chapter 6).

In the past, sufficient attention was not always paid to the influence of the ignition delay on the violence of experimental closed-bomb dust explosions. Often continuous ignition sources, like flowing resistance wire coils, were used, as opposed to short-duration sources, active for only a comparatively short interval of time, allowing control of the moment of ignition. Some consequences of using a continuous ignition source were investigated by Eckhoff and Mathisen (1977/1978). They disclosed that a correlation between $(dP/dt)_{max}$ and dust moisture content found by Eckhoff (1976) on the basis of Hartmann bomb tests, using a glowing resistance wire coil ignition source, was misleading. The reason is that a dust of a higher moisture content ignites with a longer delay than a comparatively dry dust, because the ignitability of a moist dust is lower than for a dried dust. Therefore, ignition of the moist dust with a continuous source is not possible until the turbulence has decayed to a sufficiently low level, below the critical level for ignition of the dried dust. In other words, as the moisture content in the dust increases, the ignition delay also increases. Therefore, the strong influence of moisture content on $(dP/dt)_{max}$ found earlier was in fact a combined effect of increasing dust moisture and decreasing turbulence.

Eckhoff (1987) discussed a number of the closed-bomb test apparatuses used for characterizing the explosion violence of dust clouds in terms of the maximum rate of pressure rise. It is clear that the $(dP/dt)_{max}$ from such tests are bound to be arbitrary as long as the test result is not associated with a defined state of initial turbulence of the dust cloud. In view of this, the direct measurements of the rms (root mean square) turbulence as a function of time after opening the dispersion air valve in a Hartmann bomb by Amyotte and Pegg (1989) and their comparison of the data with the data from Hartmann bomb explosion experiments by themselves and Eckhoff (1977) are of considerable interest. The results of Amyotte and Pegg's laser-doppler velocimeter measurements, obtained without dust in the dispersion system, are shown in Figure 4.43. We see that a decay by a factor of almost 10 of the turbulence intensity occurs within the same time frame of about 40–200 ms as a corresponding decay of $(dP/dt)_{max}$ in Eckhoff's (1977) experiments (Figure 4.41). We also see that the turbulence intensity increases systematically with the initial pressure in the dispersing air reservoir, that is, the increasing strength of the air blast, in accordance with the general picture indicated in Figure 4.40.

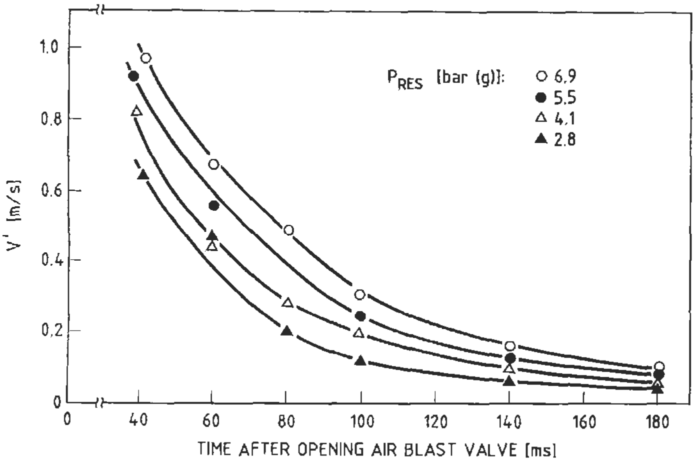


Figure 4.43 *Variation of rms turbulence velocities within 5 ms "windows" in a Hartmann bomb with time after opening of air blast valve and with initial pressure in dispersion reservoir, air only, no dust (From Amyotte and Pegg, 1989).*

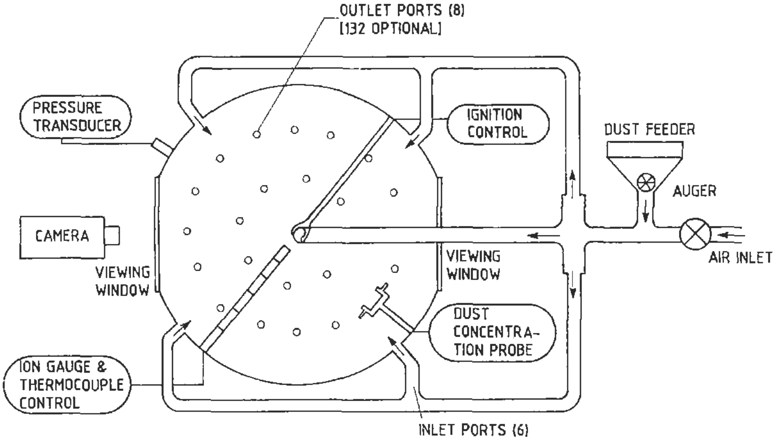


Figure 4.44 *A 0.95 m³ spherical closed bomb for studying a combustion of turbulent dust clouds (From Kauffman et al., 1984a).*

Kauffman et al. (1984a) studied the development of turbulent dust explosions in the 0.95 m^3 spherical explosion bomb illustrated in Figure 4.44. The bomb is equipped with six inlet ports and eight exhaust ports, both sets being manifolded and arranged symmetrically around the bomb shell. Dust and air feed rates were set to give the desired dust concentration and turbulence level. The turbulence level generated by a given airflow was measured by a hot-wire anemometer. The turbulence intensity v', assuming isotropic turbulence, was determined from the rms and mean velocities extracted from the hot-wire signal in the absence of dust. As pointed out by Semenov (1965), a hot-wire probe senses all velocities as positive, and therefore, a positive mean velocity is recorded even if the true mean velocity is 0. In agreement with the suggestion by Semenov, Kauffman et al. assumed that $v' = (1/2)^{1/2} \times [(\text{rms velocity})^2 + (\text{mean velocity})^2]^{1/2}$. This essentially is a secondary rms of two different mean velocities, the primary rms and the arithmetic mean of the hot-wire signal.

Kauffman et al. were aware of the complicating influence of dust particles on the turbulence structure of the air, but they were unable to account for this. It was found that the turbulence intensity, in the absence of dust, was reasonably uniform throughout the 1 m^3 vessel volume.

When a steady-state dust suspension of known concentration had been generated in the 0.95 m^3 sphere, all inlet and exhaust openings were closed simultaneously and the dust cloud ignited at the center. The rise of explosion pressure with time was recorded and $(dP/dt)_{max}$ and P_{max} determined. Figures 4.45 and 4.46 show a set of results for maize starch.

The marked increase of $(dP/dt)_{max}$ with turbulence intensity v' in Figure 4.45 was expected and in agreement with the trend in Figures 4.41–4.43. However, as shown in Figure 4.46, v' also had a distinct influence on P_{max}. At the first glance, this conflicts with the findings of Eckhoff (1977) and Amyotte and Pegg (1989) in the 1.2 liter Hartmann bomb, where there was little influence of the ignition delay on P_{max} up to 200 ms delay. However, Eckhoff (1976) discussed the effect of initial dispersion air pressure on the development of explosion pressure in the Hartmann bomb. He found a comparatively

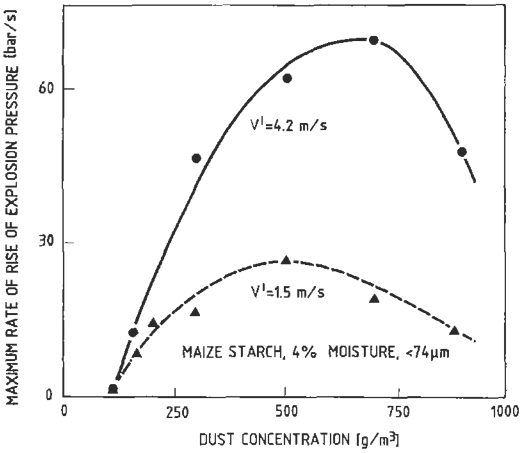


Figure 4.45 *The effect of turbulence on maximum rate of rise of explosion pressure in a 0.95 m^3 spherical closed bomb (From Kauffman et al., 1984a).*

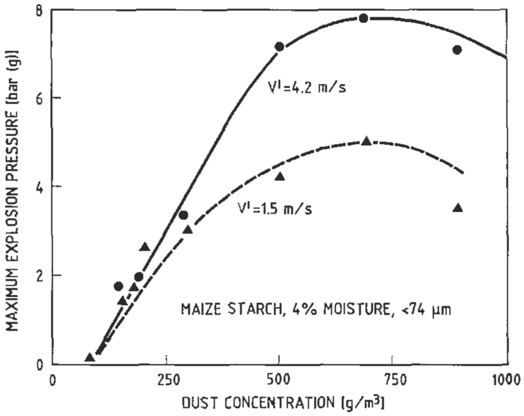


Figure 4.46 *The effect of turbulence on maximum explosion pressure in a 0.95 m^3 spherical closed bomb (From Kauffman et al., 1984a).*

steep rise of both P_{max} and $(dP/dt)_{max}$ with increasing dispersion pressure and suggested that this was probably due to a combined effect of improved dust dispersion and increased initial turbulence. A similar distinct influence on P_{max} of the intensity of the air blast used to disperse the dust was also found by Amyotte and Pegg (1989). This could be interpreted in terms of improved dust dispersion or deagglomeration, rather than turbulence, being responsible for more effective combustion and thus higher P_{max}. Therefore, the primary effect on P_{max} of increasing v' in Kauffman et al.'s (1984a) experiments could be improved dust dispersion.

The rms turbulence intensities in Amyotte and Pegg's (1989) investigation were determined by a laser-doppler velocimeter, whereas Kauffman et al. (1984a) used a hot-wire anemometer. Therefore the two sets of v' values may not be directly comparable. Amyotte and Pegg's values were generally lower than those of Kauffman et al.

Tezok et al. (1985) extended the work of Kauffman et al. (1984a) to measure turbulent burning velocities in the 0.95 m^3 spherical explosion bomb. Radial turbulent burning velocities of 0.45–1.0 m/s were measured for mixed grain dust/air and 0.70–3.3 m/s for corn starch/air in the range of turbulence intensities of 1.5–4.2 m/s and dust concentrations between 50 and 1300 g/m^3. The ratio of turbulent to laminar burning velocity was found to correlate well with the ratio of the rms turbulence velocity to laminar burning velocity as well as with the Reynolds number. Some data from experiments with <74 μm maize starch of 4% moisture content are shown in Figure 4.47. The laminar burning velocities S_L were the same as those derived by Kauffman et al. (1984a) by extrapolating measured burning velocities in the 0.95 m^3 bomb to zero turbulence intensity. The S_L value of 0.7 m/s for 700 g/m^3 is, however, considerably higher than the highest value of 0.27 m/s arrived at for corn starch/air at constant pressure by Proust and Veyssiere (1988).

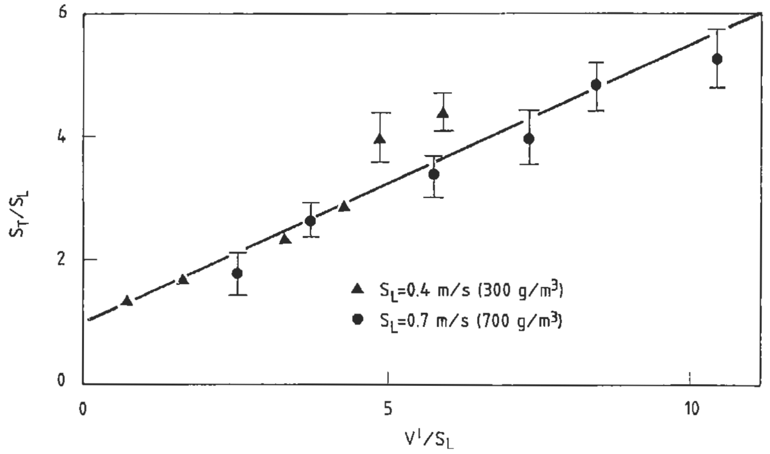


Figure 4.47 *Variation of normalized turbulent burning velocity for corn starch/air clouds, with normalized turbulence intensity of the air. The experiments were done in a 0.95 m^3 spherical closed bomb (From Tezok et al., 1985).*

Tezok et al. also conducted some indicative measurements of the total thickness of the turbulent flame, using an optical probe. They found it to be in the range of 0.15 to 0.70 m and increasing with increasing turbulence intensity and dust concentration. This would mean that the total flame thickness was on the same order as the dimensions of the experimental vessel.

It should be mentioned that Lee, Yi Kang Pu, and Knystautus (1987) studied some further aspects of the influence of turbulence on $(dP/dt)_{\max}$ and $P_{\max}$ in closed-bomb dust explosions.

In an investigation following up the work of Tezok et al. (1985), Tai et al. (1988) used laser doppler anemometry for studying turbulent dust explosions in the 0.95 m^3 explosion vessel. They found that the dust had little effect on the turbulence intensity, as compared to that in pure gas under the same conditions of turbulence generation. Turbulent burning velocities were determined for a range of dusts at turbulence intensities up to 3.3 m/s. Laminar burning velocities were estimated by extrapolating to zero turbulence intensity. The effect of turbulence and dust concentration on flame thickness was also studied.

Bradley et al. (1988) measured turbulent burning velocities in clouds of well-dispersed maize starch in air, in a fan-stirred 22 liter explosion bomb. Turbulence was varied by varying the fan speed. Isotropic turbulence in the central measurement region of the bomb was created by using four fans. Turbulent velocities and integral length scales corresponding to different conditions of stirring were measured in the stirred air, in the absence of dust, by laser-doppler velocimetry. It was found that the correlation of the ratio of turbulent to laminar burning velocities with the ratio of effective rms turbulent velocity to laminar burning velocity and the Karlovitz flame stretch factor were similar to that obtained in stirred premixed gas explosions (methane/air). Further comparative investigations of turbulent dust and gas explosions are discussed in Section 4.4.5, and in Sections 9.2.4.5 and 9.2.4.7 in Chapter 9.

4.4.3.3
K_{St} and the "Cube Root Law"

The K_{St} concept was introduced by Bartknecht (1971, 1978). He claimed (1978) that the so-called cube root law

$$(dP/dt)_{\max} V^{1/3} = \text{constant} \equiv K_{St} \tag{4.85}$$

had been confirmed in experiments with numerous dusts in vessel volumes from 0.04 m^3 and upward. The K_{St} value (bar m/s), being numerically identical with the $(dP/dt)_{\max}$ (bar/s) in the 1 m^3 standard ISO test (International Standards Organization, 1985), was denoted "a specific dust constant," which has led to some confusion. From what has been said in Sections 4.2.5.1, 4.4.3.1, and 4.4.3.2, the cube root law is valid only in geometrically similar vessels, if the flame thickness is negligible compared to the vessel radius, and if the burning velocity as a function of pressure and temperature is identical in all volumes. Furthermore, the flame surface must be geometrically similar (for example, spherical). In view of the relationships in Figures 4.40–4.43, it is clear that K_{St} is bound to be an arbitrary measure of dust explosion violence, because the state of turbulence to which it refers is arbitrary. As pointed out by Eckhoff (1984/1985), this fact has sometimes been neglected when discussing K_{St} in relation to industrial practice and may therefore need to be brought into focus again. Table 4.13 shows an arbitrary selection of K_{St} values for corn starch dust clouds in air, determined in various apparatuses. The values range from 5–10 bar m/s to over 200 bar m/s, corresponding to a factor of more than 20. Some of the discrepancies can probably be attributed to differences in moisture content and effective particle size of the starch and to different data interpretation (peak or mean values). However, differences in the turbulence of the dust clouds probably play the main role.

When using K_{St} values to size vent areas and for other purposes according to various codes, it is absolutely essential to use only data obtained from the standard test method specified for determining K_{St}. Normally, this is the method of the International Standards Organization (1985) or a smaller-scale method calibrated against the ISO method. In addition, it is necessary to appreciate the relative and arbitrary nature even of these K_{St} values (see Chapter 7).

Table 4.13 K_{St} values measured for clouds of maize starch dust in air in different closed vessels and arranged according to vessel volume: $K_{St} = (dP/dt)_{max} V^{1/3}$

Investigator	$(dP/dt)_{max}$ (bar/s)	Volume V of apparatus (m^3)	K_{St} (bar·m/s)
Bartknecht (1978)	680	0.0012	73
Nagy and Verakis (1983)	612	0.0012	66
Eckhoff et al. (1987)*	220	0.0012	23
Nagy and Verakis (1983)	413	0.009	86
Aldis, Lee, and Lai (1983)	320	0.020	87
Eckhoff et al. (1987)*	365	0.020	100
Yi Kang Pu (1988)	10–20	0.026	3–6
Yi Kang Pu (1988)	60–80	0.026	20–25
Nagy and Verakis (1983)	272	0.028	83
Bond, Knystautus, and Lee (1986)	50	0.33	34
Kauffman et al. (1984a)	72	0.95	71
Kauffman et al. (1984a)	20	0.95	20
Nagy and Verakis (1983)	136	3.12	200
Nagy and Verakis (1983)	110	6.7	209
Nagy and Verakis (1983)	55	13.4	131

*Arithmetic mean values, 11% moisture in starch.
Source: Extended and modified version of table from Pu, 1988.

It should be mentioned that Bradley et al. (1988) were able to express K_{St} in terms of a "mass burning rate" and the initial and final pressure. The K_{St} concept was then defined by equation (4.85).

4.4.4
TURBULENT FLAME PROPAGATION IN PARTLY OR FULLY UNCONFINED GEOMETRIES

The important work of Tamanini (1989), and Tamanini and Chaffee (1989) is discussed more extensively in Chapter 6 on venting of dust explosions. In the present context, it should only be briefly mentioned that explosion experiments were conducted in a 64 m^3 vented vessel at a series of different, known turbulence intensities at the moment of ignition. The turbulence intensities were measured by means of a bidirectional impact probe. For a given dust, dust concentration, and vent characteristics, the maximum pressure in the vented explosion increased systematically with increasing initial turbulence intensity in the experimental range 2–12 m/s.

Hayes et al. (1983) investigated the influence of the speed of four shrouded axial fans, mounted above the channel floor, on the dust flame speed in a horizontal channel of 1.5 m length and 0.15 m × 0.15 m square cross section, open at both ends. A cloud of dried wheat flour of mean particle size 100 μm was produced in the channel and ignited by a propane/air flame while the fans were running. Some results are shown in Figure 4.48.

It was anticipated that the flame speed would increase markedly with fan speed, and this was also observed up to a fan speed of about 1500 rpm. However, as the fan speed was increased further, the flame speed exhibited a marked decrease, to about 3000 rpm, beyond which ignition of the dust cloud by the propane flame was no longer possible.

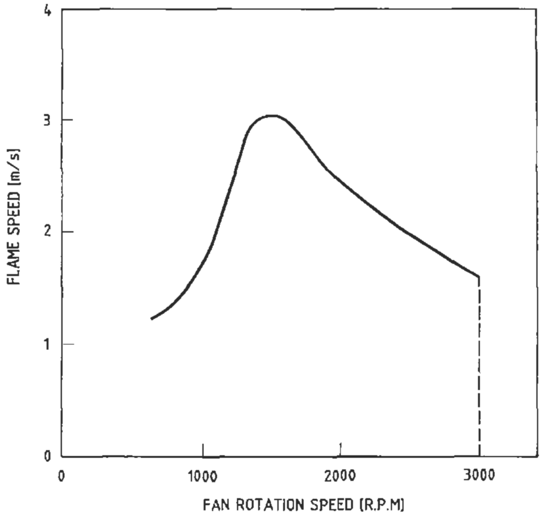


Figure 4.48 *Variation of dust flame speed in a horizontal channel with open ends, with rotational speed of four fans located in the channel, and 300 g/m^3 of dried wheat flour in air (From Hayes et al., 1983).*

Referring to the work by Chomiak and Jarosinski (1982) on quenching turbulent gas flames by turbulence, Hayes et al. (1983) attributed the falloff of flame speed in the region 1500 rpm to 3000 rpm to quenching by excessive turbulence. Turbulent flame quenching occurs when the induction time for the onset of combustion exceeds the characteristic lifetime of the turbulence eddies, so that an eddy composed of hot combustion products and unburned fluid dissipates before the unburned gas has become ignited. Hayes et al. did not discuss whether dust could have been separated out at high fan speeds in regions of nonrandom circulation flow in the channel (cyclone effect). It was confirmed, by means of hot-wire anemometry, that the degree of turbulence was proportional to the fan speed. For this reason, Hayes et al. used a fan Reynolds number as a relative measure of the degree of turbulence in the experimental channel.

Klemens et al. (1988) investigated the influence of turbulence on wood and coal dust/air flame propagation in the laboratory-scale flow loop shown in Figure 4.49.

The flow was first streamlined by being passed through a battery of stator blades upstream of the measurement section. Turbulence was then induced in the first part of the measurement section by a number of cylindrical rods or rods of V-profiles, mounted with their axes perpendicular to the main flow direction. The electric spark ignition source was located immediately downstream of the turbulizing zone, and turbulent flame propagation was observed in the remaining part of the measurement section. Experiments were conducted with two types of brown coal, a maize dust, and a wood dust—all dusts being finer than 75 μm particle size. Figure 4.50 shows the average turbulent burning velocity for maize dust/air in the loop as a function of the average normalized turbulence intensity.

Klemens et al. (1988) observed that their turbulent maize dust flame had the same characteristic nonhomogeneous structure as observed by Proust and Veyssiere (1988) for turbulent corn starch/air flames in a vertical duct.

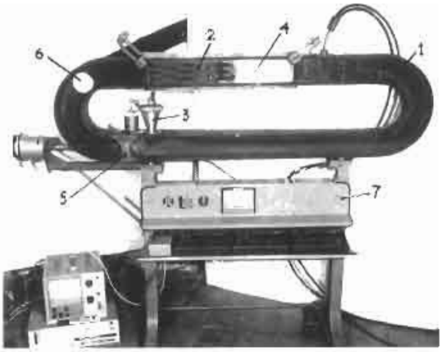


Figure 4.49 *Laboratory-scale flow loop for studying influence of turbulence on the propagation of dust/air flames:*

1. *Flow channel of cross section 80 mm × 35 mm.*
2. *Measurement section of 0.50 m length.*
3. *Dust feeder.*
4. *Ignition spark electrodes.*
5. *Fan.*
6. *Bursting membrane.*
7. *Automatic control system.*

(From Klemens et al., 1988).

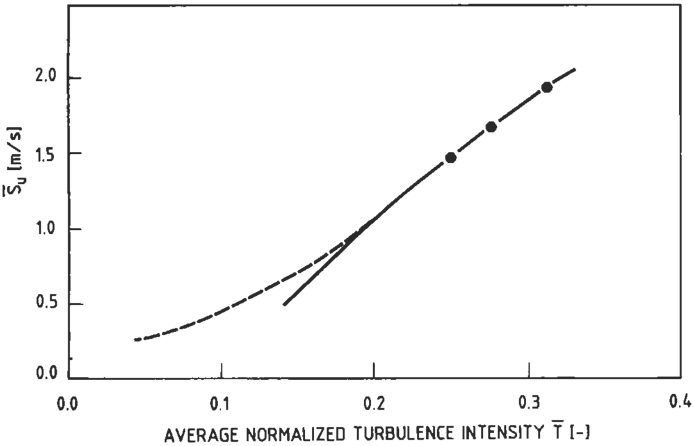


Figure 4.50 *Average turbulent burning velocity $\bar{S}$ in a cloud of maize dust in air as a function of the average normalized turbulence intensity $\bar{T}$, both quantities averaged over the 80 mm height of the channel cross section: $\bar{T} = (1/V)(V_x^2 + V_y^2 + V_z^2)^{1/2}$, where V is the overall flow velocity at a given location in the channel cross section and V_x, V_y, and V_z are the turbulence velocities in the three main directions at the same location (From Klemens et al., 1988).*

Shevchuk et al. (1986) studied flame propagation in unconfined clouds of aluminum dust in air at various levels of preignition turbulence. The clouds were generated from a set of four dust dispersers driven by a short blast of compressed air. Each disperser was charged with 1–10 kg of dust. After completion of dust dispersion, the dust cloud was ignited after a desired delay. The highest level of preignition turbulence existed immediately after completion of the dispersion. As the ignition delay was increased, the turbulence decayed; and after a sufficiently long delay, the dust cloud was essentially quiescent. Figure 4.51 gives some results.

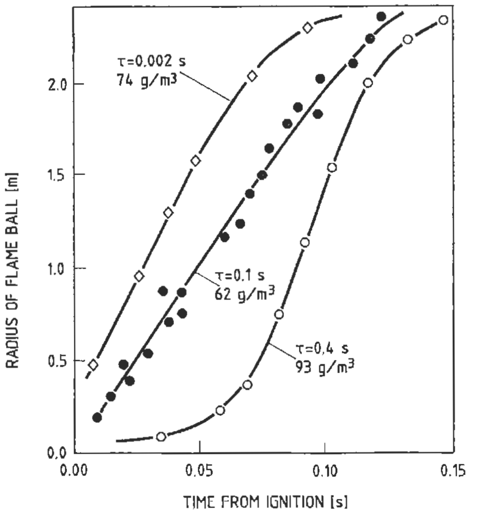


Figure 4.51 *Radius of flame ball as a function of time from central ignition of unconfined cloud of 10 μm diameter aluminum flakes in air; τ is the delay between completion of dust dispersion and effective ignition of the dust cloud. The dust concentrations are normal averages (quantity of dust dispersed at moment of ignition) (From Shevchuk et al., 1986).*

The data points for $\tau = 0.1$ s and 62 g/m^3 are from three different but nominally identical experiments. Figure 4.51 shows that the initial radial flame speed decreased systematically with increasing ignition delay, or decreasing initial turbulence, from about 30 m/s at $\tau = 0.002$ s via 20 m/s at $\tau = 0.1$ s to about 1 m/s at $\tau = 0.4$ s. The ignition delay of 0.4 s was probably sufficiently long to render the dust cloud practically laminar at the moment of ignition. However, after about 0.05 s, the flame was no longer laminar and accelerated rapidly to about 40 m/s over the very short period 0.05 to 0.07 s. Shevchuk et al. suggested that this "switch" from laminar to turbulent conditions is triggered by flame instabilities due to nonhomogeneous dust concentration, which is inevitable in a real dust cloud. They defined a special Reynolds number for establishing a criterion for the laminar-to-turbulent transition:

$$Re^* = \frac{(\text{Radius of flame ball at transition point}) \times (\text{Flame speed at transition point})}{(\text{Kinematic viscosity of air})}$$

and found that the transition generally occurred at Re^* in the range 10^4–10^5.

4.4.5
SYSTEMATIC COMPARATIVE STUDIES OF TURBULENT GAS AND DUST EXPLOSIONS

The dramatic influence of turbulence on gas explosions has been studied extensively. The investigations by Moen, Lee, and Hjertager (1982) and Eckhoff et al. (1984) are examples of fairly large-scale experiments with obstacle- and jet-induced turbulence. It has been suggested, for example, by Nagy and Verakis (1983), that there may be similarities between the influence of turbulence on gas and dust explosions. One of the first systematic comparative studies of turbulence influence on dust and gas explosions was conducted by Bond, Knystautas, and Lee (1986). They concluded that the relative burning rate variations caused by turbulence were equal in a 300 g/m^3 maize starch-in-air cloud and in premixed 7.5 vol% methane-in-air. However, they also emphasized the need for further work.

Pu (1988) and Pu et al. (1988) made further comparison of turbulent flame propagation in premixed methane in air and in clouds of maize starch in air, in identical geometries and at identical initial turbulence intensities. The experiments under turbulent conditions were conducted in closed vertical cylindrical vessels of 190 mm diameter and length either 0.91 m or 1.86 m. All experiments were conducted with initial turbulence generated by the blast of air used for dispersing the dust. The influence of ignition delay on the flame propagation and pressure development was studied. In the gas experiments, the initial turbulence was generated by a blast of compressed methane/air, from the same reservoir as used for the compressed air for dust dispersion in the dust cloud experiments. In some experiments, a battery of concentric ring obstacles were mounted in the tube for studying the influence of the additional turbulence generated by the expansion-induced flow of the unburned gas or dust cloud past the obstacles.

A comparable set of Yi Kang Pu's results are shown in Figures 4.52 (gas) and 4.53 (dust). On average, the combustion of the gas is twice as fast as that in the dust cloud. The laminar burning velocity of 550 g/m^3 maize starch in air, as determined by Proust and Veyssiere (1988), is about 0.20 m/s. Extrapolation of Zabetakis's (1965) data for methane in air to 5.5 vol% methane gives lower values, in the range of 0.15 m/s or less. It is therefore clear

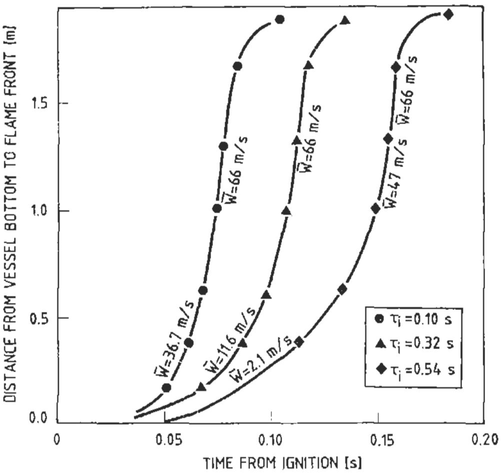


Figure 4.52 *Pressure rise and flame front location during combustion of 5.5 vol% methane/air in a 1.86 m long closed vertical tube of diameter 190 mm, as a function of time, under the influence of obstacle-induced turbulence. Three different ignition delay times τ_i are shown, and ignition is at the tube bottom (From Pu, 1988).*

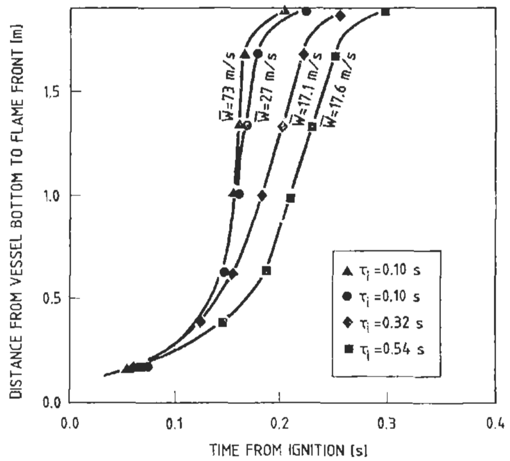


Figure 4.53 *Pressure rise and flame front location during combustion of 550 g/m^3 maize starch in air in a 1.86 m long closed tube of diameter 190mm , as a function of time, under the influence of obstacle-induced turbulence. Three different ignition delay times τ_i are shown, and ignition is at the tube bottom (From Pu, 1988).*

that the higher average turbulent flame speeds found by Yi Kang Pu for the 5.5 vol% methane in air cannot be attributed to a higher laminar burning velocity.

As the methane/air flame approached the end of the tube, the average flame speed had reached the same value of 60–70 m/s irrespective of the ignition delay (initial turbulence), which means that the obstacle-induced turbulence played the main role in the latter part of the combustion. In the dust cloud, however, the high final flame speed of about 70 m/s is reached only in the case of high initial turbulence. The role of possible dust concentration inhomogeneities causing this discrepancy is not clear.

The maximum explosion pressures were in the range 4–5 bar(g) for the gas and somewhat higher, 5–7 bar(g) for the dust.

Yi Kang Pu's work indicates that there may not be a simple one-to-one relationship between the response to flow-induced turbulence of gas and dust flames. There is little doubt that more research is needed in this area. (See Sections 9.2.4.4 and 9.2.4.7 in Chapter 9.)

4.4.6
MAXIMUM EXPERIMENTAL SAFE GAP FOR DUST CLOUDS

The *maximum experimental safe gap* (*MESG*) can be defined as the largest width of a slot that will just prevent transmission of a flame in a gas or dust cloud inside an enclosure to a similar gas or dust cloud on the outside. This definition is somewhat vague and raises several questions. It defines neither the length of the slot, the explosion pressure inside, nor the volume of the enclosure. Therefore, MESG is not a fixed constant for a given explosible cloud but depends on the actual circumstances. However, MESG is of importance in practice and, therefore, needs to be assessed. In general, it is smaller than the laminar quenching distance. This is because of the forced turbulent flow of the hot combustion products through the slot due to the pressure buildup inside the primary enclosure. Therefore, the conditions of flame transmission are in the turbulent regime and should be discussed in the context of turbulent flame propagation.

Jarosinski et al. (1987), as part of their work to determine laminar quenching distances of dust clouds, also measured MESG under certain experimental conditions. The experiments were performed in a vertical tube of diameter 0.19 m and length 1.8 m, with a battery of parallel quenching plates of 75 mm length halfway up in the tube. Laminar quenching distances were determined at constant pressure, with ignition at the open bottom end of the tube and the top of the tube closed. MESGs were determined with bottom ignition but both tube ends closed. This means that unburned dust cloud was forced through the parallel plate battery as soon as significant expansion of the combustion products in the lower ignition end of the tube had started. Turbulence then is generated in the flow between the parallel plates by wall friction and transmitted to the unburned cloud immediately downstream of the plates. When the upward propagating flame reaches the plate battery, hot combustion products are transmitted through the slots between the parallel plates, and reignition may or may not occur downstream of the plates. Under those circumstances, the MESG for 600 g/m^3 maize starch in air was found to be 1.5–2.2 mm, depending on the location of the primary ignition source. The lowest values were obtained with ignition at the tube bottom, the highest values with ignition just below the parallel plate battery. These values of MESG are not universal for 600 g/m^3 maize starch in air but relate to the actual experimental conditions.

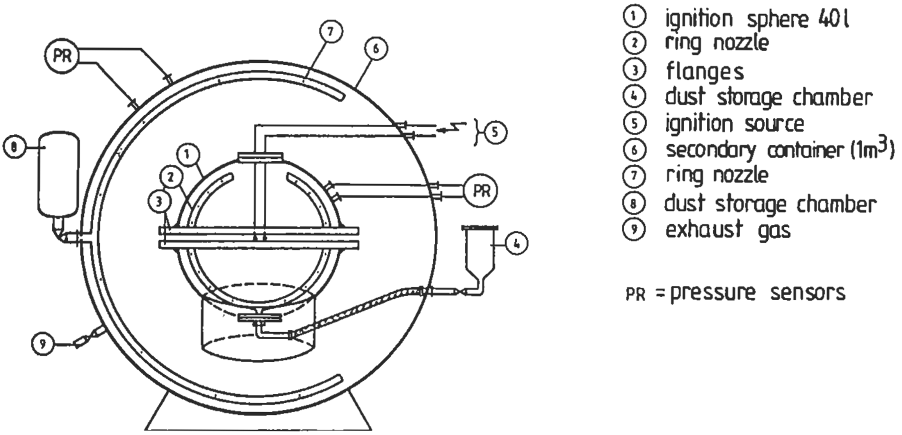


Figure 4.54 *Primary 40 liter explosion sphere inside the secondary 1 m^3 vessel for determination of MESG of dust clouds. The annular gap for possible flame transmission is between the two flanges (3) (From Schuber, 1989).*

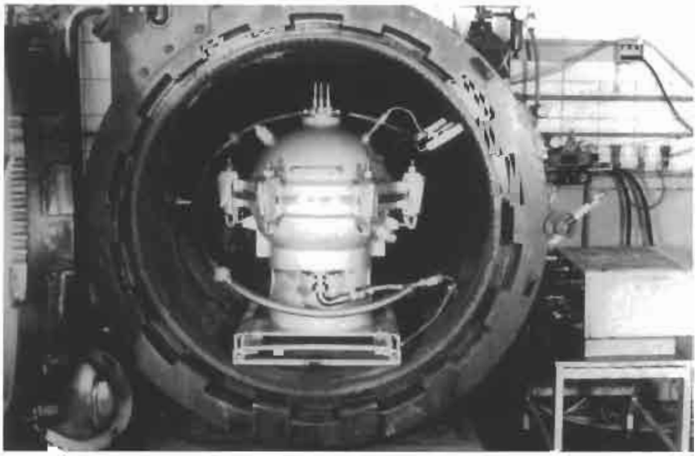


Figure 4.55 *Actual assembly of primary 40 liter and secondary 1 m^3 vessels (From Schuber, 1989).*

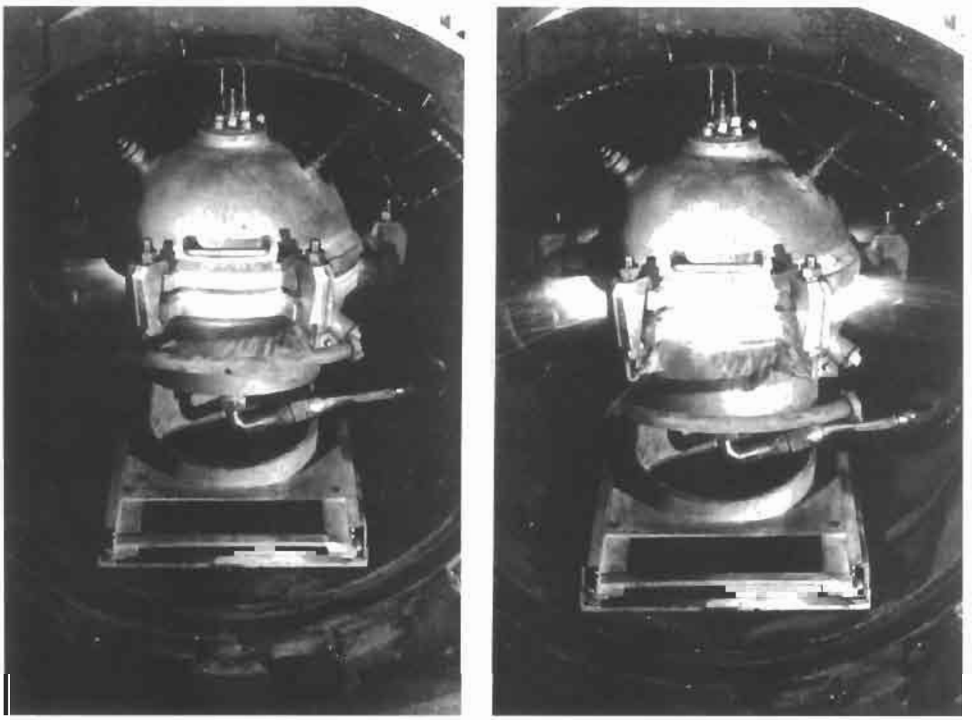
Schuber (1988, 1989) investigated the influence of various parameters on MESG. The apparatus is shown in Figures 4.54 and 4.55. Explosible dust clouds of desired concentrations were generated simultaneously in both vessels from compressed dust reservoirs, and the cloud in the primary vessel was subsequently ignited. It was then observed whether the cloud in the secondary vessel was ignited by the flame jet transmitted through the annular gap in the wall of the primary vessel. Examples of flame jets of maize starch/air that are or are not capable of igniting the secondary cloud are shown in Figure 4.56.

The dusts used in Schuber's investigation are listed in Table 4.14, together with their ignitability and explosibility properties. Table 4.14 does not contain metal dusts, such as aluminum and silicon, and Schuber emphasized that his results are limited to organic dusts and coals.

Table 4.14 Ignitability and explosibility properties of dusts used to determine MESG for dust clouds in air

Dust type	*M* [mm]	P_{max} (bar(g))	K_{St} (bar·m/s)	MIE (mJ)	*Ti* (°C)	MIE (mJ)
Wettable sulfur*	50	4.3	86	<1	260	<1
Lycopodium	30	7.6	179	2	370	4.7
Benzanthrone	27	7.2	175	2	580	6.2
Light stabilizer	<10	8.0	270	5	410	12.5
Polyethylene	123	5.5	55	10	410	25
Maize starch	<10	7.9	186	20	400	49
Pea flour	54	7.4	95	100	410	250
Coal dust I	20	7.2	141	100	500	280
Coal dust II	18	7.8	130	2000	540	5960
Saar coal	54	6.4	84	5000	500	14,200

*Wettable sulfur = 80% sulfur + 20% lignum sulphate.
M = Median particle diameter by mass.
P_{max} = Maximum explosion pressure according to International Standards Organization (1985).
K_{St} = Normalized maximum rate of pressure rise according to International Standards Organization (1985).
MIE = Minimum net electric spark energy for ignition of dust cloud with 1 mH inductance in capacitive discharge circuit.
Ti = Minimum ignition temperature of dust cloud determined in BAM furnace (see Chapter 7).
Source: Schuber, 1988, 1989.



(a) (b)

Figure 4.56 *Visible flame jets of maize starch/air transmitting from the primary to the secondary dust cloud: (a) flame jet is too weak to ignite secondary cloud, (b) flame jet will ignite secondary cloud (From Schuber, 1989).*

In general, Schuber found that MESG decreased with decreasing initial turbulence in the dust clouds. This is in harmony with the decrease of the minimum electric spark energy for ignition of both gases and dust clouds with decreasing turbulence. To ensure conservative results, Schuber's experiments to establish correlations between MESG and dust properties were conducted with comparatively low initial turbulence in the dust clouds. Schuber correlated his experimental MESG values with the product of minimum electric spark ignition energy and the dimensionless minimum ignition temperature (rightmost column in Table 4.14) and the result is shown in Figure 4.57, where 1 g is the length of the gap (width of the flanges (3) in Figure 4.54).

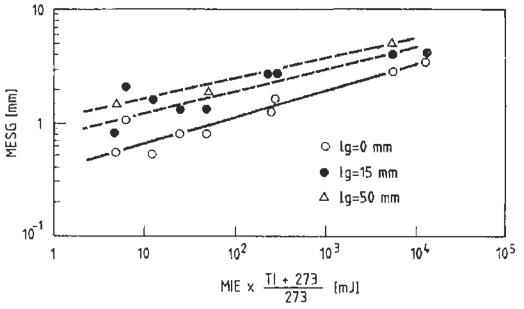


Figure 4.57 *Correlations between MESG and ignition sensitivity of dust clouds for various gap lengths (From Schuber, 1989).*

There is an increase of MESG with increasing gap length from 0 to 50 mm by a factor of 2 to 3. For a constant gap length, there is a fair correlation between MESG and the ignition sensitivity parameter used. A closer examination of this parameter reveals that $(TI + 273)/273$ is in the range 2–3 for most of the dusts in Table 4.14, which means that the double-logarithmic correlation in Figure 4.57 is essentially between MESG and MIE. Schuber found that MESG approached a constant value as 1 g approached 50 mm. This value was considerably smaller than the laminar quenching distance. For example, Schuber's value for corn starch/air at 1 g = 50 mm was 1.8 mm, whereas the laminar quenching distance found independently by Jarosinski et al. (1987) and Proust and Veyssiere (1988) was 6–7 mm. Schuber's asymptotic value of 1.8 mm agrees well with the MESG of 1.5–2.2 mm found for corn starch/air by Jarosinski et al. (1987).

An important general conclusion from Schuber's (1988) work is that, for a fairly long gap length of 25 mm, MESG for gases, vapors, and organic and sulfur dusts in air can be correlated with MIE $(TI + 273)/273$ in one single empirical equation:

$$\text{MESG (mm)} = [\text{MIE}\,(TI + 273)\,/\,273]^{0.157} \tag{4.86}$$

where MIE is in mJ and TI is in K. Equation (4.86) could, in principle, be refined by incorporating the gap length as a further parameter. For short gap lengths of a few mm, this would give a reduction of MESG as compared to values from equation (4.86) by a factor of 2–3 or more.

Schuber regarded the transmission of the flame through the slot as being primarily a process of ignition of the dust cloud downstream of the slot by the turbulent jet of hot combustion products being expelled from the slot rather than flame propagation through the slot. He attributed the strong correlation between MESG and ignition sensitivity to this.

On the other hand, it is well known that a strong correlation exists between laminar quenching distances and minimum ignition energies for gases.

The original motivation for Schuber's work was the uncertainty related to the ability of rotary locks to prevent transmission of dust explosions. He investigated results from experiments in the apparatus shown in Figure 4.58, where a rotary lock was mounted between two vessels in which dust clouds could be generated simultaneously.

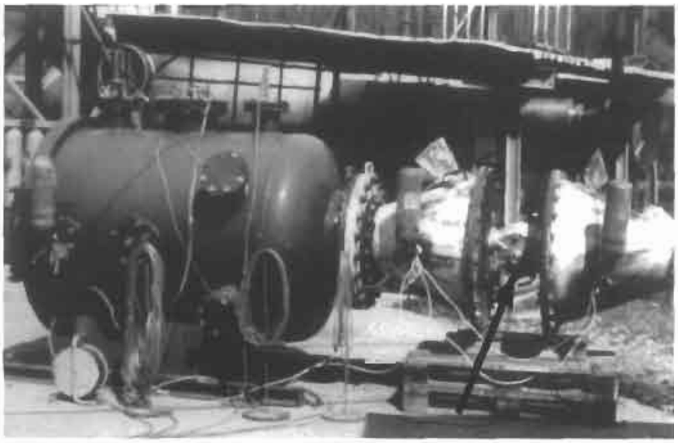


Figure 4.58 *Arrangement for investigating the ability of rotary locks to prevent transmission of the explosions (From Schuber, 1988).*

The dust cloud on one side was then ignited, and it was observed whether transmission of flame occurred to the extent that the dust cloud on the other side was also ignited. Figure 4.59 shows the essential parameters of the rotary lock.

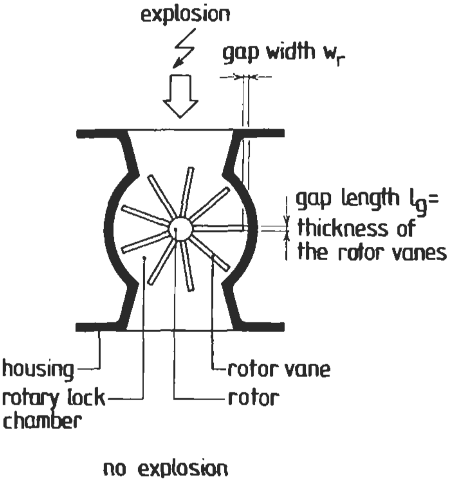


Figure 4.59 *Gap width and gap length related to explosion transmission through rotary locks (From Schuber, 1988).*

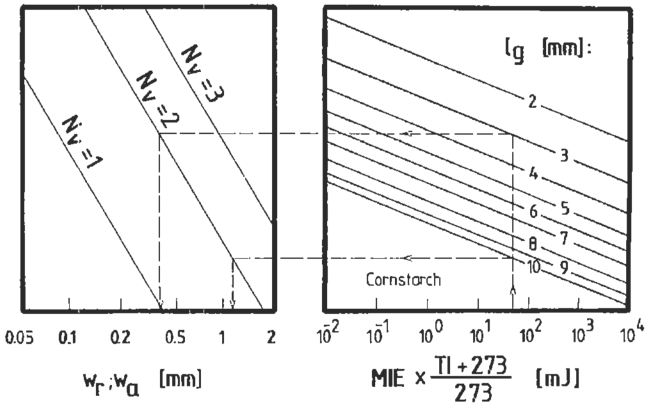


Figure 4.60 *Nomograph for estimating maximum permissible clearance w between rotor blades and housing for prevention of transmission of dust explosions through rotary locks (From Schuber, 1988).*

On the basis of numerous experiments, Schuber (1989) proposed the nomograph in Figure 4.60 as a basis for predicting maximum permissible gaps w between the edges of the rotary lock blades and the housing. The radial gap w_r is defined in Figure 4.59. The axial gap is w_a. The gap that needs consideration depends somewhat on the details of the rotor construction. N_V is the number of consecutive rotor blades that form consecutive gaps. For example, on the right-hand side of the rotor, as viewed in Figure 4.59, $N_V = 3$.

Schuber emphasized that the nomograph does not apply to metal dusts and that it is assumed that the rotor blades do not deform during the explosion. Figure 4.60 illustrates the use of the nomograph for corn starch/air for $N_V = 2$ and the two gap lengths are 3 mm and 10 mm. The maximum permissible clearances are 0.4 mm and 1.1 mm, respectively. For $N_V = 1$, the corresponding values would be about 0.1 mm and 0.25 mm, that is, considerably smaller than the values 0.9 mm and 1.1 mm given for MESG for corn starch/air at 0 and 15 mm gap lengths in Figure 4.57. This discrepancy could be due to integration of a safety margin in the nomograph. On the other hand, one would expect that much larger primary explosion volumes than 40 liters would be able to push larger quantities of burned dust cloud through the slot and therefore create more favorable conditions for ignition of the dust cloud downstream of the slot. See also Section 8.4.7 in Chapter 8.

4.4.7

ACCELERATION OF TURBULENT DUST EXPLOSIONS IN ENCLOSURES OF LARGE *L/D* (DUCTS, PIPES, GALLERIES, AND THE LIKE)

Coal mines essentially consist of long galleries of large length-to-diameter (*L/D*) ratio. Since the onset of systematic research on the propagation of coal dust explosions in mines, large-scale experimental galleries have been a main tool of investigation. According to Cybulski (1975), Hall's experiments in coal mines in the United Kingdom about 1890 was probably the first of this kind. Some years later, Taffanel (1907) reported the results of his pioneering large-scale gallery experiments in France. These experiments were conducted as a consequence of the disastrous coal dust explosion in the Courriers mine in 1906, where 1099 miners lost their lives. Similar work was subsequently initiated in Poland, Russia, Germany, and the United States.

Greenwald and Wheeler (1925) used a horizontal explosion tube of internal diameter 2.3 m and length 230 m, that is, $L/D = 100$, in their experiments. One end was normally closed, the other fully open. A pulverized nut coal, ground to 85% by mass <74 μm particle size, and containing 33% volatiles was used. The ignition source was 800 g of black powder igniting a primary cloud of 10 kg of coal dust. The main quantity of coal dust was spread along the gallery floor from the point of ignition at 61 m to the full opening of the gallery at 230 m (see Figure 4.61). The quantity of dust spread on the gallery floor was about 1500 g per m of gallery length, corresponding to a nominal dust concentration in a fully dispersed state of 360 g/m^3. No dust was spread out in the 61 m long section between the normally closed upstream end of the gallery and the ignition point.

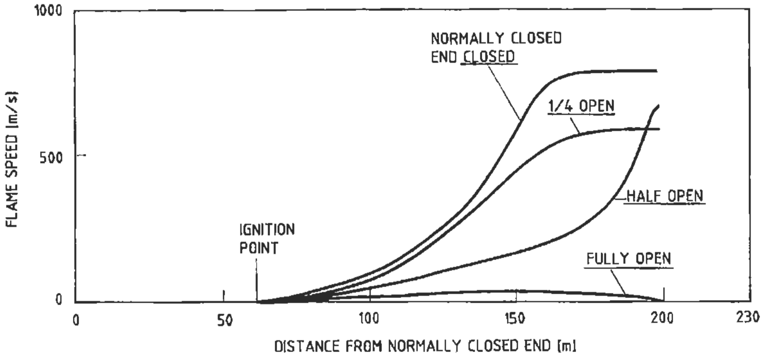


Figure 4.61 *Acceleration of coal dust explosions in a horizontal gallery of internal diameter 2.3 m and length 230 m, showing the effect of venting at the upstream, normally closed end (From Greenwald and Wheeler, 1925).*

The main purpose of Greenwald and Wheeler's experiments was to investigate the influences of the location and size of vents on the development of dust explosions in the gallery. As Figure 4.61 shows, flame speeds of up to 800 m/s were generated with the upstream end of the gallery fully closed. Whether the plateau of constant flame speed at 800 m/s beyond 165 m indicates detonation is unclear. Lindstedt and Michels (1989) observed violent, constant-velocity deflagrations supported by wall-friction induced turbulence for alkanes in air. Similar steady combustion phenomena may also exist for dust explosions in long tubes and ducts. The flame speed would then be somewhat lower than for a proper detonation. (Detonation of dust clouds is discussed in Section 4.5.)

Figure 4.61 demonstrates that venting at the upstream, normally closed, end reduced the acceleration of the explosion appreciably. With a fully open upstream end, comparatively weak explosions of maximum flame speeds around 50 m/s resulted. In this case, Greenwald and Wheeler made some interesting observations. The flame motion was markedly vibratory, and the column of dust and air preceding the flame was expelled from the gallery exit in puffs instead of in a continuous stream. The flame itself could be seen to issue from one of the openings two or three times, with a slight in-rush of air occurring between each flame appearance. This finding is in agreement with Chapman and Wheeler's (1926) observations of vibratory premixed gas flames in a laboratory tube open at both ends. They found that the "periodicity of the vibrations was that of the fundamental tone of the tube." As already discussed and illustrated in Figure 4.36, Eckhoff et al. (1987) observed the same phenomenon during dust explosions in a large vertical silo of diameter 3.7 m, height 22 m, and vented at the top, provided the ignition point was in the upper part of the silo. Greenwald and Wheeler (1925) also measured explosion pressures at various locations in the large gallery. The maximum values recorded by the low-frequency-response manometers available at that time were 5.0 bar(g), 4.8 bar(g), 3.3 bar(g), and 0.14 bar(g) for the normally fully closed end fully closed, one-quarter open, half open, and fully open, respectively. Pressure recordings further upstream were lower than this and decreased systematically with increasing distance to the downstream exit.

Fischer (1957) reported results from coal dust explosion experiments in a 260 m long experimental coal mine gallery of equivalent-circle cross-sectional diameter of 3.2 m, that is, a *L*/*D* of about 80. The main purpose of these experiments was to investigate whether deposits of stone dust on shelves in the upper part of the gallery cross section would prevent the propagation of coal dust explosions in the gallery. However, it appeared that, under certain circumstances, this stone dust had little effect and flame acceleration phenomena of the same violent type as found by Greenwald and Wheeler (1925) were observed, as shown in Figure 4.62.

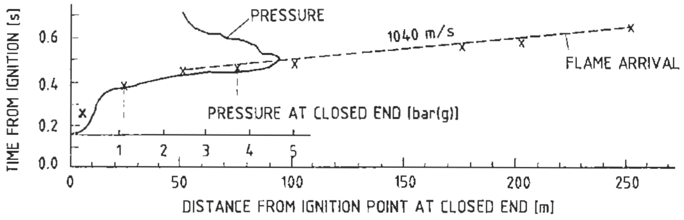


Figure 4.62 *Time of arrival of bituminous coal dust/air flames as a function of the distance from the ignition point at the closed end of a gallery of length 260 m and diameter 3.2 m, with pressure at the closed end as a function of time and nominal average dust concentration 500 g/m^3 (From Fischer, 1957).*

The coal dust explosion was initiated by an explosion of 40 m^3 methane/air at the upstream, closed end of the gallery. The gas was ignited by black powder, probably ensuring violent combustion of the gas. The blast from the gas explosion in turn swept up the coal dust layer of 4 kg per m length of gallery on the floor and initiated the self-sustained dust explosion down the entire length of the gallery. The most striking feature of Figure 4.62 is the very constant flame speed of 1040 m/s, measured from about 50 m from the closed end right to the open tube end, 200 m further down. Fischer associated this with "some kind of detonation" (see Section 4.5). The pressure versus time was recorded only at the upstream closed end of the gallery, because the explosion was so violent that all the measurement stations further down the gallery were destroyed. As can be seen, the peak pressure at the closed end was about 5 bar(g). It would be anticipated that the pressures further down the gallery were considerably higher.

Jost and Wagner (in Freytag, 1965) illustrated the various characteristic phenomena occurring during acceleration of premixed gas flames in long one-end-open tubes. There are good reasons for assuming that their overall picture, as reproduced in Figure 4.63,

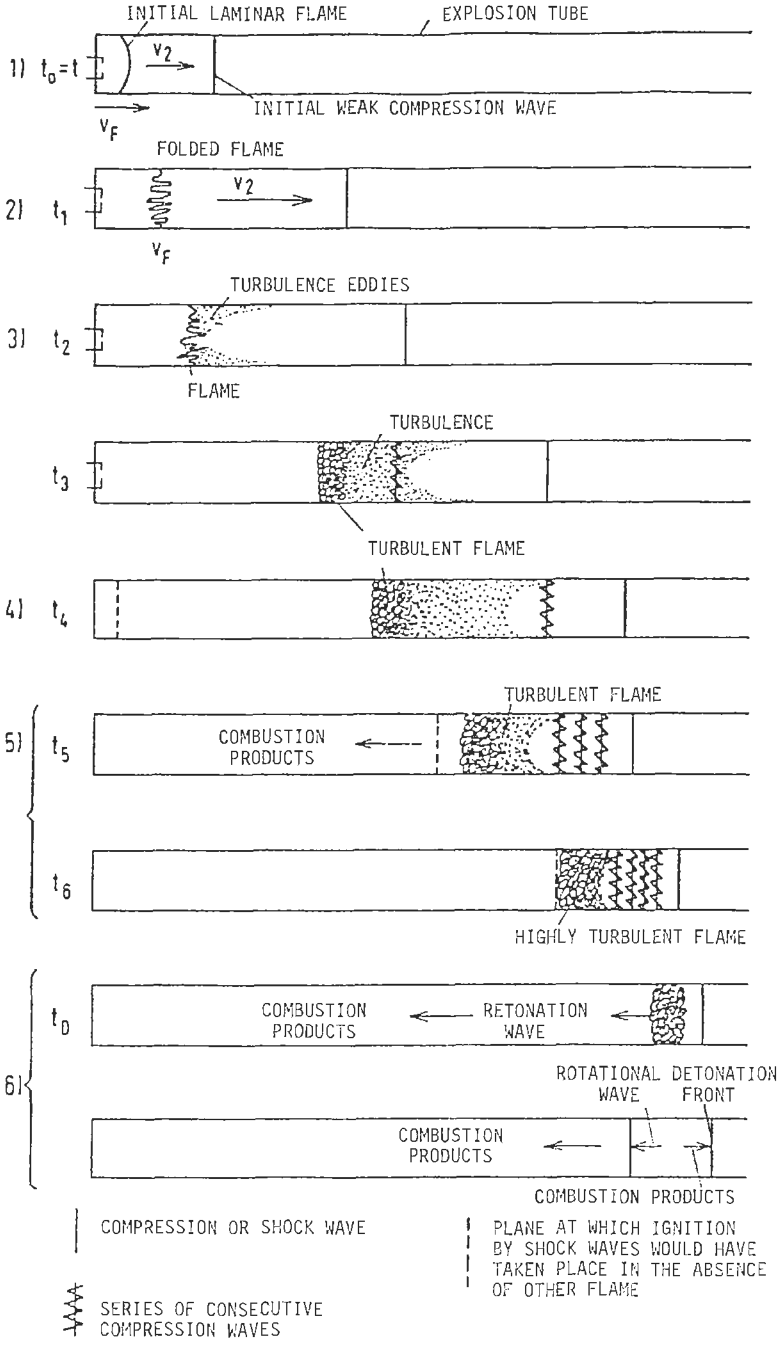


Figure 4.63 *Characteristic phenomena during acceleration of gas or dust flames in one-end-open long tubes, from laminar combustion via turbulent combustion to detonation.* V_F *is the flame speed;* V_2 *is the velocity of the unburned gas or dust cloud ahead of the flame (From Jost and Wagner, in Freytag, 1965).*

also applies to dust clouds. The only major difference is that a dust cloud needs to be generated by raising dust deposits into suspension. This means that stage 1 and possibly also stage 2 in Figure 4.63, the ignition and laminar propagation of the initial flame, may not be relevant for dust flames. As already discussed, Greenwald and Wheeler (1925) used black powder to stir up and ignite the primary dust cloud, whereas Fischer (1957) used a turbulent gas flame. However, once the primary dust explosion is underway, the blast wave generated by it entrains dust further downstream, as already discussed. Therefore, all stages of Figure 4.63, from stage 3 and downward, apply even to dust clouds. The essential reason for the flame acceleration is turbulence generated in the unburned cloud ahead of the flame due to wall friction when the cloud is pushed toward the open tube end by the expansion of the part of the cloud that has burned. When the flame front reaches the turbulent unburned cloud, the combustion rate increases. This, in turn, increases the expansion rate of the combustion products and therefore also the flow rate of the unburned cloud ahead. The result is an even higher turbulence level and further increase of the combustion rate. During all these stages, compression waves are emitted and propagate toward the open tube end. Because of heating of the cloud ahead of the flame due to adiabatic compression, each wave propagates at a slightly higher velocity than the previous one. Ultimately, therefore, they all catch up with the initial wave and form a strong leading shock front. The turbulent flame front also, due to the positive feedback mechanism of combustion rate flow rate turbulence enhanced combustion rate, eventually catches up with the leading shock wave. If the leading shock is sufficiently strong, a switch can occur in the mechanism of flame propagation. Instead of heat being transferred by turbulent diffusion behind the leading shock wave, the dust cloud may become ignited in the highly compressed state inside the leading shock. If the induction time of ignition is sufficiently short, the chemical reaction zone and the propagating shock wave then become closely coupled and propagate through the cloud at constant velocity. This is detonation. (see Section 4.5). However, as already mentioned, flame propagation at a constant high speed need not be a classical detonation but can also be a high-speed turbulent deflagration supported by wall friction induced turbulence.

Figure 4.63 shows a tube with a comparatively smooth internal wall. However, if the wall roughness is increased, the positive feedback loop of combustion acceleration becomes more effective, and acceleration up to detonation occurs over a shorter distance. Gas explosion experiments have been conducted in tubes in which the "wall friction" was increased systematically by inserting in the tube a number of equally spaced, narrow concentric rings in contact with the wall. Such experiments were in fact carried out by Chapman and Wheeler (1926) in a small laboratory-scale tube of diameter 50 mm and length 2.4 m, open at both ends. For methane/air, flame speeds of up to 420 m/s were measured as opposed to 1.2 m/s without the rings. Chapman and Wheeler were fully aware of the essential role played by flow-generated turbulence. Similar dramatic effects of such equally spaced rings were found by Moen et al. (1982) for methane/air explosions in a one-end-open large-scale tube of 2.5 m diameter and 10 m length.

These investigations are of considerable interest in relation to dust explosions in coal mines, where the supporting structures of the mine galleries would seem to have the same type of turbulence increasing effect as the concentric rings in tubes (Fischer, 1957). In the process industry, the legs of bucket elevators are long ducts with repeated obstacles.

Rae (1971) analyzed coal dust explosion experiments in various large-scale tubes and galleries of lengths in the range 100–400 m, conducted in the time period 1911–1971.

He pointed out that the initiating explosion causes events analogous to those observed in shock tubes. The initial thin turbulent dust flame entrains deposited dust and develops into the more extensive main explosion, which may in turn lead either to detonationlike phenomena, including strong shock waves, or to oscillating flames, depending on various circumstances.

Bartknecht (1971) used an external dust dispersion system by which he avoided the use of a primary explosion for initiating dust entrainment and flame propagation. He generated a dust cloud of the most explosible concentration along the whole tube length by simultaneously injecting dust from a number of equally spaced external pressurized reservoirs. (This is essentially the same dust dispersion method as specified in the 1 m^3 test approved by the International Standards Organization, 1985.) The dust cloud was ignited by a strong chemical ignitor or a pocket of exploding methane/air as soon as it had been generated. On the one hand, Bartknecht's experiments were clean and well defined. On the other hand, they differed from conditions often met in mines and other industry, where the dust is initially deposited as layers that are dispersed by the air blast preceding the flame as the explosion propagates. There may be situations, however, where Bartknecht's dispersion method corresponds to reality, for example, in pneumatic transport of explosible dust concentrations.

Figure 4.64 gives some of Bartknecht's results from experiments in 0.40 m diameter horizontal one-end-open pipes of various lengths. As can be seen, there is close correlation

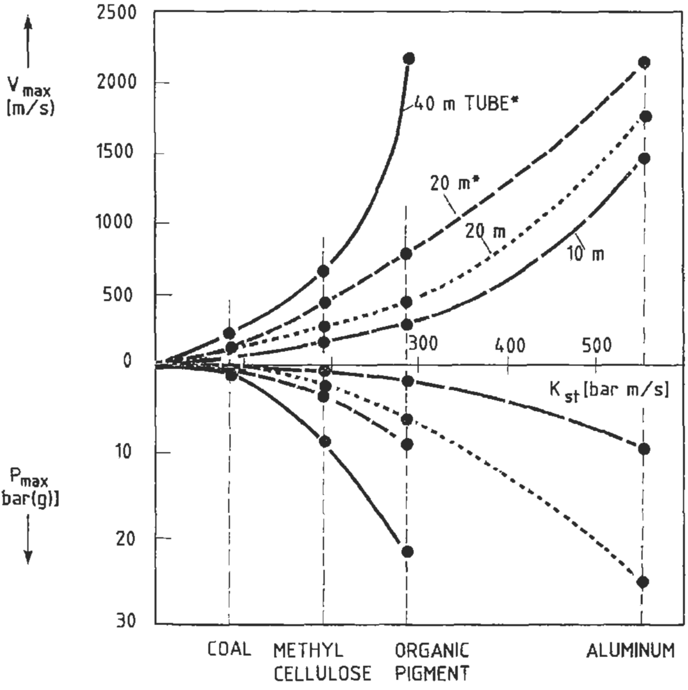


Figure 4.64 *Dust explosions in 0.40 m diameter, horizontal, one-end-open pipes of various lengths, with maximum flame speeds and maximum explosion pressures as functions of tube length and K_{St} value of dusts; * denotes enlarged pipe diameter in the ignition zone at the closed end (From Bartknecht, 1971).*

between the K_{St} value, as determined in agreement with the recommendation by the International Standards Organization (1985), and the violence of the explosions in the tubes.

The aluminum dust was comparatively coarse, having a median particle diameter on a mass basis of 30 μm, with 10% > 100 μm and 10% > 20 μm. Nevertheless, a maximum flame speed of 2200 m/s and maximum explosion pressure of 25 bar(g) was measured in a 20 m long pipe, with enlarged diameter in the ignition zone for increasing the initial "push" and establishing a high level of turbulence and burning rate at an early stage. The explosion pressures were measured by piezoelectric sensors and were those acting normal to the tube wall, that is, normal to the direction of propagation. There are reasons to believe that the 2200 m/s phenomenon observed was in fact a proper detonation (see Section 4.5).

The coal dust produced maximum flame speeds of only up to 250 m/s and maximum explosion pressures on the order of 1 bar(g). The median particle size was 22 μm, with 10% > 60 μm and 10% < 5 μm (extrapolation of data). The volatile content was not specified.

Bartknecht attributed the comparatively slow coal dust explosions to the relatively small tube diameter of 0.4 m. He also conducted coal dust explosion experiments in a much larger one-end-open tube, of diameter 2.5 m and length 130 m, with ignition at the closed end by a pocket of methane/air. With 250 g/m^3 dust, maximum flame speeds of up to 500 m/s were measured. With 500 g/m^3, the maximum flame speeds were 700 m/s or more.

Bartknecht further conducted experiments where the dust was spread as a layer along the tube floor in a quantity corresponding to 250 g/m^3 if dispersed homogeneously over the whole tube cross section. When using the same ignition source (turbulent methane/air explosion at the closed tube end) as with the predispersed clouds with which he normally worked, he found lower flame speeds and explosion pressures than with predispersed clouds. However, Figures 4.61 and 4.62 show that the layer-spreading technique can indeed give very high flame speeds if only the initiating blast is sufficiently violent. This illustrates that choosing conditions of experimentation that correspond to the actual industrial hazard is an important aspect of applied dust explosion research.

Pineau and Ronchail (1982) and Pineau (1987) described experimental research on the propagation of wheat and wood dust explosions in ducts of diameters from 25 mm to 700 mm. They pointed out that, in any industrial installation where dust extraction or pneumatic transport of powdered material is used, a number of ducts will be connected to either blowers, fans, or pumps. In addition, the arrangements may include cyclones, bag filters, hoppers and bins, and other process equipment, some of which may be interconnected by pressure balance ducts. It is therefore essential, in the case of explosible powders and ducts, to understand the mechanisms by which dust explosions may propagate in dusts. In addition to straight ducts, ducts containing bends also need to be considered, because such bends are frequent in the process industry.

In one series of experiments reported by Pineau and Ronchail (1982), straight tubes of diameters from 250 mm to 700 mm and lengths from 12 m to 42 m were used. The tubes were either closed at both ends, closed at one end and fully or partly open at the other, or fully or partly open at both ends. In some experiments, the ignition point was at a closed tube end; in others, near an open end. In one experiment it was midway down the tube. The dust was initially distributed as a layer along the tube floor, the quantity of dust per unit length of duct corresponding to the desired nominal dust concentration. Ignition was sufficiently powerful to start dust entrainment and flame propagation through the dust cloud, but subsequent propagation depended on whether a sufficiently strong flow field was generated ahead of the flame for entraining the dust further downstream. This, as expected, depended on the extent to which the tube ends were closed or open and on the location of the ignition point. Some examples are given in Figure 4.65.

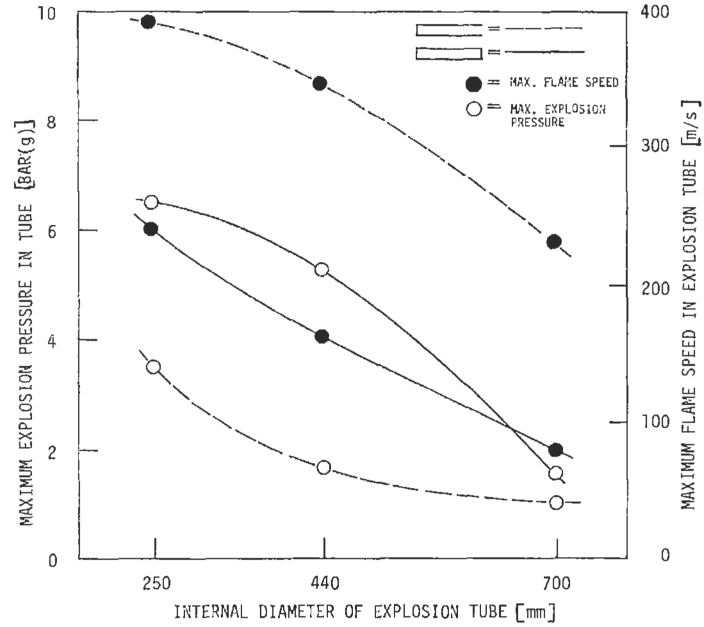


Figure 4.65 *Maximum explosion pressures and maximum flame speeds during wheat flour/air explosions in one-end-open or fully closed tubes of lengths 42 m and three different diameters. The nominal average concentration is 470 g/m³. Ignition is at the closed tube end (Replot of data from Pineau and Ronchail, 1982).*

The results for the 700 mm diameter tube show that the maximum explosion pressures were low and nearly the same; that is, 1 bar(g) for the one-end-open tube and 1.5 bar(g) for the fully closed one. In the closed tube, the low pressure means that the flame speeds and associated gas velocities were too low to cause entrainment and dispersion of the majority of the dust. In the one-end-open tube, the speed of the blast ahead of the flame was much higher, due to the venting at the open end. This, in turn, entrained the still unburned part of the dust in the tube and gave rise to a sufficiently high combustion rate in the resulting dust cloud to generate 1 bar(g) pressure in spite of generous venting. As the tube diameter decreased, the maximum flame speed increased, even in the closed tube; more dust was entrained and burned, and a higher maximum explosion pressure resulted.

Pineau and Ronchail (1982) also conducted a number of experiments in tubes of smaller diameters in the range 25–100 mm connected to a vessel in which the explosion was initiated. The tube lengths varied between 10 m and 40 m and the volume of the vessel was either 1 m³ or 0.1 m³. The influence of a 90° bend in the duct was also investigated. Furthermore, the effect of venting, either of the vessel or at the bend, was studied.

Numerous results were produced for various configurations and locations of the ignition point. Generally, the trends found can be understood on a qualitative basis in terms of increasing turbulence, dust entrainment, combustion rate, and venting, with increasing flow rate in the system. However, the complex pattern of results reemphasizes the need for a unified theoretical dust explosion model suitable for computer simulation of the course of explosions in complex, integrated systems for which specific experimental data do not exist.

Pineau and Ronchail (1982) found that powders having $K_{St} > 200$ bar m/s (International Standards Organization, 1985) can generate detonations in tubes of diameters 25–100 mm and up to 40 m length. Such detonations are associated with maximum pressures of more than 20 bar(g) and flame speeds of about 2000 m/s. This, for example, occurred with wood dust in a 25 m long tube of 100 mm diameter, connected to a 1 m^3 vessel in which the explosion was initiated. The inclusion of a 90° bend 6 m from the vessel, that is, 19 m from the open tube exit, reduced the explosion violence somewhat, but detonation still resulted in one experiment in a series of eight.

Radandt (1989) emphasized that, in industrial practice, as in dust extraction and pneumatic conveying systems, the initial dust clouds in ducts or tubes are not stagnant but flow at a considerable velocity, typically in the range 15–25 m/s. He therefore conducted a comprehensive series of dust explosion experiments with a maize starch of $K_{St} = 220$ bar m/s conveyed at various concentrations and velocities, using the experimental loop illustrated in Figure 4.66.

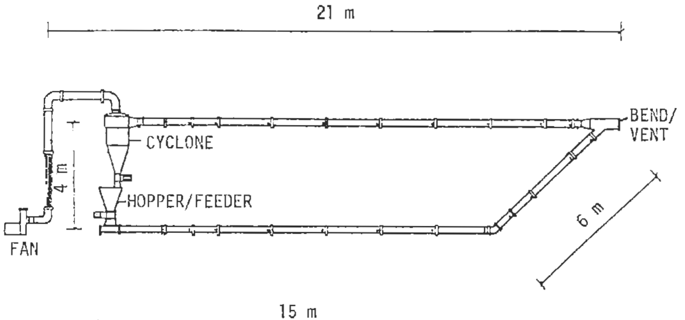


Figure 4.66 *Loop for dust explosion experiments, consisting of a dust feeder, 35 m of 200 mm diameter tube, a cyclone recycling the dust to the feeder, and a suction fan for establishing the airflow (From Radandt, 1989).*

The air was sucked into the system through the fully open tube end at the dust feeding point by the underpressure generated by the suction fan to the far left in Figure 4.66. A vent arrangement is indicated at the sharp 45° bend. Experiments were conducted both with a vent at this point and just a closed, smooth bend. The dust concentration was varied in the range 100–450 g/m^3 and the mean air velocity in the tube prior to ignition in the range 15–25 m/s. The ignition point was also varied from immediately downstream of the dust feeder to a number of other locations along the tube. A number of pressure and flame detectors were located at various strategic points. In most of the experiments, the vent at the sharp bend reduced the maximum explosion pressures in the tube as compared with pressures generated with a smooth, closed bend. However, if the dust cloud was ignited near the dust feeding point, both the maximum pressure and the flame speed were higher with venting than without. This can be explained in terms of the higher flow velocity in the tube, due to the explosion, with a vent than without. Following ignition close to the dust feeder, the vent opened when the flame propagated only part of the distance to the vent. The result was a sudden increase of the flow rate of the unburned cloud ahead of the flame and a corresponding increase of the turbulence in this cloud. Consequently, when the flame reached these turbulent regions, the combustion rate increased markedly. Under such circumstances, the flow out of the vent can easily become choked and very high explosion pressures can result. The combustion rate also increases because the pressure of the unburned cloud ahead of the flame increases. Radandt's investigation produced much valuable empirical data, which, however, reemphasizes the need for a unified computer-based model that accounts for the coupling between gas dynamics and turbulent combustion in complex systems. Works aimed at developing such models are reviewed in Section 9.2.4.7 in Chapter 9.

Tamanini (1983) investigated the propagation of dust explosions in a large-scale gallery, illustrated in Figure 4.67. A central objective was to determine the minimum quantity of dust, spread as a layer on the gallery floor, per unit gallery length, that was able to propagate a dust explosion sweeping along the gallery. A second objective was to investigate

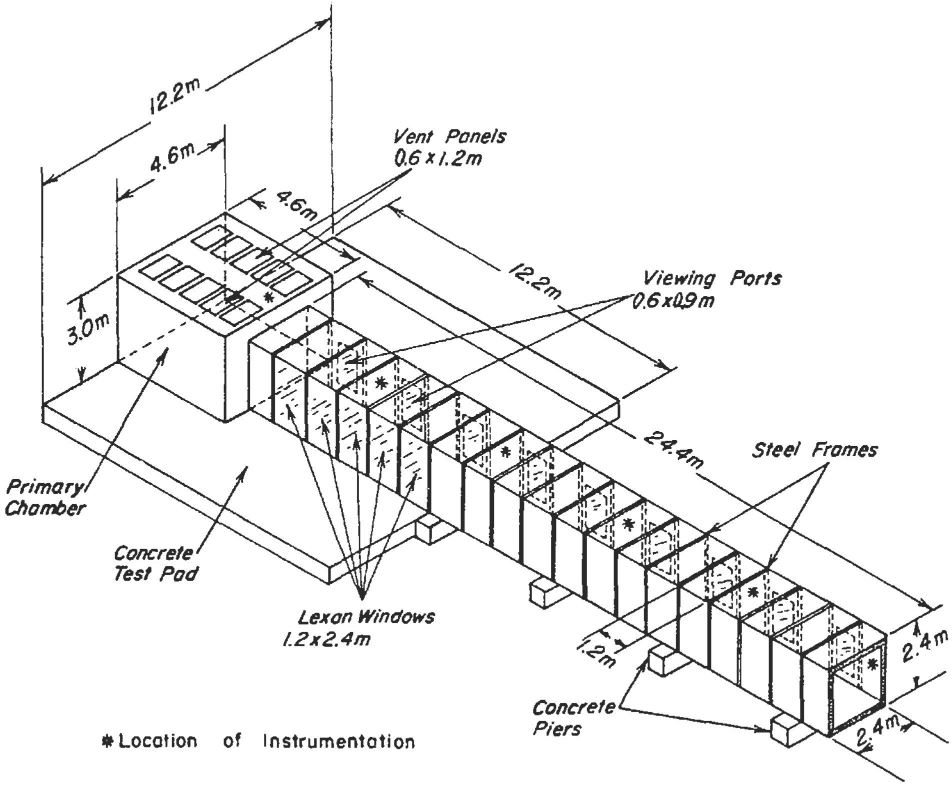


Figure 4.67 *Large-scale gallery used for investigating entrainment of dust layers and propagation of secondary explosions in a gallery due to a primary explosion in an adjacent chamber (From Tamanini, 1983).*

whether venting a primary explosion in a confined space could prevent the development of secondary explosions in adjacent areas by reducing the expansion velocities and hence the dust entrainment potential of the primary explosions in those areas. The experiments showed that a dust flame propagated down the gallery even if the mass of the dust layer, per unit length of gallery, was considerably smaller than that corresponding to the minimum explosible concentration if dispersed uniformly over the whole gallery cross section. This is because the dust was dispersed only in the lower part of the gallery volume and therefore gave real dust concentrations higher than the nominal values. In accordance with this, it was observed that the dust flame thickness was in fact considerably smaller than the height of the gallery. Such secondary dust flames were found to sweep along the gallery floor all the way to the exit, even if the dust layer on the floor was only 0.25 mm thick, representing a nominal dust concentration referred to the entire gallery volume, of only 77 g/m^3 of maize starch, that is, at the limit for upward laminar flame propagation.

Typical explosion pressures in the gallery were 0.2–0.4 bar(g) if the gallery was unvented and 0.07 bar(g) with vents close to the primary explosion chamber.

The fact that the dust entrained from the floor was distributed only in the lower part of the gallery may throw light on the results from Fischer's (1957) experiments, where stone dust barriers in the upper half of the gallery cross section under certain conditions proved entirely ineffective in damping the propagation of the coal dust explosion. Fischer suggested that the primary turbulent torus sweeping down the gallery entrained the coal dust in the lower part of the gallery cross section and the stone dust in the upper part, with little mixing of the two.

Experiments of the type conducted by Tamanini (1983) and also by the other workers who used a primary explosion to initiate dust entrainment and the main explosion depend very much on the nature of the primary explosion. Therefore, few generally valid quantitative conclusions can be drawn from such experiments until the various processes have been theoretically coupled.

Kauffman et al. (1984a) studied the propagation of dust explosions in a horizontal tube of length 36.6 m and internal diameter 0.30 m; that is, $L/D = 122$. A main objective of the experiment was similar to the one of Tamanini (1983), that is, to identify the minimum quantity of dust deposited as a layer on the internal tube wall that can propagate a dust explosion sweeping down the tube. The exhaust end of the tube terminated with a 90° bend of 2 m radius leading into a 2.5 m long tube with a number of vents in the wall but with the far downstream end closed. The ignition source, located at the far upstream end of the main tube, consisted of a 2.4 m long 50 mm diameter tube filled with stoichiometric hydrogen/oxygen. In the first 3.6 m of the main tube, a dust layer was placed in a V-channel running inside the tube parallel to the tube axis. This dust could be dispersed into a primary cloud by air blasts from a series of nozzles at the bottom of the V-channel. In the remaining 33 m of the main tube, the dust layer rested directly on the tube wall, either as strips of widths 12.5 mm or 90 mm along the tube bottom or as a thin layer around the whole tube wall. The explosions were initiated by first dispersing the dust in the V-channel, then igniting the hydrogen/oxygen mixture, which would in turn ignite the dispersed dust. The blast from this violent primary explosion would then sweep down the main tube and entrain and disperse the dust from the layer on the tube wall, as in the experiments of Greenwald and Wheeler (1925), Fischer (1957), Pineau (1987), Tamanini (1983), and in the other investigations discussed by Rae (1971).

Kauffman et al. found that, in general, for a given mass of dust layer per unit length of tube, a uniform layer around the entire tube wall produced the most violent explosions. The dusts tested included a maize starch, a mixed natural organic dust, a wheat grain dust, and an oil shale dust. Various ranges of particle sizes and moisture contents were investigated.

The strength of the primary explosion was varied by varying the initial pressure of the hydrogen/oxygen mixture and the initial quantity of dust dispersed from the V-channel. It was generally found that, for a given mass of dust per unit length of the main tube, the maximum pressure, temperature, and flame speed of the secondary explosion increased with the strength of the primary explosion. Figure 4.68 shows how the nominal minimum and maximum explosible concentrations (mass of dust layer/m^3 tube) varied with the strength of the primary explosion in terms of its maximum overpressure. Assuming a bulk density of the dust layer of 0.5 g/cm^3, a nominal concentration of 1000 g/m^3 corresponds to layer thicknesses of 0.15 mm if all the tube wall is covered and 1.6 mm and 11 mm for 90 mm and 12.5 mm layer widths, respectively.

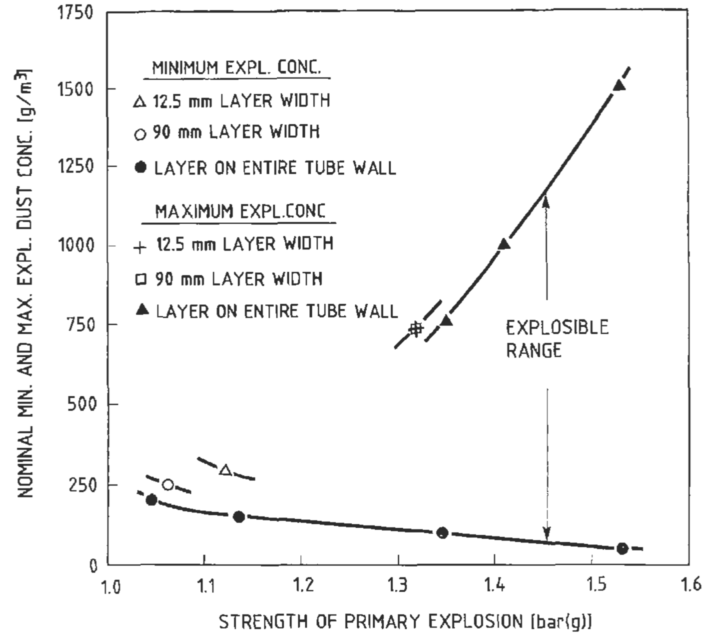


Figure 4.68 *Nominal minimum and maximum explosible concentrations for secondary explosions in a horizontal tube of length 36 m and diameter 0.30 m, as a function of the strength of the primary explosion, using mixed organic dust of <74 μm particle size and 12% moisture (From Kauffman et al., 1984).*

Figure 4.68 shows that the explosible concentration range expands at both ends as the strength of the primary explosion increases. There is a tendency of the range to shift toward higher nominal concentrations as the dust layer becomes concentrated in a narrow strip. The minimum explosible concentration of 50 g/m^3 at an explosion strength of 1.53 bar(g) is close to the value measured by Eckhoff and Fuhre (1975) for wheat grain dust of 12% moisture, in an entirely different large-scale apparatus.

In a subsequent study using the same 36 m tube facility as used by Kauffman et al. (1984a), Srinath et al. (1985) determined the maximum overpressure and maximum flame speed for a dried mixed natural organic dust and found 5.4 bar(g) and 607 m/s, respectively. A numerical code developed by Chi and Perlee (1974) for premixed gas explosions was used to solve the one-dimensional compressible flow equations for a flame propagating through a tube of the same dimension as used experimentally. The code did not, however, close the loop connecting flow, turbulence, and combustion rate, and an empirically based relationship between the turbulent burning velocity and flame propagation distance derived from the actual dust explosion experiments had to be employed. Under these circumstances, the code predicted a maximum explosion pressure of 5.89 bar(g) and a maximum flame speed of 607 m/s, in good agreement with experiments. However, as will be discussed in the next section, improved, more-comprehensive numerical code concepts for dust explosion simulation are being developed. Further works on propagation of dust explosions in long ducts and pipes are reviewed in Section 9.2.4.6 in Chapter 9.

4.4.8

THEORIES OF FLAME PROPAGATION IN TURBULENT DUST CLOUDS: COMPUTER MODELS

4.4.8.1

Background

The discussion of flame propagation mechanisms in the previous sections, in particular turbulent propagation where turbulence is generated in situ by flow produced by the explosion itself, has demonstrated the vast complexity of the turbulent flame propagation process. Simple experimental correlations are not sufficient for predicting explosion development in complex practical situations. A theory is needed that can unify all these experiments. In its comprehensive form, the theory should include the mechanisms of dust entrainment and dispersion (see Chapter 3) as an integrated element in the complex feedback interaction between the combustion of dust cloud, expansion of combustion products, gas flow ahead of the flame, turbulence in the gas flow ahead of flame, intensified entrainment and dispersion of the dust ahead of the flame—and back to intensified combustion. Increasing availability of computational power has facilitated considerable progress over the 1970s and 1980s. As reviewed in Section 9.4.2.7 in Chapter 9, comprehensive computer codes for predicting dust explosion propagation in complex industrial geometries are currently being developed. Encouraging progress has been made in the prediction of gas explosion propagation in congested geometries as, for example, in modules on offshore oil and gas production platforms or compact onshore refineries and petrochemical plants. The pioneering work by Hjertager (1982, 1984, 1986), which uses the two-equation k-ϵ model of turbulence by Jones and Launder (1972, 1973) and the combustion model of Magnussen and Hjertager (1976), should be mentioned specifically. More recently, Cant and Bray (1989) developed a theoretical model of turbulent combustion of premixed gases in closed bombs, which may also be a useful starting point for dust cloud explosion simulation.

However, in the case of dust clouds, the two-phase nature of the problem adds considerably to the complexity. The previous sections of this chapter give some elements of the present experimental and theoretical knowledge of the complex physics and chemistry involved and that must be accounted for in a comprehensive dust explosion model.

In his model of gas explosions, Hjertager (1982, 1984, 1986) used the induction time for ignition, as determined in shock tube ignition experiments, as a global measure of the chemical kinetics for the combustion reaction. As reviewed by Eckhoff (1987), similar experiments have been conducted with dust clouds and induction times for various types of dust are available. A more recent example is the induction time determination for aluminum and magnesium dust clouds in oxygen of 0.1 to 1.0 bar(abs) initial pressure by Boiko, Lotov, and Papyrin (1989).

4.4.8.2
Simplified Model by Ogle, Beddow, and Chen for Aluminum Dust/Air

Ogle, Beddow, and Chen (1988) developed their model for numerical simulation of turbulent spherical aluminum/air explosions in a closed bomb, assuming spatially uniform pressure at any instant. Due to lack of computational power, Ogle et al. were unable to use the k-ϵ model or an equivalent model for describing the turbulence. Instead, they adopted the empirical Abdel-Gayed eddy diffusivity correlation for confined turbulent combustion of premixed gases to obtain first-order approximate values of the turbulent diffusivities of heat and mass:

$$e/\upsilon = 11\, Re_{\lambda}^{0.56} \tag{4.87}$$

Here, e is the eddy diffusivity and v is the kinematic viscosity of the gas; Re_{λ} is the turbulent Reynolds number, defined as $Re_{\lambda} = v'\lambda/\upsilon$, where v' is the turbulence intensity, or characteristic fluctuating velocity component, and λ is the characteristic microscale of the turbulence. When comparing theoretical predictions with dust explosion experiments in a spherical bomb of diameter 0.34 m, Ogle et al. fixed the turbulence intensity at 0.1 m/s and the large-scale eddy size at 0.1 m in all the computations.

The model was formulated for aluminum dust/air explosions, and corresponding experiments were conducted in the 0.34 m diameter spherical bomb with a range of aluminum powders of different particle sizes and shapes. In the model, the influence of particle size and dust concentration was accounted for by assuming that the rate of oxidation of the aluminum particles in the cloud was proportional to the surface area of the particles per unit volume of dust cloud. On the assumption that $Al(liquid) + AlO \rightarrow Al_2O$ is the rate-controlling reaction in the combustion of aluminum, Ogle et al. reformulated the expression for the combustion rate in terms of consumption of molecular species, adopting the standard Arrhenius form of the reaction rate coefficient.

4.4.8.3
Model by Kjäldman for Peat/Air

Kjäldman (1987) used the k-ϵ turbulence model for homogeneous gas flow in his finite volume simulation of dust explosions in closed and vented vessels. Referring to explosion experiments in the 20 liter Siwek-sphere (Siwek, 1977) and the turbulence measurements of Kauffman et al. (1984a) in a 0.95 m^3 spherical vessel, the values of k and ϵ at the moment of ignition in the 20 liter sphere were taken as $k = 10^{-2}$ $(m/s)^2$ and $\epsilon =$

$2(m/s)^2/s$, respectively, corresponding to a turbulent time scale $k/\epsilon = 5$ ms. The particles were treated as a second hypothetical continuous phase interacting with the gas phase and having the microscopic properties of monosized peat particles of diameter d. Comparatively simple submodels of particle drying, pyrolysis or devolatilization, gas combustion, and char combustion were incorporated. The two continuous phases were assumed to interact by transport of material from the particle phase to the gas phase and transport of heat in both directions, depending on whether the gas or the char was burning. The rate of the chemical gas phase reaction was assumed to be controlled by turbulent diffusion, that is, by ϵ/k. The fuel consumption under these circumstances was calculated using the expression proposed by Magnussen and Hjertager (1976). Kjäldman estimated the role of thermal radiation to be small for the actual type of particles and used a simplified treatment to account for this effect.

Table 4.15 shows a set of corresponding experimental and computed data for peat dust explosions in a 20 liter explosion vessel extracted from Kjäldman's report. The experiments were conducted separately by Weckman (1986).

Table 4.15 Comparison of experimental and computed pressure development during peat dust/air explosions in a closed 20 liter spherical vessel

Particle diameter (μm)	Dust concentration (g/m^3)	Moisture content (weight%)	Time from ignition to pressure peak (ms)		P_{max} (bar(g))		$(dP/dt)_{max}$ (bar/s)	
			Exp.	Comp.	Exp.	Comp.	Exp.	Comp.
38	500	14	46	21	8.4	8.1	513	670
54	500	0	35	18	8.4	8.1	610	700
72	500	34	60	35	7.2	9.0	248	370
96	500	0	47	22	7.8	8.6	413	570
100	1000	13	59	34	7.8	7.2	350	280
165	500	0	45	29	7.7	9.1	395	390

Source: Kjäldman, 1987.

The data in Table 4.15 show good correlation between experimental and computed $(dP/dt)_{max}$ values for four or five of the six powders. An exception is the 100 μm powder, for which the computed value is comparatively low. This may in part be due to problems with dispersing all the dust in this experiment (20 liter Siwek sphere), which means that the real dust concentration was probably lower than the nominal one of 1000 g/m^3. The maximum pressures, both experimental and computed, are all within 7–9 bar(g), but the correlation between experiments and computations within this narrow pressure range is rather poor. On the other hand, the correlation between experimental and computed times from ignition to pressure peak is good, although there is a systematic deviation by a factor of about 2. It should be emphasized that the experiments were conducted with peat dusts of comparatively wide particle size distributions, whereas the computations were for monosized dusts of particle diameter equal to the mass average particle diameter of the real dust.

Kjäldman's contribution constitutes a further valuable step toward development of comprehensive computer models for simulation of dust explosions. The employment of the k-ϵ model of turbulence represents a significant step forward, but in the future it may be necessary to replace even the k-ϵ model with better approximations in the range of low Reynolds numbers, where it is known that k-ϵ model may fall short in reproducing reality. Furthermore, the assumption of isotropic turbulence, which is inherent in the k-ϵ model, may not be acceptable for real dust clouds. Dust explosions in industry are often comparatively slow, particularly in the initial stages, and the turbulence levels correspondingly low.

It should be mentioned that Kjäldman also used his model for some introductory computations of the pressure development in vented explosions, but experimental data were not available for comparison. Kjäldman (1989) also extended the application of his numerical model, in a slightly modified form, to simulating pulverized peat dust combustion in a 5 MW furnace for heat production. Good agreement between the experimental and the computed furnace temperature distributions was obtained.

4.4.8.4

The Clark-Smoot Model for Accelerating Coal Dust Flames

Explosions in one-end-open ducts with ignition at the closed end, as illustrated in Figure 4.63, constitutes a case where the positive feedback from combustion via expansion, flow, and turbulence and back to combustion is particularly strong. At the same time, this case is of primary practical significance in mine gallery explosions. This was the motivation for the development of a numerical model of accelerating coal dust flames in long ducts undertaken by Clark and Smoot (1985).

Like Ogle et al. (1988), Clark and Smoot adopted a comparatively simple submodel for the coupling between flow, turbulence, and combustion rate. They used an empirical correlation of the ratio between turbulent and laminar burning velocity and the turbulent Reynolds number based on the gas explosion data of Andrews et al. (1975) and data from Richmond and Liebman's (1975) and Richmond et al.'s (1978) large-scale gallery coal dust explosion experiments. The correlation was

$$S_t / S_l = C\,Re_\lambda \tag{4.88}$$

where S_t and S_l are the turbulent and laminar burning velocities, C is an empirical constant, and Re_λ is the turbulent Reynolds number defined as for equation (4.87). With the eddy viscosity μ_e equal to $v'l$, where v' is the turbulence intensity and l the macroscale of the turbulence, and introducing further correlations and assumptions, Clark and Smoot expressed Re_λ as

$$Re_\lambda = 7(\mu_e / \upsilon)^{1/2} \tag{4.89}$$

and

$$Re_\lambda^2 = 24.3[(1 + 0.096 f(Re)^2) - 1] \Bigg/ \left[1 + \frac{\rho_d}{\rho_g}\right]^{1/2} \tag{4.90}$$

Here υ is the kinematic viscosity, f is the Fanning friction factor of the gallery wall, Re the Reynolds number for the overall flow in the gallery, and ρ_d and ρ_g are the dust cloud density and gas phase density, respectively.

Clark and Smoot's work confirmed that the increasing level of turbulence in the accelerating fluid is a major driving force behind the flame acceleration in coal dust flames in coal mine galleries. Further works on modeling of turbulent dust flames are reviewed in Section 9.2.4.7 in Chapter 9.

4.5
DETONATIONS IN DUST CLOUDS IN AIR

4.5.1
QUALITATIVE DESCRIPTION OF DETONATION

Detonation is a singular, extreme mode of propagation of a flame through a premixed gas or dust cloud. The transfer of heat from the burning to the unburned cloud by molecular or turbulent diffusion, which is characteristic of the deflagration mode of explosion propagation discussed so far, is replaced by direct ignition by extreme compression of unburned cloud in a shock wave driven through the cloud at supersonic speed by the explosion itself. As will be mentioned in Section 4.5.3.2, the detailed mechanism of ignition and combustion inside the shocked detonation front is still a subject of research.

The necessary condition for self-sustained detonation propagation is that the shock wave is sufficiently strong for the volume inside it to ignite and react chemically before the shock wave has traveled a significant distance away. In this way, the shock wave and the chemical reaction zone remain closely coupled, and the shock wave speed and strength is maintained. Typical maximum detonation velocities in premixed hydrocarbon gas/air and dust/air mixtures at normal pressure and temperature and optimum fuel concentrations are in the range 1500–2000 m/s. This is on the order of 5 times the velocity of sound in the unburned and uncompressed premixed gas/air or dust cloud in air; hence, the unburned mixture obtains no gas dynamic signal from the approaching detonation front until being caught by the front itself. Therefore, reducing the maximum explosion pressure of a detonation by venting is impossible.

It follows from what has been said that a detonation in a premixed gas or a dust cloud can be initiated only by a sufficiently strong shock wave. This can be supplied by either an explosive charge or similar external means of generating the initial shock or by gradual buildup of a strong shock by turbulent acceleration of the explosion itself, as illustrated in Figure 4.63.

Wolanski (1987) gave a comprehensive review of experimental evidence and theory of dust cloud detonations up to that time.

4.5.2
EXPERIMENTAL EVIDENCE OF DETONATIONS IN DUST CLOUDS IN AIR

4.5.2.1
Experiments in Ducts and Large-Scale Galleries

Figure 4.63 illustrates how detonation may develop in ducts of large *L/D* via enhanced combustion due to flow-generated turbulence. As already mentioned in Section 4.4.7, Greenwald and Wheeler (1925) and Fischer (1957) reported that coal dust flames in one-end-open large-scale galleries, with ignition near the closed end, accelerated up to a point after which a high, constant flame speed was maintained during the remaining length of the gallery. In the case of Greenwald and Wheeler, this steady flame speed was about 800 m/s, whereas Fischer reported 1040 m/s as a maximum value in his experiments. These velocities are lower than the Chapman-Jouguet detonation velocities (see Section 4.5.3) that would be expected for coal dust in air. Therefore, Greenwald and Wheeler and Fischer may have observed the kind of constant high-velocity turbulent deflagrations described by Lindstedt and Michels (1989). However, such high-turbulence deflagrations can be nearly as violent as proper detonations. One indication of this is that, in Fischer's experiments, the pressure measurement stations in the region of the gallery of the constant, high flame speeds were destroyed by the explosion. Similar evidence of steady high-speed turbulent deflagrations of dust clouds in large-scale galleries was found by Cybulski (1952), Bartknecht (1971), and Rae (1971).

However, both Pineau and Ronchail (1982) and Bartknecht (1971) found clear evidence of proper dust detonations in ducts of smaller diameters. In these cases, steady flame speeds on the order of 2000 m/s and high peak pressures on the order of 20 bar(g) were measured, as mentioned in Section 4.4.7 and illustrated in Figure 4.64.

On this background, the contribution by Kauffman et al. (1982, 1984b) is important. They demonstrated that a steady detonation wave could propagate in clouds of oats and wheat grain dust in air, in a vertical laboratory-scale duct of square cross section 6.35 cm × 6.35 cm and length 6 m. The dust was charged into the tube at the top at a mass rate, giving the desired dust concentration during gravity settling down the tube. The main dust explosion was initiated by a local hydrogen/oxygen explosion at the bottom tube end.

Using a laser Schlieren technique, it was observed that the shock front was followed closely by an induction zone, which was in turn followed by a reaction zone, as would be expected in a proper detonation wave. The leading shock caused intense dispersion of the particle agglomerates into an optically dense cloud of primary particles within a few mm behind the shock front, where the particles ignited and burned. After combustion, the mixture was again optically transparent. The combustion process was nearly completed 0.5 m behind the shock front, corresponding to a time interval of about 0.3 ms. At an oats dust concentration of 250–270 g/m^3, slightly lower than the stoichiometric one of 300 g/m^3, the measured detonation wave velocity was 1540 m/s, which is somewhat lower than the theoretical Chapman-Jouguet (C-J) velocity at stoichiometric concentration of 1800 m/s. It would be expected, however, that the inevitable energy losses in a dust detonation would cause the real detonation velocity to be lower than the ideal C-J velocity. The highest measured peak pressure was about 24 bar, quite close to the theoretical C-J pressure at stoichiometric concentration, 22.4 bar.

Kauffman et al. (1984b) also investigated the upper and lower dust concentration limits for detonation of oats dust in air in their laboratory-scale vertical tube. They found that, even with very vigorous ignition sources, detonations could be initiated only within the narrow concentration range of approximately 200–450 g/m^3.

Further important evidence demonstrating detonations in dust clouds in air has been provided by Gardner, Winter, and Moore (1986). The dusts used were coals and included a fine British coal fraction of 87% by mass <71 μm particle size, containing 33.5% volatiles and 3.5% moisture, and an equally fine U.S. subbituminous coal fraction of 41.3% volatiles and 17.3% moisture. Coarser particle size fractions of the two coals were also tested.

The experimental arrangement consisted of a 20 m^3 ignition chamber connected to a 42 m long straight test duct of diameter 0.6 m, which was essentially open at the downstream end. Air was blown through the system at a rate giving 20–30 m/s in the duct, and dust was fed into the air stream just upstream of the 20 m^3 chamber to give the desired dust concentration, ranging from 30 g/m^3 to 850 g/m^3, in the explosion chamber and the 42 m long duct. The dust cloud was ignited in the 20 m^3 chamber by a flame jet or a chemical ignitor. The main results are summarized in Figure 4.69.

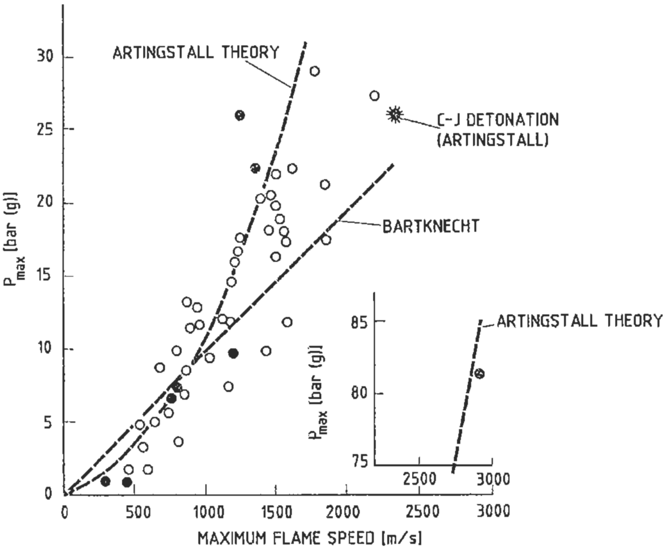


Figure 4.69 *Maximum explosion pressure versus maximum flame speed during coal dust/air explosions in a 42 m long duct of 0.6 m diameter. Particle size is 87% (mass) <71 μm: ● U.S. subbituminous coal; ○ U.K. coal (From Gardner et al., 1986).*

Figure 4.69 also gives the theoretical relationship obtained by Artingstall (1961) in solving the conservation equations for a steady-state coal dust/air deflagration. The experimental relationship found by Bartknecht (1971, 1978) is also included. Gardner et al.'s results are in good agreement with Artingstall's deflagration theory, whereas, on average, the Chapman-Jouguet detonation pressure calculated by Artingstall is significantly lower than Gardner et al.'s experimental pressures at the calculated C-J velocity of about 2350 m/s (see Section 4.5.3). The extreme experimental peak pressure value of 81 bar(g) is remarkable. However, Gardner et al. refer to Bull's argument that, at the onset of detonation, there is always a regime in which the combustion wave is overdriven before settling down to the C-J conditions. During this transient period, the detonation pressure can exceed the C-J value considerably.

Gardner et al.'s contribution supports the view that proper detonations can also occur in dust clouds and such detonations can be brought about by in situ transition of fast deflagrations to detonations via turbulent flame acceleration (DDT, deflagration-to-detonation transition), as in premixed gases.

4.5.2.2
Unconfined Dust Cloud Detonations

As discussed by Lee (1987), Borisov et al. (1984) came to the conclusion that unconfined dust clouds may be considered as practically impossible to detonate. This was because the ignition delay times of clouds in air of wheat flour and similar materials are at least one order of magnitude greater than for methane/air, which requires at least 22 kg of high explosives to detonate in the unconfined state. By assuming that the minimum detonation charge for dust clouds is proportional to the cube of the induction time, as for premixed gases, one finds that a minimum of 20 tons of high explosive would be required for direct initiation of detonation in an unconfined cloud of wheat flour in air. However, the induction time for dust clouds decreases with decreasing particle size or increasing specific surface area, and therefore unconfined detonations in clouds of very fine dusts become less unlikely than in wheat flour/air.

The only direct experimental observation of a self-sustained detonation wave in an unconfined dust cloud in air that has been traced was made by Tulis and Selman (1984) and Tulis (1984). They used aluminum dusts of various fineness and found that detonation could be initiated only with a very fine aluminum flake powder of specific surface area 3–4 m^2/g, corresponding to spherical particles of diameter smaller than 1 μm. In the first phase of this work, Tulis and Selman (1984) worked with an unconfined dust cloud of approximately cylindrical shape, 6 m in diameter and 1 m in height, containing 4.5 kg of the fine aluminum powder, corresponding to an average nominal dust concentration of 160 g/m^3. The centrally located initiator charge was 2.3 kg of high explosive. Although indications of self-sustained detonations were demonstrated in these experiments, the size of the dust cloud was too small to eliminate the influence of the initiation charge on the detonation wave propagation. Therefore, as reported by Tulis (1984), a further experiment was conducted, using three simultaneously generated aluminum flake clouds of the same size and concentration as just described, forming one large elongated flat unconfined cloud of length 10 m.

When this cloud was initiated at one end with a 2.3 kg high explosive charge, stable, self-sustained detonation was achieved. The average velocity of the detonation wave was 1750 m/s, and the peak pressures in excess of 28 bar. The corresponding calculated C-J values were 1850 m/s and 26 bar. This close agreement between experiment and theory seems to confirm that the phenomenon observed was in fact a proper, unconfined dust cloud detonation.

4.5.3
THEORIES OF DETONATION

4.5.3.1
The Chapman-Jouguet Theory

As pointed out by Lee (1987), there is no a priori reason for assuming that the classical Chapman-Jouguet theory for detonation, which has been successfully applied to premixed gases and solid and liquid explosives, does not apply even to explosible dust clouds. This theory, developed independently by Chapman (1899) and Jouguet (1905, 1906), predicts detonation front velocities, temperatures, pressures, and concentrations of reaction products. Davis (1987) discussed the slightly different approaches taken by Chapman and Jouguet. Chapman simply postulated that a detonation front is a shock wave precipitating in its wake chemical reactions that supply the energy required for maintenance of the steady propagation of the shock wave through the explosible gas. In that case, the theory of shock wave propagation through a gas could be used to describe detonation by replacing the unreacted gas behind the shock by the products of the combustion reaction and adding the heat of reaction. The resulting theory predicted a specific minimum velocity for self-sustained detonation for any given explosible mixture, which Chapman found to be in excellent agreement with the velocities measured in the gas explosion experiments conducted by Dixon (1893). Chapman therefore simply postulated that the minimum velocity predicted by his theory was the detonation velocity of the system considered.

Jouguet (1905, 1906) had been working along similar lines, but his slightly different approach revealed the important additional conclusion that the detonation wave velocity equals the velocity of sound in the hot, compressed reaction products immediately behind the shock front. The C-J theory is concerned with only the simple system, consisting of a homogeneous unreacted gas at a set of initial conditions, and the corresponding shocked reaction products, separated by an infinitely thin, plane of discontinuity. The theory results from the three equations for conservation of mass, momentum, and energy across the discontinuity, and the equation of state, as shown by, for example, Jost and Wagner (in Freytag, 1965), Glassman (1977), and Nettleton (1987). Nettleton refers to computer codes that can be used for calculating C-J parameters for various explosible gas mixtures.

As pointed out by Kuchta (1985) the detonation peak pressure for gaseous mixtures is approximately twice the maximum pressure for adiabatic constant-volume combustion of the same mixture (absolute pressures). Kuchta also gave the following equation, which relates the C-J detonation front pressure ratio to the detonation front velocity V_D:

$$\frac{P_2}{P_1} = \frac{1+\gamma_1(V_D / C_1)^2}{1+\gamma_2} \tag{4.91}$$

Here, P_2 is the detonation front pressure, P_1 is the pressure in the unreacted gas ahead of the detonation front, γ_1 and γ_2 are the specific heat ratios of the unreacted gas mixture and the reaction products, and C_1 is the sound velocity in the unreacted gas mixture.

As long as the reaction zone is very thin, as it is for many explosible gas/air mixtures if the composition does not deviate too much from the stoichiometric one, the predicted C-J parameters agree with experiments within a few percent. However, when the composition approaches the limits of detonation, where the thickness of the reaction zone becomes significant, this is no longer the case. The C-J theory is concerned with only the initial and final states of the gas and not with the route from the one state to the other. Nettleton (1987) pointed out that, close to the limits of ability to detonate, the predicted C-J detonation velocities are significantly higher, by 20% or more, than those actually measured. The discrepancies between predicted and measured pressures and densities of the flow just behind the shock front are also correspondingly large in such mixtures. Therefore, more-refined theories were required.

4.5.3.2
The ZND-Theory

The first significant steps toward explaining the details of how chemical reactions are initiated by shock compression and how the resulting energy is transferred to the flow of reaction products were taken independently by Zeldovich (1940), Neumann (1942), and Döring (1943). As pointed out by Nettleton (1987), the resulting original ZND model of gaseous detonations assumed that the leading shock wave generated a flow of the density and temperature required to initiate exothermic chemical reactions not far behind the shock (1–10 mm).

However, Lee (1987) pointed out that the one-dimensional ZND structure of the detonation front in homogeneous gaseous or liquid explosives has been found to be unstable theoretically and the ZND structure has in fact never been observed experimentally in self-sustained gaseous detonations, which rather have a cellular structure. Lee proposed that the intense turbulence generated in the shear layers at the cell boundaries causes rapid mixing of unburned mixture and combustion products and therefore plays a main role in causing ignition just behind the leading shock.

The need to account for the role of turbulence in detonation wave propagation was also emphasized by Davis (1987). By doing this, it may also be possible to describe DDT within a unified theory for turbulent flame propagation.

4.5.3.3
Dust Clouds

Wolanski et al. (1984) were concerned with the detailed structure of dust cloud detonation waves and developed a first-order model for the reaction zone, accounting for both two-phase flow effects and wall losses. The flow in the reaction zone was assumed to be one-dimensional and steady, the dust particles were assumed to be spherical and of the same temperature as the surrounding gas. A simplified dust combustion rate model was adopted, assuming a heterogeneous reaction. After tuning the constants of the model against experimental pressure profile data from the detonation of wheat dust/air, the reaction zone profiles of particle and gas velocities, temperature, and density could be computed. The calculated detonation velocities were in good agreement with experimental values.

Kulikovskii (1987) discussed the existence of convergent cylindrical and spherical C-J waves in dust clouds. The theoretical analysis revealed that the ratio between two dimensionless parameters determines the influence of the particles on the detonation wave structure. The first parameter is the ratio of solid particle volume to total dust cloud volume; the second is the product of the mean curvature of the cylindrical or spherical wave and the characteristic particle dimension. If the first parameter is much smaller than the second, the particles have negligible influence. If, however, the first parameter is on the same order or greater than the second, the particles begin to play an important role by significantly altering the flow behind the C-J wave, and the range of its existence.

In another theoretical investigation, Ishii (1983) analyzed the influence of the size distribution of the dust particle on the flow structure behind a shock front passing through a dust cloud. Main conclusions were that the particle size distribution is important and that the assumption of monosized particles, which is often adopted in theoretical work, can lead to poor predictions if the size distribution is in reality comparatively wide.

Lee (1987) anticipated some operational problems in applying the C-J theory to dust clouds because of difficulties in defining the relevant final states after compression and chemical reaction. The assumption of complete chemical equilibrium may differ significantly from actual detonation wave characteristics.

Wolanski (1988) also emphasized the complexity of the dust detonation wave, using coal dust as an example. The measured ignition delays are on the order of 10 times those of premixed hydrocarbons. This indicates that release of volatiles from the particles is the rate-controlling factor. Volatiles mix with the oxidizer gas and ignite as soon as they have been released. One cannot consider the induction period as consisting of two distinctly separable, consecutive steps, devolatilization and subsequent combustion of volatiles. It would be expected that a similar argument applies to dusts of natural and synthetic organic materials (see also Wolanski, 1987).

Fan Bao-Chun and Sichel (1988) developed a comprehensive model of the structure of dust cloud detonations, comprising both the induction and the reaction zone, without separating the two. The oxidation of the particles was treated as a heterogeneous surface reaction. Conductive heat transfer within the particles, convective heat transfer between the particles, and the gas and reaction heat release within the particles were included in the model. However, because of lack of kinetic data, some constants in the model had to be estimated by fitting theoretical predictions to experimental data. Transverse cellular structure was not accounted for by the model. According to Fan Bao-Chun and Sichel, the existence of such structure in dust cloud detonations remains to be demonstrated.

Fan Zhang (1989) investigated detonation propagation in maize starch/oxygen clouds in a horizontal tube of 140 mm internal diameter and 17.4 m length. The stoichiometric concentration of maize starch in oxygen at 1 bar(abs) is 1110 g/m^3. For an initial pressure of 1 bar(abs), stable detonation was observed over the dust concentration range from 300 to 9000 g/m^3. The highest stable detonation velocity of 1988 m/s occurred at 2000 g/m^3, and the highest detonation peak pressure of 66.9 bar(abs) at 3000 g/m^3. The corresponding values at 300 g/m^3 were 1766 m/s and 35.8 bar(abs), and at 9000 g/m^3, 1795 m/s and 43.4 bar(abs). Fan Zhang concluded, however, that the observed stable detonations could not generally be regarded as classical C-J detonations. This is because of the comparatively long total reaction time, which makes the detonation propagation dependent on the apparatus. Further works on detonations in dust clouds are reviewed in Section 9.2.4.9 in Chapter 9.

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Plate 5 *High-turbulence maize starch explosion in 500 m^3 bolted steel plate silo at Vaksdal, Norway, in April 1982 (Photographer: A. M. Fosse, Vaksdal).*

Plate 6 *Experimental site outside Bergen, Norway, with 236 m^3 steel silo, dust injection system, and instrumentation cabins. Enclosed winding staircase is along the silo wall to the left.*

Plate 7 *Vented maize starch explosion in 236 m^3 steel silo in Norway.*

Plate 8 *Maize starch explosion in 5.8 m^3 experimental bag filter unit in Norway. Vent area is 0.16 m^2. Static opening pressure of vent cover is 0.10 bar(g). Maximum explosion pressure is 0.15 bar(g).*

Plate 9 *Silicon dust explosion in the welding torch ignition test apparatus used in Norway.*

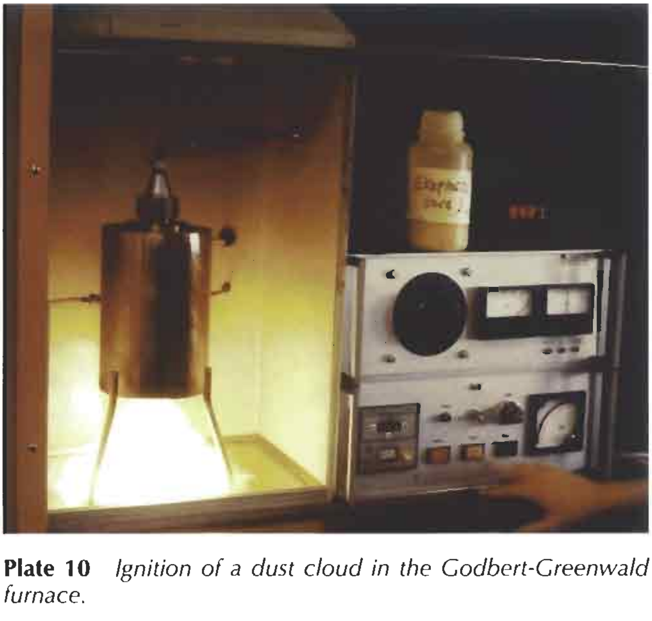

Plate 10 *Ignition of a dust cloud in the Godbert-Greenwald furnace.*

Chapter 5

Ignition of Dust Clouds and Dust Deposits: Further Consideration of Some Selected Aspects

5.1
WHAT IS IGNITION?

The word *ignition* is meaningful only when applied to substances able to propagate a self-sustained combustion or exothermal decomposition wave. *Ignition* may then be defined as the process by which such propagation is initiated.

Ignition occurs when the heat generation rate in some volume of the substance exceeds the rate of heat dissipation from the volume and continues to do so as the temperature rises further. Eventually a temperature is reached at which diffusion of reactants controls the rate of heat generation, and a characteristic stable state of combustion or decomposition is established.

The characteristic dimension of the volume within which ignition/no ignition is decided is on the order of the thickness of the front of a self-sustained flame through the mixture. This is because self-sustained flame propagation can be regarded as a continuing ignition wave exposing progressively new parts of the cloud to conditions where the heat generation rate exceeds the rate of heat dissipation. A similar line of thought applies to propagation of smoldering fires in powder deposits and layers, as discussed in Section 5.2.2.4.

In the ignition process, the concepts of stability and instability play key roles. Thorne (1985) has an instructive, simplified outline of some basic features of the instability theory of ignition, which is rendered in the following section. In most situations, diffusion, molecular as well as convective, plays a decisive role in the ignition process. Systems that can ignite may be characterized by a dimensionless number D_a, the Damköhler number, which is the ratio of the rate of heat production within the system due to exothermic chemical reactions to the rate of heat loss from the system by conduction, convection, and radiation. Often D_a is expressed as the ratio of two characteristic time constants, one for the heat loss and one for the heat generation:

$$D_a = \tau_L / \tau_G \qquad (5.1)$$

The influence of temperature on the rate of chemical reactions is normally described by the exponential Arrhenius law:

$$k = f \exp(-E/RT) \qquad (5.2)$$

where k is the rate constant, f is the preexponential or frequency factor, E is the activation energy, R is the gas constant, and T is the absolute temperature.

In general, the chemical rate of a combustion reaction may be written

$$R_C = kC_f^p C_{OR}^q \tag{5.3}$$

where $p + q = m$ is the order of the reaction, and C_f and C_{OR} are the concentration of fuel and oxygen in the reaction zone. Where the fuel is nondepleting and $q = 1$, one gets

$$R_C = kC_{OR} \tag{5.4}$$

The rate of diffusion of oxygen from the surroundings into the reaction zone is

$$R_D = D(C_{OS} - C_{OR}) \tag{5.5}$$

where D is the thermal diffusion rate constant and C_{OS} is the oxygen concentration in the surroundings.

As the temperature in the reaction zone increases, the thermal reaction rate increases according to equations (5.2) and (5.4), and a point is reached where the rate is controlled by the diffusional supply of oxygen to the reaction zone. Then, $R_C = R_D$ and the right-hand sides of equations (5.4) and (5.5) are equal. Here,

$$kC_{OR} = D(C_{OS} - C_{OR}) = C_{OS}\,\beta \tag{5.6}$$

where

$$\beta = kD/(k + D)$$

is called the Frank-Kamenetskii's overall rate constant, and k is as defined in equation (5.2). By introducing the heat of reaction Q, the rate of heat generation can, according to equation (5.6), be expressed as

$$R_G = QC_{OS}\,\beta \tag{5.8}$$

By inserting equation (5.2) into (5.7) and substituting for β in (5.8), one gets

$$R_G = \frac{QC_{OS}Df\exp(-E/RT)}{D + f\exp(-E/RT)} \tag{5.9}$$

The general expression for the heat loss from the system considered is

$$R_L = U(T - T_0)^n, \quad n \geq 1 \tag{5.10}$$

where U and n are characteristic constants for the system, T is the temperature in the reaction zone, and T_0 the ambient temperature.

Figure 5.1 illustrates the stability and instability conditions in a system that behaves according to equations (5.9) and (5.10). Figure 5.1 reveals three intersections between the S-shaped R_G curve and the heat loss curve R_L. In the figure, R_L is a straight line, corresponding to $n = 1$, which applies to heat loss by conduction only. For convection, n is 5/4 and for radiation 4. The upper (3) and lower (1) intersections are stable, whereas the intermediate one (2) is unstable. A perturbation in T at this point leads to either cooling to the lower intersection (1) or a temperature rise to the upper intersection (3). If the heat loss decreases due to changes of the constants in equation (5.10), the heat loss curve R_L

shifts to the right and the intersection points (1) and (2) approach each other and finally merge at the critical point of tangency (4). At the same time, intersection point (3), which determines the stable state of combustion, moves to higher temperatures.

If U in equation (5.10) increases, another critical point of tangency (5) is reached. If U increases further, ignition becomes impossible.

If the temperature rise ΔT of the system described by Figure 5.1 is plotted as a function of the Damköhler number, as defined in equation (5.1), a stability/instability diagram as illustrated in Figure 5.2 is obtained. The intersection and tangency points (1) to (5) in Figure 5.1 are indicated.

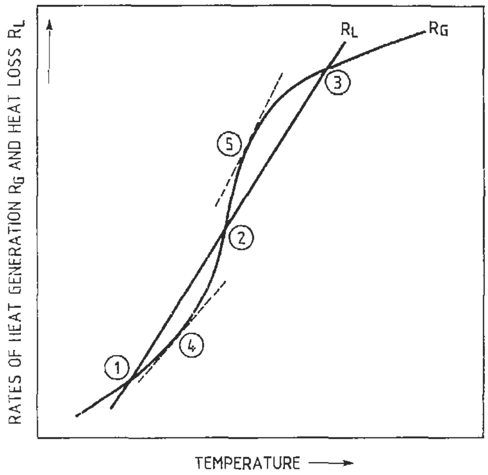

Figure 5.1 *Heat generated and heat loss as functions of temperature in the reaction zone. Explanations of features (1)–(5) are given in the text (From Thorne, 1985).*

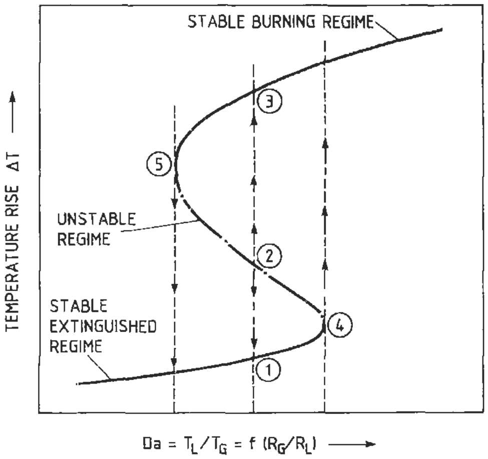

Figure 5.2 *Stability/instability diagram for a combustible system. The features of points (1)–(5) are explained in the text (From Thorne, 1985).*

The lower branch in Figure 5.2 is stable and corresponds to a slow, nonflaming reaction. The upper branch is also stable and corresponds to steady propagation of the combustion or decomposition wave. The intermediate branch is unstable. The system temperature can be raised from the ambient temperature without significant increase in the reaction rate until the ignition point (2) has been passed. Then, the system jumps to the upper stable flame propagation branch. On cooling, that is, increasing U, n, or both in equation (5.10), the rate of reaction is reduced. However, the reaction continues right down to (5) in Figure 5.2, from which the system temperature drops to a stable condition in the extinguished regime.

The scheme illustrated in Figures 5.1 and 5.2 is quite general and applicable to different types of systems. More extensive treatments of the general ignition/combustion-stability theory were given, for example, by Gray and Lee (1967), Gray and Sherrington (1977), and Bowes (1981). The classical basis for this type of analysis was established by Semenov (1959) and Frank-Kamenetzkii (1969). The book by Bowes (1984) provides a unique, comprehensive overview of the field of self-heating and ignition, not the least in solid materials, including dust layers and heaps.

Although the basic considerations implied in Figures 5.1 and 5.2 to some extent provide a satisfactory general definition of *ignition*, the precise theoretical definition has remained a topic of scientific discussion. One example is the dialogue between Lermant and Yip (1984, 1986) and Essenhigh (1986).

5.2
SELF-HEATING AND SELF-IGNITION IN POWDER DEPOSITS

5.2.1
OVERVIEWS

Bowes (1984) reported the state of the art of experimental evidence and theory up to the beginning of the 1980s. Considerable information was available, and theory for predicting self-heating properties of powders and dusts under various conditions of storage had been developed.

There were nevertheless some gaps in the quantitative knowledge, one of which is biological heating. In vegetable and animal materials such as feedstuffs and natural fibers, self-heating may be initiated by biological activity, in particular if the volume of material is large, its moisture content high, and the period of storage long. However, because the microorganisms responsible for the biological activity cannot survive at temperatures above about 75°C, biological heating terminates at this temperature level. Further heating to ignition, therefore, must be due to nonbiological exothermic oxidation, for which theory exists. It is possible, however, that the long-term biological activity in a real industrial situation may generate chemically different starting conditions for further self-heating than the conditions established in laboratory test samples heated artificially to 75°C by heat from the outside. Further research seems required in this area.

Starting with the extensive account by Bowes (1984), Beever (1988) highlighted the theoretical developments that she considered most useful for assessing the self-heating and ignition hazards in industrial situations. In spite of many simplifying assumptions, the models available appeared to agree well with experimental evidence. However, extrapolating over orders of magnitude, from laboratory scale data to industrial scale, was not recommended. Biological activity was not involved in the self-heating processes considered. See also Sections 9.2.3.3 and 9.3.5.2 in Chapter 9 for further references.

5.2.2
SOME EXPERIMENTAL INVESTIGATIONS

5.2.2.1
Isoperibolic Experiments

In the isoperibolic configuration, the outside of the dust deposit is kept at a constant temperature while the temperature development at one or more points inside the deposit is monitored. The dust sample may either be mechanically sealed from the surroundings or air may be allowed to penetrate it, driven by the buoyancy of heated gases inside the dust sample or external overpressure or suction.

Leuschke (1980, 1981) conducted extensive experimental studies of the critical parameters for ignition of deposits of various combustible dusts under isoperibolic conditions, with natural air draught through the sample, driven by buoyancy. Figure 5.3 shows a plot of the minimum ambient air temperature for self-ignition of deposits of cork dust samples of various shapes and sizes as a function of the volume-to-surface ratio of the sample.

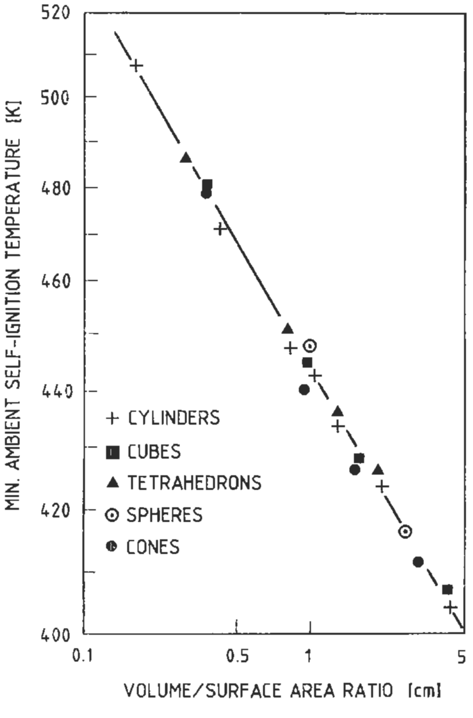

Figure 5.3 *Minimum ambient air temperature for self-ignition of cork dust deposits of various sizes and shapes as a function of the volume/surface area ratio (From Leuschke, 1981).*

This correlation can be interpreted in terms of the critical Frank-Kamenetzkii parameter for self-ignition (equation (5.11) later), which was discussed extensively by Bowes (1984). Note that the abscissa scale in Figure 5.3 is linear with the logarithm of the volume/surface area, whereas the ordinate axis is linear with the reciprocal of the temperature (K). Some further experimental results produced by Leuschke (1980, 1981) are mentioned in Section 5.2.3.2.

Hensel (1987), continuing the line of research initiated by Leuschke, investigated the influence of the particle size of coal on the minimum self-ignition temperature. Some of his results are given in Figure 5.4.

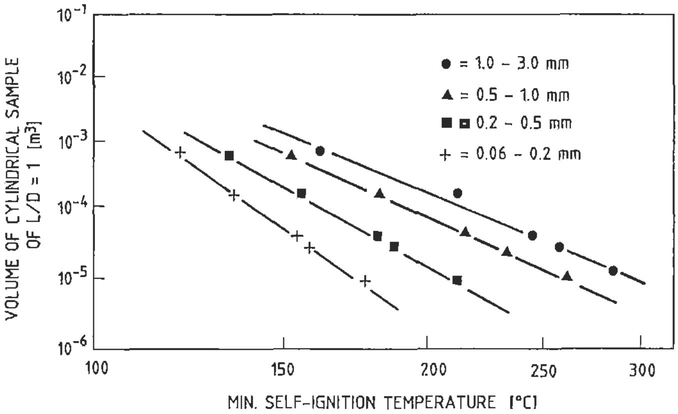

Figure 5.4 *Influence of particle size of coal of 28 wt% volatiles and 6.4 wt% ash on the minimum self-ignition temperature in a heated chamber for various sample volumes (From Hensel, 1987).*

The abscissa axis is linear with the reciprocal of the absolute temperature, which means that $1/T_{\min} = A \times \log$ (sample volume) $+ B$, where A and B are constants depending on the particle size. As shown by Hensel (1987), these data also gave linear Arrhenius plots, from which apparent activation energies could be extracted using the Frank-Kamenetzkii parameter:

$$\delta = Er^2 Q\rho f \exp(-E/RT_a)/RT_a^2\lambda \tag{5.11}$$

as the theoretical basis. Here E is the activation energy, R is the universal gas constant, f is the preexponential factor, r is the characteristic linear dimension of the dust sample, T_a is the ambient temperature (temperature of the air surrounding the dust sample in the furnace), Q is the heat of reaction per unit mass, ρ is the bulk density of the dust sample, and λ is the thermal conductivity of the dust sample.

In a further contribution, Hensel (1989) confirmed that data of the type shown in Figure 5.3, for various sample shapes, could be correlated with a good fit using the Frank-Kamenetzkii parameter (Equation (5.11)). The linear dimension r was defined as the shortest distance from the center of the powder sample to its surface.

Heinrich (1981), primarily concerned with self-ignition in coal dust deposits, produced a nomograph from which the minimum ambient air temperature for self-ignition in the deposit could be derived from measured values for the same dust and bulk density at two different, known volume-to-surface ratios. Although attractive from a practical point of view, extrapolating laboratory-scale data to a large industrial scale may, as pointed out by Beever (1988), yield misleading results.

Guthke and Löffler (1989) nevertheless proposed that reliable prediction of induction times to ignition in large scale can be obtained from activation energies derived from laboratory-scale self-heating experiments under adiabatic conditions.

5.2.2.2
Dust Deposit on a Hot Surface at Constant Temperature

Miron and Lazzara (1988) determined minimum ignition temperatures for dust layers on a hot surface, for several dust types, using the method recommended by the International Electrotechnical Commission and described in Chapter 7. The materials tested included dusts of coal and three oil shales, lycopodium spores, corn starch, grain dust, and brass powder. For a few of the dusts, the effects of particle size and layer thickness on the minimum ignition temperatures were examined. The minimum hot-surface ignition temperatures of 12.7 mm thick layers of these dusts, except grain dust and corn starch, ranged from 160°C for brass to 190°C for oil shale. Flaming combustion was observed only with the brass powder. The minimum ignition temperatures decreased with thicker layers and with smaller particle sizes. Some difficulties were encountered with the corn starch and grain dusts. During heating, the starch charred and expanded, whereas the grain dust swelled and distorted. The test was found acceptable for determining the minimum layer ignition temperature of a variety of dusts.

Tyler and Henderson (1987) conducted a laboratory-scale study to determine the minimum hot-plate temperatures for inducing self-ignition in 5–40 mm thick layers of sodium dithionite/inert mixtures. The kinetic parameters for the various mixing ratios were determined independently using differential scanning calorimetry (DSC) in both scanning and isothermal modes and by isothermal decomposition tests. This allowed measured minimum hot-plate temperatures for ignition to be compared with corresponding values calculated from theory, using a modified version of the Tyler-Jones computer simulation code. The code required no approximation of the temperature dependence, and reactant consumption was accounted for assuming first-order kinetics.

Tyler and Henderson found that the minimum hot-plate temperatures for ignition were significantly affected by the airflow conditions at the upper boundary, as predicted by theory. This must be allowed for when interpreting or extrapolating experimental data. It was further found that the simple model of Thomas and Bowes can be used to interpret experimental results, even when appreciable reactant consumption occurs.

Henderson and Tyler (1988) observed that, for certain types of dust, different experimental routes for the determination of the minimum ignition temperature of a dust layer can lead to widely differing experimental values. For sodium dithionite, experiments starting at a high temperature and working down led to an apparent minimum ignition temperature of nearly 400°C, compared to a value of about 190°C when experiments started at a low temperature, working up. The cause of this behavior was the two-stage decomposition of sodium dithionite and the problems with preparing the dust layer on the hotplate fast enough for the first-stage temperature rise to be observable at high plate temperatures, in the range 350–400°C. Similar behavior may be expected from some other materials.

5.2.2.3
Constant Heat Flux Ignition Source in the Dust Deposit

As pointed out by Beever (1984), situations may arise in industry where hot surfaces on which dust accumulates should be described as constant heat flux surfaces rather than as surfaces at constant temperature. Beever mentioned casings of electric motors, high-power electric cables, and lightbulbs that have become buried in powder or dust, as examples. Practical situations where the temperature of the hot surface is not influenced by the thermal insulation properties of dust accumulations may, in fact, be comparatively rare.

In her constant heat flux ignition experiments, Beever (1984) used samples of wood flour contained in a cylindrical stainless steel wire mesh basket of 0.8 m length and 0.1 m diameter. The ignition source was an electrically heated metal wire coinciding with the axis of the basket. To generate different ratios of the radius of the central cylindrical hot surface and the thickness of the cylindrical dust sample, the heating wire was enveloped by ceramic tubes of different diameters. Some essential properties of the wood flour are given in Table 5.1. Here, *E* is the activation energy of the exothermic chemical reaction, *R* is the gas constant, *Q* is the heat of reaction, and *f* is the preexponential frequency factor.

Table 5.1 Properties of wood flour used in self-ignition experiments reported by Beever (1984)

Bulk density, ρ	220 ± 10 kg/m^3
E/R	$1.275 \cdot 10^4$ K
Thermal conductivity, λ	0.346 kJ/mhK
$\frac{\rho \cdot Q \cdot f}{\lambda} \cdot \frac{E}{R}$	$7.678 \cdot 10^{20}$ K/m^2

Figure 5.5 shows some of Beever's experimental results for a hollow cylindrical wood flour deposit surrounding a cylindrical hot-surface ignition source. A curve predicted from an approximate theory is also shown. The agreement of the theoretical predictions, using a step-function approximation with the experimental results, is reasonable, except when the radius of the hot surface is very small in relation to the thickness of the dust layer.

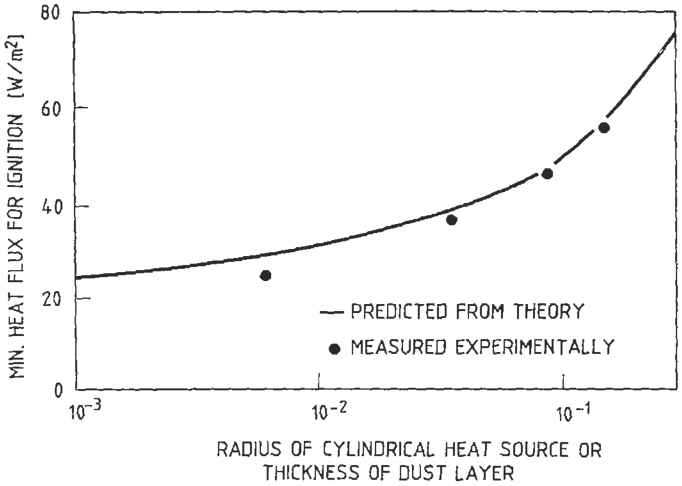

Figure 5.5 *Minimum heat flux for ignition of a centrally heated, infinitely long cylindrical wood flour deposit (From Beever, 1984).*

5.2.2.4

Ignition of Dust Layers by a Small, Electrically Heated Wire Coil Source: Propagation of Smoldering Combustion in Dust Layers

Leisch, Kauffman, and Sichel (1984) studied ignition and smouldering combustion propagation of dust layers in a wind tunnel where the top surface of the dust layer could be subjected to a controlled air flow.

The ignition source was a coil of 0.33 mm diameter platinum wire on a ceramic support. A constant power P was dissipated in the coil for a given period of time Δt, the dissipated energy being $P\Delta t$. Both P and Δt were varied systematically, and the minimum dissipated energy for ignition was determined as a function of dissipated power per unit area of the dust envelope in contact with the ignition source. Some results are shown in Figure 5.6. The points in Figure 5.6 are experimental results, whereas the dotted curve is the expected trend in the low-power end. The vertical dashed line indicates the value of power/area at which the rate of energy input is equal to the rate of heat loss from the layer. The experimental data in Figure 5.6 indicate that, for the higher values of power/area, more energy was needed to ignite the dust layer than in the lower range. According to Leisch et al., this is because, at the higher values of power/area, the combustion rate was limited by oxygen diffusion and therefore much of the heat transferred to the layer was lost by dissipation into the surroundings. At very low values of

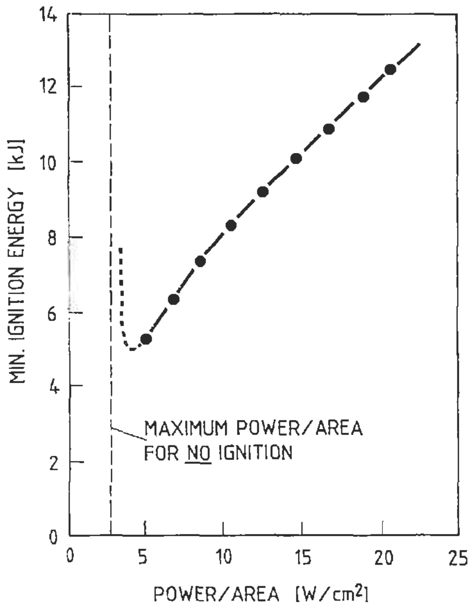

Figure 5.6 *Influence of dissipated power in a hot platinum wire coil, embedded in a layer of grain dust, per unit of area of the dust in contact with the coil, on the minimum dissipated energy required for initiating smoldering combustion in the dust layer. The thickness of the dust layer is 102 mm. The ignition source is located 12.7 mm below dust surface. No forced airflow travels past the dust surface (From Leisch et al., 1984).*

power/area, represented by the expected dotted curve, much of the energy furnished to the layer was conducted away before the reaction rate had increased significantly.

Leisch et al. (1984) also studied the propagation of smoldering combustion in layers of wood and grain dust. The studies revealed that the smoldering combustion wave had a definite structure and could be divided into four distinct regions. The initial part of the wave was characterized by discoloration of the unburned material due to pyrolysis. Pyrolysis occurred when the temperature of the unburned material reached a minimum value characteristic of that particular material. The pyrolysis products were gaseous volatiles and solid char. The volatiles escaped to the surroundings while the char remained in the layer, forming the second region of the combustion wave, the combustion zone. Oxygen from the atmosphere diffused into this zone, oxidizing the hot char, thereby releasing heat. In the case of forced airflow over the dust layer surface, the combustion zone could contain a visibly glowing subregion. The products of the combustion reaction were CO, CO_2, H_2O vapor, and solid ash. If the combustion was incomplete, some unburned char also remained. The ash and any unburned char would then form the third region of the combustion wave. The final region of the combustion wave was termed the *cavity*. Only gases (air plus combustion products) were present in this region. However, it was shown to constitute an important part of the wave structure in the presence of forced airflow. Some results from the experiments by Leisch et al. are given in Table 5.2, together with values predicted by using a numerical model developed by these authors.

Table 5.2 Comparison of results from numerical modeling of smoldering combustion in wood dust (pine) layers with results from experiments

Property	Experiment	Model
Combustion wave velocity (mm/s)	0.011 to 0.032	0.029
Char temperature (K)	500	485
Maximum temperature in combustion zone (K)	865	770
Reaction zone thickness (mm)	17	13

Source: Leisch et al., 1984.

The data in Table 5.2 refer to experiments with no forced airflow past the surface of the dust layer. With an airflow of 4 m/s, the combustion wave velocity was in the range 0.02–0.07 mm/s, about a factor of 2 higher than without forced airflow. For grain dust layers, the combustion wave velocity was 0.0035–0.008 mm/s without forced airflow and two to two and one half times higher for 4 m/s airflow. These values are lower than those for wood dust by a factor of 3 or 4.

5.2.2.5
Heat Conductivity of Dust and Powder Deposits

As Figure 5.1 illustrates, the rate of heat loss plays an important role in whether self-heating results in self-ignition. The heat conductivity of the powder deposit is a central parameter in the heat loss process. It is of interest, therefore, to consider this property more closely. Table 5.3 gives some thermal data for dusts and powders published by Selle (1957).

Table 5.3 Specific heats and heat conductivities of some combustible materials in solid and powdered form

	Density (g/cm^3)		Powder porosity (vol%)	Specific heat (J/gK)	Heat conductivity (kJ/mhK)	
Substance	**Solid**	**Powder**			**Solid**	**Powder**
Air	0.0012	—	0	1.0	0.088	—
Water	1.0	—	0	4.2	2.0	—
Aluminum	2.7	0.31	88.5	0.88	730	0.230
Sulfur	2.1	0.67	67.5	0.75	0.96	0.042
Sugar	1.6	0.65	59	1.25	2.20	0.063
Wood	0.55*	0.15	90	2.5	0.50 to 1.25***	0.059
Cork	—	0.074	95	2.5	—	0.033
Brown coal	1.16**	0.39	74	1.05	0.61	0.067

*63 vol% pores in solid.
**33 vol% pores in solid.
***Depending on orientation of fibers.
Source: Data from Selle, 1957.

The heat conductivities in Table 5.3 for the powders, except for aluminum, are very low, and in fact lower than for air. Selle did not describe the method of measurement and further analysis of his data is not possible.

However, in more recent years, John and Hensel (1989) developed a hot wire cell allowing more accurate measurement of the heat conductivity of powder and dust deposits. The cell was a vertical cylinder of diameter about 50 mm and height about 200 mm. The heat source was a straight, electrically heated resistance wire coinciding with the cell axis and generating a constant power. The temperature was measured as a function of time at a point in the powder midway between the hot wire and the cell wall. John and Hensel used the Fourier-type equation

$$\lambda = \frac{q}{4\pi} \bullet \frac{\ln(t_2/t_1)}{T_2 - T_1} \tag{5.12}$$

for calculating the heat conductivity of the powder from two measured temperatures T_1 and T_2 at times t_1 and t_2. Here, λ is the heat conductivity and q is the heat generated by the hot wire per unit time and wire length. This is a valid approach as long as the two measured temperatures are within a range where the temperature is a linear function of the logarithm of time. A set of data from measurements with this cell are given in Table 5.4.

Faveri et al. (1989) presented a theory for the heat conduction in coal piles, using the following expression for the heat conductivity λ in a powder, developed for porous oxides by Ford and Ford (1984):

$$\lambda = \lambda_s[1 - (1 - a\lambda_g/\lambda_s)\epsilon]/[1 + (a - 1)\epsilon] \tag{5.13}$$

where

$$a = \frac{3\lambda_s}{2\lambda_s + \lambda_g}$$

Table 5.4 Heat conductivities of deposits of some combustible powders and dusts determined from measurements in a hot wire cell, using equation (5.12)

Dust type	q (kJ/mh)	t_2 (h)	t_1 (h)	T_2 (°C)	T_1 (°C)	λ (kJ/mhK)
Bituminous coal	59	0.67	0.28	44.9	33.3	0.35
Cork dust	62	0.67	0.25	53.6	40.7	0.38
Wheat flour	53	0.50	0.22	35.3	27.0	0.43
Lycopodium	56	0.57	0.28	35.4	28.8	0.47
Methyl cellulose	54	0.67	0.25	37.4	30.5	0.61
Iron powder	58	0.67	0.25	29.8	23.9	0.77

Source: John and Hensel, 1989.

and λ_s and λ_g are the heat conductivity for the solid and gas, respectively, and ϵ is the porosity of the powder deposit (see Chapter 3). As long as $\lambda_s \gg \lambda_g$, equation (5.13) reduces to

$$\lambda = \lambda_s(1 - \epsilon)/(1 + \epsilon/2) \tag{5.14}$$

If this equation is applied to Selle's data in Table 5.3 for powdered sugar, the heat conductivity becomes 0.70 kJ/mhK, and for aluminum and sulfur, 58 and 0.23 kJ/mhK, respectively. All these values are considerably higher than those given by Selle. For cork dust of porosity 0.95, assuming a value of 2.2 kJ/mhK for λ_s (same as for sugar), equation (5.14) yields the value 0.074 kJ/mhK, which is lower than for air and therefore must be wrong. The reason is that the simplified equation (5.14) yields $\lambda = 0$ for $\epsilon = 1$, whereas according to physical reality $\lambda = \lambda_g$. This requirement is satisfied by the more-comprehensive equation (5.13), which, when applied to the cork data, yields a value of 0.16 kJ/mhK. This differs by only a factor of 2 from the experimental value reported for cork dust by John and Hensel (Table 5.4). If John and Hensel worked with a significantly lower porosity than 0.95, this could explain the difference.

Liang and Tanaka (1987b) used the following formula to account for the influence of temperature on the heat conductivity of cork dust:

$$\lambda = 6.45 \bullet 10^{-4}\, T + 0.1589 \text{ (kJ/mhK)} \tag{5.15}$$

For $T = 300$ K, this gives $\lambda = 0.35$ kJ/mhK, which is close to the experimental value in Table 5.4. For $T = 500$ K, equation (5.15) gives $\lambda = 0.48$ kJ/mhK.

Duncan, Peterson, and Fletcher (1988) reviewed various theories for the heat conductivity of beds of spherical particles and compared predicted values with their own experimental results for 2.38 mm diameter spheres. They found that none of the theories tested was fully adequate. In particular, the experiments revealed that gas conduction in the pores between the particles had a significant and predictable effect on the bed conductivity. For a loosely packed bed of aluminum spheres, the experimental heat conductivity was 20 and 9 kJ/mhK in nitrogen at atmospheric pressure and in a vacuum, respectively. For aluminum and a porosity ϵ of 0.35, equation (5.14) yields a bed conductivity of about 400 kJ/mhK, which exceeds the experimental values substantially.

Duncan et al. found that the heat conductivity of beds of aluminum spheres in nitrogen increased by a factor of 1.5–2.0 when the bed was exposed to a compacting pressure of about 1 MPa. This effect, which was practically absent in beds of spheres of nonductile materials, is probably due to enlargement of the contact areas between the particles in the bed by plastic deformation.

It seems that a generally applicable theory for reliable estimation of heat conductivities of powder deposits does not exist. Therefore, one must rely on experimental determination, such as by the method developed by John and Hensel (1989).

5.2.3
FURTHER THEORETICAL WORK

5.2.3.1
The Biot Number

The dimensionless Biot number is an important parameter in the theory of self-heating and self-ignition of dust deposits. It is defined as

$$Bi = hr / \lambda \tag{5.16}$$

where h is the heat transfer coefficient at the boundary between the dust deposit and its environment; r is half the thickness, or the radius, of the dust deposit; and λ is its thermal conductivity. The Biot number expresses the ease with which heat flows through the interface between the powder deposit and its surroundings, in relation to the ease with which heat is conducted through the powder. A Biot number of 0 means that the heat conductivity in the powder is infinite and the temperature distribution uniform at any time. $Bi = \infty$ implies that the resistance to heat flow across the boundary is negligible compared to the conductive resistance within the powder.

As pointed out by Bowes (1981) and Hensel (1989), the classical work of Semenov (1935) rests on the assumption that $Bi \approx 0$, whereas Frank-Kamenetzkii assumed $Bi = \infty$. Thomas (1958) derived steady-state solutions of the basic partial differential heat balance equation for finite plane slabs, cylinders and spheres from which the Frank-Kamenetzkii parameter (equation (5.11)) could be calculated for Biot numbers $0 < Bi < \infty$.

Liang and Tanaka (1987) found that the fairly complex approximate relationships between the critical condition for ignition and the Biot number originally proposed by Thomas could be replaced by much simpler formulas based on the Frank-Kamenetzkii approximate steady-state theory. Improved accuracy was obtained by adjusting the formulas to closer agreement with the more-exact general numerical solutions for a nonsteady state.

5.2.3.2
Further Theoretical Analysis of Self-Ignition Processes: Computer Simulation Models

Liang and Tanaka (1987b, 1988) used the experimental results of Leuschke (1980, 1981) from ignition of cylindrical cork dust samples under isoperibolic conditions as a reference for comprehensive computer simulation of the self-heating process in such a system. They assumed that heat did not flow in the axial direction, only radially, and arrived at the following partial differential equation for the heat balance, considering heat generation by zero-order chemical reaction and heat dissipation by radial conduction:

$$\rho C \frac{\partial T}{\partial \theta} = \frac{\lambda}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r} \right) + Qfe^{-E/RT} \tag{5.17}$$

where

r is the radial distance in cylindrical coordinates (m);
ρ is the density of the sample (kg m^{-3});
C is the specific heat of the sample (J kg^{-1} K^{-1});
θ is the storage time (h);
λ is the thermal conductivity of the sample (J m^{-1} h^{-1} K^{-1});
Q is the heat of the reaction (J kg^{-1});
f is the frequency factor of chemical reaction rate (kg m^{-3} h^{-1});
E is the activation energy (J mol^{-1});
R is the universal gas constant (J mol^{-1} K^{-1});
T is the temperature (K).

To compare predictions by equation (5.17) with the data from Leuschke (1980, 1981) for cork dust, the appropriate boundary conditions had to be specified, including a combined heat transfer coefficient of heat dissipation by natural convection and radiation from the cylindrical wall of the cork dust sample. Temperature profiles of cylindrical cork dust samples at any time could then be calculated at various ambient temperatures by solving equation (5.17) using the finite element method. The predicted radial temperature distributions at any time, the minimum self-ignition temperature, as well as the induction time to ignition, for various sample sizes, agreed well with the experimental data reported by Leuschke (1981), except at extremely high ambient temperatures.

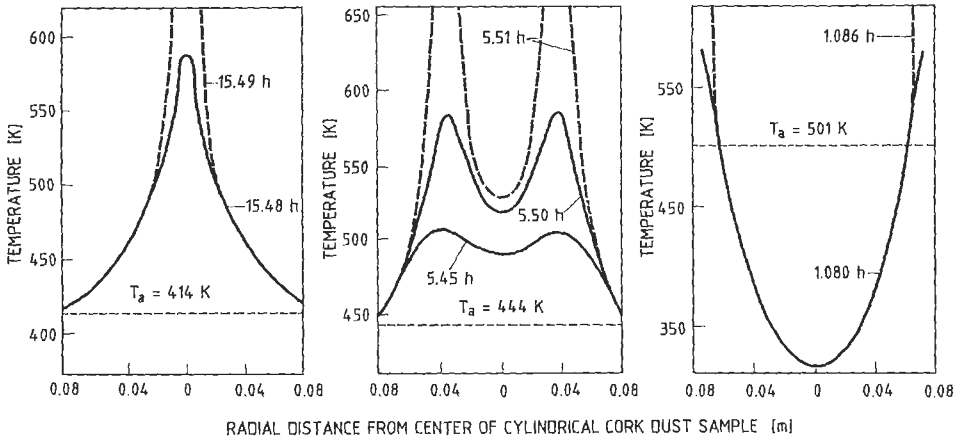

Figure 5.7 *Temperature distributions in a cylindrical cork dust sample of diameter 0.16 m just before ignition (solid lines) and just after (dashed lines), for three different ambient air temperatures T_a, using theoretical predictions by Liang and Tanaka (1987b).*

Figure 5.7 gives a set of predicted temperature profiles for cork dust samples of 0.16 m diameter, at three different ambient air temperatures. The predictions were in good agreement with the corresponding experimental data reported by Leuschke (1980, 1981).

At very low ambient air temperatures, close to the minimum for ignition (about 412 K for the 0.16 m diameter sample), ignition starts at the sample axis; whereas at high temperatures, it starts at the periphery. This is also in complete agreement with the experimental findings of Leuschke (1980).

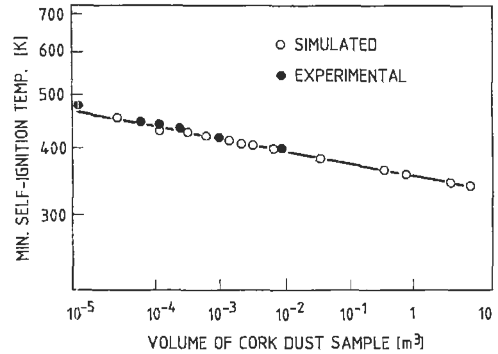

Figure 5.8 *Dependence of minimum self-ignition temperature for cylindrical cork dust samples on sample volume, using experimental data from Leuschke (1981) and computer simulation results from Liang and Tanaka (1987b, 1988).*

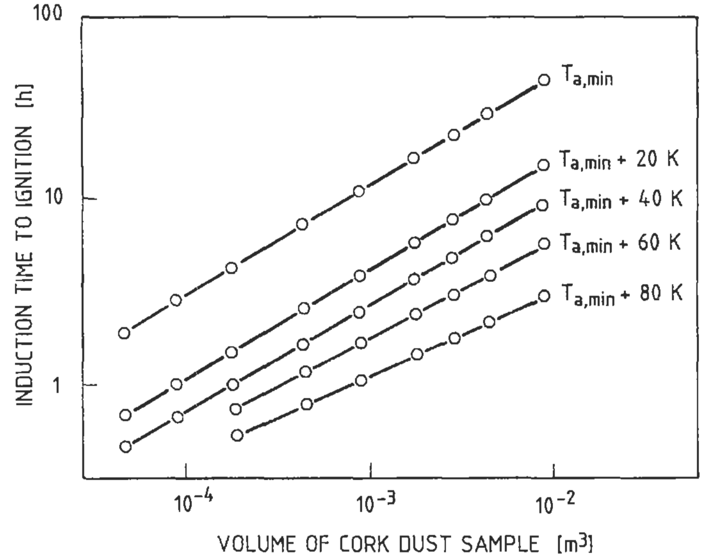

Figure 5.9 *Influence of dust sample volume and ambient air temperature on the induction time to self-ignition of cylindrical deposits of cork dust.* $T_{a/min}$ *is the minimum ambient air temperature for self-ignition, using computer simulation results (From Liang and Tanaka, 1987b).*

Figure 5.8 shows the minimum self-ignition temperature as a function of sample volume for cylindrical cork dust samples, as determined experimentally by Leuschke (1981) and by computer simulation by Liang and Tanaka (1987b, 1988).

Figure 5.9 shows the increase of the induction time to ignition (i.e., the time from introducing the dust sample into air of temperature T_a to ignition of the sample) with increasing sample volume and decreasing T_a.

Leuschke (1981) provided no data for cork dust corresponding to the simulation results in Figure 5.9. However, he gave a set of experimental data for another natural organic dust, which exhibit trends that are very close to those of the results in Figure 5.9.

The induction time to ignition is an important parameter from the point of view of industrial safety, because it specifies a time frame within which precautions may be taken to prevent self-ignition. This, in particular, applies to large volumes at comparatively low ambient temperatures, for which the induction times may be very long.

The finite element computer simulation approach offers a possibility for analyzing self-ignition hazards in a wide range of other geometrical configurations than cylinders. Dik (1987) proposed the use of the thermal impedance method for numerical prediction of critical conditions for self-ignition for various boundary conditions.

Adomeit and Henriksen (1988) developed a computer model addressing the same problem as the model used by Tyler and Henderson (1987), that is, simulation of self-ignition in dust layers on hot surfaces. It was assumed that the combustion was controlled mainly by homogeneous gas phase reactions, following an initial step of pyrolysis of the solid fuel. The system described by the model is composed of three zones, as illustrated in Figure 5.10.

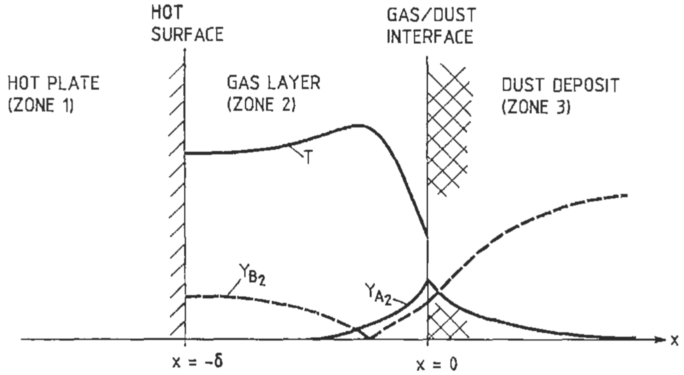

Figure 5.10 *System described by the computer simulation model for self-ignition of dust layers on hot surfaces, where Y_{A2} and Y_{B2} are the mass fractions of fuel and oxidizer in the gas phase, T is the gas temperature, δ is the thickness of the gas layer, and x is the distance from the dust/gas interface (From Adomeit and Henriksen, 1988).*

The model implied the following overall picture of the various steps in the ignition process:

1. A thin gas layer forms close to the hot surface due to initial pyrolysis of the dust. The temperature of dust closest to the hot surface reduces due to thermal insulation by the gas.
2. At a given minimum gas layer thickness, a homogeneous gas phase reaction starts in a rich premixed zone close to the hot surface.
3. A second diffusion flame zone forms between the burning premixed zone and the hot surface, receiving fuel via further pyrolysis caused by the rich primary burning zone.
4. The diffusion flame dies due to lack of an oxidizer, dropping the pyrolysis rate due to cooling by extinguishing gas.
5. The premixed flame close to dust/gas interface stabilizes.

This model seems to address the case of comparatively high hot-surface temperatures and thin dust layers. Self-ignition in comparatively thick dust layers resting on hot surfaces of quite low temperatures often occurs inside the layer rather than at the hot surface.

Beever (1984) applied the classical self-ignition theory to a dust deposit exposed to a hot surface at constant heat flux boundary conditions. She adopted the step-function approximation devised by Zaturska (1978) and found good agreement between values of the critical Frank-Kamenetzkii parameter for ignition calculated by the approximate theory and values obtained analytically by Bowes, for self-heating in a plane dust slab with constant heat flux on one face. As shown in Section 5.2.2.3, Beever also found good agreement between the predicted minimum heat flux for ignition and experimental results for cylindrical dust deposits heated by an internal concentric cylindrical constant flux heat source.

Leisch et al. (1984) were interested primarily in the propagation of a one-dimensional smoldering combustion wave in a dust layer. They obtained a numerical solution of the conservation equations for this process in good agreement with experimental results (see Section 5.2.2.4). The theoretical model also gave temperature and density profiles within the combustion wave similar to those observed experimentally. Further works on modeling are reviewed in Sections 9.2.3.3 and 9.3.5.2 in Chapter 9.

5.2.4
APPLICATIONS TO DIFFERENT POWDER/DUST TYPES: A BRIEF LITERATURE SURVEY

5.2.4.1
Coal Dust

Elder et al. (1945) studied the relative self-heating tendencies of 46 different coal samples of particle sizes finer than 6 mm, using an adiabatic calorimeter and a rate-of-oxygen-consumption meter. They found that

- The self-heating tendency increased with decreasing coal rank.
- The self-heating tendency increased with storage temperature.
- The self-heating tendency decreased with increasing preoxidation of the coal prior to the test.
- The rate of heat generation due to oxidation was proportional to the vol% oxygen in the air in contact with the coal, raised to the power of $^2/_3$.
- The rate of heat generation due to oxidation was proportional to the cube root of the specific surface area of the coal.
- Increasing the ash content in the coal decreased the self-heating tendency.
- An appreciable moisture content in the coal decreased the self-heating tendency.

Guney and Hodges (1969) reviewed the various experimental methods used up to that time for determining the relative self-heating tendencies of coals. They concluded that only isothermal and adiabatic methods would give consistent results. Shea and Hsu (1972) used an adiabatic method for studying self-heating of various dried coals and petroleum cokes at 70°C in atmospheres of oxygen or nitrogen saturated with water vapor or in dry oxygen. In a completely dry system, there was no appreciable self-heating, even in pure oxygen. The absorption of water from humid atmospheres by dry carbonaceous materials was the major origin of the primary temperature rise from 70°C to 90°C.

Chamberlain and Hall (1973) discussed the various chemical and physical properties of coals that influence their oxidizability. Continuous measurement of gases produced during the oxidation process showed that carbon monoxide gives the earliest indication of spontaneous heating.

Heinrich (1981) provided a nomograph from which minimum ambient air temperatures for self-ignition in coal dust deposits may be determined from laboratory-scale measurements of the minimum self-ignition temperatures for two powder samples of different volume to surface ratios (see also Section 5.2.2.1).

Heemskerk (1984), using both isothermal and adiabatic test methods, investigated the relationship between the rate of self-heating in coal piles and the oxygen content in the atmosphere in the range 0–20 vol% oxygen. A systematic decrease of the self-heating rate with decreasing oxygen content was found. Addition of sulfuric acid and iron salts to coal piles stimulated self-heating. Smith, Miron, and Lazzara (1988) investigated the effectiveness of 10 additives, applied as solutions in water, to inhibit self-heating in deposits of a coal of high self-ignition potential, using an adiabatic heating oven. Sodium nitrate, sodium chloride, and calcium carbonate were found to be the most effective inhibitors, whereas sodium formate and sodium phosphate stimulated the self-heating process.

Enemoto et al. (1987) studied the process leading to a fire in a new bag house installed with a cyclone separator in a pneumatic transport system for pulverized coal. By using classical Frank-Kamenetzkii-type theory and appropriate values for the thermal conductivity of the very fine coal dust (2.3 μm) and the kinetic parameters, it was confirmed that the fire was most probably caused by self-ignition in a dust deposit in the bag house.

Bigg and Street (1989) developed a mathematical computer model for simulation of spontaneous ignition and combustion of a bed of activated carbon granules through which heated air was passed. The model simulated the temporal development of temperature and gas species concentration. The model was validated against the experimental data of Hardman, Lawn, and Street (1983) and good agreement was found.

Brooks, Svanas, and Glasser (1988) formulated a mathematical model for evaluating the risk of spontaneous combustion in coal stock piles, using a personal computer. The model predicts expected trends with changes in various parameters, but comprehensive validation against experiments was not reported.

Tognotti, Petarca, and Zanelli (1988) studied self-ignition in beds of coal particles experimentally, using various cylindrical-shaped beds of diameters 17–160 mm and heights 10–80 mm. Theoretical thermal ignition models were used to interpret and extrapolate the data from the small-scale experiments. Results from additional isothermal experiments were compared with the small-scale ignition tests. The boundary conditions (Biot number) played an important part in deciding whether ignition would occur.

Takahashi et al. (1989) simulated the temperature rise with time in a coal deposit due to spontaneous oxidation, using a numerical computer model. The maximum temperature occurred at the center of the bed when the oxygen concentration inside the bed was not reduced due to the oxidation reaction, whereas it occurred near the bed surface when the oxygen concentration in the bed decreased due to the consumption. The rate of temperature rise was affected significantly by the activation energy and frequency factor of the coal oxidation. Measurement of the moisture absorbed on the oxidized coal samples showed that the loss in mass due to oxidation increased markedly at temperatures above 120°C. By assuming that the limiting temperature for significant self-heating in coal storage is 120°C, a maximum permissible size of stored coal deposit to prevent self-ignition was estimated for various types of coal.

Hensel (1988) was concerned with a similar problem, predicting maximum permissible storage periods for large coal piles. He extrapolated empirical laboratory-scale correlations between the volume/surface area ratio of the dust deposit and the induction time to ignition. An induction time of 10 years was predicted for some 20-year-old, large coal piles in Berlin, in which self-ignition had been observed repeatedly over the last years. By extrapolating the laboratory-scale data, Hensel also confirmed that the size of the actual coal piles was larger than the maximum permissible size for preventing self-ignition at average ambient air temperatures in the Berlin region.

5.2.4.2
Natural Organic Materials

Raemy and Löliger (1982) used a heat flow calorimeter for studying the thermal behavior of cereals above 20°C. When the samples were heated in sealed measuring cells, strong exothermic reactions were observed at about 170°C. These reactions were attributed mainly to carbonization of the carbohydrates in the cereals. Raemy and Lambelet (1982) conducted a similar heat flow calorimetric study of self-heating in coffee and chicory above 20°C.

In a study of the thermal behavior of milk powders, Raemy, Hurrel, and Löliger (1983) used both heat flow calorimetry and differential thermal analysis. They found that four main types of reactions are involved in the thermal degradation of milk powders. In order of increasing temperature, they are crystallization of amorphous lactose, Maillard reactions, fat oxidation, and lactose decomposition.

Self-ignition properties of fish meals were studied by Alfert and coworkers at CMI, Bergen, Norway, by storing the samples, supported by metal gauze baskets, in air at constant temperatures in the range 100–250°C. Some results were reported by Höstmark (1989). For 1- and 2-liter samples, the minimum ambient air temperatures for self-ignition were 140 and 130°C, respectively. The corresponding induction times to ignition were 5–6 and 8 hours. At ambient air temperatures exceeding 200–240°C, the dust samples ignited close to the surface after induction times on the order of 2 hours (see trend in Figure 5.7.)

5.2.4.3
Corrosion of Direct-Reduced Iron

Birks and Alabi (1986, 1987, 1988) were concerned with the special problem of self-ignition in piles of direct-reduced iron when exposed to water. The problem arose because direct-reduced iron is stored and transported in charges of considerable size, and it had been observed that the bulk material has a tendency to oxidize to an extent leading to self-ignition. Birks and Alabi investigated the various chemical reactions operating when direct-reduced iron reacts with water and the oxygen in the air.

5.2.4.4
Self-Ignition in Dust Deposits in Bag Filters in Steel Works

This problem was studied by Marchand (1988). Two specific cases were discussed to illustrate how hot spots and smoldering combustion can develop in fabric filter plants in steel works. The cause of accumulation of deposits of very fine dust fractions in the clean section of some filters and the various possibilities of ignition were analyzed. The dusts in question contained a large fraction of combustible material, including carbon, various organic compounds, and metallic iron. The typical ignition sources were burning metal droplets expelled from the molten metal and conveyed to the filter.

5.3
IGNITION OF DUST CLOUDS BY ELECTRIC SPARK DISCHARGES BETWEEN TWO METAL ELECTRODES

5.3.1
HISTORICAL BACKGROUND

Holtzwart and von Meyer (1891) were probably the first scientists to demonstrate that dust clouds could be ignited by electric sparks. They studied the explosibility of brown coal dusts in a small glass explosion vessel of 50 cm^3 capacity, fitted with a pair of platinum electrodes, between which an inductive spark could pass.

A few years later Stockmeier (1899), who investigated various factors affecting the rate of oxidation of aluminum powder, was able to demonstrate that aluminum dust, shaken up in a glass bottle, ignited in the presence of an electric spark.

Since the publication of these pioneering papers, numerous contributions to the published literature on the spark ignition of dust clouds have been produced. Indeed, they have confirmed that ignition of dust clouds by electric discharges is a real possibility and the cause of many severe dust explosions over the years, in mines as well as in industrial plants.

5.3.2
THE OHMIC RESISTANCE OF A SPARK CHANNEL BETWEEN TWO METAL ELECTRODES

Ohm's law can be applied to a spark channel just as to any other current-carrying conductor. However, the resistance per unit length of channel is not a constant but depends on the extent to which the gas in the gap between the electrodes is ionized. This in turn depends on the energy dissipation in the gap per unit time, which determines the temperature in the ionized zone. If equilibrium has been established, one would, for a given gas at a given temperature and pressure, expect a consistent relationship between the gap resistance per unit length and the current flowing through the gap. This has been investigated for air at atmospheric pressure and normal temperature by several workers, as summarized in Figure 5.11.

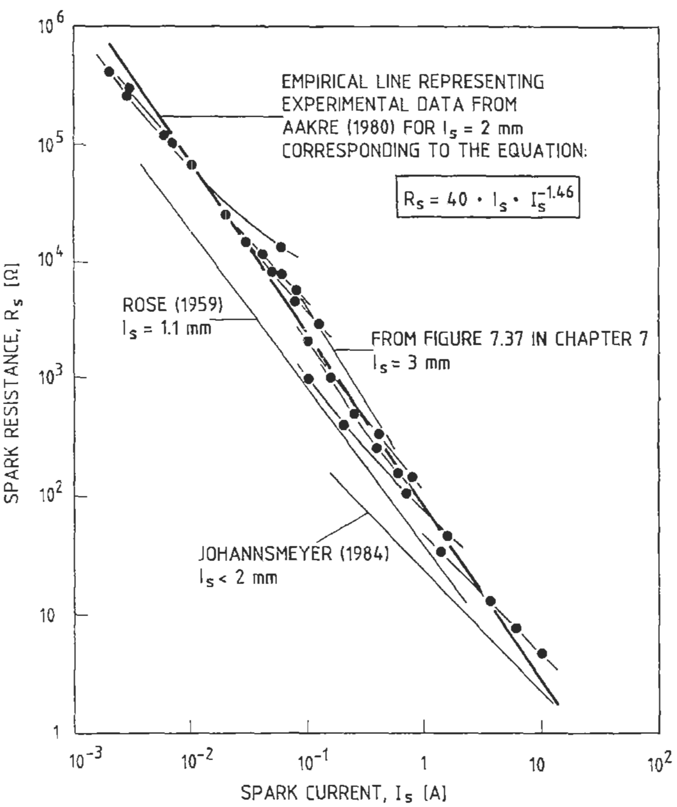

Figure 5.11 *Spark gap resistance R_s as a function of spark current I_s for capacitive spark discharges across a 2 mm spark gap in air at normal pressure and temperature (Data from Aakre, 1980). Comparison with data for shorter gaps from Rose (1959) and Johannsmeyer (1984), and for a 3 mm gap from Figure 7.37 (in Chapter 7). l_s is the length of the spark gap in mm.*

If it is assumed that the spark resistance for a given current is proportional to the spark gap length, the data from Rose (1959) for a 1.1 mm gap length should be shifted upward by a factor of 1.8 and the data from Figure 7.37 in Chapter 7 downward by a factor of 1.5. The gap length for Johannsmeyer's (1984) data is not known, but it is shorter than 2 mm. It therefore seems as all the data tend to group reasonably well around the data from Aakre (1980), if adjusted to a gap length of 2 mm.

The empirical correlation of all the data in Figure 5.11 yields

$$R_s = 40 \bullet l_s I_s^{-1.46} \tag{5.18}$$

Normally, the ohmic energy dissipation E_s in the spark gap, often called the *net spark energy*, is determined experimentally by simultaneous measurement of the spark current I_s and the spark gap voltage V_s as functions of time during the discharge, and subsequent calculation using the equation

$$E_s = \int_0^{t_{\max}} I_s V_s \, dt \tag{5.19}$$

However, assuming that Ohm's law is valid at any time,

$$V_s = R_s I_s \tag{5.20}$$

and substitution of (5.18) into (5.20) yields

$$V_s = 40 \cdot l_s I_s^{-0.46} \tag{5.21}$$

which, when substituted into (5.19), gives

$$E_s = 40 \cdot l_s \int_0^{t_{\max}} I_s^{0.54} dt \tag{5.22}$$

This equation offers a possibility for determining the ohmic energy dissipation in the spark gap, that is, the net spark energy, by measuring the spark current $I_s(t)$ only. Figure 5.12 shows a correlation of net spark energies determined from equations (5.19) and (5.22), using the experimental data from Aakre (1980). As can be seen, the agreement is within a factor of 2 for $E > 0.1$ mJ. It remains to be seen whether equation (5.18) is a reasonable approximation even outside the range covered by the data in Figure 5.11.

Equations (5.18) and (5.20) can also be used to express E_s as an integral of V_s instead of I_s.

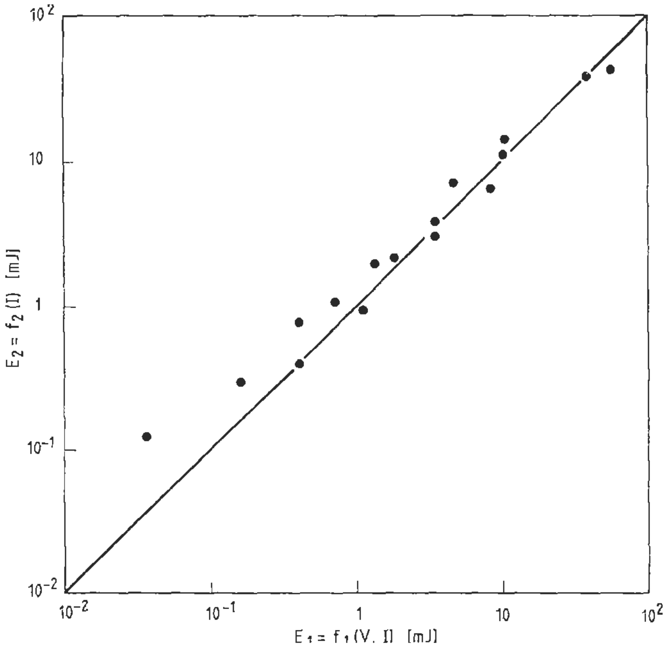

Figure 5.12 *Correlation between spark energies E_1 determined from simultaneous measurement of spark gap voltage V_s and spark current I_s, as functions of time, and energies E_2 determined from the spark current measurements only, using the empirical correlation of spark current and spark resistance per unit length of spark gap in Figure 5.11.*

5.3.3
INFLUENCE OF SPARK DISCHARGE DURATION ON THE MINIMUM ELECTRIC SPARK IGNITION ENERGY FOR DUST CLOUDS

5.3.3.1
Displacement of Dust Particles by Blast Wave from Spark Discharge

The strong influence of the spark discharge duration on the minimum spark energy for ignition of dust clouds was probably first discovered by Boyle and Llewellyn (1950). They were able to demonstrate that the minimum capacitor energy $\frac{1}{2}CV^2$, C being the capacitance and V the initial capacitor voltage, capable of igniting clouds of various powders in air decreased quite considerably when a series resistance was introduced in the discharge circuit. Some results obtained by Boyle and Llewellyn are shown in Figure 5.13.

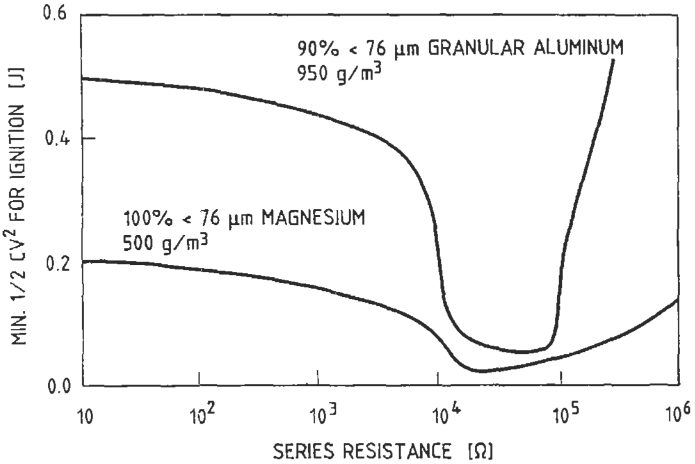

Figure 5.13 *Results from ignition of dust clouds by capacitive sparks, using an additional series resistance in the discharge circuit (Data from Boyle and Llewellyn, 1950).*

As can be seen, the minimum $\frac{1}{2}CV^2$ for ignition decreased by a factor of about 10 both for granular aluminum and magnesium, when a series resistance of 10^4–10^5 Ω was added to the discharge circuit. Similar trends were also found by these workers for dust clouds of ferromanganese, zinc, silicon, and sulfur.

Boyle and Llewellyn expressed their results in terms of stored capacitor energy $\frac{1}{2}CV^2$. However, a large series resistance in the spark discharge circuit, during discharge, absorbs a significant fraction of the capacitor energy, so that the energy delivered in the spark gap is considerably lower than $\frac{1}{2}CV^2$. This fraction has been determined experimentally by various workers, as shown by Eckhoff (1975). From independent investigations, it can be concluded that, with the capacitances used by Boyle and Llewellyn and using a series resistance in the range 10^4–10^7 Ω, the net spark energies were only on the order of 5–10% of the stored capacitor energy $\frac{1}{2}CV^2$.

This, in turn, means that, in the experiments of Boyle and Llewellyn, an inclusion of a series resistance of 10^4–10^5 Ω in the discharge circuit reduced the minimum net spark energy for ignition to only 1%, or perhaps even less, of the energy required without additional series resistance.

In a later investigation, Line, Rhodes, and Gilmer (1959) ignited steady-state wall-free and wall-confined 25 mm and 50 mm diameter columns of lycopodium spores in air by electric sparks. Some results for 25 mm columns are shown in Figure 5.14.

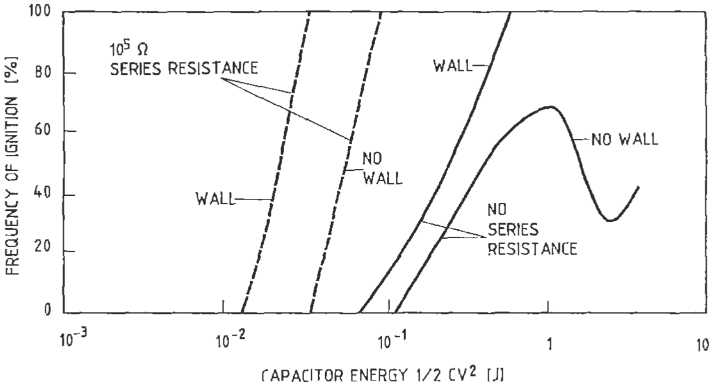

Figure 5.14 *Frequency of ignition of a 25 mm diameter stationary column of 80 g/m³ of lycopodium in air, as a function of capacitor energy, showing the effect of wall confinement and additional series resistance in the discharge circuit (Data from Line et al., 1959).*

As can be seen both for wall-free and confined dust columns, the stored capacitor energies required for producing a given probability of ignition decreased roughly by a factor of 10 if a series resistance of 10^5 Ω was included in the discharge circuit. Both the order of magnitude of the decrease and the order of magnitude of the series resistance giving this maximum decrease agree with the corresponding figures found by Boyle and Llewellyn for other powders.

Line et al. attributed the dramatic influence of spark discharge time to decreasing the disturbance of the dust cloud by the blast wave from the spark discharge as the discharge time increased and the spark energies decreased. In the case of high stored capacitor energies and short discharge times, using high-speed filming, they were able to observe the formation of a dust-free zone around the spark before ignition got under way.

Smielkow and Rutkowski (1971) conducted an independent study of the influence of spark discharge duration on the minimum ignition energy of dust clouds. As in the work of Line et al. (1959), the spark discharge duration was increased by either adding a very large series inductance (0.1–1.0 H) or a large series resistance (0.45–0.90 MΩ). Reductions in the minimum ignition energies ($\frac{1}{2}CV^2$) on the order of a factor of 10 was observed, as by Line et al.

Eckhoff (1970) conducted further studies of the ignition of clouds of lycopodium spores in air by capacitor sparks of comparatively high energies and short discharge times. Some results are given in Figure 5.15.

The results in Figure 5.15 are in accordance with those for no wall and no series resistance in Figure 5.14. Even with spark energies of nearly 10 J, the frequency of ignition is lower than 100%. The most probable reason for this is that there is a "knife edge" competition between the heat transfer from the spark to the surrounding dust, which promotes

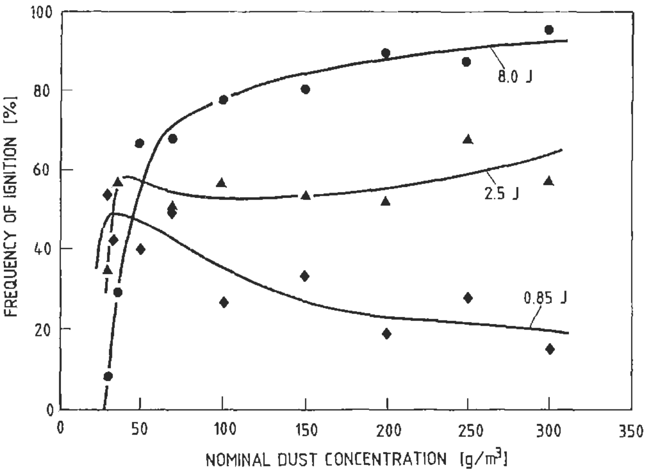

Figure 5.15 *Probability of electric spark ignition of clouds of lycopodium in air as a function of dust concentration, for three different spark energies. Spark discharge duration is 5–10 μs. External circuit resistance is 0.01 Ω. Circuit inductance is 2 μH. Spark gap length is 2.7 mm (From Eckhoff, 1970).*

ignition, and the mechanical separation of the dust from the hot spark kernel by the blast wave, which counteracts ignition. The results in Figure 5.14 even show a drop in the frequency of ignition as the spark energy increases from 1 J to 3 J. Eckhoff and Enstad (1976) demonstrated that the blast wave from capacitive discharges of durations on the order of 1 μs and energies of 100–200 mJ, could push a 4 × 5 mm paper pendulum, supported by thin threads, an appreciable distance from the spark. The results are given in Table 5.5.

Table 5.5 Displacement distances of a 4 × 5 mm paper pendulum due to blast waves from capacitive spark discharges (initial distance between paper and spark gap is 1 mm)

		Displacement distance (mm)	
Spark energy (mJ)	**Length of spark gap (mm)**	**"Short" spark**	**"Long" spark**
10	0.1	<0.5	0
25	0.2	2.5	0
100	1.0	12	<0.5
300	2.0	35	1

Source: Eckhoff and Enstad, 1976.

Table 5.5 clearly demonstrates that as the spark energy increased beyond 100 mJ, the displacement of the paper by "short" sparks was appreciable. On the other hand, as the spark energy decreased below 10 mJ, the displacement was practically negligible even for the "short" sparks, which means that the minimum ignition energy may not necessarily increase with decreasing discharge duration in the range of low spark energies below 10 mJ. This was confirmed by the results of Parker, discussed later. However, first, the theoretical analysis by Enstad (1981) of the interference of the blast from a "short" spark discharge with the surrounding dust particles is outlined. Enstad made the following assumptions:

- The spark discharge time is very short, less than 0.1 μs for a 1 J spark and less than 0.01 μs for a 1 mJ spark. This means that the spark discharge is completed before any significant expansion of the hot gas has taken place.
- The maximum temperature (i.e., the temperature immediately after completion of the very short heating period and prior to the onset of the subsequent expansion of the hot gas) is estimated at 60,000 K, based on the peak temperature of 50,000 K in a 2 μs, 1 J spark found experimentally by Krauss and Krempl (1963).
- The initial spark is spherical; the rapid expansion of the hot gas sphere to ambient pressure, following the discharge, is adiabatic; and a rectangular radial temperature distribution in the hot gas is maintained throughout this process. The equation of state for ideal gases and the expressions $C_v = 5/2R$ and $C_p/C_v = 1.5$ apply.
- After completion of the rapid expansion, the hot gas is cooled to ambient temperature by heat conduction into the surrounding gas. This process, involving diffusion of both heat and mass, is described by the equation

  $$\frac{\partial u}{\partial \theta} = u^3 \left\{ \frac{\partial^2 u}{\partial x^2} + \frac{2}{x} \bullet \frac{\partial u}{\partial x} \right\} \tag{5.23}$$

  where u is a dimensionless function of the spark temperature, x is a dimensionless expression of the distance from the spark center, and θ is a dimensionless expression of the time.
- The upward movement of the hot gas due to buoyancy is neglected.
- The radial distribution of gas pressure is assumed rectangular throughout the supersonic expansion of the hot gas to ambient pressure.
- The particles are first accelerated by the extremely rapid passage of the shock front through the particle and by the rapid outward flow of expanding gas following the shock front. At a certain point, the particle velocity, because of the inertia, overtakes the gas velocity; and from this stage on, the particle velocity gradually decreases.
- Depending on the Reynolds number, *Re*, either the laminar drag

  $$K_l \frac{24}{Re} \bullet \frac{\rho}{2} V^2 A_p \tag{5.24}$$

  or the turbulent drag

  $$K_t = \frac{\rho}{2} V^2 A_p \tag{5.25}$$

  acts on the particles during the acceleration as well as during the subsequent retardation process.

The theoretical treatment by Enstad confirmed that a dust-free zone, separating the dust cloud from the hot gas core, may in fact be established. As an example, the theoretical results for a "short" 1.5 J spark discharge in a cloud of lycopodium in air are summarized in Figure 5.16. The distance of a dust particle from the spark center is given as a function of the time after spark discharge and the initial position of the particle. Beyond a given instant, depending on the initial particle position, the particle to spark center distance decreases with time. This is because, beyond this point, the settling velocity of the particles in quiescent air (≈2 cm/s for lycopodium) dominate, and the particles above the spark approach the hot gas core.

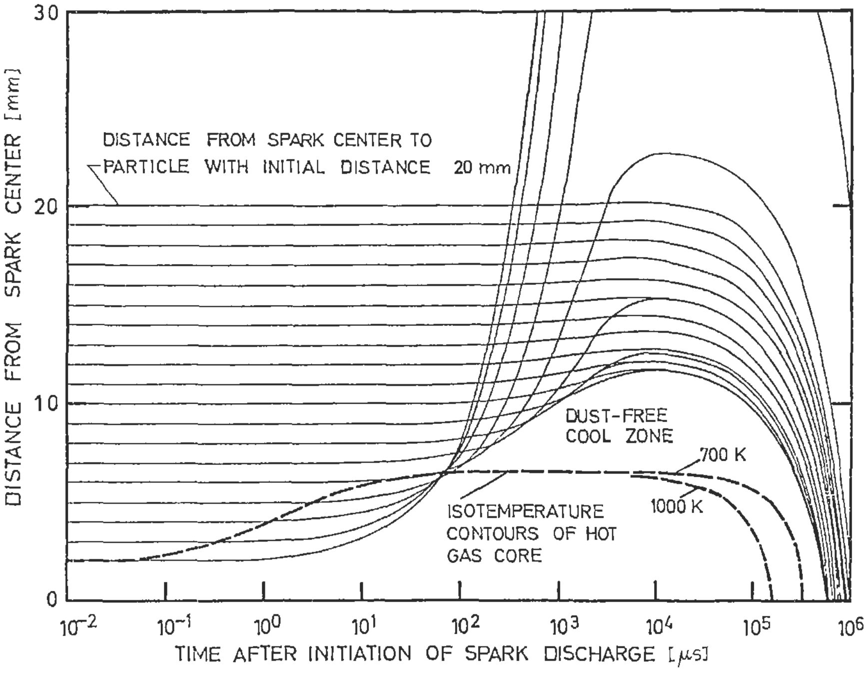

Figure 5.16 *Summary of theoretical prediction of positions of dust particles and radius of the hot gas kernel following a "short" discharge of a 1.5 J electric spark in a cloud of lycopodium in air (From Enstad, 1981).*

The 1000 K and 700 K radii of the hot gas sphere as functions of time are also given in Figure 5.16. The minimum ignition temperature of lycopodium clouds in air at atmospheric pressure, as determined in the standard Godbert-Greenwald furnace, is about 700 K. From Figure 5.16, it therefore follows that a dust-free, cool zone, separating the dust cloud from the incendive part of the hot gas core, is gradually formed from 100 μs after the spark discharge and onward, making ignition impossible. Figure 5.16 indicates that, from less than 1 μs to about 100 μs after the spark discharge, particles with initial positions 2 to 5 mm from the spark center are trapped in the spark. However, this is unlikely to cause ignition, because the induction period for "long" spark ignition of lycopodium clouds in air, as shown by high-speed photography by Line et al. (1959), is on the order of 1 ms.

It is of interest to note that the radius of the dust-free zone 2 ms after spark discharge, as predicted by Figure 5.16, is in close agreement with the experimental value of about 10 mm found by Line et al. (1959) for the same spark energy, type of dust, and instant after spark discharge.

The Schlieren flash photograph of a rising hot spark kernel in Figure 5.17 may suggest that Enstad's assumption, that the buoyancy of the spark kernel can be neglected, may not be entirely valid.

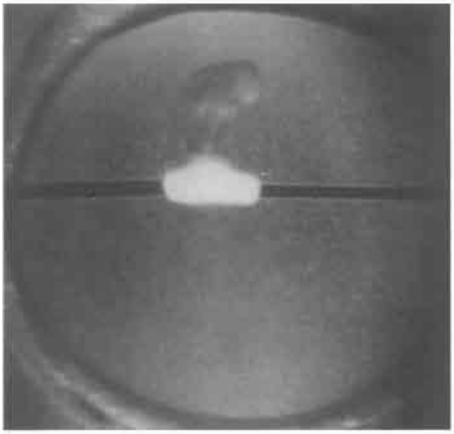

Figure 5.17 *Open-shutter Schlieren flash photo of rising hot spark kernel following an electric spark discharge in a cloud of lycopodium in air. Spark energy is 4.3 mJ. Spark discharge duration is 28 μs. The delay from initiation of spark discharge to flash is 500 μs. Spark gap width is 4 mm. Electrode diameter is 0.5 mm. The luminous spark image is due to self-radiation during the discharge 472–500 μs before the Schlieren flash. The discharge did not ignite the dust cloud, but some individually burning dust particles are visible just above the luminous spark channel (Courtesy of S. J. Parker).*

5.3.3.2
Optimum Spark Discharge Duration for Ignition

A specific study of this aspect was performed by Matsuda and Naito (1983). For lycopodium and <105 μm cork dust in air, they found the lowest minimum ignition energies for spark durations in the range 0.1–1.0 ms.

The current in an overdamped R-C-L series discharge circuit, after an initial rapid rise to its maximum value, is given by the equation

$$I = \frac{V_0}{R} \exp(-t/RC) \tag{5.26}$$

where V_0 is the initial capacitor voltage, R is the total circuit resistance, C is the capacitance, and t is the time. By defining the discharge duration as the time required for the current to decrease to 1% of the initial value at $t = 0$, equation (5.26) yields

$$t = 4.6 \cdot RC \tag{5.27}$$

The values of R and C that gave the most incendiary sparks in the investigation by Boyle and Llewellyn (1950) and Lines et al. (1959) indicate that the lowest minimum ignition energies were found for discharge durations in the rate 0.1–1.0 ms. Furthermore, the optimum duration appeared to decrease with decreasing minimum net spark ignition energy.

The influence of discharge duration on the minimum electric spark ignition energy of dust clouds was studied systematically by Parker (1985). He used a method of electric spark generation by which the energy and duration of the unidirectional spark discharges

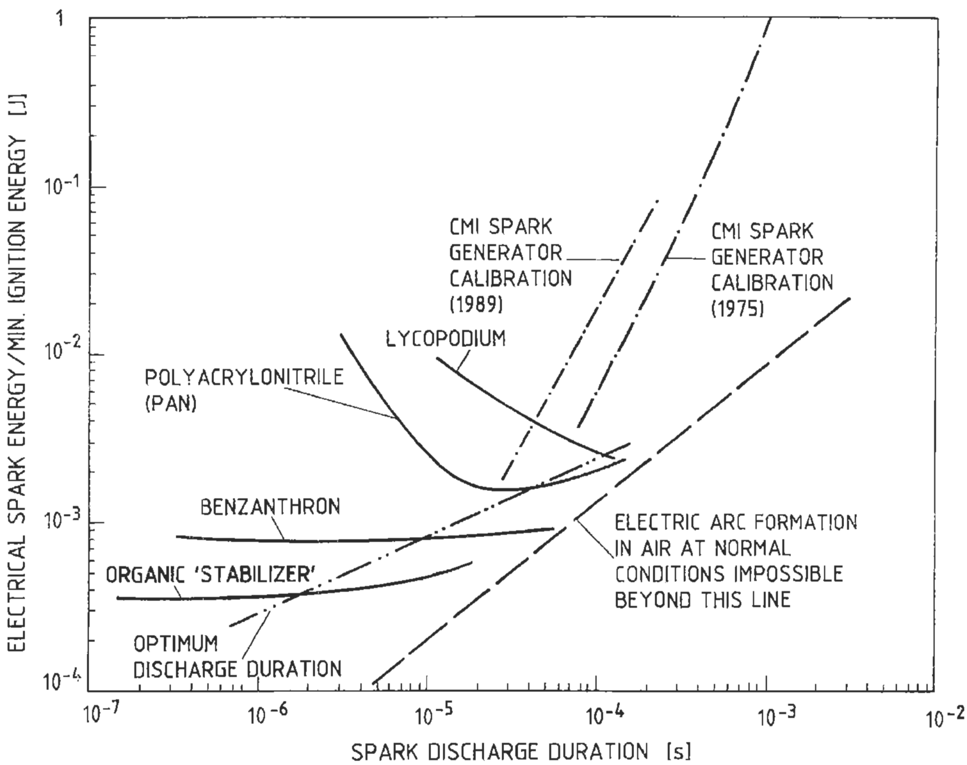

Figure 5.18 *Minimum electric spark ignition energies of approximately 5% probability of ignition for four powders as functions of spark discharge duration, as determined by Parker (1985). Electric energy of sparks is from CMI-spark generator, as a function of spark discharge duration (From Eckhoff, 1975).*

could be varied independently in a controlled manner. Parker investigated four different dusts in air, and the results are summarized in Figure 5.18.

For two of the dusts (lycopodium and PAN), there seemed to be a fairly distinct region of optimal discharge durations. For shorter durations, the minimum ignition energy increased markedly. For the two other dusts, however, this effect was absent. As indicated in Figure 5.18, an optimum discharge duration line may be drawn through the results for the four powders. For comparison the spark duration/spark energy characteristic of the CMI discharge circuit (see Chapter 7) has also been included in Figure 5.18. This refers to an R-C-L circuit of inductance $L \geq 1$ mH, for which the discharge will normally be a damped oscillation. The discharge time may then be defined as the time needed for the exponential damping factor to decrease to 1% of the initial maximum value. The discharge duration then equals

$$t = 9.2 \cdot L/R \tag{5.28}$$

which corresponds to equation (5.27) for the overdamped case.

As Figure 5.18 shows (Parker, 1985), there is a limit to the combination of spark discharge duration on spark energy that can be realized in practice. This is because a stable arc phase cannot exist unless the degree of ionization of the gas, which is determined by the spark current, exceeds a certain minimum level.

In Chapter 7, the concept of electric spark ignition sensitivity profile is discussed in connection with a standard test for ignition of dust layers by electric sparks (Figure 7.33). In fact, Parker's results for the four dusts in cloud form, as presented in Figure 5.18, are electric spark ignition sensitive profiles. The influence of the spark discharge duration on the minimum ignition energy is important for adequate use of test data in practice. For example, very low minimum ignition energies determined by the standard discharge circuits of $L \geq 1$ mH discussed in Chapter 7 may not be relevant for assessing the electrostatic spark ignition hazard in an industrial plant. This is because high inductance values are unlikely to occur in accidental electrostatic discharge circuits in industry.

As discussed in Section 1.1.4.6 in Chapter 1, several kinds of electrostatic discharges in air do not occur across two well-defined, sharp electrodes and therefore don't have such a well-defined shape as the discharge in Figure 5.17. In such cases, which will not be discussed any further in the present context, one could expand the concept of an ignition sensitivity profile to that of an ignition sensitivity surface for a given dust cloud, by adding a spark geometry dimension, as illustrated in Figure 5.19. The definition of an appropriate geometric parameter would, however, require careful consideration.

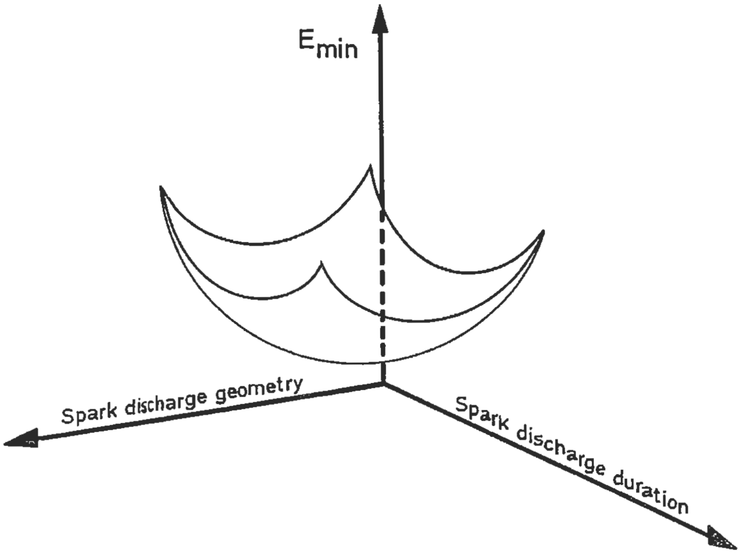

Figure 5.19 *Schematic illustration of the possible concept of electric spark ignition sensitivity surface of an explosible dust cloud.*

5.3.4
INFLUENCE OF SOME FURTHER PARAMETERS ON THE MINIMUM IGNITION ENERGY OF DUST CLOUDS

5.3.4.1
Movement/Turbulence of Dust Clouds

The marked increase of the minimum ignition energy for premixed gases with the turbulence intensity of the gas mixture has been demonstrated by various workers, including Ballal and Lefebvre (1977) and Bradley and Lung (1987). One would expect a similar influence of the turbulence intensity of dust clouds on their minimum ignition energies, as indicated by Figure 1.40 in Chapter 1. Figure 5.20 gives some supplementary data by Smielkow and Rutkowski (1971).

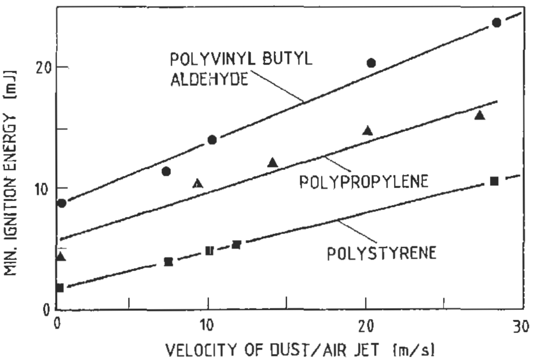

Figure 5.20 *Influence of velocity of dust cloud through spark gap region on the minimum electric spark ignition energy for three plastic dusts of particle size <75 µm (From Smielkow and Rutkowski, 1971).*

These workers dispersed a given quantity of dust from a small cup into the spark gap region by means of an air jet of known velocity. The minimum ignition energies of three dusts, using a 0.1–1.0 H inductance in the capacitive spark discharge circuit, were measured as functions of the estimated velocity of the dispersed dust cloud through the spark gap region. As can be seen from Figure 5.20, a systematic increase of the energy required for ignition, with the dust/air velocity, was found.

5.3.4.2
Spark Gap Length

This effect was studied by Ballal (1980), using quasi-laminar dust clouds of various materials. A set of results are given in Figure 5.21 that indicate a systematic increase of the optimum spark gap length for ignition with increasing minimum ignition energy at the

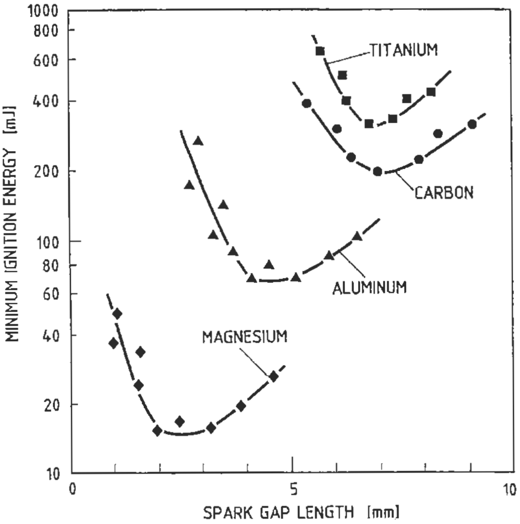

Figure 5.21 *Influence of electrode gap length on the minimum ignition energy of clouds of four metal dusts in air at atmospheric pressure. Dust concentration corresponds to equivalence ratio 0.65. Surface/volume mean particle size is 40 μm (From Ballal, 1980).*

optimum gap length. This is consistent with the general picture for premixed gases, for which a close correlation between quenching distance and minimum ignition energy has been established.

Norberg, Xu, and Zhang (1988) found that the optimum spark gap length for igniting clouds in air of various easily ignitable powders was in the range 6–8 mm. The capacitive sparks were of the short-duration type (low series inductance and resistance). The minimum ignition energies were in the range 1–6 mJ.

5.3.5
THEORIES OF ELECTRIC SPARK IGNITION OF DUST CLOUDS

Smielkow and Rutkowski (1971) derived a semi-empirical equation for the minimum electric spark ignition energy of dust clouds. Their experiments disclosed the following empirical relationship:

$$E_{\text{min}} = AS_f^{-3.56} \tag{5.29}$$

where E_{min} is the minimum ignition energy (mJ) and S_f is the spatial laminar flame front speed (cm/s) of the dust cloud in question, and A is a constant.

The semi-empirical equation was obtained by inserting a Mallard-le Chatelier-type expression for S_f (see Section 4.2.1 in Chapter 4) into equation (5.29).

In their theoretical analysis, Kalkert and Schecker (1979) used the basic equation in the Jost theory for ignition of premixed gases:

$$\lambda\left(\frac{\partial^2 T}{\partial r^2} + \frac{2\partial T}{r\partial r}\right) = \rho c \frac{\partial T}{\partial t} \tag{5.30}$$

as the point of departure. Here, λ is the heat conductivity of the gas, T is the temperature, r is the radius, ρ is the gas density, c is the specific heat of the gas at constant pressure, and t is the time.

By making several simplifying assumptions, they were able to derive the following equation for $E_{\min}$:

$$E_{\min} = (4\pi\,\kappa)^{3/2}\rho c\left[\frac{ln2}{12}\frac{\rho_s c_s}{\lambda}\right]^{3/2} T_f d^3 \tag{5.31}$$

where $\kappa = \lambda/(\rho \times c)$ is the "temperature conductivity" of air, d is the diameter of the dust particles (monosized), ρ_s and c_s are the density and specific heat of the particle material, and T_f is the flame temperature (defined as 1300 K).

A central feature of equation (5.31) is that $E_{\min} \sim d^3$. Figure 1.30 in Chapter 1 shows the close agreement between predictions by equation (5.31) and experimental values for polyethylene dust. (Note: $E_{\min}$ and MIE are interchangeable notations for the minimum electric spark ignition energy.)

Klemens and Wojcicki (1981) were specifically interested in modeling the electric spark ignition of coal dust clouds in air. They were able to validate their model predictions against unique experimental evidence of the development of the spark kernel and subsequent establishment of self-sustained flame propagation through the dust cloud away from the spark. An example is shown in Figure 5.22.

The overall physical picture of the ignition process on which the model of Klemens and Wojcicki was based is as follows: During and following the spark discharge, the dust particles and the air in the vicinity of the spark kernel are heated. As a consequence, volatiles are evolved from the particles, mix with air, and the mixture ignites. As the temperature increases further, the oxidation of the solid particle phase (coke) begins.

The temperature in the spark kernel and its close vicinity decreases with time due to heat drain. However, if ignition occurs, a flame front appears at the same time, at a certain distance from the spark axis, and starts to propagate outward at the laminar flame speed of the coal dust/air cloud in question.

The rate of energy delivery to the spark channel during spark discharge was taken into account in the mathematical model. Typically, the duration of a 50 mJ spark is about 0.10 ms. It was assumed that the energy density along the radius of the spark channel was linear at any instant. Plane, cylindrical, and spherical models all were formulated.

Numerical simulations, using the model, were carried out, employing the establishment of a flame front propagating at a defined speed, as the criterion of ignition. In other words, whenever the spark energy exceeds the minimum ignition energy, the region over which the temperature rises is not limited to the spark region but spreads into the mixture at the speed corresponding to the fundamental burning velocity of the dust cloud.

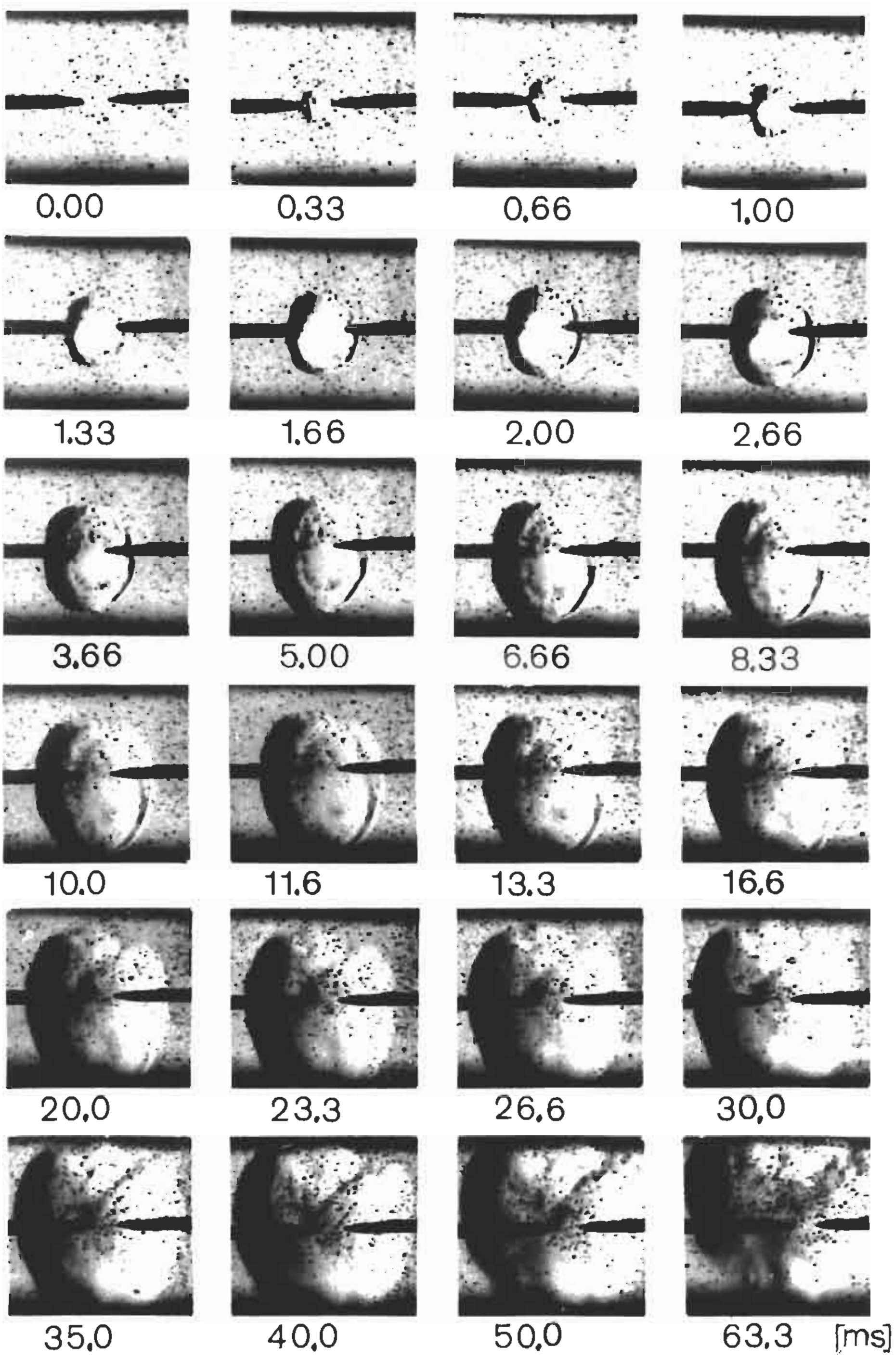

Figure 5.22 *Electric spark ignition of a cloud of ignite dust in air. Dust concentration is 106 g/m^3. Spark energy is 3.0 J. Spark discharge duration is 0.10 ms (From Klemens and Wojcicki, 1981).*

Gubin and Dik (1986) developed a mathematical model assuming that the oxidation occurred as a heterogeneous reaction between oxygen from the gas phase and the particle surface. They further assumed that the spark discharge initially generated a certain quantity of heat located within a narrow channel in the spark gap. The heat drain from the channel to the surroundings was assumed to occur essentially by conduction, radiation and convection being neglected. The basic heat balance equation was of the same form as that derived by previous workers. As in the case of other workers, the ignition criterion was the establishment of self-sustained laminar flame propagation in the dust cloud. It would appear that Gubin and Dik may not have been aware of the other investigations mentioned previously.

5.4
IGNITION OF DUST CLOUDS BY HEAT FROM MECHANICAL RUBBING, GRINDING, OR IMPACT BETWEEN SOLID BODIES

5.4.1
BACKGROUND

Whether or not metal sparks or hot spots from accidental impacts, rubbing operations, and the like between solid bodies can initiate dust explosions has remained a controversial issue for a long time. Many attempts have been made at resolving the puzzle by analyzing past accidents with the objective to identify the ignition sources. A summary with reference to the grain, feed, and flour industry is given in Table 5.6.

Table 5.6 Percentage of dust explosions in the grain, feed, and food industry assumed to be initiated by "friction sparks" or unknown sources

Investigation no.	Period	Number of explosions	% Ignited by "friction sparks"	% Unknown	% "Friction sparks" + unknown
1	1860–1973	535	20	46	66
1	1949–1973	128	17	27	44
2	1941–1945	91	54	18	72
3	1958–1975	137	9	62	71
4	1965–1980	83	28	5	30–35

Source: Pedersen and Eckhoff, 1987.

As can be seen, "friction sparks" are claimed to play a significant part. If one further takes into account that it is often tacitly implied that a substantial part of the "unknowns" may have been initiated by some untraceable source, such as metal sparks and electrostatic discharges, the friction spark becomes the most suspect of all the potential ignition sources.

The situations in which metal sparks and hot spots can be generated in an industrial process plant fall into two main categories. The first is grinding and cutting operations, by which continuous, dense showers of sparks are produced and comparatively large hot spots may be generated. The second is single accidental impacts.

5.4.2
SPARKS AND HOT-SPOTS FROM RUBBING, GRINDING, AND MULTIPLE IMPACTS

The ability of metal sparks or hot spots from grinding operations to ignite dust clouds has been demonstrated by several researchers. The experiments by Leuschke and Zehr (1962) are probably the first ones in which dust clouds were ignited by grinding wheel metal sparks. However, no clouds of organic dusts ignited. Zuzuki, Takaoka, and Fujii (1965) ignited different coal dusts using both sparks and hot spots from a piece of steel in contact with a grinding wheel rotating at 23–47 m/s peripheral velocity. Allen and Calcote (1981) conducted similar experiments, in which metal sparks were generated by pressing a steel rod against a rotating grinding wheel. By retarding and focusing the spark stream, it was possible to ignite clouds of natural organic dusts such as corn starch and wheat grain dusts.

Kachan et al. (1976) studied the ignition of clouds of coal dust by metal sparks or hot spots generated by the cutters of a coal cutting machine, when cutting pyrite and sandstone at a speed of 1.5–2.0 m/s. The coal dust contained 24% volatiles or more, and 85% was finer than 75 μm. The dust concentration was 100 g/m^3. Using pyrite containing more than 35% sulfur, and with a load per cutter of 1–3 kW, the probability of ignition was practically 100%. However, the coal dust cloud did not ignite until after 15–80 s of continuous cutting with sparking, depending on the load. This long delay suggests that the ignition source was not the spark shower but a hot spot generated either at the cutter tip or on the pyrite surface just behind the cutter.

Ritter (1984a, 1984b) and Müller (1989) conducted extensive studies of ignition of dust clouds by sparks and hot surfaces generated by scratching, grinding, and multiple-impact processes. They used the concept of equivalent electric spark energy for characterizing the ignition potential of the various scratching, grinding, and impact sources studied. This was done by first determining the lowest concentration of a given dust in air at which an essentially quiescent dust cloud could be ignited by the heat source investigated. The minimum electric spark ignition energy at this particular dust concentration was then determined and taken as the equivalent electric spark energy of that particular heat source.

Ritter and Müller found linear correlations between the minimum ignition temperature of the dust cloud determined by the BAM furnace (Chapter 7) and the logarithm of the equivalent minimum electric spark ignition energy, for the various ignition sources investigated, as illustrated in Figure 5.23.

The example indicated by dot-dashed lines says that a dust cloud of minimum ignition temperature 615°C cannot be ignited by flint sparks from grinding or scratching unless its minimum ignition energy is lower than about 20 mJ. Similar correlations were found for sparks and hot spots from multiple impacts.

Unfortunately the type of relationships illustrated in Figure 5.23 are not generally applicable because in practice grinding, scratching, and impact processes may differ

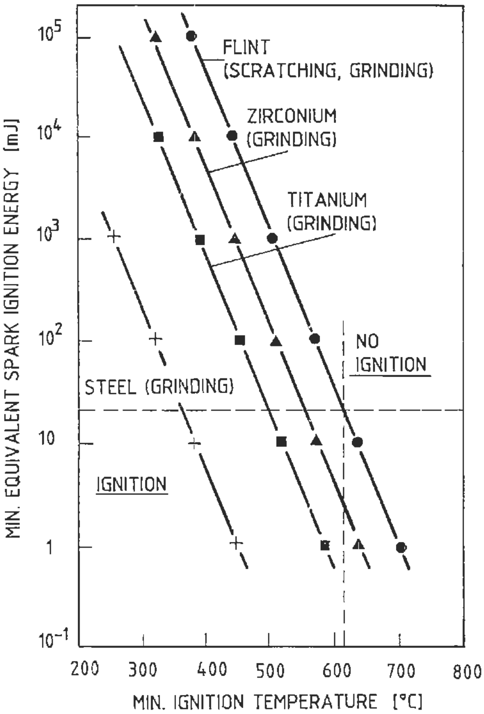

Figure 5.23 *Correlation between minimum ignition temperature of dust clouds (BAM furnace) and minimum equivalent electric spark ignition energy for various scratch and grinding ignition sources (From Müller, 1989).*

from the specific ones used in the experiments of Ritter and Müller. However, their approach is an interesting attempt at resolving a very complex matter.

Dahn and Reyes (1987), using a 20 liter explosion vessel, studied ignition of transient dust clouds by grinding sparks generated by forcing a metal rod against a rotating grinding wheel located within the vessel. A striking feature, shown in Table 5.7, is the negative result obtained with the two aluminum rods. This is in accordance with the discussion in Section 1.1.4.5 in Chapter 1.

5.4.3
SPARKS, HOT SPOTS, AND FLASHES FROM SINGLE ACCIDENTAL IMPACTS

Pedersen and Eckhoff (1987) studied the ignition of clouds of corn starch and grain dust in air by sparks, hot spots, and thermite flashes from single accidental impacts, using the apparatus described in Section 7.12.2 in Chapter 7 and illustrated in Figures 7.40 and 7.41. They investigated impacts of net energies up to 20 J and tangential velocities of approach from 10 m/s to 25 m/s. Table 7.2 in Chapter 7 gives some results from ignition with titanium

Table 5.7 Ignition of dust clouds by metal sparks and hot spots generated by forcing a metal rod against a rotating grinding wheel (rod diameter 6.3 mm; contact force 13.2 N; estimated contact time between rod and wheel before ignition <1 s)

Dust cloud properties			Minimum peripheral grinding wheel speed for ignition using various metal rod materials (m/s)			
Dust tested	Particle size (μm)	Dust concentration (g/m³)	1018 Mild steel	316 Stainless steel	3003-H14 Aluminum	6061-T6 Aluminum
M6 (propellant)	<75	250	12.4	13.5	NI*	NI
M30Al (propellant)	<75	410	11.2	13.5	NI	NI
M31Al (propellant)	<150	320	10.4	14.0	NI	NI
CBI (igniter)	<150	410	8.8	14.0	NI	NI
Black powder	<75	250	11.6	14.0	NI	NI
Pittsburgh coal dust	<75	350	10.0	NI	NI	NI
Corn starch	<75	350	8.0	14.0	NI	NI

*NI = No ignition up to a peripheral grinding wheel speed of 20 m/s.
Source: Dahn and Reyes, 1987.

impacts against rusty steel (thermite flash ignition). A positive correlation between the frequency of ignition and the minimum electric spark ignition energy is indicated.

Single impacts with steel as the spark-producing material generated a very low number of sparks as compared to the number produced by titanium under the same impact conditions. The temperatures of individual steel sparks, however, could reach the same level as those of titanium sparks (~2500°C).

Impacts of standard quality aluminum against rusty steel generated no sparks nor any other luminous reaction at all, only a thin smear of aluminum atop the rust (see Section 1.1.4.5 in Chapter 1). Impacts with hard aluminum-containing alloys were not investigated.

In most cases, ignition by titanium sparks (e.g., from titanium against concrete) was observed very close to the point of impact. However, occasionally ignition was also observed 10–30 cm downstream of the impact point. Ignition by a single metal spark was never observed. A fairly dense cluster of sparks seemed necessary to ignite the clouds of corn starch.

Any moving object in the dust cloud reduces the ignition sensitivity of the cloud in the vicinity of the object by inducing turbulence. The experiments showed that, at a given net impact energy, the ignition frequency dropped when the impact velocity increased. Therefore, at a given net impact energy, objects generating low turbulence represent a greater ignition hazard than objects generating high turbulence. This was illustrated by an experiment in which the impacting object on the spring-loaded arm (Figure 7.40) was withdrawn slightly, allowing it, once the arm was released, to pass just above the anvil without touching it. Instead, an electric spark was discharged at the point where the impact would normally have occurred and the frequency of ignition measured as a function of electric spark energy for various tangential arm-tip velocities. The results are shown in Figure 5.24.

The microscopic nature of the anvil surface is decisive for the spark formation process. For example, impacts against worn concrete surfaces exposing naked stone and gravel faces produced considerably more sparks than impacts against a fresh concrete surface covered with cement.

The overall practical conclusion of the investigation by Pedersen and Eckhoff (1987) is that, up to net impact energies of 20 J, tangential accidental single impacts between

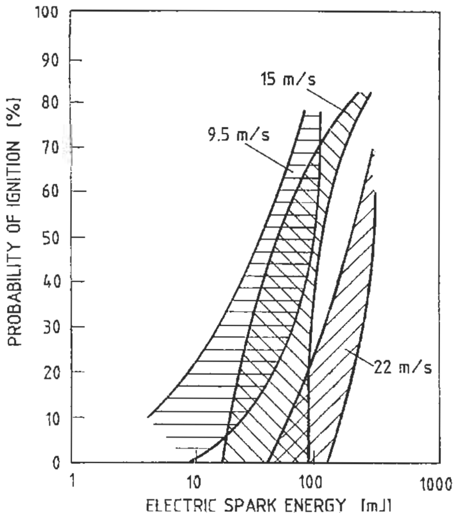

Figure 5.24 *Effect of tangential "impact" velocity on ignition sensitivity of clouds of lycopodium in air. Delay between "impact" and electric spark discharge is 0.3–10 ms. Envelopes embrace the experimental points (From Pedersen and Eckhoff, 1987).*

various types of steel and between steel and rusty steel or concrete are unable to ignite clouds of grain and feed dust or flour, even if the dusts are dry. Impacts of standard quality aluminum against rusty steel will not generate even visible sparks. In the case of titanium, the sparks produced can initiate explosions in clouds of dried corn starch but not in clouds of starch containing 10% moisture or more, not even in the case of thermite flashes. However, for net impact energies ≫20 J the situation may be different.

5.5
IGNITION OF DUST CLOUDS BY HOT SURFACES

5.5.1
EXPERIMENTAL STUDY OF THE INFLUENCE OF SIZE OF THE HOT SURFACE

The decrease of the minimum ignition temperatures of explosible gas mixtures with increasing hot surface size has been known for a long time. A classic investigation of this subject is by Silver (1937). A similar dependence of the minimum ignition temperature on the area of the hot surface would be expected for dust clouds. Figure 5.25 gives some experimental data from Pinkwasser (personal communication, 1989) confirming this expectation.

The three smallest surfaces were 10 mm long pieces of heated wire of thickness 0.7, 1.2, and 6.0 mm, respectively, bent as a U. The largest surface of 1000 mm^2 was obtained by coiling 50 mm of the 6.0 mm diameter wire. Figure 5.25 also gives the BAM furnace minimum ignition temperatures of the three dusts, assuming a hot surface area of about 2000 mm^2.

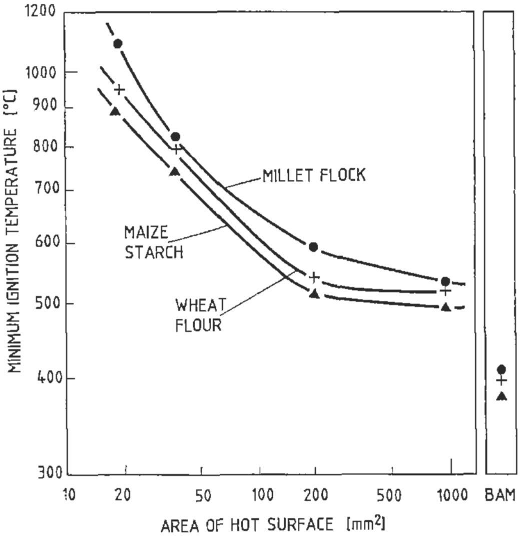

Figure 5.25 *Influence of the area of hot surface on the minimum ignition temperature of clouds of natural organic dust in air compared with results from BAM furnace tests (hot surface area is approximately 2000 mm2) (From Pinkwasser, 1989).*

5.5.2
THEORIES FOR PREDICTING THE MINIMUM IGNITION TEMPERATURES OF DUST CLOUDS

In their theoretical investigation, Mitsui and Tanaka (1973) focused on the influence of particle size on the minimum ignition temperature. They considered a spherical dust cloud, inside which heat was generated by combustion and from which heat was lost due to convection and radiation. They then assumed a combustion rate with an Arrhenius-type exponential temperature dependence and proportional to the total particle surface area in the spherical dust cloud. The critical ignition condition was specified as the rate of heat generation due to chemical reaction being equal to the rate of heat loss. The resulting equation seemed to predict an influence of particle size in good agreement with experimental results when using a tuning constant depending on the dust chemistry.

A similar study, focusing particularly on the geometry of the Godbert-Greenwald furnace (see Chapter 7), was undertaken by Takigawa and Yoshizaki (1982). They investigated natural organic dusts and found a reasonably good agreement between measured and numerically predicted dependence of minimum ignition temperature on particle size. The numerical model calculations further revealed that the residence time of the dust particles in the furnace largely affects the ignition process. It was concluded that the steady-state solution of the minimum ignition temperature is not applicable to the ignition process in the Godbert-Greenwald furnace. Comparison of model predictions with experimental data from other workers confirmed the validity of the predicted effect of the residence time of the dust particles in the furnace on the minimum ignition temperature.

Nomura and Callott (1986) modified the Cassel-Liebman theory to make it account for the influence of the residence time of the dust particles in the hot furnace. The theory suggested that it is possible for the ignition temperature of monosized coal particles of about 50 μm diameter to be minimal even for a limited residence time.

The theory was extended to dust clouds with a distribution of particle sizes. It was shown that there exists a range of size distributions for which the possibility of ignition is at a maximum. The calculated results were presented as Rosin-Rammler charts, indicating the size distributions most sensitive to ignition.

Higuera, Linan, and Trevino (1989) analyzed the heterogeneous ignition of a cloud of spherical monodisperse coal particles injected instantaneously in the space between two parallel isothermal walls. They focused on the range of large gas/particles thermal capacity ratios, for which the temperature difference between the particles and the gas is important. Radiative heat transfer was accounted for using the Eddington differential approximation, and heat conduction between the particles and the gas was also included in the model. Heat release was assumed to occur at the surface of the particles through the heterogeneous reaction $C(s) + {}^{1}/_{2}O_2 \rightarrow CO$, obeying an Arrhenius law with large activation energy. Critical conditions for ignition were determined on the basis of a quasi-steady treatment. The effects of the ratio of gas temperature to wall temperature, the conduction/radiation parameter, and the size of the reacting dust cloud relative to the optical length was explained.

Tyler (1987) was concerned with the problem of scaling ignition temperatures of dust clouds from laboratory test apparatus to industrial scale. In particular, he focused on the Godbert-Greenwald furnace (see Chapter 7). As pointed out by Tyler, there seems to be no single physical/chemical pattern for ignition of a dust cloud. In substances like sulfur and polyethylene, the minimum ignition temperatures are high enough to allow complete evaporation or pyrolysis to form gaseous fuels. At the other extreme are metals of minimum ignition temperatures, at which neither the metal nor its oxide vaporizes fully. In the first case, the exothermic oxidation process almost certainly takes place in the gas phase, whereas in the second it occurs at the surface of or within the particle (see also Section 4.1 in Chapter 4). However, these differences may not be important in the establishment of the unstable state of ignition that precedes a fully developed flame.

Tyler developed a Semenov-type mathematical model of the ignition of a dust cloud in a heated environment (furnace). However, validation of the model was difficult. No reliable activation energies were found in the literature that could be definitely attributed to the heat release reaction that occurs at the ignition temperature, and Tyler pointed out that the activation energy could be quite different from that associated with a fully fledged flame; indeed, the dominant mechanism could well be different in the two situations. Nevertheless useful parametric studies could be performed. For example, the model predicted comparatively large changes of the minimum ignition temperature with furnace diameter. The Godbert-Greenwald furnace has a diameter of 37 mm. For a furnace diameter of 300 mm and a dust with a Godbert-Greenwald value of 1000 K, the model predicted a minimum ignition temperature at least 150°C lower than the Godbert-Greenwald value.

However, few experimental data were traced for the influence of increased furnace diameter on the minimum ignition temperature except when comparing data from the new U.S. Bureau of Mines furnace (see Chapter 7) and the Godbert-Greenwald furnace. The ratio of the two furnace diameters is 2.7, and therefore significant differences in the minimum ignition temperatures from the two apparatuses are expected. However, the picture offered by existing data was inconclusive. For some dusts, the experimental Godbert-Greenwald value was even lower than that from the new furnace.

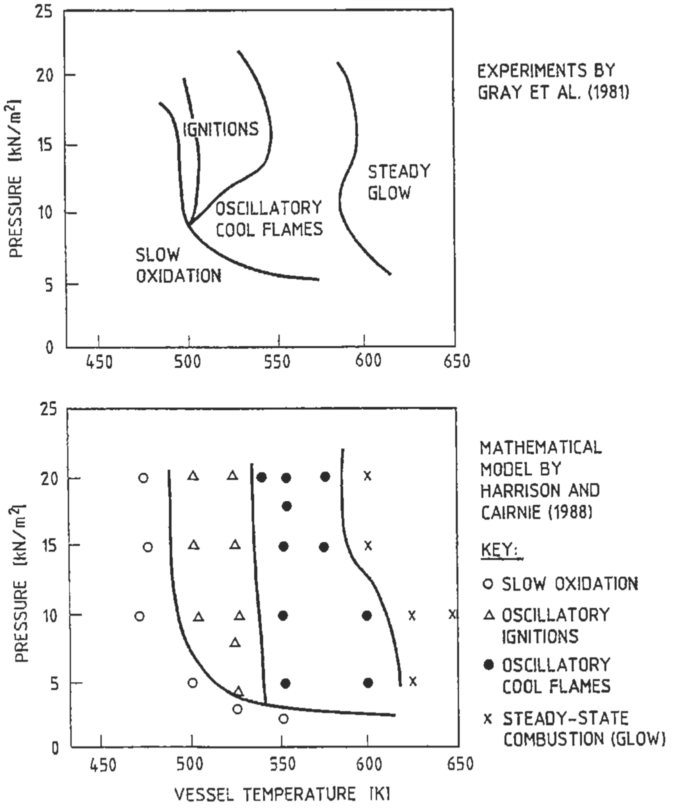

Figure 5.26 *Comparison of experimentally observed and numerically predicted ignition diagrams for acetaldehyde/air in a continuously stirred 0.5 liter glass bulb (From Harrison and Cairnie, 1988).*

Tyler concluded that there was no theoretical model by which data from Godbert-Greenwald furnace tests could be transformed to minimum ignition temperatures in the more-complex practical situations in industry. He suggested that stirred reactor ignition experiments, as performed successfully for combustible gas mixtures, could provide a more fundamental understanding of dust cloud ignition processes. Such experiments may yield appropriate activation energies for the ignition processes, which may be used to scale minimum ignition temperatures more reliably. The study of ignition of acetaldehyde/air mixtures, by Harrison and Cairnie (1988) and Harrison et al. (1988), taking this approach, is an excellent example of its potential. Figure 5.26 shows a comparison of experimentally determined and theoretically predicted ignition diagrams for the acetaldehyde/air system.

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Chapter 6

Sizing of Dust Explosion Vents in the Process Industries: Further Consideration of Some Important Aspects

6.1
SOME VENT SIZING METHODS USED IN EUROPE AND THE UNITED STATES

6.1.1
VENT RATIO METHOD

This and other methods were reviewed by Schofield (1984), Lunn (1984), and Field (1984). The vent ratio method requires that $P_{red} \leq 0.14$ bar(g) and that the opening pressure and inertia of the vent cover are small. The *vent ratio* is defined as vent area per unit of enclosure volume. Originally, a fixed vent ratio, determined by the maximum rate of pressure rise in the 1.2 liter Hartmann bomb (see Chapter 7), was specified for a specific dust. However, as the enclosure volume gets larger, the required vent area increases more than if geometrical similarity is used for scaling, and unreasonably large vents result. For example, with a vent ratio of 1 m^2/6 m^3, a 6 m^3 spherical vessel would need only 6% of the sphere surface for venting, whereas a huge sphere of 24,000 m^3 volume would need the entire surface. Because of this, the vent ratio method was modified by reducing the required ratio as the enclosure volume increases. It has not been possible to trace the experimental basis for the vent ratio method. The method was, however, widely used, for example, in the United Kingdom. Note that Table A.4 in Section A.2.7 in the Appendix provides data for converting K_{st} values to corresponding Hartmann bomb $(dp/dt)_{max}$ values.

6.1.2
"NOMOGRAPH" METHOD

This method was originally designed by Verein deutscher Ingenieure (1979), but later it was also adopted for the United States by the National Fire Protection Association (1988).

The nomograph method rests partly on the results of extensive large-scale experimentation by Donat (1971) and Bartknecht (1978) and partly on theoretical analysis by Heinrich (1974). A self-contained system for vent sizing was developed. It consists of the 1 m^3 ISO standard test (see Chapter 7) to determine a maximum rate of pressure rise used as the characteristic of the explosion violence of a given dust (K_{St} value) and a series of nomographs from which vent areas can be estimated, using K_{St}, the enclosure volume, the maximum explosion pressure P_{red}, and the static opening pressure of the vent cover P_{stat} as parameters. The relevance of the "nomograph" method is tied to the nature of the large-scale experiments on which it rests. These experiments were conducted with dust clouds generated by blowing the dust into the experimental enclosures from pressurized reservoirs through narrow nozzles, ensuring uniform, well-dispersed, and highly turbulent dust clouds. Consequently, the burning rate for a given dust (see Chapter 4) was very high, in fact too high to be representative of the dust clouds in most industrial situations. In spite of this, the nomograph method has been widely used. As discussed in Section 9.3.7.5 in Chapter 9, the conservative vent sizing approach of Verein deutscher Ingenieure (1979) has been adopted as a basic also in a recent European CEN standard, but venting area requirements may be eased if supported by adequate experimental evidence.

Lunn, Brookes, and Nicole (1988) extended the VDI 3673 nomographs from 1979 to K_{St} values as low as 10 bar m/s and P_{red} values down to 0.05 bar(g). The experiments on which this extension was based were of the same kind as those forming the basis of the original nomographs, that is, of very high turbulence and dust dispersion. Therefore, the extended nomographs are subject to the same basic limitations as the original VDI nomographs. This is illustrated in Figure 6.1, in which maximum pressure/vent area correlations predicted by the extended nomographs are shown together with experimental

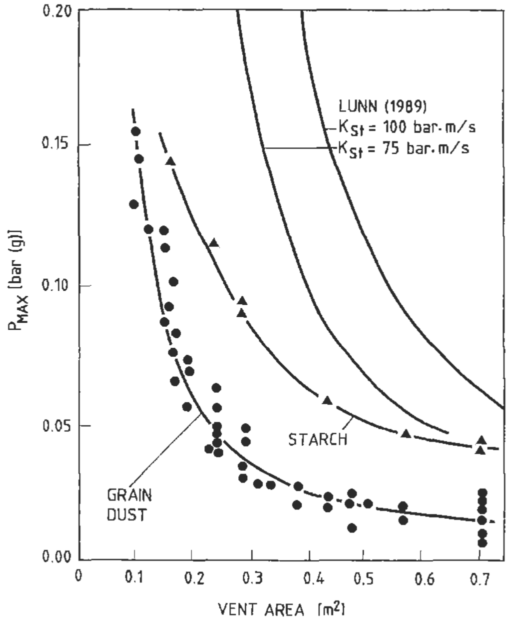

Figure 6.1 *Experimental correlations between the vent area and maximum explosion pressure for grain dust and starch explosions in a 2.8 m³ cubical vessel. Vents were covered with hinged metal doors or glass panes in pivoted frames (From Brown and Hanson, 1933). Comparison with correlations was suggested by Lunn (1989).*

data from the investigation by Brown and Hanson (1933). It is felt that the experiments of Brown and Hanson were considerably closer to the reality most often encountered in industry than those on which the nomograph method was based. This exemplifies that much excellent experimental work that was performed in the past on various aspects of the dust explosion problem often seems to be overlooked by some more recent investigators. The paper by Brown and Hanson indeed deserves to be read carefully even today.

The dusts used by Brown and Hanson were dried to less than 8% moisture, and it seems reasonable to assume that their K_{St} values would not have been lower than the values 75 and 100 bar m/s used for comparison with the Lunn predictions. If the starch was from corn, a K_{St} of 100 bar m/s is a low estimate.

Comparisons between "nomograph"-method predictions and data from more recent realistic experiments are given in Section 6.2.

6.1.3
THE SWEDISH METHOD

In this method, issued by Danielson (1981), the explosion violence classification of the dust is by $(dP/dt)_{max}$ from standard 1.2 liter Hartmann bomb tests (see Chapter 7), as in the vent ratio method. Dusts are classified in three groups:

Group 1: $(dP/dt)_{max} \leq 300$ bar/s.
Group 2: 300 bar/s $< (dP/dt)_{max} <$ 600 bar/s.
Group 3: $(dP/dt)_{max} \geq 600$ bar/s.

The required vent area per unit enclosure volume is specified for each of the three groups, but the value decreases with increasing enclosure volume. For Group 1 dusts and hinged vent panels of maximum mass 20 kg/m^2, the tabular relationship between vent area A (m^2), volume V (m^3), and P_{red} (bar(g)) can be approximated by the equation

$$A = \frac{0.019}{P_{red}^{0.5}} \bullet V^{0.635} \tag{6.1}$$

For Group 2 dusts and using hinged vent covers of maximum mass 12 kg/m^2, the Swedish method corresponds approximately to the equation

$$A = \frac{0.044}{P_{red}^{0.5}} \bullet V^{0.685} \tag{6.2}$$

For enclosures of $L/D > 3$, the Swedish method requires that the enclosure be divided into the minimum number of fictitious subvolumes needed for all of these to have $L/D \leq 3$. The required vent area for the actual enclosure is then the sum of the areas calculated for all the fictitious subvolumes.

After the enforcement of the European Union "Atex 100a" Directive (see Chapter 8) in 2003, continued use of the traditional Swedish venting guidelines will be harmonized with common European requirements.

6.1.4
THE NORWEGIAN METHOD (MODIFIED DONAT METHOD)

The method most often used in Norway and described by Eckhoff (1988) is a slightly modified version of the method of Donat (1971), based on Hartmann bomb assessment of $(dP/dt)_{\max}$. The modification consists in the use of continuous graphs, obtained by interpolation and extrapolation of Donat's tabulated data. For elongated enclosures of length-to-equivalent-diameter ratios exceeding 4, the enclosure should be divided into the number of fictitious subvolumes required for an L/D of each subvolume to be ≤ 4. The vent area for each subvolume is assessed individually, and the sum of all the areas is taken as the total area required for venting the enclosure.

After the enforcement of the European Union "Atex 100a" Directive (see Chapter 8) in 2003, continued use of the traditional Norwegian venting guidelines will be harmonized with common European requirements.

6.1.5
THE RADANDT SCALING LAW FOR VENTED SILO EXPLOSIONS

Bartknecht (1987) indicated that equation (6.3), derived by Radandt,

$$P_{\text{red}} = (bV^c)/(A - aV^c) \tag{6.3}$$

could be used for scaling vent areas for silos. In this equation, which was also presented by Radandt (1989), A (m^2) is the vent area, P_{red} (bar(g)) is the maximum explosion pressure in the vented silo, V (m^3) is the silo volume, and a, b, and c are empirical constants depending on the K_{St} value of the dust. P_{stat} is assumed to equal 0.1 bar(g), and P_{red} must not exceed 2 bar(g). For K_{St}, = 200 bar m/s, that is, the upper limit of the dust explosion class St 1, the constants are $a = 0.011$, $b = 0.069$, and $c = 0.776$, based on results from experiments in a 20 m^3 silo with direct injection of dust from a conventional pneumatic transport line. It is not clear, however, how the volume scaling constant was obtained.

Eckhoff (1991) investigated equation (6.3) by comparing data from silo explosions of twice the linear scale used by Radandt with Radandt's data. As shown by Eckhoff (1987), the violence of explosions in vented large-scale silos of $L/D = 6$ are strongly dependent on the location of the ignition point. For this and other reasons, it appears that Radandt's equation (6.3) may not be entirely satisfactory as a general scaling law for silo vent areas.

6.1.6
OTHER VENT SIZING METHODS

Some further methods that have been suggested for sizing dust explosion vents are also discussed by Schofield (1984) and Lunn (1984). They include the K-factor method investigated by Gibson and Harris (1976), the Schwab and Othmer Nomograph, the equivalence coefficient method by Maisey (1965a), and the method by Rust (1979), the latter three based on $(dP/dt)_{\max}$ from the 1.2 liter Hartmann bomb. A review of literature on further developments in design of dust explosion venting systems is given in Section 9.3.7.5 in Chapter 9.

6.2

COMPARISON OF DATA FROM RECENT REALISTIC FULL-SCALE VENTED DUST EXPLOSION EXPERIMENTS WITH PREDICTIONS BY VARIOUS VENT SIZING METHODS

6.2.1

EXPERIMENTS IN LARGE SILOS OF $L/D \leq 4$

The experiments by Matusek and Stroch (1980) in a 500 m^3 silo of $L/D = 3$ should be mentioned. Unfortunately, however, explosibility data for the dusts used were not provided, and the results are therefore difficult to analyze in a general context.

A series of experiments in a 500 m^3 silo of $L/D = 4$ was reported by Eckhoff and Fuhre (1984). A cross section of the silo is shown in Figure 6.2.

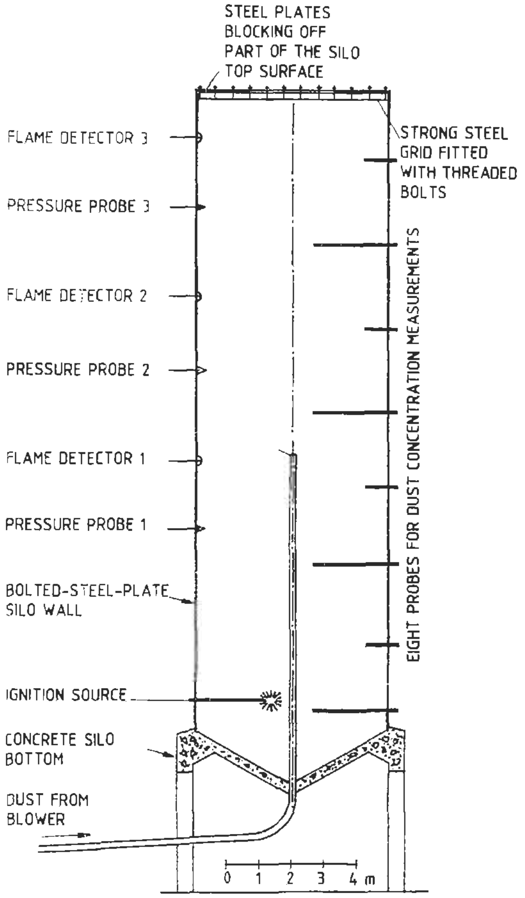

Figure 6.2 *Cross section of 500 m^3 silo used in vented dust explosions experiments in Norway (From Eckhoff and Fuhre, 1984).*

The silo was one of a complex of several partly condemned bolted steel plate silos that were made available for dust explosion experiments. Pneumatic injection of dust through a 200 mm Ø pipeline was used for generating explosible dust clouds in the silo. With wheat grain dust, about 300 kg of dust was blown into the silo per experiment. With corn starch the quantity was somewhat less, about 200 kg. A larger quantity was required for the wheat grain dust because dispersion was not complete due to fibrous particles, and lumps settled to the silo bottom before all the dust had been injected. The ignition point was close to the silo bottom. In all experiments but one, dust injection was terminated a few seconds before ignition, allowing the dust cloud to become comparatively quiescent. The experimental results for wheat grain dust as well as corn starch explosions are shown in Figure 6.3, together with predictions based on some of the vent sizing methods discussed or mentioned in Section 6.1.

The vent cover used in the experiments was a sheet of plastic with a low static opening pressure, on the order of 0.01–0.02 bar(g). The final, exceptional corn starch explosion,

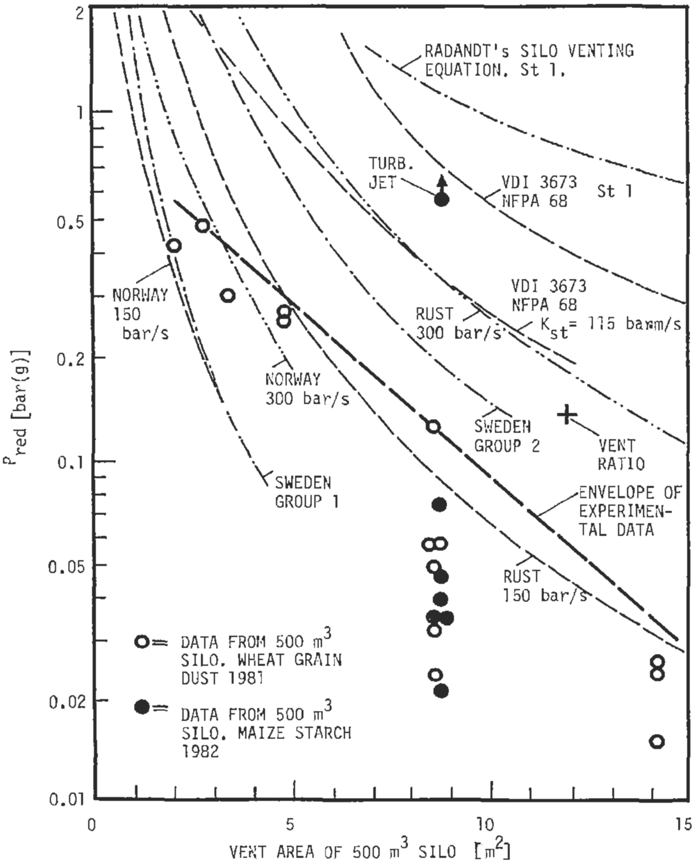

Figure 6.3 *Results from vented corn starch and wheat grain dust explosions in a 500 m^3 silo cell in Norway. Comparison is made with predicted P_{red}/vent area correlations by various vent sizing methods in current use. P_{red} means the maximum pressure in the vented enclosure during the explosion (From Eckhoff and Fuhre, 1984, with adjustments by Eckhoff, 1990).*

Figure 6.4 *High-turbulence corn starch explosion in 500 m³ bolted steel plate silo at Vaksdal, Norway, in April 1982 (Photographer: A. M. Fosse, Vaksdal). For a much clearer picture, see Color Plate 5.*

Figure 6.5 *Damaged 500 m³ silo after explosion shown in Figure 6.4.*

named *turbulent jet*, was so violent that the silo wall (nailed steel plates) ruptured, at about 0.6 bar(g), as shown in Figure 6.4. As seen in Figure 6.5, this produced an additional vent of about 50 m^2, which prevented the pressure from rising even further.

In this exceptional experiment 300 kg of starch had been charged to the dust feeding system, and dust was still being injected at full rate when the ignition source was activated. Such a configuration, with dust being blown upward in the silo from a point about halfway up on its axis, is probably not a realistic situation in an industrial silo. However, the dramatic result demonstrates that even the conservative VDI 3673 from 1979 may, in certain cases of particularly high turbulence levels, specify too small vent openings.

All the other experimental results in Figure 6.3 show that, in the case of a large enclosure of 500 m^3 and $L/D = 4$, VDI 3673 from 1979 and NFPA 68 from 1988 oversize the vent by at least a factor of 2–3, if the K_{St} value of 115 bar m/s for the corn starch used in the experiments is applied, and at least by a factor of 5, if the common St 1 nomograph is used. The Rust method agrees well with the wheat grain dust experiments (150 bar/s in the Hartmann bomb) but oversizes the vents for the corn starch (300 bar/s) by a factor of 3. The "vent ratio" method, which simply requires half the silo top as vent for keeping P_{red} equal to maximum 0.14 bar(g), oversizes the vent in this particular case by a factor of 2:3. Radandt's equation gives exceptionally large vents, but the small length-to-diameter ratio of four of the 500 m^3 silos may be too small to make Radandt's constants for "silos" applicable.

Both the Swedish and the Norwegian vent sizing methods are comparatively liberal, suggesting P_{red} values that are in fact lower than the experimental maximum values. An argument in defense of such a liberal approach is that vent sizing involves risk-analytical considerations rather than being a fully deterministic problem (see Section 6.6). In the 500 m^3 silo explosion experiments, researchers attempted to create a worst-case situation in terms of both dust concentration and location of the ignition point.

6.2.2

EXPERIMENTS IN SLENDER SILOS OF $L/D \approx 6$

Sizing of vents for large, slender silos of the kind frequently used in the grain, feedstuffs, and food industries remains a controversial subject. However, during the 1980s, valuable information has been gained through large-scale experiments. Two experimental programs were run in parallel, one in Norway, reported by Eckhoff, Fuhre, and Pedersen (1987) and Eckhoff et al. (1988), and one in Switzerland and the Federal Republic of Germany, reported by Radandt (1985, 1989) and Bartknecht (1987). Both silos had *L/D* values close to 6, but the volume of the Norwegian silo was 236 m^3, whereas that of the Swiss-German one was only 20 m^3. A cross section of the Norwegian silo is shown in Figure 6.6, and a picture of the experimental site in Figure 6.7.

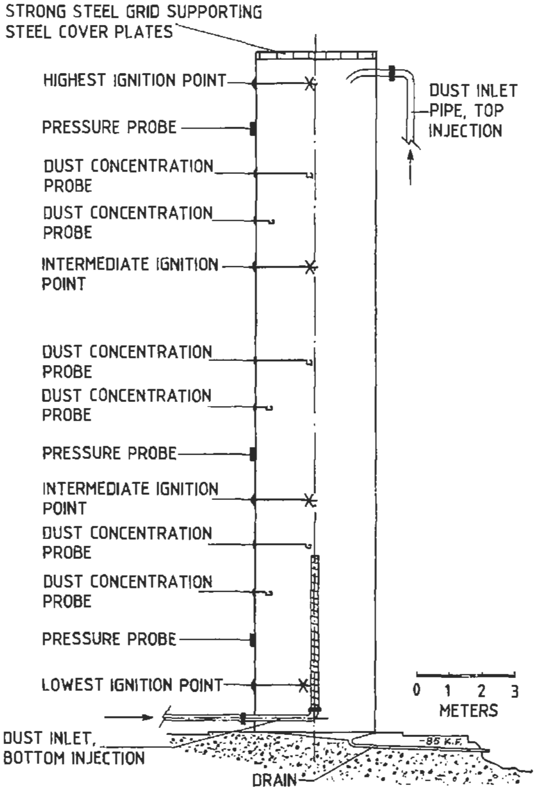

Figure 6.6 *236 m^3 silo in Norway for dust explosion experiments, L/D = 6 (From Eckhoff et al., 1987).*

Figure 6.7 *Experimental site outside Bergen, Norway, with 236 m³ steel silo, dust injection system and instrumentation cabins. An enclosed winding staircase runs along the silo wall to the left. For a much clearer picture, see Color Plate 6.*

The vent was located in the silo roof, and the silo was instrumented with dust concentration probes of the type shown in Figure 1.76 in Chapter 1 and pressure sensors, and the ignition point could be shifted over the entire length, from top to bottom. Dust was injected pneumatically from either the bottom or the top, as indicated in Figure 6.6. Air of the desired flow rate was supplied by a Roots blower, and dust was fed into the airflow at the desired mass flow rate. Before ignition, the airflow was stopped and the dust cloud allowed to calm down for a few seconds. Figure 6.8 shows venting of a corn starch explosion in the 236 m^3 silo.

In the experiments by Eckhoff et al. (1988), the vent opening was located in the silo wall near the top, as opposed to in the silo roof. This reduced the maximum explosion pressures somewhat, but otherwise the results were similar to those from roof venting.

Radandt apparently assumed that the effects observed in the comparatively small 20 m^3 silo are also representative of larger silos. However, results from the 236 m^3 silo experiments suggest that this is not a valid assumption in general. A more detailed discussion of this problem is given by Eckhoff (1989).

One set of results from the two silo sizes for which the vent areas were fairly close to geometric similarity is given in Figure 6.9. The hatched envelope of all experimental data for the 236 m^3 silo shows a dramatic decrease of the maximum explosion pressure when the ignition point was moved upward along the silo axis, whereas the hatched strip enveloping the data for the 20 m^3 silo shows very little of this effect. The discrepancy is

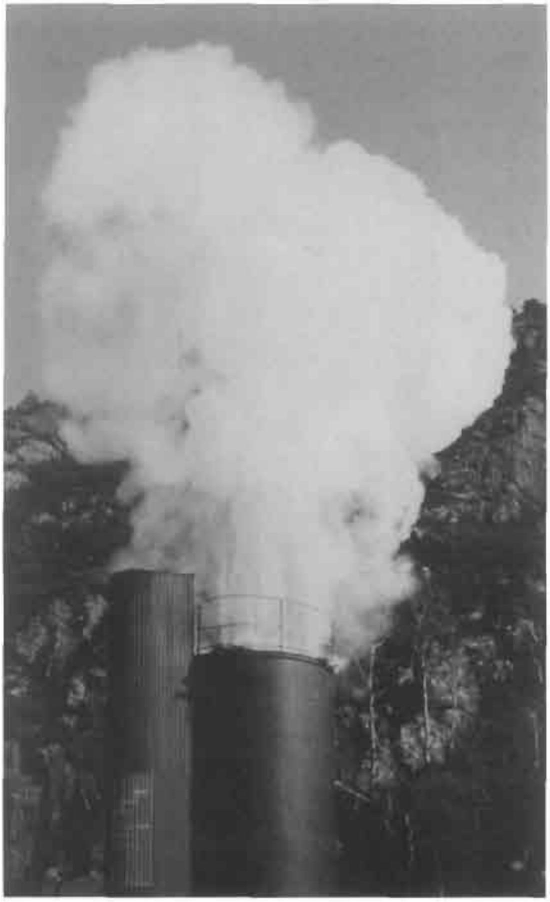

Figure 6.8 *Vented corn starch explosions in 236 m³ steel silo in Norway. For a much clearer picture, see Color Plate 7.*

most probably due to the different ways in which the dust clouds were generated in the silos and the difference between the silo heights (10 m and 22 m), as discussed by Eckhoff (1989).

In the 236 m^3 silo, the dust cloud was essentially quiescent at the moment of ignition. There is little doubt that the marked increase of the maximum explosion pressure as the ignition point was shifted downward in the silo was caused by flame acceleration due to expansion-induced flow. This is in complete accordance with what has been found in the past in numerous dust and gas explosion experiments in one-end-open tubes, ducts, and galleries.

In the 20 m^3 silo, the strong, turbulent dust jet, extending from the top of the silo and several meters downward, was maintained during the ignition and explosion process. This most probably caused very rapid propagation of any flame initiated at the top of the silo to the central parts. This would explain why the top ignition and central ignition gave almost the same explosion pressures. In bottom ignition, the initial flame propagation was probably comparatively slow. But, as soon as the flame front reached the turbulent dust zone in the central parts of the silo, a much more rapid flame propagation pattern, similar to that generated by central ignition, probably developed.

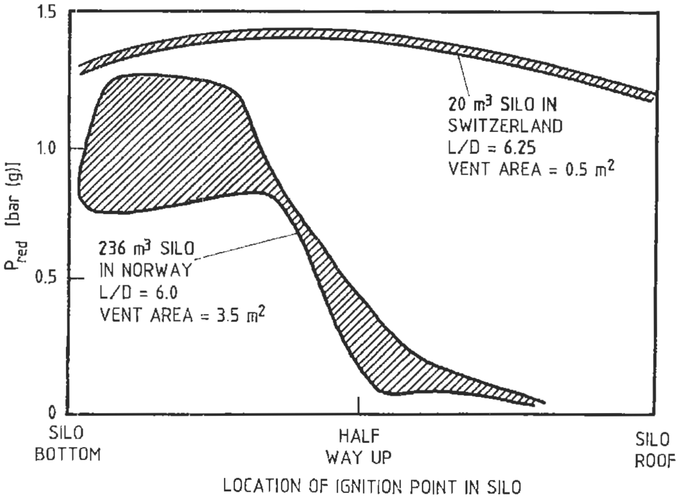

Figure 6.9 *Influence of location of the ignition point in the silo on maximum vented explosions pressure, with a comparison of trends in 20 m³ and 236 m³ silos (From Eckhoff, 1990).*

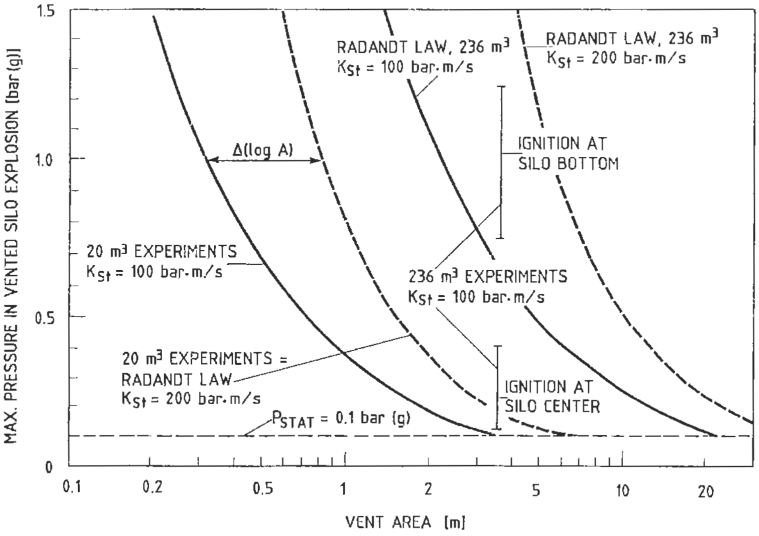

Figure 6.10 *Comparison of Radandt's scaling law for silo vent sizing and experiments in a 236 m³ vented silo in Norway (From Eckhoff, 1990).*

In Figure 6.10, predictions by Radandt's equation (6.3) are compared with the results of the experiments in the 236 m³ silo.

The dotted curves are obtained by means of equation (6.3) for 20 m³ and 236 m³ volumes, using the constants given by Radandt for dust class St 1. The upper limit of St 1 is $K_{St} = 200$ bar m/s, and it was assumed that the dotted curves apply exactly to this K_{St} value. In the absence of further information, it was then assumed that the ratios between the vent areas for $K_{St} = 200$ bar m/s and 100 bar m/s for the 20 m^3 silo and a given maximum pressure also apply to the 236 m^3 silo (geometrical similarity). This makes it possible to estimate theoretical Radandt predictions for $K_{St} = 100$ bar m/s, even for 236 m^3, by shifting the Radandt curve for 200 bar m/s and 236 m^3 to the left by Δ (log A).

The actual experimental maximum explosion pressures found in the 236 m^3 silo of $L/D = 6$ are partly considerably higher, partly considerably lower than the estimated Radandt value for $K_{St} = 100$ bar m/s. On the other hand, even the highest experimental pressure of 1.2 bar(g) is significantly lower than the Radandt value of 1.75 bar(g) for $K_{St} = 200$ bar m/s (St 1 dusts).

It must be concluded that, so far, the relevance of and experimental and theoretical basis for the simple scaling law suggested by Radandt have not been fully substantiated.

All the dust clouds in the large-scale silo experiments reported by Eckhoff and coworkers were generated by pneumatic pipeline injection, in accordance with typical industrial practice. After a series of experiments using the VDI-method for dust cloud generation, as described by Radandt (1983), Bartknecht and Radandt decided to adopt pneumatic pipeline injection, even in their 20 m^3 silo experiments, as discussed by Bartknecht (1988). This was a significant decision, reflecting the appreciation of the need for conducting experiments in accordance with reality in industry. In fact, Bartknecht and Radandt took a further, most relevant step, by adding experiments in which the dust was not injected directly into the silo but via a cyclone at the silo top. In this way, the dust cloud in the silo, generated by discharge of dust from the cyclone bottom via a rotary lock, was neither well dispersed nor very turbulent. The published results from using the latter method, which are traced, are limited to one data point for corn starch shown in Figure 6.11. For a vent area of 1.3 m^2, the maximum explosion pressure generated by dropping the dust from a cyclone at the silo top via a rotary lock was only 0.2 bar(g), whereas direct pneumatic injection gave about 0.5 bar(g) and the traditional, artificial VDI-method (discharge of dust from pressurized bottles) about 0.75 bar(g). Figure 6.11 illustrates the need for applying a differentiated approach to sizing of dust explosion vents and further full-scale experiments under realistic industrial conditions.

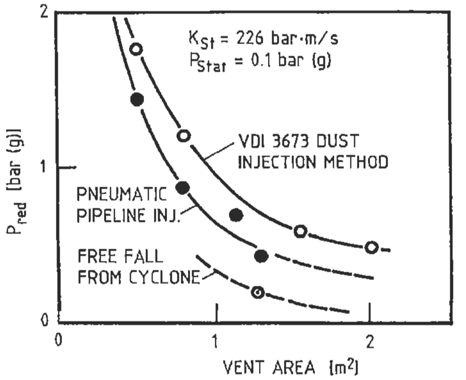

Figure 6.11 *Results from vented corn starch explosions in a 20 m^3 silo, demonstrating the marked influence of the mode of dust cloud generation on the maximum pressure P_{red} in the silo during the vented explosions (Data from Bartknecht, 1987, 1988).*

The pneumatic injection experiments in the 20 m^3 silo gave substantial scatter in the experimental maximum explosion pressures, as discussed by Bartknecht (1988). The P_{red} data in Figure 6.11 are the highest values obtained for each vent area, which means that the curve for direct pneumatic injection is quite conservative. This kind of scatter, which is also apparent in Figure 6.3, emphasizes the relevance of applying risk-analytical considerations in vent sizing (see Section 6.6).

6.2.3
PNEUMATIC PIPELINE INJECTION EXPERIMENTS IN VESSELS OF SMALL *L/D*

It was noted with considerable interest when the German-Swiss "school" of dust explosion venting research started to use industrial pneumatic pipeline transport systems for generating dust clouds even in vessels of small *L/D*. Siwek (1989a, 1989b) discussed a series of explosion experiments in which the dust clouds were generated in this way in vented enclosures of 10, 25, and 250 m^3, respectively. Some results for corn starch are reproduced in Figure 6.12 together with the VDI 3673 recommendations from 1979. Experimental results for two quite high dust cloud injection velocities are given. For all three enclosure volumes, the dust entered the vessel through a 90 mm Ø nozzle at

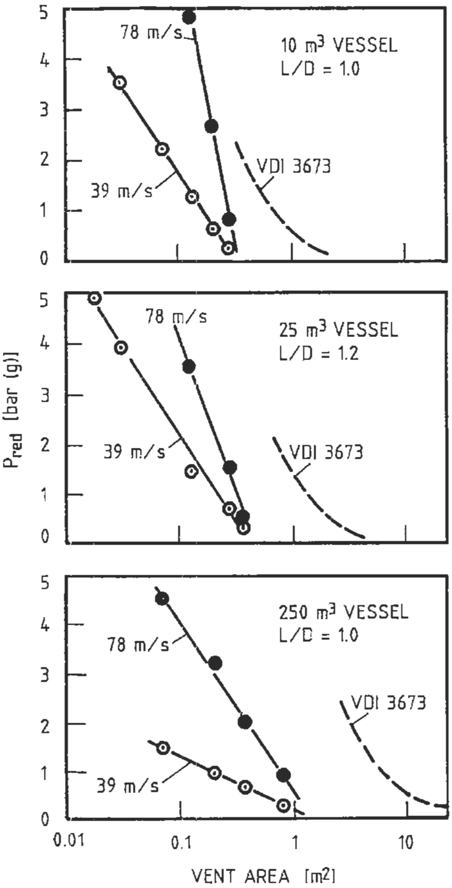

Figure 6.12 *Results from vented corn starch explosions experiments (low-moisture starch of* $K_{St} = 226$ *bar m/s) in vessels of various volumes. Pneumatic injection of dust into vessels is through a 90 mm Ø nozzle located at the vessel apex, pointing vertically downward. Dust jet velocities are 78 and 39 m/s. Dust concentration in the jet is 12.5 kg/m*^{3}*,* $P_{stat} =$ *0.1 bar(g). Comparison is made with VDI 3673 (1979 edition) predictions (Experimental data from Siwek, 1989a).*

the vessel top, which generated a strong dust jet vertically downward into the vessel. For all three volumes the predicted VDI 3673 areas are substantially larger than those found experimentally for any given P_{red} (note that the vent area scale in Figure 6.12 is logarithmic). The discrepancy increases systematically with increasing enclosure volume. For example, for $P_{red} = 0.5$ bar(g), the VDI 3673 vent area for the 10 m^3 vessel is 3.7 times the experimental value even for the highest injection velocity of 78 m/s. For the 25 m^3 vessel, the corresponding factor is 5.4 times; and for the 250 m^3 vessel, as large as 8.3 times. The reason for this trend could be the following: The relative influence of the dust jet, with respect to inducing turbulence in the vessel and thereby increasing the combustion rate, must necessarily decrease with vessel volume. In the experiments forming the basis of VDI 3673 from 1979, the systems for dispersing the dust into the vessels were scaled up with the vessel size until the desired, very high turbulence level had been reached even in large volumes. Such experimental conditions are extremely conservative and must lead to grossly oversized vents for large empty volumes of moderate *L/D*.

The systematic trend in Figures 6.12 of 78 m/s yielding more violent explosions than 39 m/s is probably due to increase of both the degree of turbulence and the degree of dust dispersion (deagglomeration) with the velocity of the dust cloud jet.

It is important to note that the experimental data in Figure 6.12 are not generally valid for pneumatic injection of the corn starch used. Upward injection from the bottom or sideways injection might give different results. Furthermore, the written account indicates that Siwek (198a) did not investigate lower corn starch concentrations in the feeding pipe than 2–3 kg/m^3. In the closed 1 m^3 standard ISO vessel (see Chapters 4 and 7), this particular starch gave the most violent explosions for 0.6–0.7 kg/m^3. It could well be, therefore, that more violent explosions would have resulted in Siwek's experiments, if the dust concentration in the feeding pipe had been in this range.

Siwek (1989a) also used wheat flour ($K_{St} = 75$ bar m/s) and Technocel ($K_{St} = 170$ bar m/s) in his experiments. He found a systematic increase of P_{red} with K_{St} for the three dusts for the test conditions investigated.

6.2.4
EXPERIMENTS IN JAPAN ON VENTING OF DUST EXPLOSIONS IN A 0.32 m^3 CYCLONE

Vented dust explosion experiments in a 1.2 m^3 cyclone under realistic industrial conditions were reported by Tonkin and Berlemont (1972) and Palmer (1973). As shown by Eckhoff (1986), the vent area requirements in these realistic experiments were considerably smaller, by a factor of 5, than those prescribed by VDI 3673 (1979). Similar cyclone explosion experiments were conducted in Japan more recently by Hayashi and Matsuda (1988). Their apparatus is illustrated in Figure 6.13.

The volume of the cyclone vessel was 0.32 m^3, its total height 1.8 m, and the diameter of the upper cylindrical part 0.6 m. Dust clouds were blown into the cyclone through a 150 mm diameter duct. The desired dust concentration was acquired by independent control of the airflow through the duct (suction fan at downstream end of system) and the dust feeding rate into the airflow. The dust trapped in the cyclone dropped into a 0.15 m^3 dust collecting chamber bolted to the bottom outlet. The exhaust duct of 0.032 m^2

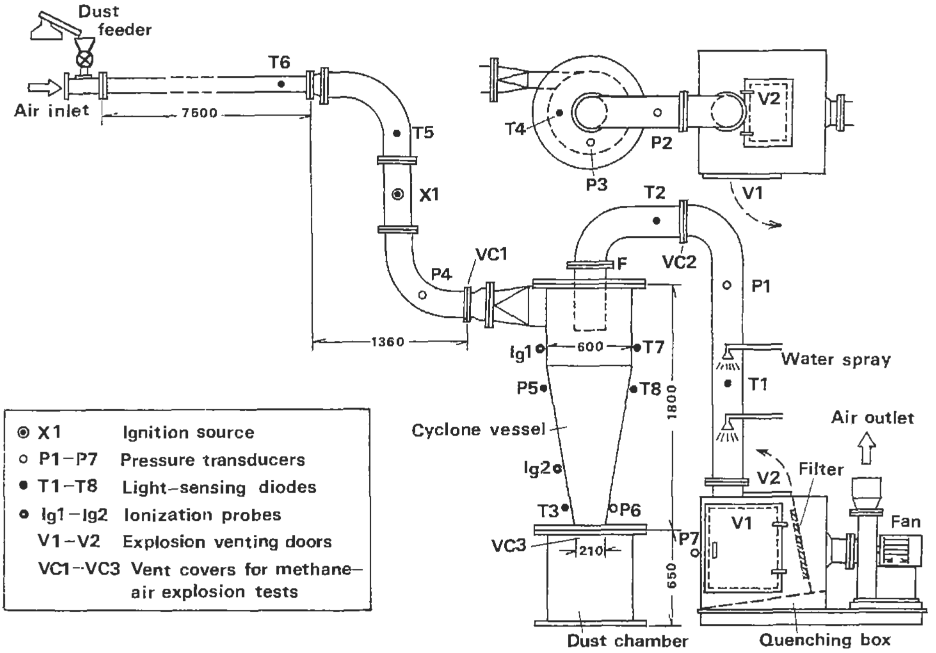

Figure 6.13 *Experimental cyclone plant for studying dust explosion development under realistic industrial condition (From Hayashi and Matsuda, 1988).*

cross section and 3 m length ended in a 0.73 m^3 cubical quenching box fitted with two vents of 0.3 m^2 and 0.1 m^2, respectively. The venting of the cyclone itself was through the 0.032 m^2 exhaust duct and the almost 10 m long 0.008 m^2 dust feeding duct. During explosion experiments, two water-spraying nozzles for flame quenching were in operation in the exhaust duct to protect the fan just outside the quenching box. The ignition source was a 5 kJ chemical igniter located in the dust feeding duct about 2 m upstream of the cyclone. Two different polymer dusts were used in the experiments, an ABS resin dust of median particle size 180 μm and an ethylene-vinyl acetate (EVA) copolymer dust of median particle size 40 μm.

In addition to the realistic "dynamic" explosion experiments, Hayashi and Matsuda (1988) conducted a series of experiments with the same two dusts, using an artificial "static" dust cloud generation method, very similar to that used in the experiments being the basis of the VDI 3673 (1979 edition). As illustrated in Figure 6.14, the dust feeding duct was then blocked at the entrance to the cyclone, which reduced the effective vent area slightly, to 0.032 m^2.

A system of two pressurized dust reservoirs and perforated tube dispersion nozzles were employed to generate the dust clouds. The 5 kJ ignition source was located inside the cyclone, halfway up on the axis (indicated by X2). The ignition source was activated about 100 ms after onset of dust dispersion.

Envelopes embracing the results of both series of experiments are given in Figure 6.15. As can be seen, the artificial, "static," method of dust dispersion gave considerably

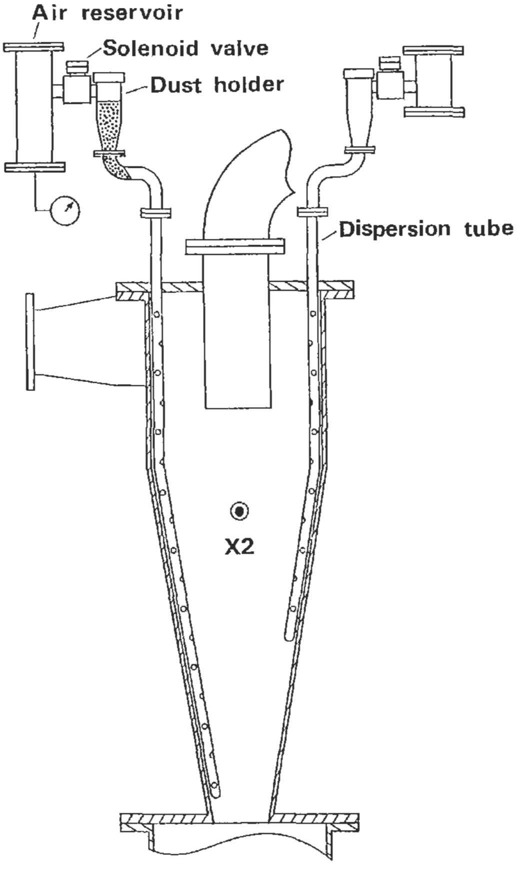

Figure 6.14 *A 0.32 m³ cyclone modified for generation of dust clouds by high-pressure injection through perforated dust dispersion tubes (From Hayashi and Matsuda, 1988).*

higher maximum explosion pressures in the cyclone, than the realistic, "dynamic," method. This is in accordance with the results of the earlier realistic cyclone experiments of Tonkin and Berlemont (1972). It is of interest to compare the "static" results in Figure 6.15 with predictions by VDI 3673 (1979 edition). A slight extrapolation of the nomographs to 0.32 m^2 vent area, assuming St 1 dusts, gives an expected maximum overpressure of about 2.5 bar(g), which is on the same order as the highest pressures of 1.5 bar(g) measured for the artificial "static" dust dispersion method and much higher than the pressures measured in the realistic experiments.

The NFPA 68 (1988 edition) includes an alternative nomograph that covers all St 1 dusts that do not yield higher P_{max} in standard closed bomb tests than 9 bar(g). This nomograph gives much lower P_{red} values than the standard nomograph, in particular for small volumes. In the 0.32 m^3 cyclone with a 0.032 m^2 vent, the alternative nomograph gives P_{red} equal to 0.50 bar(g), which in fact is close to the realistic experimental values. This alternative nomograph originates from Bartknecht (1987) and represents a considerable liberalization, by a factor of 2 or so, of the vent area requirements for most St 1 and St 2 dusts. However, the scientific and technical basis for this liberalization does not seem to have been fully disclosed in the open literature.

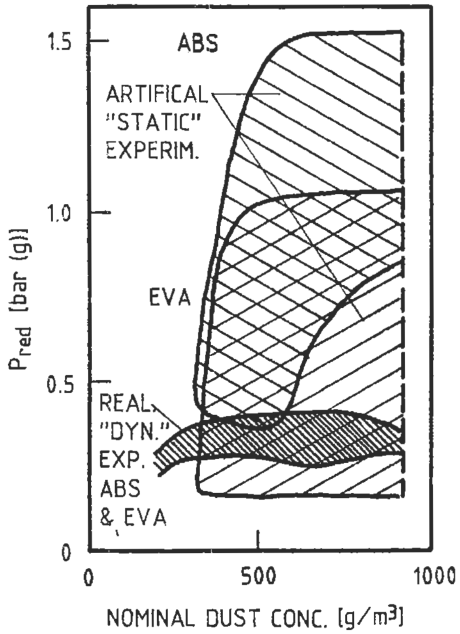

Figure 6.15 *Results from vented dust explosions in a 0.32 m³ cyclone using two different polymer dusts and two different methods of dust clouds generation, 0.03–0.04 m² open vents with ducts (Data from Hayahsi and Matsuda, 1988; from Eckhoff, 1990).*

6.2.5
REALISTIC EXPERIMENTS IN BAG FILTERS

6.2.5.1
Vented Explosions in a 6.7 m³ Industrial Bag Filter Unit in the United Kingdom

Lunn and Cairns (1985) reported on a series of dust explosion experiments in a 6.7 m³ industrial bag filter unit. The experiments were conducted during normal operation of the filter, which was of the pulsed-air, self-cleaning type. Four different dusts were used, and their K_{St} values were determined according to ISO (1985) (see Chapter 7). The ignition source was located in the hopper below the filter bag section. In the experiments of main interest here, the vent was in the roof of the filter housing. Hence, to get to the vent, the flame had to propagate all the way up from the hopper and through the congested filter bag section. The results from the experiments are summarized in Figure 6.16, together with the corresponding VDI 3673 (1979 edition) predictions.

Figure 6.16 first shows that the P_{red} in the actual filter explosions were mostly considerably lower than the corresponding VDI 3673 predictions and close to the theoretical minimum value 0.1 bar(g) at which the vent cover ruptured. Second, there is no sensible correlation between the VDI 3673 ranking of expected pressures according to the K_{St} values and the ranking actually found.

Lunn and Cairns (1985) also reported on a series of dust explosion experiments in a generously vented 8.6 m³ empty horizontal cylindrical vessel of $L/D \approx 6$. The same dusts were used as in the filter experiments, but the dust clouds were generated "artificially" by injection from pressurized reservoirs as in the standard VDI 3673 method. In spite of the similarity between the dust dispersion method used and the VDI 3673 dispersion method, there was no correlation between P_{red} and K_{St}.

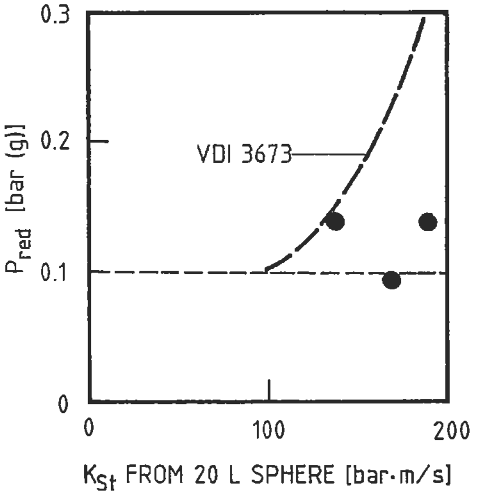

Figure 6.16 *Maximum explosion pressure P_{red} measured in dust explosions in an industrial 6.7 m^3 bag filter unit in normal operation, P_{stat} = 0.1 bar(g). (data from Lunn and Cairns, 1985). Comparison with VDI 3673 (1979 edition) (From Eckhoff, 1990).*

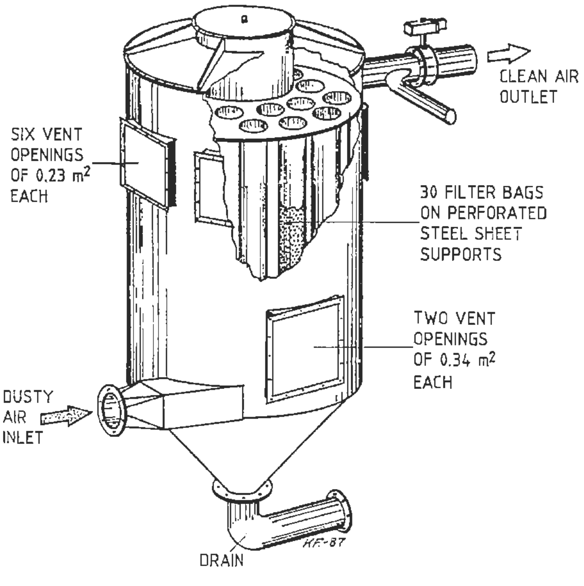

Figure 6.17 *A 5.8 m^3 experimental bag filter in Norway (From Eckhoff et al., 1989).*

6.2.5.2
Vented Explosions in a 5.8 m^3 Bag Filter in Norway

These experiments were reported in detail by Eckhoff, Alfert, and Fuhre (1989). A perspective drawing of the experimental filter is shown in Figure 6.17 and a photograph of a vented maize starch explosion in the filter in Figure 6.18.

Dust explosions were initiated in the filter during normal operation. A practical worst-case situation was realized by blowing dust suspensions of the most explosible concentration into the filter at 35 m/s and igniting the cloud in the filter during injection. Four

Figure 6.18 *Maize starch explosion in a 5.8 m^3 experimental bag filter unit in Norway. Vent area is 0.16 m^2. Static opening pressure of the vent cover is 0.10 bar(g). Maximum explosion pressure is 0.15 bar(g). For a much clearer picture, see Color Plate 8.*

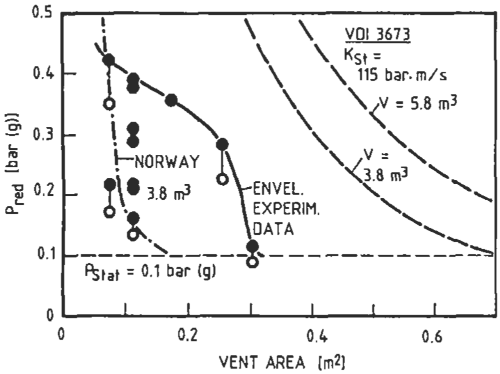

Figure 6.19 *Results from vented peat dust explosions in a 5.8 m^3 filter at P_{stat} = 0.1 bar(g). Comparison is made with VDI 3673 (1979 edition) and vent sizing method used in Norway (Eckhoff, 1988). Injected dust concentration is 600 g/m^3; ● = dust section of filter; ○ = clean section of filter (From Eckhoff, 1990).*

dusts were used: maize starch and peat dust, both having K_{St} = 115 bar m/s, and polypropylene and silicon dusts, both having K_{St} = 125 bar m/s. Considerable effort was made to identify worst-case conditions of dust concentration and ignition timing. At these conditions, experimental correlations of the vent area and P_{red} were determined for each dust.

As shown in Figure 6.19, the peat dust gave significantly lower explosion pressures than those predicted by VDI 3673 (1979), even if the predictions were based on the volume of the dusty filter section (3.8 m^3) only.

Figure 6.20 summarizes the results for all four dusts. As can be seen, the explosion pressures measured were generally considerably lower than those predicted by VDI 3673 (1979 edition) for all four dusts as long as the ignition source was a nitrocellulose flame. However, the singular result obtained for silicon dust ignited by a silicon dust flame emphasizes the different nature of initiation and propagation of metal dust flames as compared with flames of organic dusts (see the discussion in Eckhoff et al., 1989, and Chapter 4.)

As illustrated by Figure 6.19, P_{red} scattered considerably, even when the nominal experimental conditions were identical. This again illustrates the risk-analytical aspect of the vent sizing problem (see Section 6.6). Figure 6.19 suggests that VDI 3673 is quite conservative, whereas the method used in Norway is quite liberal, in agreement with the picture in Figure 6.3.

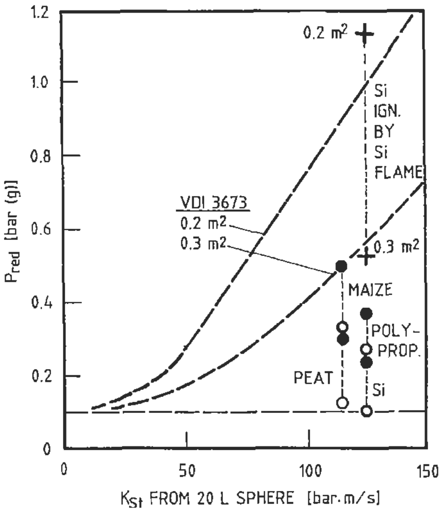

Figure 6.20 *Maximum explosion pressures for four dusts in a vented 5.8 m³ filter at two vent areas, as functions of* K_{St} *determined by the 20 liter Siwek sphere:*

● = *0.2 m² vent area* } *nitrocellulose flame ignition*
○ = *0.3 m² vent area*

+ = *silicon dust flame ignition of silicon dust*
P_{stat} = *0.1 bar(g)*

Comparison is made with the VDI (1979 edition) predictions for 3.8 m³ volume (dusty section of filter) (From Eckhoff, 1990).

In Figures 6.20 and 6.21, the 5.8 m³ filter results for all four dusts are plotted as functions of K_{St} from 1 m³ ISO standard tests and $(dP/dt)_{max}$ from Hartmann bomb tests (see Chapter 7).

Predictions by various vent sizing methods have also been included for comparison. The data in Figure 6.20 show poor correlation between the maximum explosion pressures measured in the filter at a given vent area and the maximum rates of pressure rise determined in standard laboratory tests. Although the K_{St} values of the four dusts were very similar, ranging from 115 to 125 bar m/s, the P_{red} (nitrocellulose flame ignition) for the four dusts varied by a factor of 2–3.

In the Hartmann bomb case, Figure 6.21 indicates a weak positive correlation between P_{red} and $(dP/dt)_{max}$ for nitrocellulose ignition, but it is by no means convincing. Figure 6.21 also gives the corresponding correlations predicted by three different vent sizing methods based on Hartmann bomb tests. Both the Swedish and the Norwegian methods are quite liberal. The Rust method oversizes the vents for the organic dusts excessively for $(dP/dt)_{max} > 150$ bar/s. There is, however, fair agreement with the data for silicon dust ignited by a silicon dust flame.

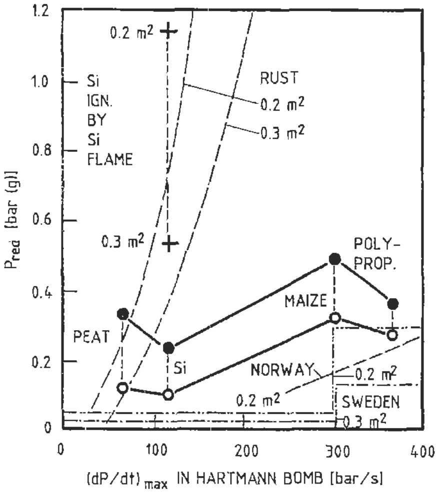

Figure 6.21 *Maximum explosion pressures for four dusts in a vented 5.8 m^3 filter at two vent areas, as functions of $(dP/dt)_{max}$ determined by the Hartmann bomb:*

● = *0.2 m^2 vent area* } *nitrocellulose flame ignition*
○ = *0.3 m^2 vent area*

+ = *silicon dust flame ignition of silicon dust*
P_{stat} = *0.1 bar(g)*

Comparison is made with VDI (1979 edition) predictions for 3.8 m^3 volume (dusty section of filter) (From Eckhoff, 1990).

The use of closed-bomb tests for predicting the violence of accidental dust explosions in industrial plants was discussed by Eckhoff (1984/1985; see also Chapter 7).

6.2.6

OTHER LARGE-SCALE EXPERIMENTS RELEVANT TO INDUSTRIAL PRACTICE

Some quite early work that is still of considerable interest and practical value deserves attention. The pioneering work of Greenwald and Wheeler (1925) on venting of coal dust explosions in long galleries is discussed in Section 4.4.7 in Chapter 4.

A set of results from the comprehensive investigation by Brown and Hanson (1933) on venting of dust explosions in volumes typical of the process industry were reproduced in Figure 6.1. The paper by Brown and Hanson describes a number of interesting observations and considerations, including the effect of the location and distribution of the vents and the influence of the size and type of ignition source.

Brown (1951) studied the venting of dust explosions in a 1.2 m diameter, 17 m long horizontal tube with and without internal obstructions. The tube was either closed at one end and vented at the other or vents were provided at both ends. In some experiments, an additional vent was provided in the tube wall midway between the two ends. The location of the ignition point was varied.

Brown and Wilde (1955) extended the work of Brown (1951) by investigating the performance of a special hinged vent cover design on the explosion pressure development in a 0.76 m diameter, 15 m long tube with one or more vents at the tube ends or in the tube wall.

Pineau, Giltaire, and Dangreaux (1974, 1976), using geometrically similar vented vessels of L/D about 3.5 and volumes 1, 10, and 100 m^3, investigated the validity of the vent area scaling law $A_2 = A_1(V_2/V_1)^{2/3}$. They concluded that this law, which implies geometrical similarity even of vent areas, was not fully supported by the experiments. However, as long as the dust clouds were generated in similar ways in all three vessel sizes and the ignition points were at the vessel centers, the experiments were in agreement with the law $A_2 = A_1(V_2/V_1)^{0.52}$.

Pineau, Giltaire, and Dangreaux (1978) presented a series of experimentally based correlations for various dusts between vent area and vessel volume for open and covered vents, with and without vent ducts. Both bursting membranes and spring-loaded and hinged vent covers were used in the experiments.

Zeeuwen and van Laar (1985) and Wingerden and Pasman (1988) studied the influence of the initial size of the exploding dust cloud in a given vented enclosure on the maximum pressure developed during the vented explosion.

The investigation showed that the pressure rise caused by the explosion of a dust cloud filling only part of a vented enclosure is higher than would be intuitively expected. Even if the dust cloud is considerably smaller than the enclosure volume, it is usually necessary to size the vent as if the entire volume of the enclosure were filled with explosible cloud.

Gerhold and Hattwig (1989) studied the pressure development during dust explosions in a vented steel silo of rectangular cross section. The length-to-equivalent-diameter ratio could be varied between 2 and 6. The explosion pressure and flame front propagation histories were measured using a measurement system similar to that illustrated in Figure 6.6. The influence of the key parameters of industrial pneumatic dust injection systems on the explosion development was investigated, in particular injection pipe diameter, airflow, and dust-to-air ratio. The general conclusion was that the maximum pressures generated with realistic pneumatic injection were substantially lower than those predicted by the VDI 3673 (1979 edition) guideline.

6.3
VENT SIZING PROCEDURES FOR THE PRESENT AND NEAR FUTURE

6.3.1
BASIC APPROACH AND LIMITATIONS

As shown in Section 6.2, realistic vented dust explosion experiments, conducted mostly during the 1980s, demonstrated that none of the vent sizing codes in use up to 1990 are fully adequate. It is proposed, therefore, that for the present and near future, sizing of dust explosion vents be primarily based on the total evidence from realistic experiments that is available at any time.

The following suggestions presuppose that the initial pressure in the enclosure to be vented is atmospheric. Furthermore, the vent covers must open completely within times comparable to the opening times of standard calibrated rupture diaphragms. In the case of heavier, and reversible, vent covers, such as hinged doors with counterweights or spring-loaded covers, additional considerations are required. The same applies to the use of vent ducts and the new, promising vent closure concept that relieves the pressure but retains the dust and flame, thus rendering vent ducts superfluous (see Section 1.4.6 in Chapter 1).

6.3.2
LARGE EMPTY ENCLOSURES OF *L/D* < 4

As shown in Figure 6.3, a large empty enclosure of volume 500 m^3 and $L/D = 4$, in the absence of excessive dust cloud turbulence, requires considerably smaller vents than those specified by VDI 3673 (1979 edition) or NFPA 68 (1988 edition). This also applies to the more liberal St 1 nomograph for constant-volume pressures $P_{max} < 9$ bar(g), proposed by Bartknecht (1987; not included in Figure 6.3). As shown in Figure 6.12, even more dramatic reductions in vent area requirements were found in a 250 m^3 spherical vessel. In this case, the vent area actually needed was only one-eighth that specified by VDI 3673 (1979 edition).

When sizing vents for large enclosures of $L/D \leq 4$, the exact vent area reduction factor as compared with VDI 3673 (1979 edition), has to be decided in each case, but it should certainly not be greater than 0.5. In some cases, it may be as small as 0.2–0.1.

6.3.3
LARGE, SLENDER ENCLOSURES (SILOS) OF *L/D* > 4

The only investigation of vented dust explosions in vertical silos of $L/D > 4$ and volumes >100 m^3 that has been traced is that described in Section 6.2.2. The strong influence of the location of the ignition source on the explosion violence, as illustrated in Figure 6.9, is a major problem. It is necessary, in each specific case, to analyze carefully what kind of ignition sources are likely to occur and what locations within the silo volume ignition have a significant probability (Eckhoff, 1987). For example, if the explosion in the silo cell can be assumed to be a secondary event, initiated by an explosion elsewhere in the plant, ignition will probably occur in the upper part of the silo by flame transmission through dust extraction ducts or other openings near the silo top. In this case, a vent of moderate size serves the purpose, even if the *L/D* of the silo is large. However, the analysis might reveal that ignition in the lower part of the silo is also probable, for example, because the dust has a great tendency to burn or smolder. In this case, even the entire silo roof, in some situations, may be insufficient for venting, and more sophisticated measures may have to be taken to control possible dust explosions in the silo.

6.3.4
SMALLER, SLENDER ENCLOSURES OF *L/D* > 4

The data of Bartknecht (1988) and Radandt (1985, 1989a) from experiments in the 20 m^3 silo constitute a useful reference point. Further data for a 8.7 m^3 vessel of $L/D = 6$ is found in the paper by Lunn and Cairns (1985). However, it is necessary to pay adequate attention to the way in which the dust clouds are generated in the various experiments and select experimental conditions that are as close as possible to the conditions prevailing in the actual industrial enclosure (see Figure 6.11). Depending on the way in which the dust cloud is generated in practice, vent area reduction factors, with reference to VDI 3673 (1979), may vary between 1.0 and 0.1.

6.3.5
INTERMEDIATE (10–25 m^3) ENCLOSURES OF SMALL *L/D*

The experimental basis is that of the VDI 3673 guideline (1979 edition) with highly homogeneous, well-dispersed, and turbulent dust clouds and the more recent results for much less homogeneous, less well-dispersed clouds (Figure 6.12). The vent area requirements identified by these two sets of experiments differ by a factor of up to 5. Adequate vent sizing therefore requires that the conditions of turbulence, dust dispersion, and level and homogeneity of dust concentration for the actual enclosure be evaluated in each case.

6.3.6
CYCLONES

Two realistic investigations have been traced (Tonkin and Berlemont, 1972, and Hayashi and Matsuda, 1988), and both suggest a significant vent area reduction in relation to VDI 3673 (1979 edition). The early investigation by Tonkin and Berlemont using a cyclone of 1.2 m^3, indicates an area reduction factor of 0.2. The more recent investigation by Hayashi and Matsuda, using a smaller cyclone of 0.32 m^3, indicates a factor of about 0.5. Hence, for organic St 1 dusts ($K_{St} \leq 200$ bar m/s) there seems to be room for vent area reductions with reference to the VDI 3673 (1979 edition) by factors in the range 0.5–0.2. However, for metal dusts, such as silicon, although there is no direct evidence from cyclone explosions with such dusts, the VDI 3673 (1979 edition) requirements should probably be followed, as in the case of filters (see Section 6.3.7).

6.3.7
BAG FILTERS

The experimental basis is the evidence in Figures 6.16 and 6.19–6.21, produced by Lunn and Cairns (1985) and Eckhoff et al. (1989). If ignition inside the filter itself is the most probable scenario (no strong flame jet entering the filter nor any significant pressure piling prior to ignition), the vent area requirements of VDI 3673 (1979 edition) for St 1 dusts can be reduced by at least a factor of 0.5. If the dust concentration in the feeding duct to the filter is lower than the minimum explosive concentration, the vent area may be reduced even more.

However, in the case of some metal dusts, such as silicon, primary ignition in the filter itself may be less probable and ignition is accomplished by a flame jet entering the filter from elsewhere. In this case, it is recommended that the vent area requirements of VDI 3673 (1979 edition) be followed.

6.3.8
MILLS

The level of turbulence and degree of dust dispersion in mills vary with the type of mill. The most severe states of turbulence and dust dispersion probably occur in air jet mills. The experimental technique for dust cloud generation used in the experiments on which VDI 3673 (1979 edition) is based is likely to generate dust clouds similar to those in an air jet mill. For this reason, it seems reasonable that VDI 3673 (1979 edition) be used without modification for sizing vents for this type of mill. In mills generating dust clouds that are less turbulent and less well dispersed, it should be possible to ease the vent area requirements, depending on the actual circumstances.

6.3.9
ELONGATED ENCLOSURES OF VERY LARGE *L/D*

This enclosure group includes galleries in large buildings, pneumatic transport pipes, dust extraction ducts, bucket elevators, and the like. In such enclosures, severe flame acceleration can take place because of the turbulence produced by expansion-generated flow in the dust cloud ahead of the flame. In extreme cases, transition to detonation can occur (see Chapter 4). The generally accepted main principles for venting of such systems should be followed. Either the enclosure must be made sufficiently strong to sustain even a detonation and furnished with vents at one or both ends or a sufficient number of vents have to be installed along the length of the enclosure to prevent severe flame acceleration. Chapter 8 of the National Fire Protection Association (1988) provides more useful detailed advice. Further evidence of how dust explosions propagate in long ducts under realistic process conditions was presented by Radandt (1989b), as discussed in Chapter 4.

6.3.10
SCALING OF VENT AREAS TO OTHER ENCLOSURE VOLUMES AND SHAPES AND TO OTHER P_{red} AND DUSTS

The number of reported realistic vented dust explosion experiments is still limited. It may therefore be difficult to find an experiment described in the literature that corresponds sufficiently closely to the case wanted. A procedure for scaling is therefore needed. The National Fire Protection Association (1988) suggests the following simple equation intended for scaling of vent areas for weak structures of $P_{\text{red}} \leq 0.1$ bar(g):

$$A = \frac{CA_s}{P_{\text{red}}^{0.5}} \qquad (6.4)$$

Here, A is the vent area, A_s is the internal surface area of the enclosure, and P_{red} is the maximum pressure (gauge) in the vented explosion. C is an empirical constant expressing the explosion violence, based on experimental evidence. By using the internal surface area as the scaling parameter for the enclosure "size," the enclosure shape is accounted for, such that an elongated enclosure of a given volume gets a larger vent than a sphere of the same volume.

Equation (6.4) was originally intended for the low-pressure regime only, but its form presents no such limitations. Therefore, this equation may be adopted even for $P_{red} >$ 0.1 bar(g) and used for first approximation scaling of vent areas from any specific realistic experiment, to other enclosure sizes and shapes, other P_{red} values, and other dusts. At the outset, the constant C should be derived from the result of the closest realistic experiment from which data are available. Subsequent adjustment of C should be based on additional evidence or indications concerning influence of dust type, turbulence, and so forth.

Most often, this approach will imply extrapolation of experimental results, which is always associated with uncertainty. Therefore, the efforts to conduct further realistic experiments should be continued.

6.3.11
CONCLUDING REMARKS

Over the last decade our understanding of the dust explosion venting process has increased considerably. Unfortunately, however, this has not provided us with a simple, coherent picture. On the contrary, new experimental evidence gradually forces us to accept that dust explosion venting is a very complex process. What may happen with a given dust under one set of practical circumstances may be far from what happens in others. Therefore, the general plant engineer may no longer be able to apply some simple rule of thumb and design a vent in 5 minutes. This may look like a step backward, but in reality it is how things have developed in most fields of engineering and technology. Increasing insight and knowledge reveals that apparently simple matters are in fact complex and need the attention of somebody who could make them a specialty and from whom others could get advice and assistance.

On the other hand, some qualitative rules of thumb may be indicated on a general basis. One example is Figure 6.22, which shows how, for a given type of dust, the violence of

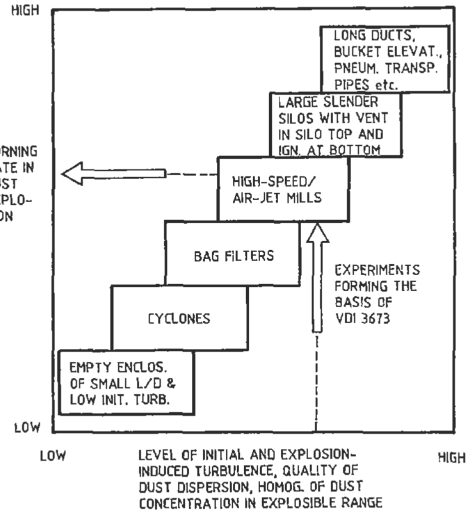

Figure 6.22 *Qualitative illustration of correlation between degree of dust dispersion, level of dust cloud turbulence, and presence of homogeneous explosible dust concentration for a given dust in various industrial situations and the burning rate of the dust cloud.*

the dust explosion, or the burning rate of the dust cloud, depends on the geometry of the enclosure in which the dust cloud burns. Turbulence and dust dispersion induced by flow is a key mechanism for increasing the dust cloud burning rate.

6.4

INFLUENCE OF ACTUAL TURBULENCE INTENSITY OF THE BURNING DUST CLOUD ON THE MAXIMUM PRESSURE IN A VENTED DUST EXPLOSION

This problem was studied specifically by Tamanini (1989), who conducted vented dust explosion experiments in a 64 m^3 rectangular enclosure of base 4.6 m × 4.6 m and height 3.0 m. The vent was a 5.6 m^2 square opening in one of the four 14 m^2 walls of the enclosure. Details of the experiments were given by Tamanini and Chaffee (1989).

The dust injection system essentially was of the same type as illustrated in Figure 4.39 and discussed in Section 4.4.3.1 in Chapter 4. It consisted of four pressurized-air containers, each of 0.33 m^3 capacity and 8.3 bar(g) initial pressure, connected to four perforated dust dispersion nozzles. Two nozzle sets (i.e., eight nozzles) were mounted on each of two opposite walls inside the chamber. The dust was placed in four canisters, one for each of the pressurized-air containers, located in the lines between the pressurized containers and the dispersion nozzles. On activation of high-speed valves, the pressurized air was released from the containers, entrained the dust, and dispersed into a cloud in the 64 m^3 chamber via the 16 nozzles. The high-speed valves were closed again when the pressure in the pressurized containers had dropped to a preset value of 1.4 bar(g).

As illustrated in Figures 4.40–4.42 in Chapter 4, this type of experiment generates transient dust clouds characterized by a comparatively high turbulence intensity during the early stages of dust dispersion and subsequent marked fall-off of the turbulence intensity with increasing time from the start of the dispersion. This means that the turbulence level of such a dust cloud at the moment of ignition can be controlled by controlling the delay between start of dust dispersion and activation of the ignition source.

Tamanini (1989) and Tamanini and Chaffee (1989) used this effect to study the influence of the turbulence intensity at the moment of ignition on the maximum pressure generated by explosion of a given dust at a given concentration in their 64 m^3 vented chamber. The actual turbulence intensity in the large-scale dust cloud at any given time was measured by a bidirectional fast-response gas velocity probe, in terms of the rms (root mean square) of the instantaneous velocity.

However, Tamanini and Chaffee (1989) also found that, during the dispersion air injection into the 64 m^3 chamber, a strong mean flow accompanied the turbulent fluctuations, at least in certain regions of the chamber. Furthermore, despite the injection of the air charge through a large number of distributed points, the flow field in the chamber was highly nonuniform, with the nonuniformity continuing during the decay part of the transient turbulence when the discharge of the air containers was complete. However, it was pointed out that the observed deviation of the flow field from uniformity is probably representative of the situation in actual process equipment and complicates the application of flame velocity data obtained in homogeneous turbulence to practical situations in industry. It also complicates the correlation of turbulence data with overall flame propagation characteristics.

To characterize the turbulence intensity in the 64 m^3 enclosure for a given small time interval by a single figure, the rms values found for that time interval at a large number of probe locations were averaged. Figure 6.23 gives a set of data showing a clear correlation between the maximum pressure in the vented explosion and the average rms of the instantaneous fluctuating turbulence velocity as measured by the pressure probes.

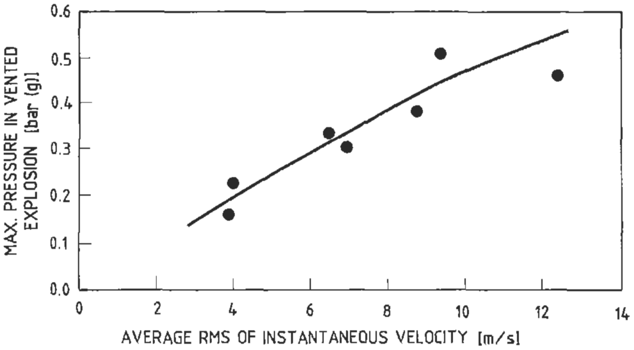

Figure 6.23 *Influence of turbulence intensity of burning dust cloud on maximum pressure in vented maize starch explosion in a 64 m^3 rectangular chamber. Starch concentration is 250 g/m^3. Vent size is 5.6 m^2. Ignition source is a 5 J chemical igniter at the chamber center (From Tamanini, 1989).*

The contribution of Tamanini and coworkers is particularly valuable because it suggests that a quantitative link between systematic venting experiments, in which the turbulence is quantified, and the real industrial explosion hazard may be obtained via measurement of characteristic turbulence levels in dust clouds in industrial process equipment.

Tamanini and Chaffee (1989) encountered problems when trying to correlate maximum rates of pressure rise from 20 liter sphere tests with the maximum pressures in large-scale vented explosions. This is in agreement with the findings illustrated in Figures 6.20 and 6.21. See also Sections 9.2.2.2, 9.2.2.3, 9.2.4.4, and 9.3.7.5 in Chapter 9.

6.5
THEORIES OF DUST EXPLOSION VENTING

6.5.1
INTRODUCTORY OUTLINE

As described in Section 1.4.6.1 in Chapter 1, the maximum explosion pressure in a vented explosion, P_{red}, is the result of two competing processes:

- Burning of the dust cloud, which develops heat and increases the pressure.
- Flow of unburned, burning, and burned dust cloud through the vent, which relieves the pressure.

In most cases, the two processes are coupled via expansion-induced flow of the dust cloud ahead of the flame, which increases the turbulence of the unburned dust cloud and hence its burning rate. In a comprehensive theory of dust explosion venting, it is necessary to include a mathematical description of this complex coupling. As discussed in Chapter 4, this has to some extent been possible in advanced modeling of gas explosions in complex geometries, where the turbulence is generated by flow past comparatively large geometric obstacles. It is to be expected that the current rapid progress in gas and dust explosion modeling will soon result in comprehensive theories and computer simulation codes for conventional venting configurations in the process industry. Further works on this subject are reviewed in Sections 9.2.4.7, 9.2.4.8, and 9.3.7.5 in Chapter 9.

However, in the meantime, several less-comprehensive, more-approximate theories are in use, in which it is assumed that the burning of the dust cloud and the flow out of the vent can be regarded as independent processes. In all the theories traced, it is assumed that the burning rate of the dust cloud in the vented enclosure can, in some way or other, be derived from the burning rate of the same dust in a standard closed-bomb test. The theories vary somewhat in the way in which this derivation is performed, but in general none of the existing venting theories seem to handle the complex burning rate problem satisfactorily. As Table 4.13 in Chapter 4 shows, K_{St} values from dust explosions with the same dust in closed bombs of various volumes and design can vary substantially, depending on dust concentration, degree of dust dispersion, and dust cloud turbulence.

When using a given K_{St} value, or a maximum-rate-of-pressure-rise value, as input to the various existing theories, the relevance of the laboratory test conditions yielding the value, in relation to the dust cloud state in the actual industrial situation to be simulated, must be evaluated. See also Section 9.2.4.8 in Chapter 9 for further approximate theories.

The second part of the venting theories, describing the flow out of the vent, is generally based on the classical, well-established theory for flow of gases through orifices.

A third common feature of existing theories is the use of the fact that, at the maximum explosion pressure, P_{red}, in the vented enclosure, the first derivative of pressure versus time is 0. This means that the rate of expansion of the dust cloud inside the enclosure due to the combustion equals the rate of flow through the vent. An alternative formulation is that the incremental pressure rise due to combustion equals the incremental pressure drop due to venting.

In the general gas dynamics theory for venting pressure vessels, one must distinguish between the two cases subsonic and sonic flow. If the ratio of internal to external pressure exceeds a certain critical value, the flow is governed by the upstream conditions only; whereas at lower pressure ratios, the pressure drop across the orifice plays a main role. For a vent of small diameter compared with the vessel size (e.g., as in Figure 6.18) and neglecting friction losses, the critical pressure ratio equals

$$\frac{P_c}{P_0} = \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \tag{6.5}$$

where γ is the ratio of the specific heat of the gas at constant pressure and volume. For air and most combustion gases generated in dust explosions in air, this value is about 1.8–1.9, which corresponds to a pressure inside the vessel of 0.8–0.9 bar(g) at normal atmospheric ambient pressure. For most conventional process equipment, the maximum permissible explosion pressure in the vented vessel is lower than 0.8–0.9 bar(g), and in such cases, the flow out of the vent is subsonic. However, in the case of quite strong process units, such as certain types of mills, the pressure ratio P_c/P_0 during the first part of the venting process may exceed the critical value, and the sonic flow theory applies.

The following sections include only venting theories that were developed specifically for dust explosions. However, as long as the dust cloud is regarded as a combustible continuum, there is little difference between the theoretical treatment of a dust and a gas explosion, apart from the dust dispersion and initial turbulence problem. Therefore, reference should be made at this point to some central publications on gas explosion venting, including Yao (1974); Anthony (1977/1978); Bradley and Mitcheson (1978a, 1978b); McCann, Thomas, and Edwards (1985); Epstein, Swift, and Fauske (1986); and Swift and Epstein (1987).

6.5.2
THEORY BY MAISEY

An early attempt to develop a partial theory of dust explosion venting was made by Maisey (1965a). As a starting point, he used a simple theory for laminar gas explosion development in a closed spherical vessel, with ignition at the center. The radial laminar flame front speed was, as a first approximation, assumed to be a constant for a given fuel. For dusts, it was estimated from Hartmann bomb test data (see Chapter 7). A central assumption was that the maximum pressure in a closed-bomb test is proportional to the laminar radial flame speed. However, Maisey fully appreciated that, in the Hartmann bomb test, as in any closed-bomb dust explosion test, the dust cloud is turbulent and that turbulence increases the flame speed. He suggested that Hartmann bomb test data be converted to equivalent turbulent flame speeds, corresponding to the turbulence level in the test. However, because this turbulence level is probably higher than in dust clouds in most industrial plants, Maisey recommended a reduction of this equivalent Hartmann bomb flame speed, according to the actual industrial situation.

The second main part of the venting problem, the flow of gas and dust out of the vent opening, was not treated theoretically by Maisey, who instead used various experimental results to derive semi-empirical correlations between maximum vented explosion pressure and vent area for various enclosure volumes and closed-bomb flame speeds.

6.5.3
THEORY BY HEINRICH AND KOWALL

Heinrich and Kowall (1971), following the philosophy outlined in Section 6.5.1 and considering subsonic flow, arrived at the following expression for the pressure equilibrium at the maximum pressure P_{red}:

$$\left(\frac{dP_{\text{ex}}}{dt}\right)_{P_{\text{red}}V} = \alpha\frac{A}{V}\left(\frac{2RT}{M}P_{\text{red}}(P_{\text{red}} - P_0)\right)^{1/2} \tag{6.6}$$

where the left-hand side expresses the rate of rise of explosion pressure in the enclosure at the pressure P_{red}, had the vent been closed for an infinitely small interval of time, and

A is the vent area (m^2);
V is the volume of the vented enclosure (m^3);
R is the universal gas constant = 8.31 J/(K mol);
T is the temperature (K);
M is the average molecular weight of the gas to be vented (kg);
P_{red} is the maximum explosion pressure in the vented enclosure (bar(abs));
P_0 is the ambient (normally atmospheric) pressure (bar(abs));
α is the vent coefficient (–), equal to 0.8 for sharp-edged vents.

By rearranging equation (6.6), the vent area A can be expressed as a function of the other parameters, including the hypothetical rate of pressure rise at P_{red}, had the vent been closed.

Heinrich and Kowall discussed the problems in quantifying the latter key parameter for dust explosions. They correlated results from actual dust explosion venting experiments, using vessel volumes up to 5 m^3, with maximum rate of pressure rise values from the 1.2 liter Hartmann bomb (see Chapter 7).

It was then assumed that the "cube root law" (see Section 4.4.3.3 in Chapter 4) could be applied:

$$\left(\frac{dP_{ex}}{dt}\right)_{P_{red}V_{encl}} = \left(\frac{dP_{ex}}{dt}\right)_{P_{red}V_{Hartm}} \left(\frac{V_{Hartmn}}{V_{encl}}\right)^{1/3} \tag{6.7}$$

It was concluded that the Hartmann bomb data could be correlated with the large-scale data via equations (6.6) and (6.7) using correction factors in the range 0.5–1.0. However, Heinrich and Kowall encouraged the development of a new closed-bomb test method that would yield maximum rates of pressure rise closer to industrial reality.

In a subsequent investigation, Heinrich and Kowall (1972) discussed the influence on P_{red} of replacing the point ignition source normally used in the large-scale experiments with a turbulent flame jet. Whereas flame-jet ignition caused a considerable increase of $(dP/dt)_{max}$ in closed vessel experiments, the increase of P_{red} in vented experiments was comparatively small. As discussed in Section 1.4.4.1 in Chapter 1 and illustrated in Figure 1.78, this conclusion can by no means be extended to flame jet ignition in general. In some cases, such as with strong jets from long ducts, appreciably higher P_{red} values than with point source ignition must be expected.

In his further studies, Heinrich (1974) incorporated experimental data from other workers and proposed a set of nomographs for calculating vent areas, using maximum rates of pressure rise from the 1 m^3 closed Bartknecht vessel (subsequently made an ISO standard) for identifying the combustion rate. The underlying assumption was a positive, monotonic correlation between $(dP_{ex}/dt)_{P_{red}}$ in the vented explosion and $(dP_{ex}/dt)_{max}$ in the closed bomb, which was indicated by some experimental data. Heinrich's nomographs formed an essential part of the basis of the VDI 3673 (from 1979) and NFPA 68 (from 1988).

Heinrich (1980) gave a useful analysis of the theory of the flow of a compressed gas from a container into the surrounding atmosphere after a sudden provision of a vent opening. Both the adiabatic and the isothermal cases were considered. The gas dynamic analysis was also extended to two and three vessels coupled by ducting. Good agreement with experiments was demonstrated.

Lunn et al. (1988) and Lunn (1989) applied the Heinrich-Kowall theory for extending the nomograph method for vent sizing to the region of low maximum explosion pressures.

6.5.4
THEORY BY RUST

Rust (1979) based his theory on considerations very similar to those of Heinrich and Kowall, using maximum rates of pressure rise from closed-bomb tests for assessing an average burning velocity in the vented explosion via the cube root law. The weakest point in Rust's theory, as in all theories of this category, is the assessment of the burning velocity of the dust cloud.

6.5.5
THEORY BY NOMURA AND TANAKA

The process studied theoretically by Nomura and Tanaka (1980), being identical with that considered by Yao (1974) for gases, is illustrated in Figure 6.24. They envisaged a boundary surface *x-x* sufficiently close to the vent for essentially all the gas in the vessel being to the left of the surface and sufficiently apart from the vent for the gas velocity through the surface to be negligible. They then formulated a macroscopic energy balance equation for the flow system describing the venting process, assuming that all the pressure and heat energy was located to the left of the *x-x* line in Figure 6.24 and all the kinetic energy to the right.

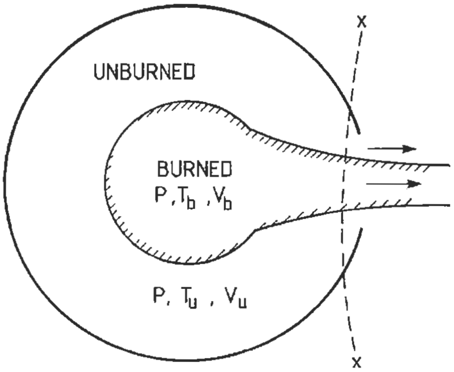

Figure 6.24 *Conceptual model of explosion venting (From Nomura and Tanaka, 1980).*

Although the approach taken by Nomura and Tanaka is somewhat different from those of Heinrich and Kowall and Rust, the basic features are similar and in accordance with what has been said in Section 6.5.1. It may appear as if Nomura and Tanaka were unaware that Heinrich and Kowall (1971) used equation (6.7) to estimate the rate of pressure rise in the vented enclosure from standard closed-bomb test data.

Nomura and Tanaka correlated their theoretical predictions with experimental data from various workers and found that the calculated vent areas were about three times the experimental ones. Their analysis confirmed that $A/V^{2/3}$ = constant seems to be a sensible scaling law for enclosures of length-to-diameter not much larger than unity.

6.5.6
THEORETICAL ANALYSIS BY NAGY AND VERAKIS

Nagy and Verakis (1983) first offered a comprehensive analysis of the physical process of venting of a vessel containing compressed air, applying classical gas dynamics theory, as done by Heinrich (1980). Both the sonic and subsonic regimes were explored. They then formulated the theory of the thermodynamics of the combustion process and finally discussed the combustion rate in more qualitative terms. The combustion part of the theory was of the same nature as that of closed vessel explosions reviewed in Section 4.2.5.1 in Chapter 4.

Nagy and Verakis first developed a one-dimensional theory for unrestricted subsonic venting of a dust explosion in a long cylinder with the vent at one end. Three cases were considered: ignition at the closed cylinder end, at the vent, and at the center. Turbulence generation due to flow of unburned cloud toward the vent was not considered. The one-dimensional theory was then extended to the spherical configuration illustrated in Figure 6.24. The corresponding theory for sonic venting was also formulated.

The treatment by Nagy and Verakis provides a basis for formulating various equations connecting maximum pressure and vent area, assuming that $dP/dt = 0$ at the maximum pressure, using vessel shape, ignition point, and flow regime as parameters.

However, Nagy and Verakis were not able to formulate a comprehensive burning rate theory. They applied the simplified two-zone model of combustion, assuming a very thin flame and a burning velocity $S_u\alpha$, where S_u is the laminar burning velocity and $\alpha > 1$ is a turbulence enhancement factor. The product $S_u\alpha$ was estimated from closed-bomb experiments with the dust of interest.

Nagy and Verakis further extended their theory to the case where the bursting pressure of the vent cover is significantly higher than the ambient pressure. Theoretical predictions were compared with experimental data from dust explosions in a 1.8 m^3 vented vessel.

6.5.7
THEORY BY GRUBER ET AL.

In their study, Gruber et al. (1987) applied the same basic gas dynamics considerations as previous workers to analyze the flow through the vent. The influence of the turbulence on the combustion rate was accounted for by multiplying the laminar burning velocity with a turbulence factor, as done by Nagy and Verakis (1983). Gruber et al. included a useful discussion of the nature and magnitude of the turbulence factor, by referring to more recent work by several workers. In particular, attempts at correlating empirical turbulence factors with the Reynolds number of the flow of the burning cloud were evaluated.

6.5.8
THEORY BY SWIFT

Swift (1988) proposed a venting equation implying that the maximum pressure in the vented vessel is proportional to the square of the burning velocity of the dust cloud. A turbulence factor, obtained from correlation with experimental data, was incorporated in the burning velocity, as in the case of Nagy and Verakis.

6.5.9
THEORY BY URAL

The special feature of this theory, compared with those just outlined, is the assumption that the pressure rise in the unvented explosion can be described by the simple function shown in Figure 6.25.

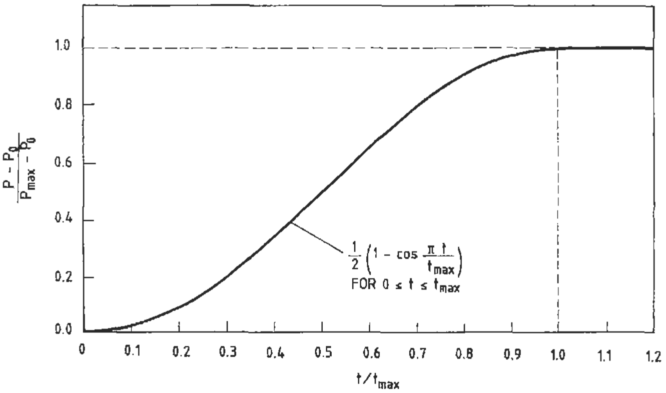

Figure 6.25 *Mathematical approximation for the shape of the pressure rise curve for the unvented explosion used in the venting theory of Ural (1989).*

This implies that the maximum rate of pressure rise in the unvented explosion equals

$$\left(\frac{dP}{dt}\right)_{max} = \frac{\pi}{2t_{max}}(P_{max} - P_0) \tag{6.8}$$

where P_{max} and P_0 are the maximum and initial pressures and t_{max} is the time from ignition to when the maximum pressure has been reached. The explosion rate is then essentially characterized by the single parameter t_{max}. By means of the generalized form of equation (6.7), experimental values of $(dP/dt)_{max}$ from closed-bomb tests may be converted to $(dP/dt)_{max}$ for the actual enclosure, without venting, and then to the corresponding t_{max} using equation (6.8), which may be used in the venting theory to predict maximum vented explosion pressures, P_{red}. It is then assumed that the rate of heat release in the vented explosion versus time is the same as in the unvented explosion.

As for the other theories discussed, a central requirement for obtaining reasonable predictions is that the state of the dust cloud in the closed-bomb test used for predicting the explosion violence corresponds to the state of the dust cloud in the vented explosion of concern.

6.5.10
CONCLUDING REMARKS

In all the theories just outlined, the modeling of the burning rate of the dust cloud is incomplete. The situation may be improved by making use of systematic correlations of burning rates and initial dust cloud turbulence intensities determined experimentally in controlled explosion experiments and measurements of typical turbulence intensities in various industrial plants. The studies of Tamanini and coworkers, discussed in Section 6.4, constitute a valuable step in this direction. The approach for the future is probably further development of the type of more comprehensive theories discussed in Section 4.4.8 in Chapter 4.

6.6
PROBABILISTIC NATURE OF THE PRACTICAL VENT SIZING PROBLEM

6.6.1
BASIC PHILOSOPHY

This aspect of the venting problem was treated by Eckhoff (1986). Section 1.5.1 in Chapter 1 gives a general overview of the probabilistic element in designing for dust explosion prevention and mitigation.

Consider a specific process unit, part of a specific industrial plant in which one or more specific combustible materials are produced or handled in powdered or granular form. The process unit can be a mill, a fluidized bed, a bucket elevator, a cyclone, a storage silo, or any other enclosure in which explosible dust clouds may occur.

Assume that the plant can be operated for 1 million years from now, with no systematic changes in technology, operating and maintenance procedures, knowledge and attitudes of personnel, or in any other factor that might influence the distribution of the ways in which dust clouds are generated and ignited. One can then envisage that a certain finite number of explosion incidents will occur during the 1-million-year period. Some of these will be only weak "puffs" whereas others will be more severe. Some may be quite violent. Because it is assumed that "status-quo" conditions are reestablished after each incident, the incidents will be distributed at random along the time axis from now on to a million years ahead.

The enclosure considered is equipped with a vent opening. The expected maximum pressure P_{max} generated in vented explosions in the enclosure will, by and large, decrease with increasing vent size. This is illustrated in Figure 6.26. If the vent area is unnecessarily large, like A_1, the distribution of expected explosion pressures will be well below the maximum permissible pressure P_{red}. On the other hand, if the vent is very small, like A_3, a considerable fraction of all explosions will generate pressures exceeding the maximum permissible one. (Note that the A_2 and A_3 cases in Figure 6.26 illustrate the pressures that would have been generated had the enclosure been sufficiently strong to withstand even $P_{max} > P_{red}$.)

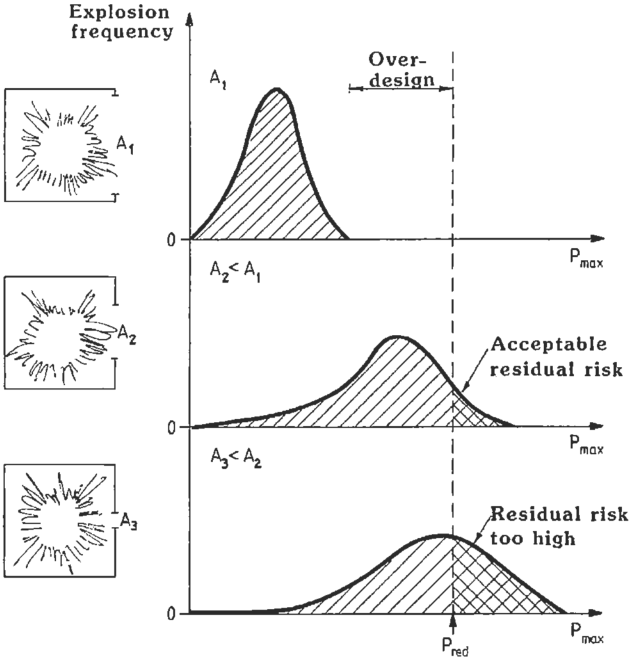

Figure 6.26 *Distribution of maximum explosion pressures generated in a given process unit, fitted with vents of different sizes, by the same 1-million-year population explosions. The unit of explosion frequency is number of explosions per million years per unit of pressure. The areas under the frequency curves then give the total number of explosions in 1 million years and are therefore the same for the three cases.*

In the case of A_2, the vent size is capable of keeping a clear majority of all explosion pressures below P_{red}. If the fraction of the explosions that generates $P_{max} > P_{red}$ represents a reasonable risk, A_2 constitutes an adequate vent size for the case in question. However, the decision as to whether the fraction of expected destructive explosions is acceptable depends on several considerations. The first is the expected total number of incidents of ignition of a dust cloud in the enclosure in the 1-million-year period. This number is strongly influenced both by the standard obtained with respect to elimination of potential ignition sources and the standard of housekeeping. If these standards are comparatively low, the overall chance of cloud ignitions is comparatively high. Consequently, it is necessary to require that the fraction of all expected explosions that will not be taken care of by a vent be comparatively small to ensure that the expected number of destructive explosions is kept at an acceptable level. On the other hand, if the probability of dust cloud ignition is low, one can rely on a smaller vent than if the standard of housekeeping and the efforts to eliminate ignition sources were inadequate. This is illustrated in Figure 6.27.

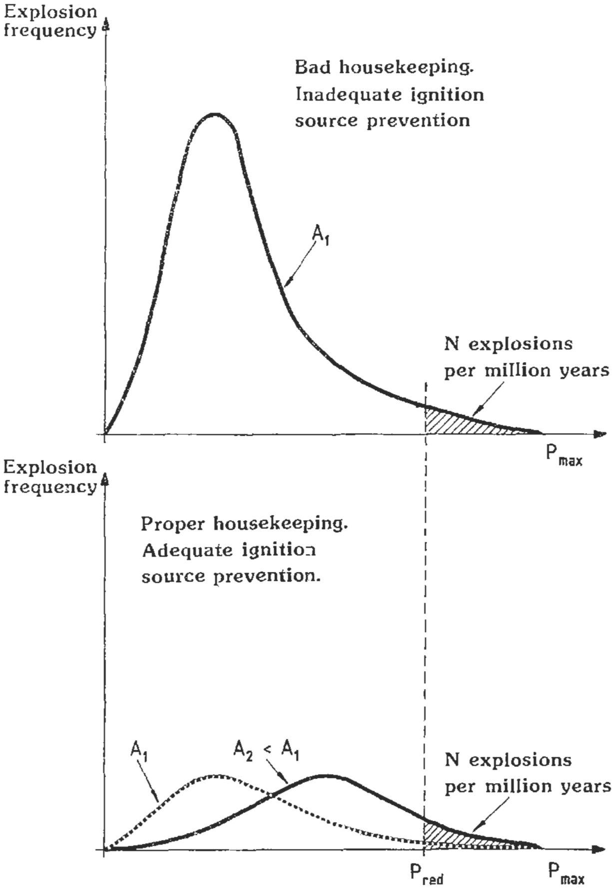

Figure 6.27 *The reduction of necessary vent area resulting from reduction of the overall probability of dust cloud ignitions: N is the maximum acceptable number of destructive explosions per 1 million years.*

Risk is often defined as the product of the expected number of a specific type of undesired event in a given reference period and the consequence per event. When specifying the maximum acceptable number N of destructive explosions in the 1-million-year period (i.e., the maximum acceptable number of explosions of $P_{max} > P_{red}$), it is therefore necessary to take into account the expected consequences of the destructive explosions. This comprises both possible threats to human life and health and possible damage to property.

In principle, the standard of explosion prevention can be so high that the total number of expected explosions in the 1-million-year period is on the same order as the acceptable number of destructive explosions. In such cases, it is questionable whether installing a vent would be advisable at all.

Figure 6.26 illustrates the "random" variation of the expected combustion rate for a specific process unit in a specific plant handling a specific dust. However, if the dust chemistry or the particle size distribution is significantly changed, the distributions of P_{max} also changes. For example, if the particle size is increased and a systematic reduction of combustion rate results, all three distributions in Figure 6.26 are shifted toward lower P_{max} values. The small vent area A_3 may then turn out to be sufficient. Alternatively, the average running conditions of the process could be altered in such a way that a significant systematic change in the dust cloud turbulence or concentration within the process unit would result. This would also cause the distributions in Figure 6.26 to change, rendering the original vent size either too small or unnecessarily large.

A general illustration of the consequence of any significant systematic change of this kind is given in Figure 6.28.

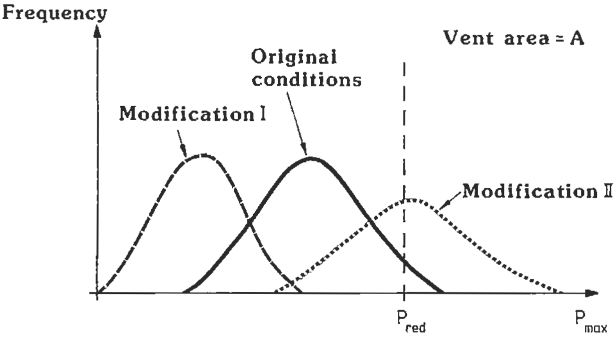

Figure 6.28 *Illustration of the influence of modifying dust properties or process design on the distribution of P_{max}.*

If the system is altered in such a way that the dust cloud combustion rates generally are reduced (Modification I in Figure 6.28), the original vent size A is unnecessarily large. On the other hand, if the alteration generally leads to increased explosion violence (Modification II in Figure 6.28), the original vent area might be too small.

6.6.2
THE "WORST CREDIBLE EXPLOSION"

The discussion in Section 6.6.1 exposed a central problem in prescribing an adequate vent size for a given purpose: Identification of the "worst-case" explosion to be designed for. In some venting cases and guidelines, the choice of "worst case" is rather conservative, with respect to dust concentration, turbulence level, and degree of dust dispersion. In defense of this approach, it has been argued that the venting code ensures safe venting under all circumstances encountered in practice. However, extreme conservatism may not be the optimal solution. Excessive overdesign of vents quite often imposes significant, unnecessary practical problems and costs, both in finding a suitable vent location that does not conflict with other design criteria and in designing excessive vent cover arrangements. Furthermore, providing a large vent opening may significantly reduce the strength of the process unit to be vented, necessitating complicating reinforcement for maintaining the original strength.

Conservative, rigid venting requirements may cause industry to conclude that venting is not applicable to its problem at all, and no vents are provided. This situation has been quite common in the case of large storage silos in the grain, feed, and flour industry. The alternative venting philosophy outlined in Section 6.6.1 implies that even a modestly sized vent may add significantly to the safety standard of the plant by being capable of providing adequate relief for the majority of the expected explosions.

Results from realistic experiments of the kind discussed in Section 6.2 and by Eckhoff (2003), combined with proper knowledge about the actual industrial process and plant, constitute the existing basis for assessing the "worst credible explosion." In the future, systematic studies of different selected representative scenarios can probably be conducted by using comprehensive computer simulation models.

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Chapter 7

Assessment of Ignitability, Explosibility, and Related Properties of Dusts by Laboratory-Scale Tests

7.1

HISTORICAL BACKGROUND

Since the beginning of this century, considerable work has been carried out in many countries on assessing the explosion hazard of various types of combustible dusts by laboratory testing. Palmer (1973) gave an informative account of the status in three or four countries up to the beginning of the 1970s. The more recent summary by Field (1983) included some significant developments in the late 1970s and work conducted in even further countries.

In the United States, the U.S. Bureau of Mines has, since its establishment in 1910, conducted studies of ignitability and explosibility of dusts. At the beginning, the investigations were mainly on coal dusts, but from 1936, the work was extended to all sorts of agricultural, industrial, and other dusts (Jacobson et al., 1961; Jacobson, Nagy, and Cooper, 1962; Jacobson, Cooper, and Nagy, 1964; Nagy, Dorsett, and Cooper, 1965; Dorsett and Nagy, 1968). Equipment and procedures were developed to investigate the various ignitability and explosibility properties, as described by Dorsett et al. (1960). More recently, more-refined test methods were developed by the U.S. Bureau of Mines, as discussed by Hertzberg, Cashdollar, and Opferman (1979) and Hertzberg, Conti, and Cashdollar (1985). Lee et al. (1982) proposed that some of the traditional U.S. Bureau of Mines test methods be improved by including more refined diagnostic instrumentation. The Committee on Evaluation of Industrial Hazards (1979) suggested some additional methods for testing the ignitability and electrical resistivity of dust layers. Schwab (1968) focused on the central problem of interpreting the results of the laboratory-scale U.S. Bureau of Mines tests in terms of the real industrial hazards and practical means of dust explosion prevention and mitigation.

In the United Kingdom, systematic testing of dust ignitability and explosibility was undertaken by Wheeler at the Safety in Mines Research Establishment (SMRE) from early in this century. However, in the 1960s, much of this work, except for coal dust explosion research and testing, was transferred to the Joint Fire Research Organization, now the Fire Research Station, at Borehamwood. Raftery (1968) discussed the early work carried out by this organization on testing of dusts for ignitability and explosibility, and it appears that the experimental procedures and equipment were to a large extent similar to those of the U.S. Bureau of Mines. More recently, some of the test methods in the United Kingdom were modified or replaced by new ones, as discussed by Field (1983). Gibson (1972) described some further test methods used by the chemical industry in the United Kingdom, whereas Burgoyne (1978) related the results of the various test methods to means of preventing and mitigating the industrial hazard.

In Germany, Selle (1957) gave an account of the quite extensive work on dust explosion testing carried out, in particular, at the Bundesanstalt für Materialprüfung (BAM) in Berlin in the first half of this century.

Leuschke (1966a, 1967) presented updated comprehensive accounts of the various test methods used at the BAM, whereas Heinrich (1972) discussed some fundamental problems related to applying data from such methods in practical safety engineering. In a later paper, Leuschke (1979) discussed the problem of classifying the explosion hazard to be associated with a given dust on the basis of test data. Other, more-recent survey papers covering the scene in the Federal Republic of Germany include those of Ritter and Berthold (1979), Beck and Glienke (1985), and Hattwig (1987). In addition to BAM, BVS at Dortmund-Derne and the large chemical companies in the Federal Republic of Germany have conducted extensive research on development and assessment of test methods related to ignitability and explosibility of dusts. Verein deutscher Ingenieure (1988) summarized the status in the Federal Republic of Germany at the end of the 1980s.

An overview of comparatively early corresponding work conducted in the German Democratic Republic was given by Kohlschmidt (1972).

Zeeuwen (1982) and Zeeuwen and Laar (1984) presented tests and methods of interpretation of test results used by TNO in the Netherlands. In Italy, work on test methods has been conducted by Stazione Sperimentale per i Combusibili (Milan) and in Spain by Laboratorio Oficial J. M. Madariaga (Madrid).

Poland has a long tradition in coal dust explosion research and testing. The work by Cybulski (1975) gained international recognition. Much valuable work on initiation and propagation of dust explosions in industry has been conducted at The Technical University of Warsaw and other Polish universities.

Testing of dust ignitability and explosibility in France has been carried out mostly by CERCHAR near Paris. An account of the status on apparatuses and procedures by the end of the 1970s was given by Giltaire and Dangréaux (1978). It is interesting to note that a tensile strength test was used to assess the cohesiveness of the powders and dusts (see Chapter 3).

In Switzerland, the extensive work by Ciba-Geigy AG dominated the development of methods for testing the ignitability and explosibility properties of dusts during the 1970s and 1980s. The pioneering contribution by Lütolf (1971) should be mentioned specifically. He described a complete system for testing ignitability and explosibility of dust clouds as well as the flammability of dust layers. The system, which also incorporated some test methods developed by others than Ciba-Geigy AG, was designed to satisfy the requirement that all test results for a given powder or dust should be available within 24 hours of receipt of the sample by the test laboratory. Lütolf's quick-tests still seem adequate for the purpose they were intended to serve. More recently, comprehensive accounts of the test methods used by the Swiss process industries was given by Siwek and Pellmont (1986), Bartknecht (1987), and Siwek (1988).

Laboratory tests for dust ignitability and explosibility have been developed and investigated extensively by various organizations in USSR. The Research Institute of Material Science Problems in Kiev played a key role in this respect. Nedin, Nejkov, and Alekseev (1971) described some of the test methods in use at this institution by about 1970. Some supplementary information was provided by Eckhoff (1977). Much work has also been conducted by the USSR Academy of Sciences in Moscow. Efimokin et al. (1984) produced an industrial standard for determination of the ignitability and explosibility parameters of dust clouds. Korolchenko and Baratov (1979) argued against the earlier practice in USSR, by which safety measures against dust explosions were specified on the basis of a measured value of the minimum explosible concentration only.

Significant work on testing of dust ignitability and explosibility has also been carried out at the University of Sydney in Australia; at the Indian Institute of Technology, Kharagpur, and the Central Building Research Institute, Roorkee, both in India; and at various universities in Japan.

Similar research and development is also being conducted at several universities in the Peoples Republic of China, among which the Northeast University of Technology in Shenyang plays a central role.

In Scandinavia, the Chr. Michelsen Institute (from 2001 GexCon AS) in Bergen, Norway, has been the central institution for ignitability and explosibility testing of dusts since about 1974. Eckhoff (1975a) described the initial phase of the buildup of the laboratory, whereas Pedersen (1989) gave a recent summary of the test methods in use. During her stay at the Chr. Michelsen Institute, Racke (1989) produced a summary of commercially available equipment for testing ignition sensitivity, thermal stability, and combustibility properties of reactive chemicals, including dusts. As part of a research program on ignitability and explosibility of peat dust, the Central Research Laboratory of Finland established a laboratory comprising a limited range of test methods. See also Section 9.4 in Chapter 9.

7.2

A PHILOSOPHY OF TESTING THE IGNITABILITY AND EXPLOSIBILITY OF DUSTS: THE RELATIONSHIP BETWEEN TEST RESULT AND THE REAL INDUSTRIAL HAZARD

As discussed in Chapter 1, a dust explosion in industry may be initiated by a variety of ignition sources, among which smoldering dust and powder, open flames, hot surfaces, and electric sparks are perhaps the most important. The ignition may be prevented by eliminating ignition sources, inerting the dust cloud, and in certain cases, maintaining the dust concentration below the lower explosible limit. Should an explosion nevertheless be initiated, damage may be prevented or limited by precautions such as the use of process units of small volumes separated by explosion chokes or fast-acting valves, explosion suppression, using explosion-proof equipment, venting, and proper housekeeping.

The purpose of the various laboratory tests for ignitability and explosibility of dusts is to provide the quantitative data for the various hazards related to dust explosions and fires required to design relevant safety precautions. However, the relationship between the laboratory test conditions and real life in industry is not always straightforward. The general situation is illustrated in Figure 7.1

The test method produces a quantitative measure of some property of the dust, which is supposed to be related to the particular hazard in question. However, before statements

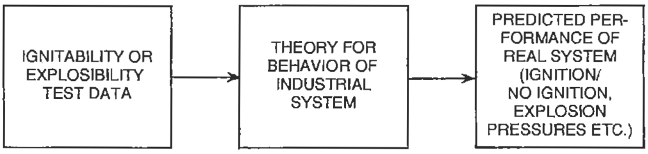


Figure 7.1 *Overall context of ignitability and explosibility testing.*

can be made about the real hazard, the test result must be passed through an adequate theory of the industrial system and transformed to a useful statement on the behavior of the system.

Figure 7.1 is a "philosophical" model, which becomes useful only when the contents of the boxes are adequately specified. There are two extremes for the testing box to the left: The first is full-scale realistic testing in true copies of industrial plants; the other is measurements of basic behavior of particles and molecules. In the first case, there is no need for the coupling theory, because what is measured in the left-hand box is, by definition, what happens in the box to the right. In the second case, however, a very detailed, comprehensive theory is required to transform the fundamental test data to real system performance.

It could be argued that one should generally aim at testing on a fairly basic level and develop corresponding, complex theories. However, the rational approach seems to be to take a more balanced view. To make an optimal choice on the level of resolution, some questions need to be answered: How good are the available measurement techniques? How good are the theories? How much resolution is really needed for adequate design in practice?

Consider for example the ignition of dust clouds by electric sparks. In practice, there are many kinds of sparks, as discussed in Section 1.1.4.6 and in Chapter 5. When electrically conducting wires are broken, break flashes occur and the spark energy is determined by the self-induction of the system and the current. In other situations, the spark arises from capacitive discharge from nongrounded, electrically conductive bodies. Further, there are brush discharges from nonconducting surfaces, corona discharges, propagating brush discharges, lightning discharges, and discharges from powder heaps. So, how should one assess the electric spark ignition hazard?

The actual measurements, symbolized by the left-hand box in Figure 7.1, can take many forms. For example, one could construct a full-scale copy of the industrial plant, introduce the powder or dust in a realistic way, and see whether ignition results. However, as a general approach to hazard identification, this would not be very practical.

A more-realistic approach would be to design a range of separate laboratory tests, one exposing the dust cloud to capacitive sparks from nongrounded electrical conductors, another to break flashes, and further special tests to other kinds of electrostatic discharges. In addition, one would have to visit the industrial plant and measure the relevant parameters, such as capacities, voltages, and inductivities, and estimate likely discharge energy levels from theory (intermediate box in Figure 7.1). By comparing these theoretical energies with the minimum ignition energies measured in the various test apparatus, one could determine whether the electric discharge ignition hazard in the plant would be significant.

A third, more-fundamental approach would be to characterize the electric discharge ignition sensitivity of the dust in more basic terms, for example, as a function of the distribution of spark energy in space and time, as discussed in Chapter 5. However, in this case, the theory needed to relate the test result to real system behavior would have to be considerably more detailed and complex, perhaps too complex to be manageable at present. Furthermore, the measurements would be very demanding in themselves.

Therefore, whenever a test method is designed to identify real, specific industrial hazards, one has to ask the basic strategic question: What is the most suitable level of resolution and generality of experiment and associated theory? Figure 7.2 gives an introductory overview of the various test methods to be considered in the following sections.

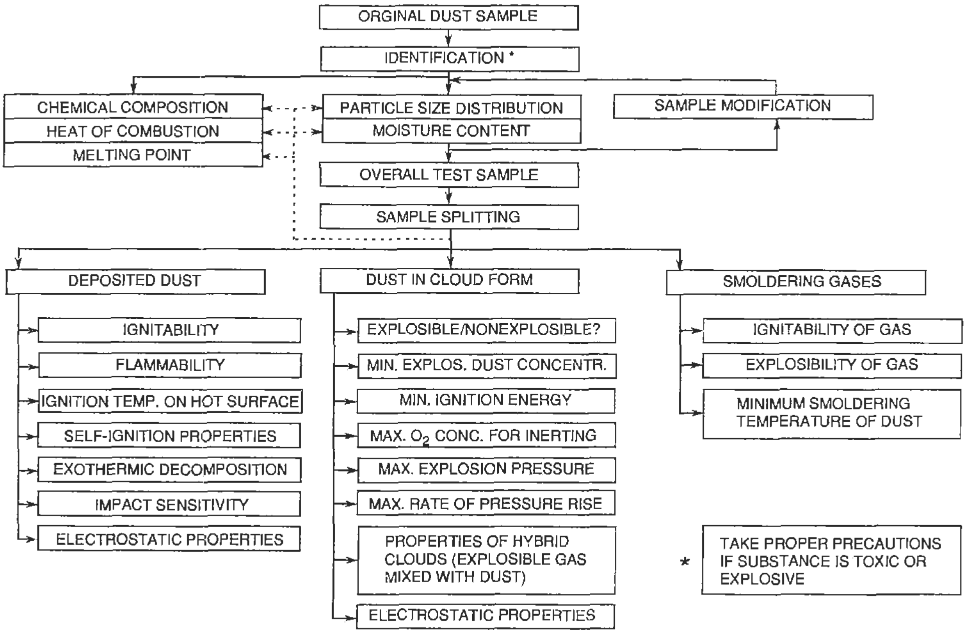


Figure 7.2 *Diagram of possible tests for assessing ignitability and explosibility properties of dusts (Slightly modified, translated version of original by Verein deutscher Ingenieure, 1988).*

7.3
SAMPLING OF DUSTS FOR TESTING

As part of a general philosophy of testing, a few words must also be said about the need for representative dust samples. Chemistry, including moisture content and particle size and shape distributions, have a vital influence on both ignition sensitivity and explosibility. Therefore, if the dust sample tested is not representative of the dust or powder in the industrial process of concern, even the most perfect pair of test method and theory (Figure 7.1) will yield misleading assessments of the real industrial hazard.

It is useful to distinguish between two different levels of sampling. The first, and often most crucial, is the initial collection of dust in the industrial plant. Chemical composition, moisture content, and particle size in samples taken from the main product stream, a dust filter, and a shelf or beam in the workroom may vary substantially. It is important, therefore, that the initial sample be collected at a location and under operational conditions that ensure it is really representative of the dust that creates the dust explosion hazard to be assessed.

Allen (1981) described methods for collecting dust/powder samples from bulk material in terms of

- Sampling from a moving stream of powder.
- Sampling from a conveyor belt or chute.
- Sampling from a bucket conveyor.
- Bag sampling.
- Sampling spears.
- Sampling from wagons and containers.
- Sampling from heaps.

If the dust sample is to be collected from a gas stream, special precautions are required to ensure representative sampling. As discussed by Allen, these relate to both the design of the sampling equipment and the way in which the equipment is used. Whenever the sample is obtained by suction from a gas stream, it is important to ensure that the sampling conditions are isokinetic. Otherwise a sample of nonrepresentative particle size distribution can result.

Once the main dust or powder sample has been collected, it remains to divide it into smaller subsamples, down to the level required for a single dust ignitability or explosibility test. For some tests, this can mean quantities as small as 0.1 g. If the initial main sample is a bag of 50 kg, in which significant segregation of particle sizes may exist, picking samples of 0.1 g directly from the bag may not ensure the required degree of representation in the samples. To solve the problem of producing representative subsamples, various apparatuses and methods have been developed. Allen (1981) distinguished among

- Scoop sampling.
- Coning and quartering.
- Table sampling.
- Chute splitting.
- The spinning riffler.
- Other devices.

In general, the spinning riffler has proven to yield the most homogeneous subsamples, and this method is therefore recommended in most cases. Figure 7.3 shows a large spinning riffler used for splitting large bag-size samples of grain dust into a number of subsamples. However, even a subsample of about 1 kg is very large compared with the very small quantities, down to 0.1 g, required for some ignitability or explosibility tests. Therefore, further subdivision may be necessary, and much smaller spinning rifflers than that shown in Figure 7.3 have been developed for this purpose.

Figure 7.3 *Large spinning riffler used at the Chr. Michelsen Institute, Norway, for splitting large natal samples of grain dust into 26 subsamples.*

7.4

MEASUREMENT OF THE PHYSICAL CHARACTERISTICS OF DUSTS RELATED TO THEIR IGNITABILITY AND EXPLOSIBILITY

7.4.1

PARTICLE SIZE DISTRIBUTION AND SPECIFIC SURFACE AREA

Particle size analysis is a large field of research and development in itself, and the main purpose of this section is to reemphasize the major role played by particle size and shape and their distributions in deciding the ignitability and explosibility of a dust of a combustible material (see Chapter 1). The book by Allen (1981) is a main source of further information, concerning both the basic theory of particle size distributions and the various experimental methods available. Allen grouped the various methods in the following main categories:

- Sieving (woven-wire and electroformed micromesh).
- Microscopy (light microscopy, transmission electron microscopy [TEM], and scanning electron microscopy [SEM]).
- Sedimentation in liquids (incremental and cumulative, gravitational and centrifugal).
- Electrical sensing zone.
- Light scattering.
- Permeametry and gas diffusion.
- Gas adsorption.

Some of the methods yield the full particle size distribution, others only a mean particle size or specific surface area. Fast, computer-aided theoretical analysis of raw data can yield refined information. It is important to realize that the various groups of methods listed detect different basic particle properties, and therefore the definitions of particle size, and hence also the size distributions derived for a given powder of nonspherical particles, differ for the various method groups. Nevertheless, as long as the particle shape is not extreme, such as long fibers or thin flakes, the discrepancies are normally moderate.

However, as discussed in detail in Chapter 3 and Section 1.3.3 in Chapter 1, powders and dusts of very small particles are difficult to disperse, particularly in a gas. Therefore, differing degrees of dispersion may give rise to considerable discrepancies in the apparent size distributions obtained for a given dust by various methods. For example, dry sieving of very fine, cohesive powders may leave significant residues of apparently coarse particles, which are in fact just agglomerates of very fine particles. Such agglomerates may be easily dispersed in liquid by using a suitable surfactant, ultrasonic, or both. Consequently, a method based on suspending and dispersing the powder in a liquid may yield a much finer size distribution than the dry-sieving method. The question is then which method gives the most realistic size distribution in relation to that of the dust clouds generated in the industrial plant (see Section 1.3.3 and Chapter 3).

These circumstances should be kept in mind when selecting methods for particle size analysis in the context of assessment of ignitability and explosibility of dust clouds.

7.4.2
DISPERSIBILITY

The significance of this property of powders and dusts with respect to the ignitability and explosibility of clouds produced from them has been discussed in Section 1.3.3 and Chapter 3. However, neither the definition of *dispersibility* in practical terms nor the development of adequate techniques for measuring this property is a straightforward task.

Eckhoff and Mathisen (1977/1978), investigating the rate of pressure rise during dust explosions in the 1.2 liter Hartmann bomb, used the apparatus shown in Figure 7.4 to assess the degree of dust dispersion generated by the standard dispersion system of the Hartmann bomb. Figure 7.5 shows the actual apparatus, mounted on top of the Hartmann bomb dispersion cup and dismantled. The main principle is that dispersed dust is collected on a double-stick tape mounted on a microscope slide fixed to the adjustable circular metal plate. The particles on the microscope slide are analyzed with respect to size either by light microscope or SEM. The quantity of dust dispersed must not exceed the limit that still allows the individual particle units in the cloud, whether single primary particles or stable agglomerates, to appear as detached entities on the tape.

Figure 7.6 gives the number frequency distributions of maize starch agglomerates (see Figure 1.33 in Chapter 1) collected on the tape when dispersing 1.5 g of starch by the standard dispersion process of the Hartmann bomb. In this case, there was no influence of moisture content, which means that the agglomerates were held together by other means than liquid bridges. The content of agglomerates was about 30% on a number basis and approximately 90% on the basis of mass, irrespective of moisture content.

Ural (1989a) reviewed the literature on tests methods related to the dispersibility of dusts and powders. A classic method was proposed by Professor Andreasen in Denmark in 1939. Two cubic centimeters of powder were poured through a narrow slit into a vertical tube of 2.5 m height and 45 mm diameter. The particles were separated to some extent as they fell through the air, and the percentage of the powder mass that had not settled to the bottom of the tube in 6 seconds was determined. Since the individual particles could

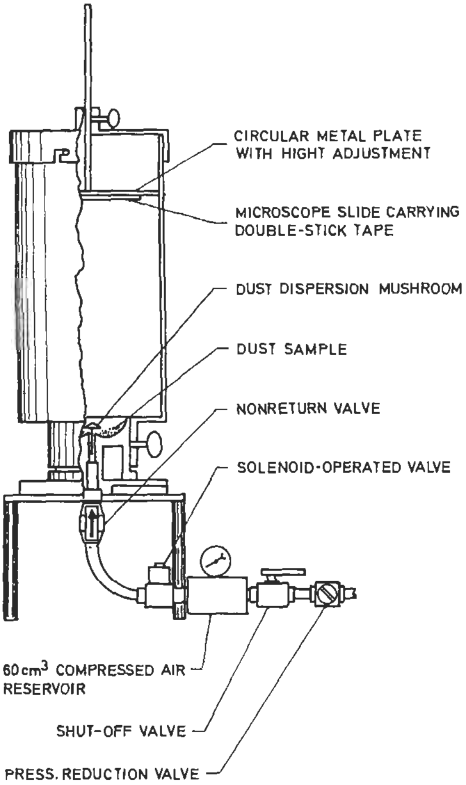


Figure 7.4 *Apparatus for assessing the degree of dispersion in dust-clouds in the 1.2 liter Hartmann bomb (From Eckhoff and Mathisen, 1977/1978).*

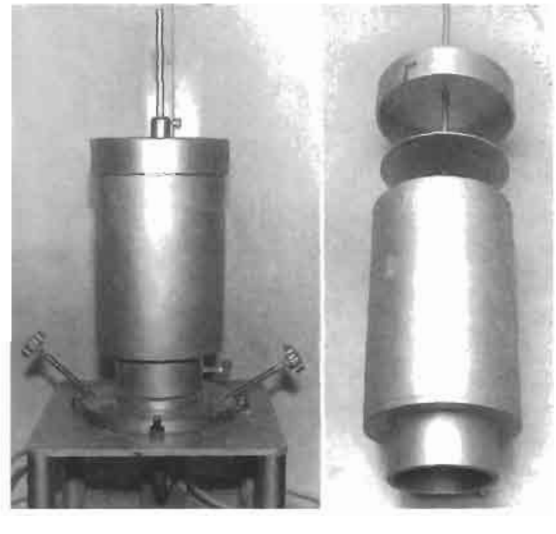


Figure 7.5 *Apparatus for assessing the degree of dispersion in dust clouds in the Hartmann bomb, assembled on the dust dispersion cup of the Hartmann bomb (left) and dismantled (right).*

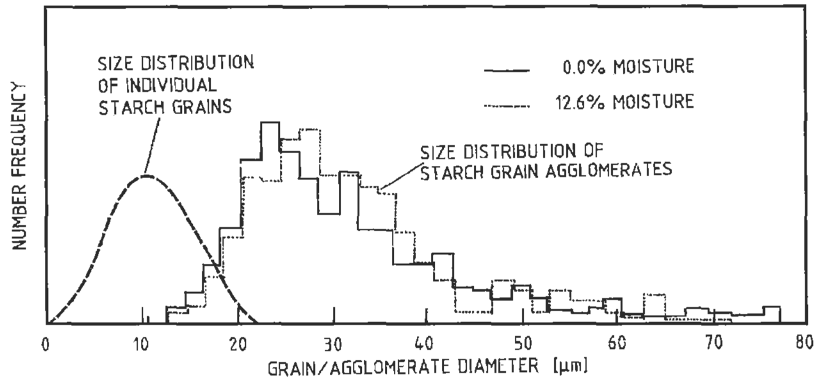


Figure 7.6 *Size distribution of maize starch grain agglomerates collected in the apparatus shown in Figures 7.4 and 7.5. The width and shape of the number size distribution of individual starch grains is indicated by the dotted line (From Eckhoff and Mathisen 1977/1978).*

not have reached the bottom in this time, Andreasen assumed that this figure represented the percentage of dispersed powder, which he called *dispersibility*. However, because some of the unsettled material could well be small agglomerates of tiny particles, this assumption may not have been entirely valid.

Another, semiquantitative test method was described by Carr (1965). The apparatus consisted of a vertical plastic tube of length 330 mm and internal diameter 100 mm, supported with its lower edge 100 mm above a 100 mm diameter watch glass. A 10 g sample of material was dropped "en masse" through the cylinder from a height of 600 mm above the watch glass. The material remaining on the watch glass was weighed, and the difference from the initial mass equaled the amount dispersed during the experiment.

Ural also quoted two ASTM (American Society for Testing and Materials) test methods related to dust dispersibility. One of these (Standard D547-41) is intended for determining an index of dustiness of coal and coke. The other (Standard D4331-84) assesses the effectiveness of dedusting agents for powdered chemicals.

Ural (1989a, 1989b) was specifically concerned with quantifying the ability of dust layers to become entrained by blasts from primary explosions and thus give rise to secondary dust explosions. His aim was to design experimental test methods that were simple and easy to perform but nevertheless measure fundamental quantities that could be used as input to mathematical models.

Two parameters were identified to play important roles in determining the dispersibility of powders affecting the severity of secondary explosions. The first was the settling velocity distribution of the dust and the second the entrainment threshold of a dust layer. Therefore, two apparatuses were built to classify powders according to these properties.

The settling velocity apparatus, shown in Figure 7.7, yields the settling velocity distribution of a powder sample dispersed by means of a reproducible and controllable aerodynamic disturbance. A given quantity of dust is first placed inside the dust disperser located in the upper part of the vertical tube. Details of the disperser are shown in the expanded illustration in Figure 7.8.

The air pulse entrains the dust and forces the dust/air suspension through the narrow gap between the open ends of the two tubes constituting the main body of the disperser.

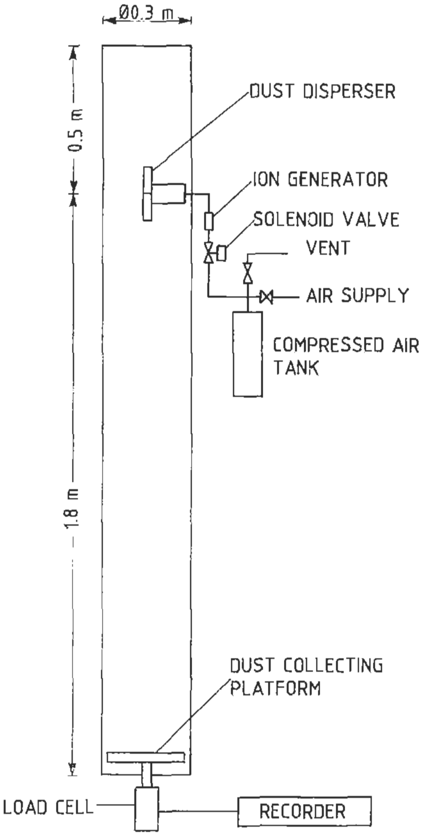


Figure 7.7 *A schematic view of the Factory Mutual Research Corporation (FMRC) settling velocity apparatus (From Ural, 1989a).*

The diffuser, consisting of a pair of flanges, ensures that the dust cloud generated in the upper part of the settling velocity apparatus (Figure 7.7) has no significant vertical momentum. The purpose of the ion generator is to reduce the agglomeration due to electrostatic forces. The dust then settles under gravity and gradually accumulates on the bottom plate, which is supported by a load cell permitting continuous recording of the accumulated dust mass. Accumulated mass versus time is used as the primary quantification of the dispersibility of the powder. By varying the intensity of the air pulse and the width of the annular slot of the disperser, the dispersibility of a given powder can be determined as a function of basic dispersion parameters, such as air velocity and viscous shear force. The operating range of this apparatus in terms of particle size is from a few μm to 100 μm, that is, in the range of primary interest in the context of dust explosions.

The second test method proposed by Ural (1989a) was the Factory Mutual Research Corporation (FMRC) liftoff apparatus for measuring the critical air velocity for liftoff of dust particles from a thin layer on a horizontal surface. A cross section of the basic apparatus is shown in Figure 7.9. The dust layer is spread evenly across a horizontal 380 mm Ø circular plate. A second circular plate of diameter 300 mm and a central hole of 25 mm Ø and rounded edges is mounted above and parallel with the dust layer plate, with a gap that can be varied from 3 mm to 13 mm. A given inward airflow in the gap between the plates is established by creating an underpressure in the vertical tube connected to the central hole in the upper plate. Because of the diminishing flow cross section, the inward

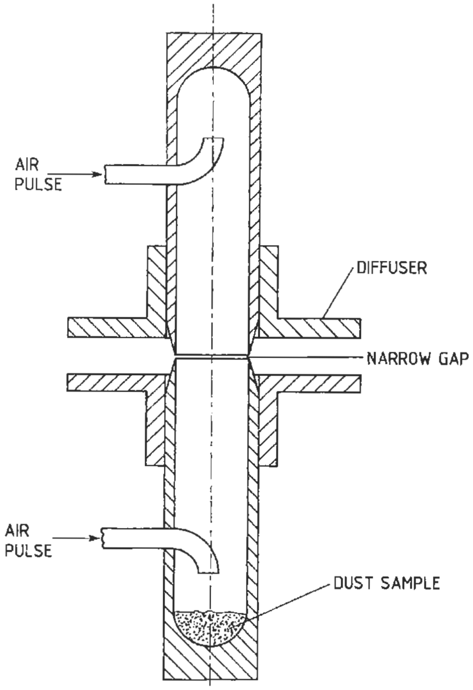


Figure 7.8 *Dust disperser for FMRC settling velocity apparatus (From Ural, 1989a).*

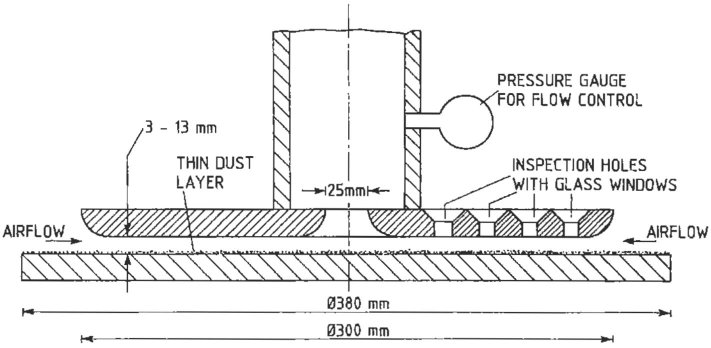


Figure 7.9 *The FMRC liftoff apparatus for assessing the dispersibility of thin dust layers (From Ural, 1989a).*

radial flow velocity of the air increases with decreasing distance from the plate center. When the airflow has been properly adjusted to the dust layer in question, the particles inside a circle of diameter smaller than 380 mm is lifted off the plate by the airflow, whereas the particles outside this circle remain in the dust layer. As long as this critical circle for liftoff can be reasonably well identified, a corresponding average critical air velocity for liftoff can also be identified. As would be expected from powder-mechanical considerations (see Chapter 3), the critical average linear air velocity for liftoff is not constant for a given cohesive dust but depends on the degree of compaction of the dust layer. Figure 7.10 gives a set of results for maize starch layers generated by three different compaction methods.

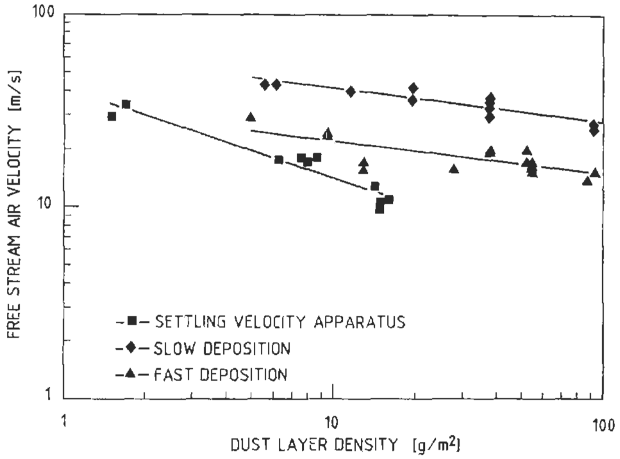


Figure 7.10 *Free stream air velocity required for 50% removal of maize starch as a function of mass of dust m² of layer, for three different dust deposition methods (From Ural, 1989a).*

The layer bulk density was highest with the fast deposition method and lowest when the layer was produced using the settling velocity apparatus illustrated in Figure 7.7. As Figure 7.10 shows, the average critical air velocity for liftoff decreased with decreasing bulk density and with increasing mass of dust per m^2 of dust layer.

Further development of the test procedures may make Ural's tests an attractive candidate for a standard method both for acquiring fundamental data and for relative ranking of dispersibility and dustability of dusts.

7.4.3
POWDER MECHANICAL PROPERTIES

The relationships between the mechanical bulk properties of a powder and the ease with which it can be dispersed into a dust cloud are discussed in detail in Chapter 3. Cohesion and tensile strength are two parameters often used for characterizing the cohesiveness of bulk powders. Test apparatuses in use are shown in Figures 3.5 and 3.6. However, both cohesion and tensile strength vary with the bulk density, or the degree of compaction, of the powder, and therefore, just a single figure may not be useful unless the method of preparing the powder sample is specified.

Other, relative powder mechanical test parameters that may be related to dispersibility include compressibility, angle of repose, angle of fall, and angle of difference (Ural, 1989a).

7.4.4
MOISTURE CONTENT

As discussed in Chapter 3 and illustrated by Figure 3.3, moisture in a powder can increase the powder cohesiveness considerably. Section 1.3.1 illustrates the strong influence of the dust moisture content on both ignitability and explosibility of the dust.

A range of measurement methods are available for determining the moisture content of dusts and powders. Cuckler (1987) gave a useful overview. The oldest, most common method of determining the moisture content consists of heating the sample to ensure complete drying. Moisture is calculated on the basis of the weight difference between the original and dried samples. The method is applicable to most powders and dusts and requires no unusual operator skill. Semiautomatic drying and weighing ovens are available. The moisture content is then indicated directly by the weighing scale built into the oven. Problems may arise if heating the material also causes loss of volatile products other than water. It is essential that the material is completely dry at the time of final weighing, and that an accurate weighing is made. The oven method is widely used and often serves as the primary standard for calibration of electrical and other indirect methods. Typical drying conditions for laboratory-scale samples are 3–4 hours at 105°C and subsequent cooling in a desiccator. Dried hygroscopic materials must be protected from a humid atmosphere before weighing. Materials that pyrolyze at temperatures around 100°C may be dried at a lower temperature under vacuum. Materials that oxidize in air at normal drying temperatures may be dried in an inert atmosphere, such as nitrogen.

Electrical conductivity methods are based on the relationship between DC resistance and moisture content for wood, textiles, paper, grain, and similar materials. Specific resistance plotted against moisture content results in an approximately straight line up to the moisture saturation point. Beyond the saturation point, conductivity methods are unreliable. This point varies from approximately 12% to 25% moisture, depending on the type of material.

Electrical capacitance methods are based on the difference in dielectric constant between dry and moist material. The dielectric constant of most vegetable organic materials is between 2 and 5 when dry, whereas water has a dielectric constant of 80. Therefore, the addition of small amounts of moisture to these materials causes a considerable increase in the dielectric constant. The sample being measured forms part of a capacitance bridge circuit, which has radio-frequency power applied from an electronic oscillator. Electronic detectors measure bridge unbalance or frequency change, depending on the method employed.

Some instruments use the absorption of electromagnetic energy when passed through the material. Typical frequencies are below 10 MHz. This method gives the best results for materials composed of polar materials. The electromagnetic energy is passed through the polar material and the water molecules transform some of the energy into molecular motion.

Microwave absorption may also be used for measuring moisture content in powders. The principle of operation is based on the fact that the water molecule greatly attenuates the transmitted signal with respect to other molecules in the material in the S and X band frequencies. In the case of the K-band microwave frequencies, the water molecule produces molecular resonance. No other molecules respond to this particular resonant frequency, making the frequency most specific to moisture.

Some instruments for measuring moisture content are based on absorption of infrared radiation when such radiation is passed through the sample material. The water molecule becomes resonant at certain infrared frequencies and thus the amount of energy absorbed by the water absorption band is a measure of the moisture content.

More refined methods include the Karl Fischer technique and a special distillation technique. When specifying the moisture content in terms of a percentage, it should be made clear whether this figure refers to the total mass, including the moisture, as 100% or whether the 100% is the dry mass only.

7.4.5
ELECTRICAL RESISTIVITY

The significance of electrical resistivity of powders and dusts in the context of process safety is dual. First, the possibility of accumulating hazardous electrostatic charges and voltages in an industrial process increases with increasing electrical resistivity powder. Second, the chance of dusts that penetrate into electric and electronic equipment giving rise to short-circuits and equipment failure increases as the dust resistivity decreases. From the point of view of the dust explosion hazard, both situations may lead to generation of ignition sources.

A method for determining the electrical resistivity of powders/dusts has been developed by the International Electrotechnical Commission (1993). The test cell, illustrated in Figure 7.11, consists of two metal electrodes resting on a nonconducting base plate (glass or PTFE).

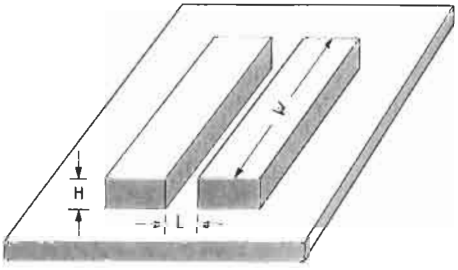


Figure 7.11 *Test cell for determination of the electrical resistivity of dust layers being evaluated by the International Electrotechnical Commission (1993).*

The right-angled prismatic dust sample of length W and cross section H-L fills the gap between the electrodes. The actual dimensions are $W = 10$ cm, $H = 1.4$ cm, and $L = 1.25$ cm. The recommended width of the electrodes is 3.3 cm and the thickness of the base plate, 0.5–1.0 cm. Two glass bars of height 1.4 cm are placed across the ends of the electrodes to keep the dust sample in place. The dust to be tested is conditioned at a relative air humidity of 50 ± 5% and 20–25°C and should normally pass a 71 μm test sieve. The moisture content of the dust and any changes of it during the resistivity test must be reported.

During a test, the resistance R_0 of the empty test cell is first determined with the two glass bars in position across the electrode ends. Then, a weighed amount of dust is poured into the cell and the excess dust scraped off and weighed, to determine the weight of the test sample and its bulk density. The resistance R_s of the dust-filled cell is then measured for a range of cell voltages from 110 to 2000 V. In general, $R_0 > 10\,R_s$, and the resistivity ρ of the dust is then approximately equal to

$$\rho = R_s \bullet \frac{HW}{L}\ (\Omega\ \mathrm{cm}) \tag{7.1}$$

If $R_0 < 10\, R_s$,

$$\rho = R_s \bullet \frac{R_0}{R_0 - R_s} \bullet \frac{HW}{L} \,(\Omega\ \text{cm}) \tag{7.2}$$

The resistivity normally varies somewhat with the applied voltage.

A dust is considered to be conductive, and therefore capable of short-circuiting electrical and electronic equipment when admitted inside such equipment, if $\rho \leq 10^5\ \Omega$ cm ($10^3\ \Omega$ m).

7.5

CAN CLOUDS OF THE DUST PRODUCE EXPLOSIONS AT ALL? YES/NO SCREENING TESTS

Before embarking on more specific tests, it is sometimes considered desirable to perform an introductory test to determine whether the powder or dust in question can produce a dust explosion at all. However, a very first screening should always be made by looking at the chemistry of the compound, which will tell whether or not it can produce significant quantities of heat by oxidation to stable products. If this is not the case, dust explosions can be excluded and testing is unnecessary.

To perform an introductory yes/no test requires having a reasonably sized cloud of the dust, of concentration in the most explosive range (often 500–1000 g/m^3), and expose it to a sufficiently powerful ignition source. *Sufficiently powerful* implies that, whenever a dust cloud able to propagate a self-sustained flame is tested, ignition will take place.

The matter of how such a yes/no test should be designed is still being discussed. The tests used in various countries differ considerably, in particular with respect to the ignition source.

As described by Palmer (1973) and Field (1983), the ignition sources traditionally used in the United Kingdom are electric sparks and glowing electrically heated metal wire coils. The decision as to whether the dust tested is explosible is based on visual observation of flame propagation following the dispersion of varying amounts of dust around a continuous train of electric sparks or a brightly glowing ignition coil in a vertical Perspex or glass tube of length 30 cm or 50 cm and diameter 6.4 cm. A dust is considered explosible if a dust flame becomes clearly detached from the ignition source. Normally, the dust is first tested in the condition as received by the laboratory, apart from removal of particles larger than 1400 μm from the sample by sieving. However, if clouds of the dust "as received" do not propagate a self-sustained flame, a dust sample is dried at 105°C in air for 1 hour and retested. If flame propagation still does not take place, the dry sample is sieved and individual size fractions tested, down to 25 μm. For some dusts, only the finest fractions, representing less than 1% of the bulk sample, can propagate dust flames. However, even in such cases, the dust is regarded as explosible. This is because fine fractions may segregate out and become dispersed separately in an industrial situation.

In some countries in continental Europe, very powerful pyrotechnical ignitors, of energy about 10 kJ, are used in yes/no tests. Lee et al. (1983) discussed the production and performance of this kind of ignitor. Closed 1 m^3 or 20 liter explosion bombs are often employed as test vessels (see Sections 7.15 and 7.16), and significant pressure rise is taken as an indication of explosion. However, some European countries have also adopted the modified Hartmann tube originally proposed by Lütolf (1971) for the yes/no test. In this apparatus, the ignition source is a comparatively weak electric spark. The argument put forward in defense of this approach is that none of the dusts classified as nonexplosible in the modified Hartmann tube test ever caused explosions in the chemical industry. Bartknecht (1978), on the other hand, warned against the use of the modified Hartmann tube test for yes/no screening, unless the spark ignition source is replaced by a glowing resistance wire coil with a temperature of at least 1000°C.

In Norway, a pragmatic approach was taken, based on the experience that a welding torch flame seems to be among the strongest ignition sources encountered in industrial practice. The actual test apparatus is shown in Figure 7.12. A vertical tube of length 40 cm and diameter 14 cm, open at both ends, is fitted with a U-shaped dust dispersion tube and an acetylene/oxygen welding torch. A quantity of the powder is placed at the bottom of the dispersion tube, and a controlled blast from a compressed air reservoir disperses the dust into a cloud in the tube, which is then immediately exposed to the hot flame from the welding torch. The amount of powder and the dispersion air pressure are varied to produce optimal conditions for ignition. When a dust flame occurs, its maximum height, color, and apparent violence are assessed by the observer. Figure 7.13 shows a photograph of a welding-torch-flame ignition test.

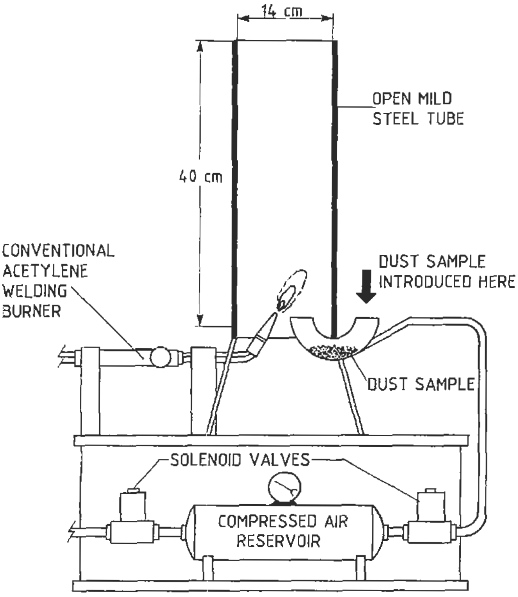


Figure 7.12 *Welding torch ignition test apparatus used in Norway (Chr. Michelsen Institute) for assessing whether or not a dust cloud is explosible.*

The discussion of the yes/no test problem continues (see Section 9.4.4 in Chapter 9), and a final, fully universal solution is not yet within sight. But, whenever the first screening is positive, that is, the dust cloud catches fire, the screening test has fulfilled its

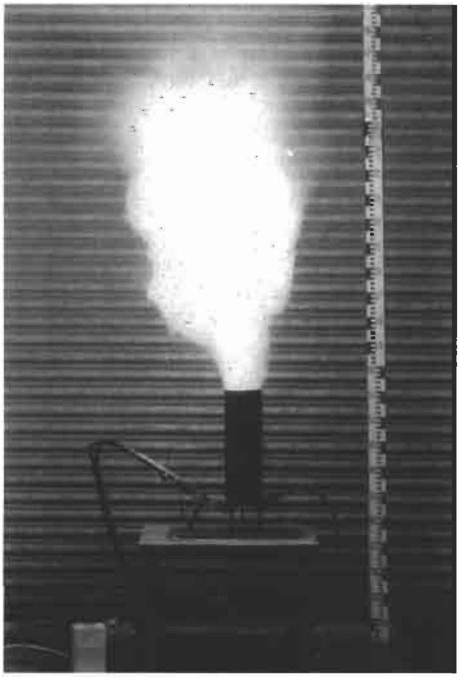


Figure 7.13 *Silicon dust explosion in the welding torch ignition test apparatus used in Norway. For a much clearer picture, see Color Plate 9.*

objective, no matter which test it is. Then, further, more specific testing may be required. The various methods used can be grouped in three main categories:

- Tests for ignition sensitivity of dust deposits and clouds.
- Tests for limiting conditions for flame or glow propagation in dust clouds and deposits.
- Tests for maximum rise and rate of rise of explosion pressure in dust clouds.

Before discussing the various test methods, however, some special tests concened with evolution of explosible gases from heated dusts should be mentioned.

7.6
CAN HAZARDOUS QUANTITIES OF EXPLOSIBLE GASES EVOLVE FROM THE DUST DURING HEATING?

7.6.1
THE INDUSTRIAL SITUATION

If the oxygen supply is limited, which often is the case if smoldering takes place in large powder deposits in closed vessels, CO and other combustible gases can be produced, which can mix with the air and form an explosible gas cloud above the powder deposit. If the smoldering fire propagates to the surface of the powder deposit, the gas mixture can be ignited (see Figure 1.9 in Chapter 1). The primary gas explosion can then throw dust layers on walls, shelves, beams, and so forth into suspension and give rise to considerably more extensive and severe secondary explosions, which can be either hybrid (mixture of explosible gas and dust) or pure dust explosions.

Some organic substances decompose exothermally and release combustible gaseous products even in the absence of oxygen. This possibility represents a particular hazard.

7.6.2
LABORATORY TESTS

7.6.2.1
The BAM Method

The apparatus developed by BAM and shown in Figure 7.14 illustrates the common main idea. A given quantity of dust is placed in a test tube, which is enclosed in a copper block that can be heated to any desired temperature up to 580°C. The test tube exit is connected to the bottom of a furnace with temperature control. When the upper furnace is kept at a temperature significantly higher than the minimum ignition temperature of the smoldering gases, it represents a severe ignition source. If the lower copper block furnace is then heated to a temperature where smoldering occurs, smoldering gases leave the test tube and enter the upper furnace, where they mix with the air in the furnace. If significant quantities of smoldering gases are evolved over some time, an explosible mixture with air sooner or later occurs in the upper furnace, and becomes ignited. If, on the other hand, the smoldering gas evolution is very small, the explosible concentration may not be reached within a reasonable test period.

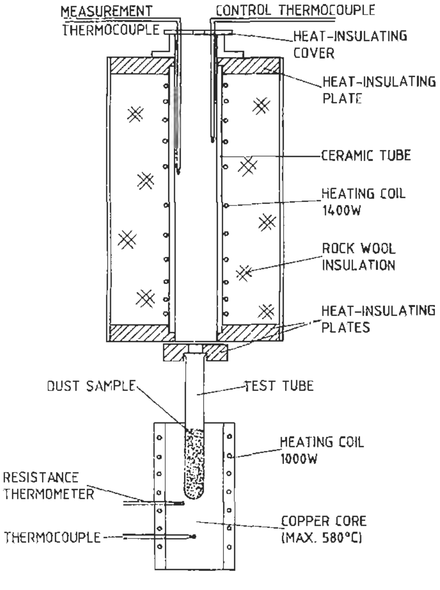


Figure 7.14 *Furnace for assessing the minimum temperature for evolution of combustible smoldering gases from dusts and the minimum ignition temperature of mixtures of such gases and air (Drawing based on BAM, 1974).*

The BAM apparatus also permits quantitative determination of the minimum heating temperature for evolution of hazardous quantities of smoldering gases, as well as the minimum temperature in the upper furnace for ignition of explosible mixtures of such gases and air.

7.6.2.2
The ASTM Method

The American Society for Testing and Materials (1989) prepared a test method to determine the temperature limits of flammability of chemicals in general, which also includes a procedure for testing powders and dusts. A sample of 50 cm^3 volume is placed at the bottom of a spherical 5 liter glass bottle, which is kept at the desired elevated temperature by a flow of heated air sweeping through the casing in which the bottle is contained. A magnetic stirrer in the bottle ensures that the smoldering gas produced is mixed continuously with the main bulk of gas and air in the bottle. Hence, there is a reasonably homogeneous gas concentration throughout the 5 liters. The flammability of the gas/air mixture is tested by means of an electric spark discharged close to the center of the bottle.

7.6.2.3
Lütolf's Method

Figure 7.15 shows the quick-test method proposed by Lütolf (1978). Test tube (a) is for collecting the smoldering gases for other test purposes. Test tube (b) allows simple direct testing of whether ignitable quantities of smoldering gases are produced at the selected heating block temperature. Test tubes (c) and (d) allow detection of any exothermal decomposition of the dust or powder at the selected block temperature.

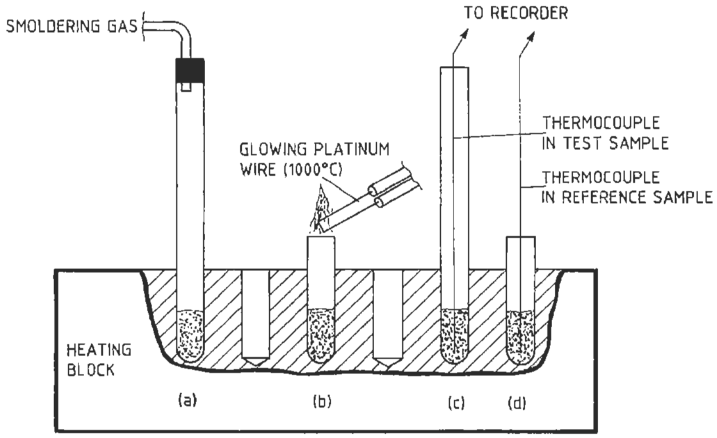


Figure 7.15 *Method for testing the ignitability of smoldering gases from decomposition of dusts and possible exothermal effects during decomposition (From Lütolf, 1978).*

7.7
IGNITION OF DUST DEPOSITS AND LAYERS BY SELF-HEATING OR HOT SURFACES

7.7.1
THE INDUSTRIAL SITUATION

Smoldering combustion, or glow fires, in powder or dust deposits can give rise to explosions in several ways. Smoldering lumps from the fire zone can be transported to areas containing explosible dust clouds and initiate dust explosions there. This may, for example, happen if the smoldering combustion takes place in a hopper that feeds powdered material to a larger storage silo via pneumatic transport. When powder is discharged from the hopper into the pneumatic line, for example, through a rotary lock, the smoldering zone eventually also reaches the hopper outlet, and smoldering lumps get into the pneumatic line and are transported to the larger silo. If the smoldering lumps are not quenched during transportation to the silo and the silo contains an explosible dust cloud, the result can easily be a dust explosion.

Smoldering combustion can start as a slow, gentle process in the powder deposit at quite low temperatures, in some cases, even at normal room temperature. Smoldering combustion can also be initiated by a hot object, which is either fully embedded in the dust deposit or on which the deposit lies. The hot object can be a piece of metal, for example, a bolt or a nut that has loosened somewhere in the plant and been carried along with the process stream and heated by repeated impact against the internal walls of process equipment. Eventually, it may come to rest embedded in a powder deposit in a silo, a bucket elevator boot, or elsewhere in the plant. Alternatively, the hot object can be an overheated bearing or another larger hot object covered with a layer of powder or dust.

Further details are given in Sections 1.1.4.2, 1.4.2.2, 1.4.2.4, and 1.4.2.5 in Chapter 1; see also Chapter 5.

7.7.2
LABORATORY TESTS

7.7.2.1
Semiquantitative Flammability Test

The foundation of this method was laid by Lütolf (1971) and full descriptions were given by Siwek and Pellmont (1986) and the Verein deutscher Ingenieure (1988). The apparatus and procedure are illustrated in Figure 7.16.

For tests at ambient temperature, a ridge of the dust of triangular cross section is placed on a ceramic plate and one of the ends touched with a white-glowing platinum wire, as shown in Figure 7.16(a). For tests at elevated temperatures, the sample holder shown in Figure 7.16(b) is used and the sample placed in a glass tube heated to the desired temperature. A small airflow of about 0.2 m/s through the glass tube must be ensured.

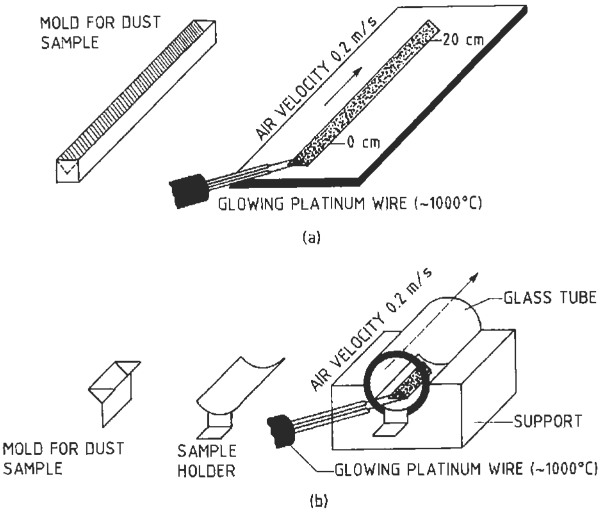


Figure 7.16 *Method for testing flame propagation ability of dust layers at ambient (a) and elevated (b) temperatures (From Siwek and Pellmont, 1986).*

Section A.1.2.9 in Appendix 1 describes the way in which results from tests with the apparatus shown in Figure 7.16 are classified, and Table A1 in Appendix 1 gives experimental results for a range of dusts.

7.7.2.2
Hot-Plate Test for Minimum Ignition Temperature Determination

The apparatus, which is shown in Figure 7.17, consists of a modified electric hot plate, a temperature-control unit, three thermocouples, and a two-channel recorder.

The hot-plate is kept at a given temperature, which is read by one of the thermocouples and displayed on one of the recorder channels.

On the surface of the plate is laid a metal ring, with a diameter of 100 mm and a height of either 5 mm or 15 mm. The powder sample to be tested is placed in the metal ring and carefully leveled off to the height of the ring. A thermocouple is placed in the sample

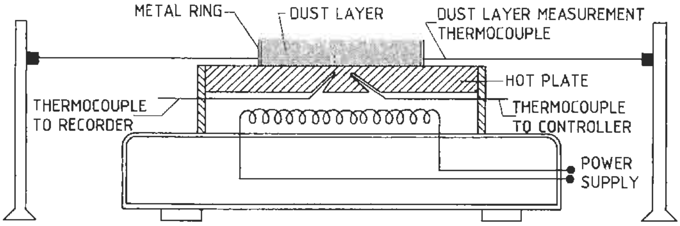


Figure 7.17 *Apparatus for determining the minimum temperature of a hot plate that causes ignition of a dust layer on the hot plate (Part of a method produced by the International Electrotechnical Commission, 1994).*

through holes in the metal ring. The sample temperature is displayed on the second recorder channel. The third thermocouple is used to regulate the plate temperature.

The test procedure is specified in detail by the International Electrotechnical Commission (1994). Typical outcomes of a test are illustrated in Figure 7.18.

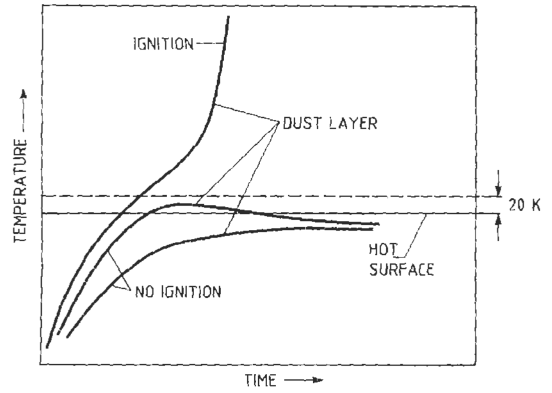


Figure 7.18 *Typical categories of results from measurement of temperature development in dust layers using the apparatus in Figure 7.17. The minimum temperature rise of 20 K for ignition as indicated in the figure was, in the final IEC-standard (1994), replaced by a considerably more liberal requirement.*

Originally, it was proposed that the temperature in the dust sample must exceed the hot-plate temperature by more than 20°C for the test to be recorded as ignition. However, in the final standard a considerably higher temperature rise was required. Tests are conducted repeatedly until the minimum hot-plate temperature for ignition has been identified. This is defined as the lowest hot-plate temperature that gives ignition, rounded off to the nearest value in °C divisible by 10.

It is important to note that the minimum hot-plate ignition temperature decreases systematically with increasing dust layer thickness. If the values for two different layer thicknesses have been determined, simplified theory enables estimation of the values for other thicknesses, as shown by Bowes and Townshend (1962).

In the context of the possible IEC-test method, the similar German DIN test, using a dust layer thickness of 5 mm, should be mentioned. Data from this method are given in Table A1 in Appendix 1.

7.7.2.3
Original U.S. Bureau of Mines Test

In the test originally used by the U.S. Bureau of Mines and described by Dorsett et al. (1960), a small basket of metal gauze is filled with the powder and placed in a furnace through which air of constant, known temperature flows at a slow, specified rate. The temperature within the powder bed is monitored continuously, and by increasing the air temperature in steps, a level is reached at which the temperature in the powder sample begins to rise above that of the surrounding air. This critical air temperature is taken as the minimum ignition temperature of the powder in question.

However, this temperature is not a true powder constant but depends on the experimental conditions, in particular on the size of the powder sample tested, as shown in Section 7.7.2.5, and the airflow.

7.7.2.4
The Grewer-Furnace Test

Grewer (1971) developed a more refined version of the original U.S. Bureau of Mines test. A cross section of the Grewer furnace is shown in Figure 7.19.

The furnace has six vertical cylindrical cavities in which small metal gauze baskets are placed. One of the baskets contains an inert reference sample, the other five hold test samples. The furnace can be programmed to give a specific rate of temperature rise, such as 1°C/min. The temperature at which a test sample temperature starts to rise faster than that of the inert reference sample is taken as the minimum ignition temperature of that sample. Figure 7.20 shows an example of a set of results.

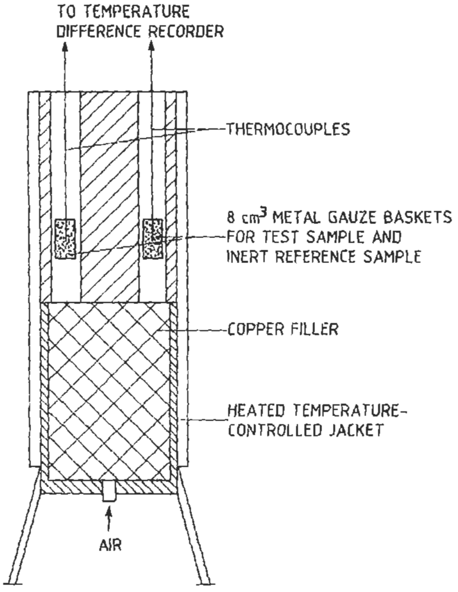


Figure 7.19 *Grewer furnace for determination of minimum ignition temperatures of dust deposits (From Grewer, 1971).*

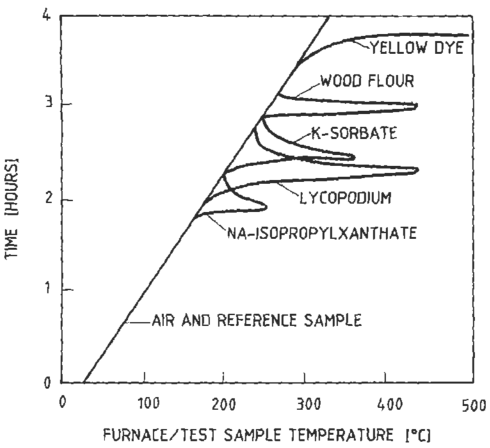


Figure 7.20 *Example of temperature recordings during a 4-hour test of five combustible powders in the Grewer furnace (From Grewer, 1971).*

7.7.2.5
Storage of Bulk Powder Samples in a Heated Atmosphere

The apparatus used for this test is shown in Figure 7.21. The sample is suspended in a metal gauze basket in a heating chamber through which a given flow of preheated air circulates. The ambient air temperature and the temperature inside the powder sample are measured and the difference recorded. If the temperature in the powder sample rises beyond that of the air but no higher than 400°C, the phenomenon is named *self-heating*. Temperature rises beyond 400°C are named *self-ignition*.

Figure 7.22 illustrates the typical linear relationship between the minimum ignition temperature and the sample size. Further details concerning self-heating and self-ignition processes are given in Chapter 5.

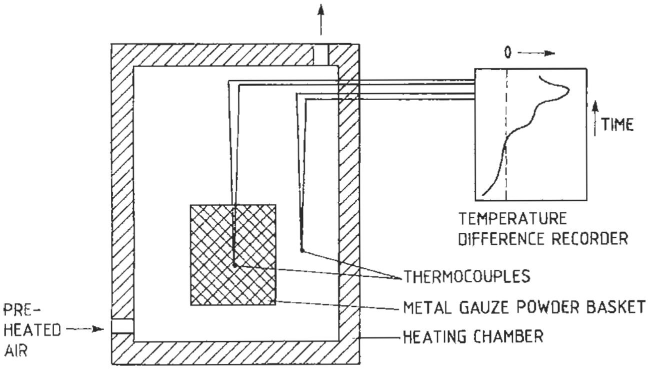


Figure 7.21 *Apparatus for storage of bulk powder samples in a heated atmosphere (From Verein deutscher Ingenieure, 1988).*

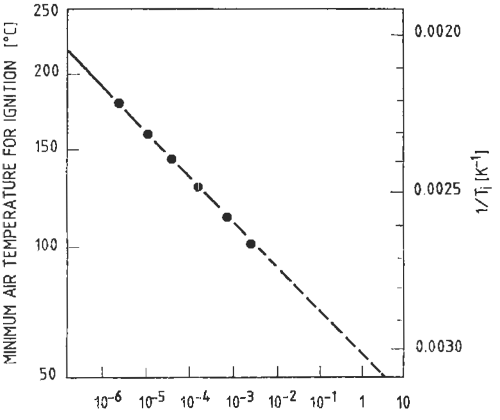


Figure 7.22 *A typical series of results from the determination of the minimum ambient air temperatures T_i leading to ignition of different sizes of geometrically similar samples of a given powder (From Verein deutscher Ingenieure, 1988).*

7.7.2.6
Other Methods

Standard instruments for differential thermal analysis (DTA) have been used for fast screening of self-heating and self-ignition properties of dusts and powders.

Bowes (1984) wrote an updated, comprehensive account of the state of the art on theories and experiments on self-heating in powder deposits by 1983–1984. Since that date, further development has taken place, and new instruments for detailed studies of the rate of reaction as a function of temperature, under adiabatic conditions, are commercially available. As described by Townsend and Tou (1980), such "accelerating rate calorimeters" (ARCs) are essentially highly computerized adiabatic calorimeters. During an ARC experiment, the sample is maintained in a near-to-perfect adiabatic condition, while time, temperature, and pressure data are automatically collected and stored. The data can then be processed by computers. An ARC is illustrated in Figure 7.23.

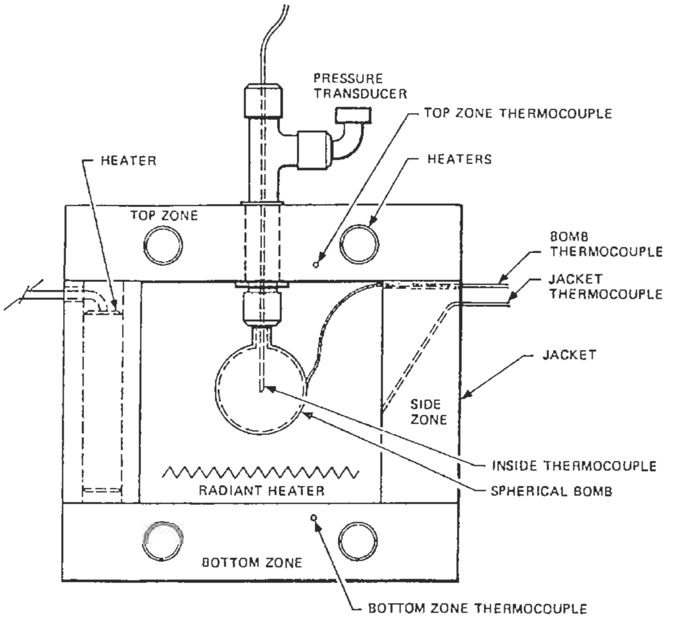


Figure 7.23 *Accelerating rate calorimeter for assessing exothermal behavior of a substance, including powders and dusts, under adiabatic conditions (From Townsend and Tou, 1980).*

In addition to ARC, differential scanning calorimetry (DSC) is in use, as discussed by Snee (1987). DSC implies measurements of the rate at which heat must be transferred to or from the test sample to maintain it at the same temperature as an inert reference sample. The reference sample temperature is usually increased at a predetermined linear rate (constant temperature rise per unit time).

Grewer et al. (1989) and Racke (1989) gave comprehensive reviews of instrumentation and procedures in use for assessing the exothermal behavior of reactive chemicals, including powders and dusts.

7.8
MINIMUM IGNITION TEMPERATURE OF DUST CLOUDS

7.8.1
THE INDUSTRIAL SITUATION

Hot surfaces capable of igniting dust clouds exist in a number of situations in industry, such as in furnaces and burners and dryers of various kinds. In addition, hot surfaces can be generated accidentally by overheating bearings and other mechanical parts.

If an explosible dust cloud is generated in some uncontrolled way in the proximity of a hot surface with a temperature above the actual minimum ignition temperature, a dust explosion can result. It is important, therefore, to know the actual minimum ignition temperature and take adequate precautions to ensure that temperatures of hot surfaces in areas where explosible dust clouds can occur do not rise to this value.

However, the minimum ignition temperature is not a true constant for a given dust cloud but depends on the geometry of the hot surface and the dynamic state of the cloud (see Chapter 5).

7.8.2
LABORATORY TESTS

7.8.2.1
Godbert-Greenwald Furnace

In the United States, as described by Dorsett et al. (1960), the ignition temperature of dust clouds in contact with a hot surface was traditionally determined in the Godbert-Greenwald furnace. In this apparatus, the internal surface of a vertical cylindrical ceramic tube, open at the lower end, is kept at a known, constant temperature and a sample of the powder is dispersed as a dust cloud into the tube from above by a blast of air. The automatically controlled temperature of the internal wall of the tube is changed in steps and the experiment repeated until the minimum temperature for ignition has been identified. In the United Kingdom, the same furnace has been used for many years, as described by Raftery (1968) and Field (1983).

The International Electrotechnical Commission (IEC) investigated the performance of the Godbert-Greenwald furnace through several round-robin test series involving several central test laboratories in Europe and the United States. The influences of a number of details of the apparatus itself and of the experimental procedure were studied and details of apparatus and procedure specified more closely. The resulting, improved Godbert-Greenwald furnace test was proposed as a standard for determining minimum ignition temperature of dust clouds. The essential details concerning both apparatus and procedure are given in the standard produced by the IEC (1994). This includes details of the central ceramic tube, which is fitted with a special spiral groove for the heating element, and two holes for the two thermocouples. One of the holes penetrates the wall, allowing the measuring thermocouple junction to be in direct contact with the internal wall of the ceramic tube. Specifications of the way of generating the air blast for dispersing the dust are also given. Figure 7.24 illustrates a version of the Godbert-Greenwald furnace that is in agreement with that being evaluated by the IEC on the essential points. Figure 7.25 shows a photograph of a Godbert-Greenwald furnace test.

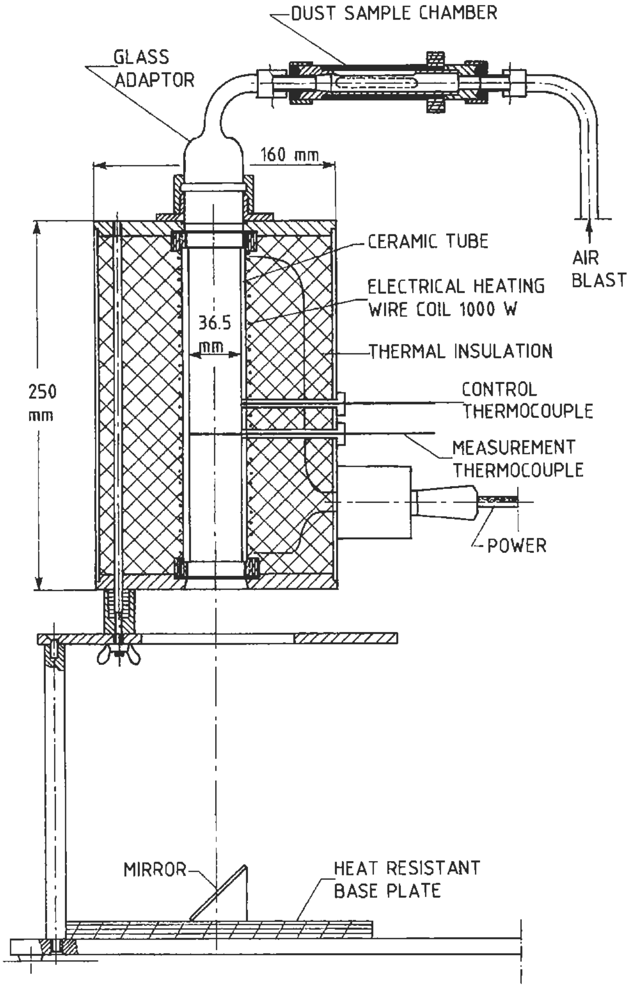


Figure 7.24 *The Godbert-Greenwald furnace for determination of the minimum ignition temperature of dust clouds, a design produced by International Electrotechnial Commission (1994).*

Griesche and Brandt (1976) used a Godbert-Greenwald furnace modified in such a way that dust clouds of known concentrations could be passed through the furnace at a desired constant velocity. They investigated the influence of the dust cloud velocity, or the mean residence time of the dust in the furnace, on the minimum ignition temperature. The results, given in Figure 7.26, show that the minimum ignition temperature decreased quite significantly with increasing residence time. A conventional Godbert-Greenwald test on the same

Figure 7.25 *Ignition of a dust cloud in the Godbert-Greenwald furnace. For a much clearer picture, see Color Plate 10.*

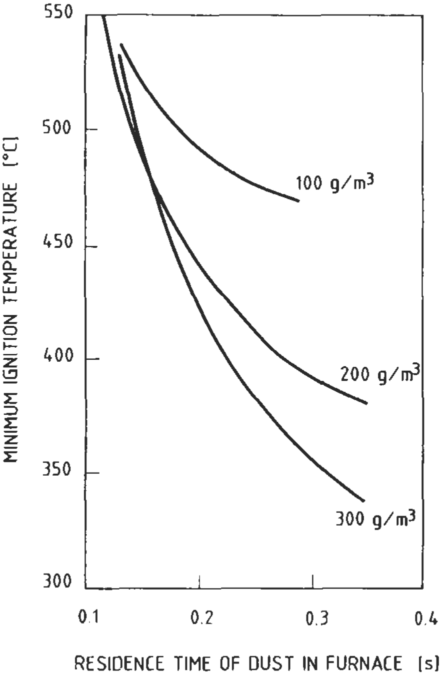


Figure 7.26 *Influence of the residence time of dust clouds in the Godbert-Greenwald furnace on the minimum ignition temperature, with three different concentrations of brown coal dust (From Griesche and Brandt, 1976).*

coal dust gave a minimum ignition temperature of 310°C. This is lower than all the data in Figure 7.26, but about 100°C higher than the very low value found for a residence time of >1 s and 500 g/m^3 dust concentration. This evidence should be kept in mind when applying data from standard Godbert-Greenwald furnace tests in industrial practice.

7.8.2.2
BAM Furnace

In Germany, an alternative furnace was developed by Bundesanstalt für Materialprüfung, as described by Leuschke (1966a, 1966b). The furnace is illustrated in Figure 7.27.

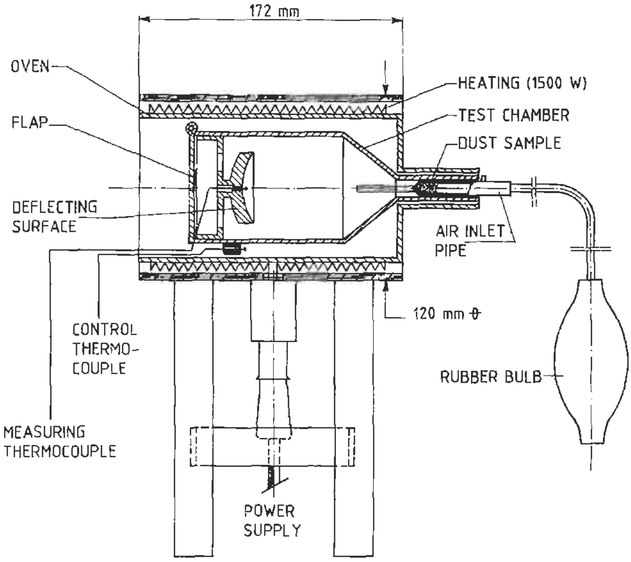


Figure 7.27 *BAM furnace for determination of the minimum ignition temperature of dust clouds (Courtesy of J. Lütolf, formerly of Ciba-Geigy AG).*

The experimental procedure is similar to that of the Godbert-Greenwald furnace, but the generation of the dust cloud is manual, by pressing a rubber bulb. The cloud is directed against a circular concave metal disk of about 20 cm^2 area and known temperature.

However, because of the horizontal geometry, the BAM furnace allows dusts that do not ignite directly in suspension to settle on the hot internal bottom of the furnace. In this way, smoldering gases can develop, which can ignite at a lower temperature than that required for direct ignition of the dust cloud. Ignition of smoldering gases normally occurs with a noticeable delay with respect to the dispersion of dust in the furnace. Because the BAM-furnace test method considers such delayed ignition of smoldering gases as equivalent to the ignition of the dust cloud, the minimum ignition temperatures determined by this test method can be lower than those determined in the Godbert-Greenwald furnace for the same dusts. Figure 7.28 shows data from comparative tests of the same dust in the Godbert-Greenwald and the BAM furnace. In this case, the difference is relatively small, about 20°C.

7.8.2.3
Newer U.S. Bureau of Mines Furnace

This furnace, which was described in detail by Conti et al. (1983), is shown in Figure 7.29. The volume of the ceramic chamber is 1.2 liters. This apparatus was included as an equal possibility together with the Godbert-Greenwald and BAM furnaces in a draft by Rogerson (1989) for a possible new standard for measurement of the minimum ignition

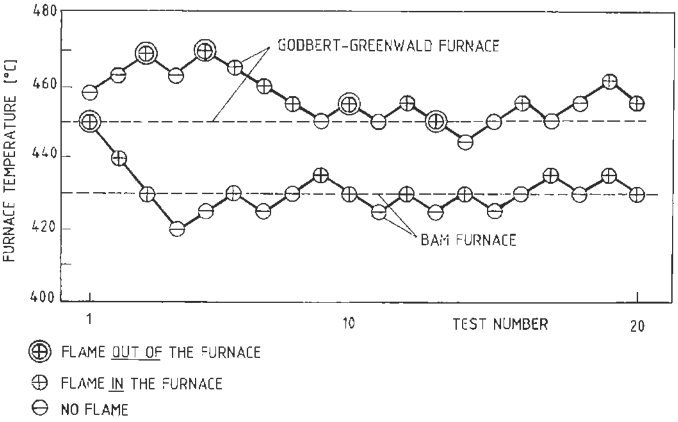


Figure 7.28 *Comparison of results from determination of the minimum ignition temperature of American lycopodium by two different furnaces, dust sample dispersed in each test is 1.6 cm³ (Private communication from Leuschke, BAM, Berlin, 1975).*

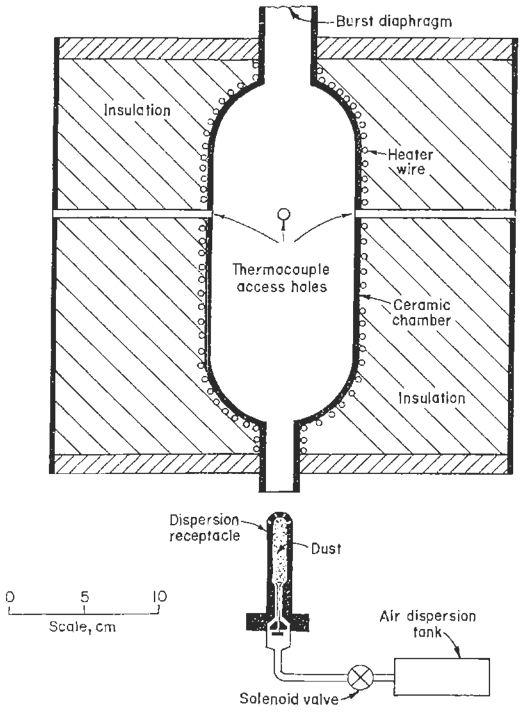


Figure 7.29 *Newer 1.2 liter U.S. Bureau of Mines furnace for determination of the minimum ignition temperature of dust clouds (From Conti et al., 1983).*

temperature of dust clouds. Conti et al. (1983) showed that, for organic materials and coals, the new furnace gave minimum ignition temperatures from 15–90°C lower than those from the Godbert-Greenwald furnace. Closer agreement with the BAM furnace would be expected for some dusts.

7.8.2.4
Further Comparison of Test Methods

Hensel (1984) compared the minimum ignition temperatures for a range of dusts, using four different apparatuses: the original and a modified BAM furnace and the original and a modified Godbert-Greenwald furnace. The BAM furnace was modified by replacing the rubber bulb for manual dust dispersion with an automatic system, as used with the Godbert-Greenwald furnace. The Godbert-Greenwald furnace was modified by doubling its length, which increased the residence time of the dust in the furnace. The results are given in Table 7.1.

Table 7.1 Comparison of minimum ignition temperatures of dust clouds in air determined in four different test furnaces

Name of substance	Minimum ignition temperature of a dust cloud (°C)				Maximum temperature difference (K)
	Godbert-Greenwald furnace		BAM furnace		
	IEC	Long	Manual	Automatic	
1. Sugar	420	420	360	340	80
2. Wheat flour	490	470	410	375	115
3. Dextran	400	380	370	340	60
4. Lycopodium	460	455	430	425	35
5. Tobacco additive	560	540	540	510	50
6. Painting powder (a)	570	570	530	490	80
7. Painting powder (b)	500	520	490	460	60
8. Painting powder (c)	470	480	460	450	30
9. Aluminum	560	515	510	510	50
10. Alloy (10% Zr)	430	380	380	370	60
11. Zircaloy fines	400	390	350	340	60
12. Brown coal	410	400	440	410	40
13. Pitch coal	590	560	560	560	30
14. Lignin	460	450	500	470	50
15. Pittsburgh coal	580	570	590	580	20
16. Plastic (a)	370	390	400	390	30
17. Plastic (b)	370	370	380	375	10
18. Plastic (c)	490	480	480	450	40
19. Plastic (d)	520	500	480	450	70
20. Plastic (e)	400	370	390	370	30
21. Chipboard dust	510	480	450	450	60

Source: Hensel, 1984.

With the exception of powders 7, 8, and 16 in Table 7.1, the long version of the Godbert-Greenwald furnace gave the same values as or lower values than the standard version. However, the differences were mostly moderate and no more than 50°C. The modification of the BAM furnace also led to a slight reduction of the minimum ignition temperatures.

7.9
MINIMUM ELECTRIC SPARK IGNITION ENERGY OF DUST LAYERS

7.9.1
THE INDUSTRIAL SITUATION

It is well known that explosible dust clouds can be ignited by electric sparks and arcs that occur in switches and motors and in short-circuiting caused by damaged cables. In addition, some categories of electrostatic discharges may initiate dust explosions in industry, as discussed in Sections 1.1.4.6 and 1.4.2.7. Hazardous electrostatic discharges include capacitive sparks, propagating brush discharges, and discharges from powder heaps.

The probability of a given dust layer or dust cloud being ignited by an electric spark not only depends on the spark energy but indeed on the distribution of this energy in time and space. This is discussed in greater detail in Chapter 5. In dust layers, the dependence on spark discharge duration is incorporated in the standard test procedure described in Section 7.9.2.2.

7.9.2
LABORATORY TESTS

7.9.2.1
Original U.S. Bureau of Mines Test

This method was described by Dorsett et al. (1960). The standard dust layer thickness tested was 1.6 mm. The layer rested on a 25 mm diameter steel plate that also served as the negative electrode. The positive needle point electrode, connected to a capacitor bank charged to 400 V, was lowered by hand toward the surface of the dust layer until a spark discharge occurred. After an ignition occurred, the steel plate was cleaned, a new dust layer formed, and the process repeated at progressively lower capacitance values until the lowest that gave at least 1 ignition in 20 trials was identified. The minimum ignition energy was defined as $\frac{1}{2}CV^2$, where C is the capacitance and V is the charging potential of 400 volts.

7.9.2.2
Nordtest "Fire 016"

This method, described by Nordtest (1982), is intended to be used primarily for pyrotechnics and explosives in pulverized form. It may, however, be applied to human-made and natural combustible materials, which, when distributed as a thin layer resting on a flat metal surface, can propagate self-sustained combustion. The test apparatus is illustrated in Figures 7.30 and 7.31.

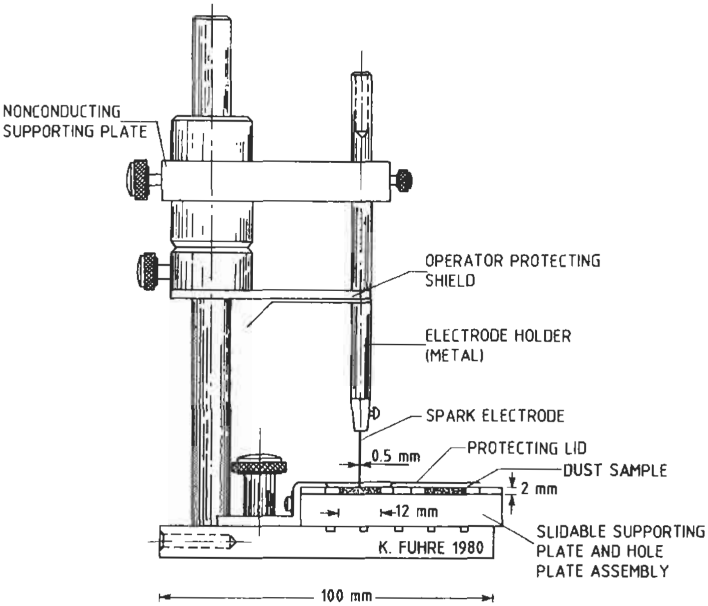


Figure 7.30 *Cross section of Nordtest apparatus to determine the electric spark ignition sensitivity of dust layers (From Nordtest, 1982).*

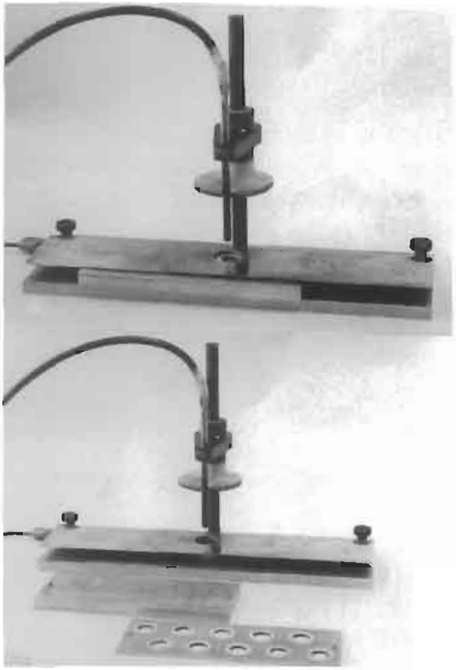


Figure 7.31 *Nordtest apparatus to determine the electric spark ignition sensitivity of dust layers: (top) assembled as in Figure 7.30, (bottom) slidable supporting plate and hole plate removed and shown separately.*

The dust or powder is poured gently into the disk-shaped cavities formed by the slidable supporting plate/hole plate assembly and excess dust is removed by a scraper. Plane, circular dust or powder samples of thickness 2 mm and diameter 12 mm are thus obtained. The metal bottom of the cavities acts as one of the two electrodes forming the spark gap. A thin tungsten wire pointing downward toward the dust or powder layer, with its tip just above the dust or powder surface, acts as the second electrode.

Electric sparks of the desired net energies and discharge times are passed through the sample, one at a time, and it is observed whether ignition occurs. An electric spark generator that permits independent variation of spark energy and spark duration is required. Figure 7.32 shows one type of generator used.

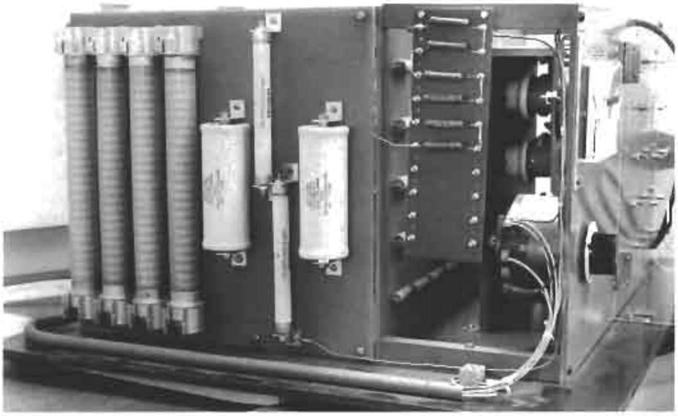


Figure 7.32 *Electric spark generator for determining electric spark ignition sensitivity profiles of dust layers.*

Twenty identical tests are carried out at each combination of net spark energy and discharge time, yielding a frequency of ignition in the range 0–100%. After each spark discharge, the dust or powder sample is shifted horizontally to allow each spark to pass through dust or powder not exposed to previous sparks. If ignition occurs, the sample tested is discarded and the test continued with a new sample.

The minimum electric spark ignition energy, defined as the net spark energy yielding an ignition frequency of 5%, is determined for various spark discharge durations Δt. The ultimate result of the test is an electric spark sensitivity profile $E_{\min}(\Delta t)$, as illustrated in Figure 7.33.

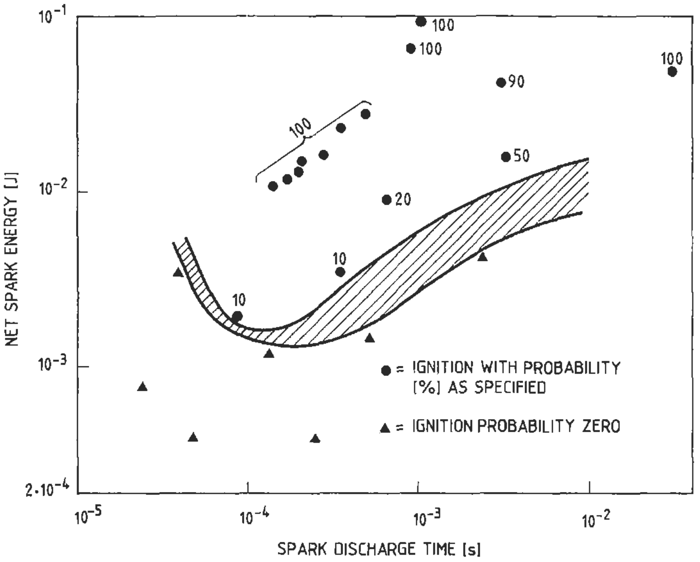


Figure 7.33 *Electric spark ignition sensitivity profile according to Nordtest (1982) for layers of a specific pyrotechnical product. The shaded area represents a profile for ignition probabilities P (%) for which 0 < P < 10.*

7.10
MINIMUM ELECTRIC SPARK IGNITION ENERGY OF DUST CLOUDS

7.10.1
THE INDUSTRIAL SITUATION

Most of what has been said in Section 7.9.1 also applies to dust clouds. Whenever relating results from laboratory tests to practice, it is important to account for the influence of both the spatial and temporal energy distribution in the discharge on the minimum spark energy for ignition. Relevant aspects are considered in Chapters 1 and 5.

7.10.2
LABORATORY TESTS

7.10.2.1
Original U.S. Bureau of Mines Method

The apparatus used by Dorsett et al. (1960) was essentially as illustrated in Figure 7.34. An appropriate quantity of dust was placed in the dispersion cup at the bottom of the 1.2 liter plastic cylinder and dispersed by a blast of air deflected by a conical "hat," as indicated. A spark was discharged across the electrodes synchronously with the transient appearance of the dust cloud in the spark gap region. A photograph of a dust explosion

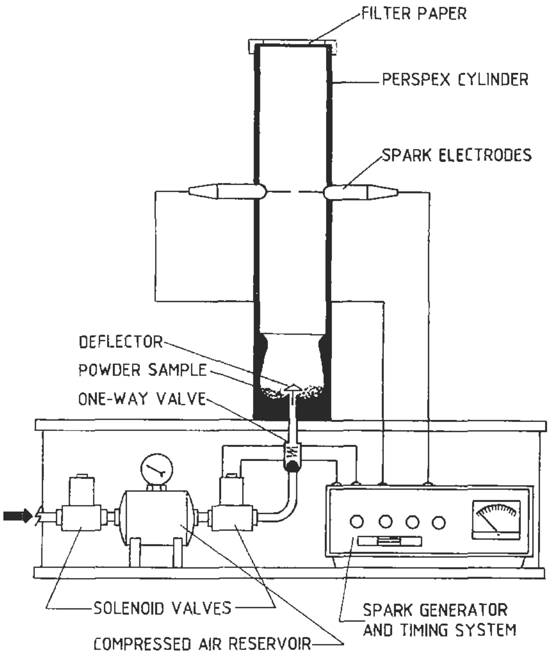


Figure 7.34 *Apparatus for determining the minimum ignition energy of dust clouds.*

in this type of apparatus is shown in Figure 7.35. However, the energies of the electric sparks used in the original U.S. Bureau of Mines test were not satisfactorily defined, due to the design of the spark discharge circuit, shown in Figure 7.36(a). The spark energy was generated by discharging the capacitor C at a DC voltage V through a step-up transformer. It was assumed that the spark energy equaled $^1/_2CV^2$, but some energy was inevitably lost in the transformer. A tentative correlation among the numerous $^1/_2CV^2$ values reported by U.S. Bureau of Mines over the years and the real electric spark energies is indicated in Figure A.1 in Appendix 1.

7.10.2.2
Direct Discharge of High-Voltage Capacitors

Direct discharge of capacitors at sufficiently high voltages to ensure direct breakdown of the spark gap, as illustrated in Figure 7.36(b), has also been used for test purposes. However, because of the high voltage, energy losses in the switch needed to synchronize the discharge with the dust cloud may be appreciable. Sophisticated elements such as thyratrons have been employed to solve this problem.

However, the spark and dust cloud can also be synchronized by incorporating a third, auxiliary spark electrode in the spark gap configuration. By discharging just a very small energy in the gap between one of the main electrodes and the auxiliary electrode, the main discharge is initiated. This method was used with success by Franke (1978).

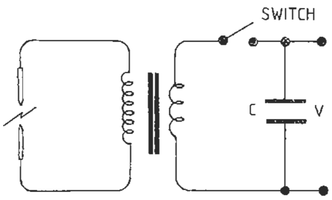
Mechanical synchronization constitutes a further possibility. Prior to the experiment, the capacitor is charged to the high voltage required with the spark gap sufficiently long

Figure 7.35 *Silicon dust explosion following electric spark ignition in an apparatus of the type illustrated in Figure 7.34.*

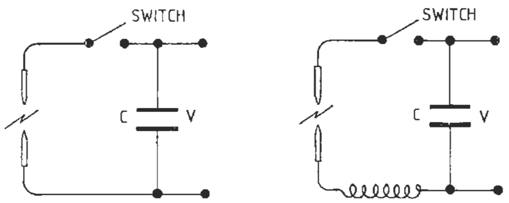
for breakdown to be impossible at that voltage. Pneumatically or spring-driven displacement of one spark electrode toward a shorter spark gap, allowing sparkover, is synchronized with the occurrence of the transient dust cloud, for example, via solenoids. Boyle and Llewellyn (1950) were probably among the first to use the electrode displacement method. Its drawback is that the actual spark gap distance at the moment of the discharge is not known.

One way of avoiding the synchronization problem is to work with a semistationary dust cloud and charge the high-voltage capacitor slowly until breakdown occurs naturally at the fixed spark gap distance chosen. Because of arbitrary variations, the actual voltage at breakdown differs from trial to trial and must be recorded for each experiment to obtain the actual given spark energy $^1/_2CV^2$.

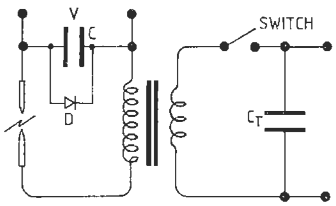
Figure 7.36(b) illustrates two versions of the direct high-voltage discharge circuit, with and without a significant series inductivity, on the order of 1 mH. This difference can be significant with respect to the igniting power of sparks of similar energies. The induction coil makes the spark more effective as an ignition source by increasing the discharge duration of the spark. Such an induction coil is automatically integrated in both the original U.S. Bureau of Mines circuit and the CMI circuit, as shown in Figures 7.36(a) and 7.36(c) (see Chapter 5 for further details concerning the influence of the spark discharge duration).



(a) LOW-VOLTAGE CAPACITOR DISCHARGED THROUGH TRANSFORMER (ORIGINAL U.S. BUREAU OF MINES CIRCUIT)



(b) DIRECT DISCHARGE OF HIGH-VOLTAGE CAPACITOR WITHOUT AND WITH INDUCTANCE



(c) CMI-DISCHARGE CIRCUIT

Figure 7.36 *Three electric spark discharge circuits used to determine the minimum ignition energy of dust clouds.*

If the test is to simulate a direct electrostatic discharge of an accidentally charged non-grounded electrically conducting object, the use of a discharge circuit with low inductance (left of Figure 7.36(b)) seems most appropriate.

7.10.2.3
The CMI Discharge Circuit

The method for synchronization of dust cloud and spark discharge developed by the Chr. Michelsen Institute (see Eckhoff, 1975b) is illustrated in Figure 7.36(c). The method is similar to the three-electrode technique in the sense that an auxiliary spark discharge is employed to break down the spark gap, but the use of a third electrode is avoided. The energy of the auxiliary spark is about 1–2 mJ. The CMI method requires that the spark energy be measured directly, in terms of the time integral of the electrical power dissipated in the spark gap. Figure 7.37 shows the traces of voltage and current for a spark

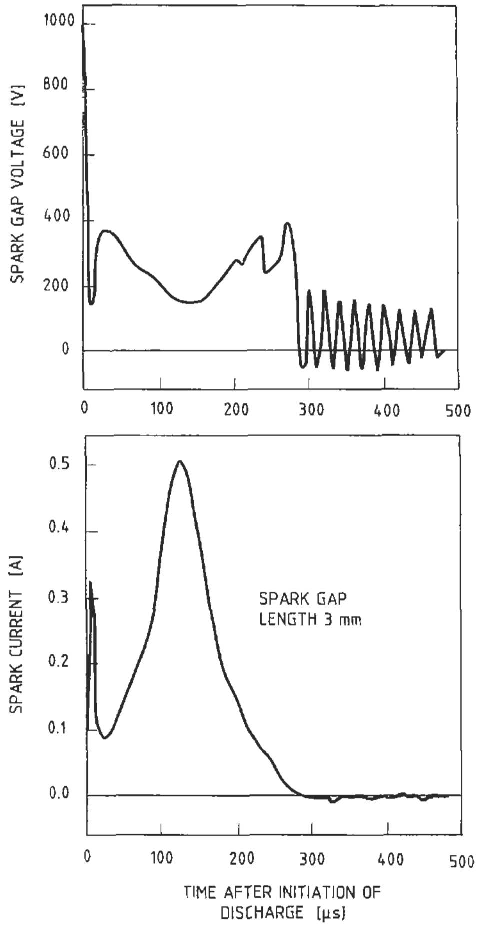


Figure 7.37 *Spark gap voltage and spark current versus time during discharge of a 13 mJ electric spark from the CMI spark generator. The spark discharge duration is 280 µs. The energy of the trigger spark (spike to the far left) is about 1–2 mJ.*

of net electrical energy 13 mJ produced by the CMI circuit. The spark discharge was completed after about 280 μs.

The general apparatus used by the CMI was as shown in Figure 7.34, that is, similar to that originally developed by the U.S. Bureau of Mines.

7.10.2.4
A Newer International Standard Method

As a part of its efforts to standardize safe design of electrical apparatus in explosible atmospheres, the International Electrotechnical Commission (1994) produced a new test method for the minimum ignition energy of dust clouds. The method is to a large extent based on work conducted by an international European working group and summarized by Berthold (1987).

The detailed design of the apparatus to be used in the IEC test method, in terms of explosion vessel, dust dispersion system, synchronization method, and so on is not specified, but some suitable apparatuses are mentioned, including direct high-voltage discharge circuits as well as the CMI circuit. However, no matter which apparatus is chosen, the spark generating system must satisfy the following requirements:

- Inductance of discharge circuit ≥1 mH.
- Ohmic resistance of discharge circuit <5 Ω.
- Electrode material is stainless steel, brass, copper, or tungsten.
- Electrode diameter is 2.0 mm.
- Electrode gap is 6 mm.
- Capacitors are low-inductance type, resistant to surge currents.
- Capacitance of electrode arrangement is as low as possible.
- Insulation resistance between electrodes is sufficiently high to prevent significant leakage currents.

It will be necessary to take account of the possible influences of dust concentration, dust cloud turbulence, and degree of dust dispersion on the test result. Preliminary tests must be carried out to adjust the dust dispersion conditions and the ignition delay, so that prescribed minimum ignition energies are actually measured for three specified reference dusts.

Starting with a value of spark energy that reliably causes ignition of a given concentration of the dust being tested, the dust concentration being itself a variable, the test energy is successively halved until no ignition occurs in 10 successive tests. The minimum ignition energy is defined to lie between the highest energy at which ignition fails to occur in at least ten successive attempts to ignite the dust/air mixture and the lowest energy at which ignition occurs within 10 successive attempts.

7.11
SENSITIVITY OF DUST LAYERS TO MECHANICAL IMPACT AND FRICTION

7.11.1
THE INDUSTRIAL SITUATION

This hazard applies primarily to powders and dusts with explosive properties, that is, those that can react or decompose exothermally with no oxygen supply from the air. Strong exothermal reactions may be initiated in layers of such materials if they are exposed to high mechanical stresses and fast heating by impact or rubbing, either accidentally or as part of an industrial process.

7.11.2
LABORATORY TESTS

7.11.2.1
Drop Hammer Tests

As summarized by Racke (1989), a number of impact or friction sensitivity test methods have been developed in several European countries, as well as in the United States

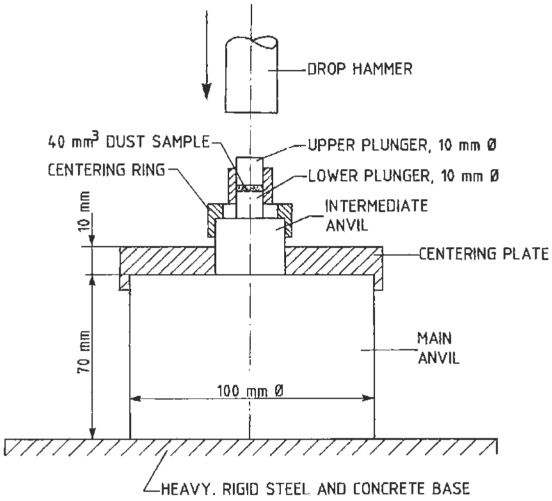


Figure 7.38 *Drop hammer test for dust layers by Koenen, Ide, and Swart (1961). Drop hammer mass is 5 kg and height of fall is 1 m (From Verein deutscher Ingenieure, 1988).*

and Japan. The most common design concept for the impact test is the drop hammer, as illustrated in Figure 7.38.

The Verein deutscher Ingenieure (1988) also mentioned a very similar test by Lütolf (1978) as a suitable standard method. In the Lütolf test, the dust sample size is about 0.10 g and the theoretical maximum drop hammer impact energy 39 J (5 kg, 0.8 m). Up to 10 trials are conducted and observations are made with respect to occurrence of explosion, flame, smoke, or sparks. If all 10 tests are negative, a new test series is conducted with the dust samples wrapped in thin aluminum foil (10 μm thickness), in case the aluminum should have a sensitizing effect on a possible exothermal reaction. If the tests with aluminum are positive, a new test series without aluminum is conducted.

The American Society for Testing and Materials (1988a) adopted the U.S. Bureau of Mines drop hammer method as their standard. Using a fixed drop hammer weight (2.0 or 3.0 kg), the drop height H_{50} giving 50% probability of a positive reaction is determined. The lower is H_{50}, the more sensitive the material is to impact ignition. In the test description, it is emphasized that the observation of the reaction of the sample is one of the difficult points in impact sensitivity testing. A positive test result is defined as an impact that produces one or more of the following phenomena: (a) audible reaction, (b) flame or visible light, (c) definite evidence of smoke (not to be confused with a dust cloud of dispersed sample), and (d) definite evidence of discoloration of the sample due to decomposition. The problem arises with reactions that yield no distinguishable audible response, no flame, and little sample consumption. The decision concerning reaction/no reaction in these cases must be based primarily on the appearance of the sample after the test. The impact in most cases compresses the sample into a thin disk, portions of which may adhere to the striking tool surface, the anvil, or both. One should then inspect the tool and anvil surfaces and look for voids in the powder disk and discoloration due to decomposition in areas where voids occur. If there is discoloration from decomposition, the test trial is to be considered positive. If there are small voids but no discoloration, the trial should be regarded negative. In the case of doubt as to whether or not discoloration is present, the trial is to be regarded negative. If the only evidence is a slight odor or a small amount of smoke, which may be a dust cloud from the dispersed sample, the trial should also be considered negative.

7.11.2.2
Friction Tests

As pointed out by Racke (1989), several different friction tests have been devised, including three described by Gibson and Harper (1981). One of these is illustrated in Figure 7.39.

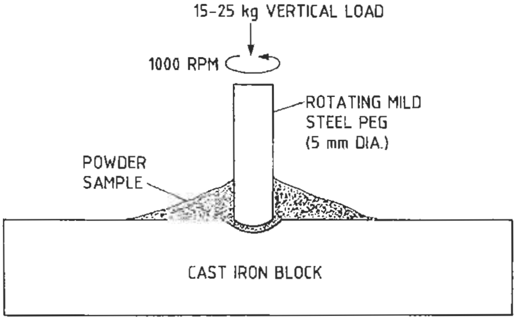


Figure 7.39 *Example of laboratory method for testing the sensitivity of powders to mechanical rubbing or friction (From Gibson and Harper, 1981).*

7.12
SENSITIVITY OF DUST CLOUDS TO IGNITION BY METAL SPARKS, HOT SPOTS, OR THERMITE FLASHES FROM ACCIDENTAL MECHANICAL IMPACT

7.12.1
THE INDUSTRIAL SITUATION

Dense clouds of metal sparks and hot surfaces are easily generated in grinding and cutting operations. Such operations are therefore generally considered as hot work, which should not be permitted in the presence of ignitable dusts or powders.

However, the evaluation of the ignition hazard associated with accidental impacts is less straightforward. Such impacts can occur due to misalignment of moving parts in powder processing equipment, for example, in grinders and bucket elevators. Or foreign bodies such as stones and tramp metal can get into the process line. Whether or not metal sparks and hot spots or thermite flashes from single accidental impacts between solid bodies can initiate dust explosions has remained a controversial issue for a long time. It now seems that, in the past, "friction sparks" have been claimed to be the ignition sources of dust explosions more often than one would consider reasonable on the basis of more-recent evidence. However, as long as the necessary conditions for such impacts to be capable of initiating dust explosions have been unidentified, one has been forced to maintain the hypothesis that such sparks may be hazardous in general. This, in turn, has forced industry to take precautions that may have been superfluous and caused fear that may have been unnecessary.

Generation of metal sparks or hot spots by accidental mechanical impacts is a complex process, involving a number of variables, such as the

- Chemistry and structure of the material of the colliding bodies.
- Physical and chemical surface properties of the colliding bodies.
- Shapes of the colliding bodies.
- Relative velocity of the colliding bodies just before impact.
- Impact energy (kinetic energy transformed to heat in an impact).
- Likelihood of single or repeated impacts.

Whether a given dust cloud will be ignited by a given impact not only depends on the specific dust properties, but also on the

- Dust concentration and dynamic state of the dust cloud.
- Composition, temperature, and pressure of the gas phase.

In view of the great number of variables and the lack of an adequate theory, it is clear that the ignition experiments on the basis of which the practical hazard is to be assessed should resemble the practical impact situation as closely as possible.

7.12.2
LABORATORY TESTS

No standardized test methods have been traced so far, but the ability of metal sparks and hot spots from grinding and cutting to ignite dust clouds has been demonstrated in laboratory tests by several researchers, including Leuschke and Zehr (1962); Zuzuki, Takaoka, and Fujii (1965); Allen and Calcote (1981); and Ritter (1984) (see Chapter 5).

Laboratory test methods for the incendivity of single accidental mechanical impacts seem to be less numerous. A test apparatus developed by Pedersen and Eckhoff (1987) is illustrated in Figure 7.40.

The basic principle of impact generation is that a spring-loaded rigid arm, which can swing around a fixed axis and carries the test object at its tip, is released and hits a test anvil tangentially at a known velocity. Depending on the normal contact force during impact, the peripheral velocity of the tip of the arm is more or less reduced. By knowing the mass distribution of the arm and the peripheral velocity of its tip just before and just after impact, the impact energy can be estimated in terms of loss of kinetic energy of the arm. The impact force is varied by varying the excess length of the arm compared with the distance from the arm axis to the anvil.

Figure 7.41 gives an expanded view of the test object holder at the arm tip. The dust cloud was generated by dispersing a given quantity of dust from a dispersion cup by a short blast of air. The dust concentration of the transient cloud near the point of impact, at the moment of impact, was measured by a calibrated light attenuation probe (see Figure 1.76 in Chapter 1).

Figure 7.42 shows some typical results from experiments with the apparatus shown in Figure 7.40. Further details of this kind of experiments are discussed in Chapter 5.

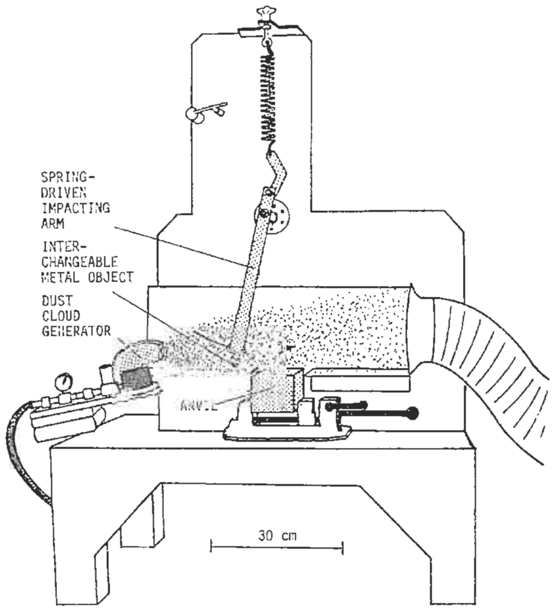


Figure 7.40 *Apparatus for determining the sensitivity of dust clouds to ignition by a single accidental mechanical impact (From Pedersen and Eckhoff, 1987).*

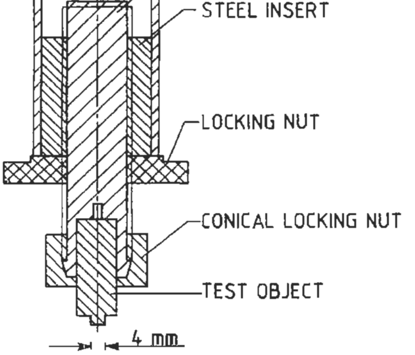


Figure 7.41 *Expanded view of test object holder of apparatus shown in Figure 7.40 (From Pedersen and Eckhoff, 1987).*

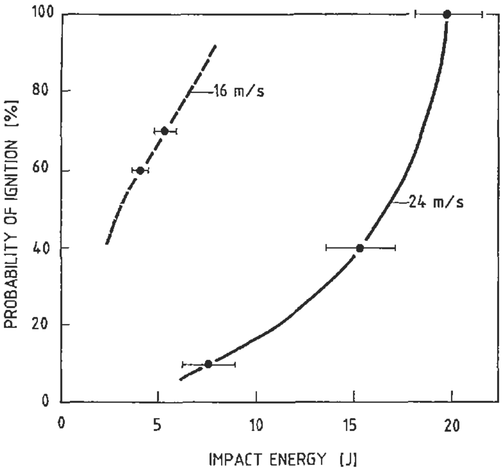


Figure 7.42 *Frequency of ignition of clouds of dried maize starch in air as a function of impact energy at 16 m/s and 24 m/s peripheral velocity of approach of the arm tip. Bars indicate ±1 standard deviation. Impacts are between titanium and rusty steel (thermite flashes) (From Pedersen and Eckhoff, 1987).*

Because of the lack of generally accepted test methods, it has been suggested that the sensitivity of a dust cloud to ignition by metal sparks or hot spots from accidental impacts may be correlated to the sensitivity of ignition by other sources, such as electric sparks. As discussed in Chapter 5, Ritter (1984) found a correlation involving both the minimum electric spark ignition energy and the minimum ignition temperature as determined by the BAM furnace. Table 7.2 indicates a correlation with the minimum electric spark ignition energy alone.

Table 7.2 Results from single-impact ignition tests of dust clouds of different minimum electric spark ignition energies, using a 20 J thermite flash impact between titanium and rusty steel

Dust	Minimum electric spark ignition energy (mJ)	Frequency of ignition in impact tests (%)
Corn starch, dried	<4.5	100
Lycopodium	6	100
Barley protein	13	10
Barley starch	18–22	0
Corn starch, 10–11% moisture	27–36	0
Barley fiber	47–59	0

Source: Pedersen and Eckhoff, 1987.

7.13
MINIMUM EXPLOSIBLE DUST CONCENTRATION

7.13.1
THE INDUSTRIAL SITUATION

For a given type of explosible dust, dispersed as a cloud in air, there is a reasonably well-defined minimum quantity of dust per unit volume of air below which the dust cloud cannot propagate a flame (see Chapter 4 for a full discussion). In theory, therefore, one could eliminate the possibility of dust explosions by ensuring that the dust concentration does not exceed this minimum limit. In practice, however, most process equipment in plants where powders are manufactured and handled always contain large quantities of powder, and hence this principle of preventing dust explosions is not practical in general. However, the principle may be adapted in practice to some types of process equipment (see Section 1.4.3.2).

One example is dust extraction systems designed to extract a relatively small quantity of fine dust from a coarse main product, as in grain silo plants. In such cases, the concentration of dust in the system can often be controlled to some extent by controlling the flow of air. It is then essential, however, that the air velocity is maintained sufficiently high to prevent dust from depositing on the walls of the ducting and so forth, since such deposits, if redispersed, may form clouds of explosible concentration.

Another type of equipment that can be protected by keeping the dust concentration sufficiently low is systems for electrostatic powder painting. In such systems, the concentration of particles in the air is relatively uniform and fairly easy to control. In fact, several countries have imposed specific maximum permissible average dust concentrations in the spraying booth, based on estimates of the minimum explosible dust concentration (see Section 1.5.3.5).

7.13.2
LABORATORY TESTS

Experimental determination of the minimum explosible dust concentration is discussed in detail in Section 4.2.6.2 in Chapter 4. This also includes comparison among the various test methods in use.

7.13.2.1
Tests Developed in the United States

In the standard test used in the United States and United Kingdom for a number of years and described by Dorsett et al. (1960), a known quantity of the powder was dispersed as a cloud in a slim, vertical, cylindrical container of 1.2 liter volume and exposed to a continuous spark ignition source. Starting with very small powder quantities and repeating the test with steadily increasing amounts, a critical quantity was reached at which the dust cloud ignited. The critical mass of dust, divided by the volume of the test container, was taken as the minimum explosible dust concentration (MEC).

It was felt that the traditional test method was not fully satisfactory. On the one hand, the continuous ignition source was located in the lower part of the vertical, elongated explosion vessel; and this would allow the dust cloud, rising from the dispersion cup of the vessel bottom, to become ignited before having been fully dispersed throughout the entire vessel volume. Hence, the real concentration of dust in the cloud at the moment of ignition was likely to be higher than the nominal concentration estimated by dividing the mass of dust dispersed by the total vessel volume. This error generally leads to underestimation of the MEC. On the other hand, the traditional ignition source was a continuous train of relatively weak electric sparks that may not have been sufficiently energetic to ignite dust clouds of concentrations near the true limit for self-sustained flame propagation. This would generally yield overestimation of the MEC. The effects of these two factors tend to cancel each other, and this may be the reason for the surprisingly good agreement obtained in some cases between MEC values from the traditional small-scale lab test and large-scale experiments. For example, Jacobson et al. (1961) found that various grain dusts and starches all had MECs on the order of 50 g/m^3 in the small lab-scale test, which compares favorably with the value 60 g/m^3 found for a typical wheat grain dust containing 10% moisture in industrial-scale experiments by Eckhoff and Fuhre (1975).

However, such good agreement between the small-scale test and large-scale conditions would not be expected to be the general rule. For this reason, considerable efforts have been made in several countries during the 1980s to develop an improved test for the MEC.

In the United States, Hertzberg et al. (1979) at the Bureau of Mines first developed an 8 liter explosion vessel in which transient dust clouds of quite homogeneous concentration distributions could be generated. An important conclusion from these studies was that determination of true MEC values requires a strong ignition source. Therefore, Cashdollar and Hertzberg (1985) subsequently developed a 20 liter explosion vessel that would yield meaningful results even with quite strong ignition sources.

A cross section of the 20 liter vessel is shown in Figure 7.43. A photograph of the opened vessel, showing one of the light attenuation probes for measuring the dust concentration development in the transient dust cloud, is given in Figure 7.44.

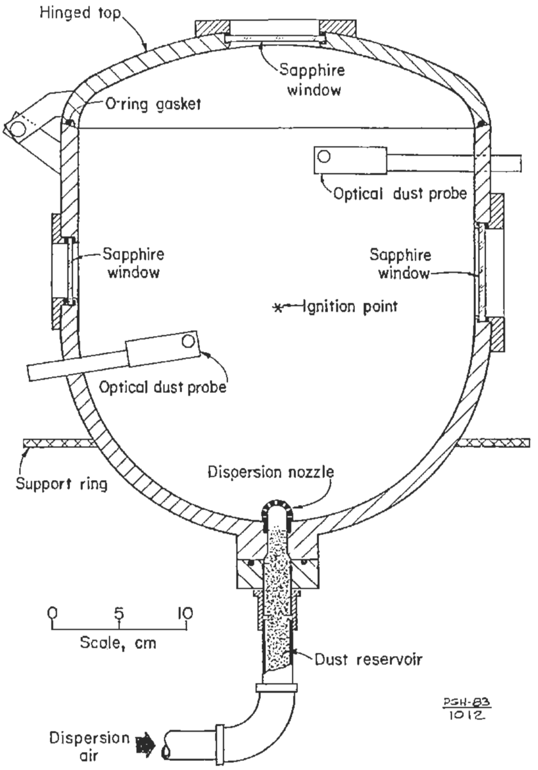


Figure 7.43 *Cross section of U.S. Bureau of Mines' 20 liter explosion vessel for determination of the minimum explosible concentration and other parameters of explosible dust clouds (From Cashdollar and Hertzberg, 1985).*

Figure 7.44 *Photograph of opened 20 liter U.S. Bureau of Mines explosion vessel, showing one of the light attenuation probes for measuring dust concentration (Courtesy of K. L. Cashdollar, U.S. Bureau of Mines, Pittsburgh).*

Favorable agreement was obtained between minimum explosible concentrations found for coal dust in large-scale mine experiments and in the 20 liter vessel (Cashdollar et al., 1987). The ignition source used in the 20 liter sphere was then a strong chemical ignitor of calorific energy about 2500 J. The criterion of explosion was that the explosion pressure in the closed vessel should rise to at least twice the absolute initial pressure. For atmospheric initial pressure this means at least 1 bar(g). In addition, the maximum rate of pressure rise should exceed 5 bar/s.

7.13.2.2
German and Swiss Closed Bombs

Both the 1 m^3 ISO vessel developed by Bartknecht and the 20 liter Siwek vessel are discussed in Chapter 4 and further details are given in Sections 7.16 and 7.17. With the same ignition source and explosion criterion as used by Cashdollar and Hertzberg, the Siwek sphere should yield comparable results. If, however, the 10 kJ ignitor prescribed for the Siwek sphere to determine P_{max} and K_{St} values is used, too low minimum explosible concentration values would be expected for some dusts.

The 1 m^3 ISO vessel would be expected to yield the most reliable assessment of the minimum explosible concentration. Because of the large volume of the dust cloud, even a very strong ignition source of 10 kJ would not interfere with the main phase of dust cloud propagation. However, just because of its large size, the 1 m^3 test is not very suitable for routine testing, and smaller, laboratory-bench-scale methods are needed.

7.13.2.3
Nordtest Fire 011

The Nordtest (1989) method was designed specifically to meet the need of a reliable bench-scale test for the minimum explosible concentration of dust clouds. The apparatus consists of three main parts:

- A 15 liter explosion vessel with a dust dispersion system.
- An ignition system.
- A dust concentration measurement system.

Figure 7.45 shows a maize starch explosion in the 15 liter Nordtest vessel.

The test procedure consists of two consecutive steps. First, weighed quantities of the dust are dispersed into clouds in the 15 liter explosion vessel by a suitable, defined blast of air and exposed to an effective ignition source. The dispersion mushroom shown in Figure 7.46 is an essential part of the dust dispersion system.

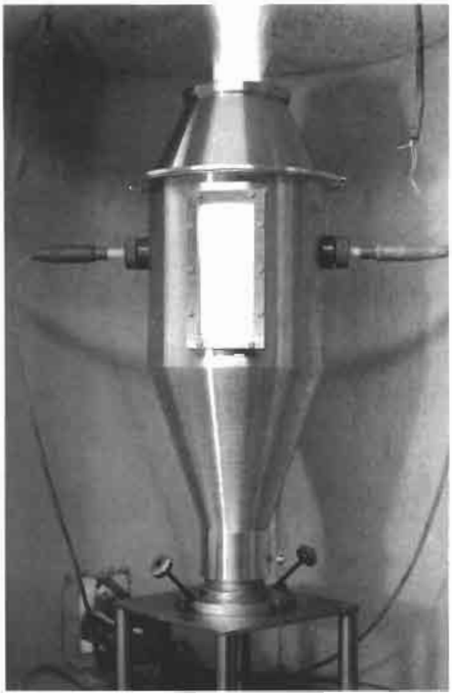


Figure 7.45 *Maize starch explosion in a 15 liter Nordtest Fire 011 vessel. The ignition source is a strong electric arc between two thin metal electrodes.*

The driving pressure and duration of the air blast are set to yield a reasonably homogeneous dust cloud in the vessel, as judged visually by the operator. Optimum dispersion conditions depend on particle size, shape, density, and mass of dust to be dispersed. Immediately after completion of dispersion, the ignition source, positioned centrally within the cloud, is activated. By varying the dispersed mass of dust and conducting 10 tests with each mass, the mass yielding a probability of explosion of 50% is estimated by interpolation.

Figure 7.46 *Dispersion mushroom for Nordtest Fire 011 (right) compared with the IEC version for the Hartmann bomb (left). The length of the match is approximately 50 mm.*

The ignition source recommended for the test is a 200 W electric arc of 0.1 s duration. The arc is passed across a 3 mm spark gap between two 1.6 mm Ø metal electrodes. The arc discharge is initiated by the closing action of the solenoid valve of the dust dispersion system. The ignition source must under no circumstances be less effective than this arc. However, in exceptional cases, the ignitability of the dust to be tested can be so low that a more-effective ignition source may be required. *Explosion* (i.e., a positive test result) is defined as independent flame propagation through the experimental dust cloud to the extent that the flame, observed visually, is clearly detached from the ignition source.

In the second step of the test procedure, the actual local dust concentration in the vicinity of the ignition source, at the same instant as the ignition source would be activated in the first step, is determined using the dust mass giving 50% of ignition and exactly the same dust dispersion method as in the ignition tests. The arithmetic mean of five consecutive concentration measurements is taken as the minimum explosible dust concentration.The version of the 15 liter vessel used in the second step is shown in Figure 7.47, and the basic principle of the traversing dust sampling cylinder is illustrated in Figure 7.48.

7.13.2.4
International Standards

The International Electrotechnical Commission (1990) evaluated a test method based on the 20 liter Siwek (1988) sphere. Nordtest (1989) and the 1 m^3 vessel of the International Standards Organization (1985a) are alternative methods.

The explosion criterion is that the maximum explosion pressure should be at least 1.5 bar(g). This includes the pressure of 1.1 ± 0.1 bar(g) generated by the powerful chemical 10 kJ ignitor only, without dust. Tests are conducted with successively decreasing dispersed dust masses in steps of 0.2 g until a mass is reached at which the maximum pressure is lower than 1.5 bar(g) in three consecutive tests with the same dispersed dust mass. The minimum explosible concentration is then assumed to lie between the highest nominal concentration (dispersed mass divided by vessel volume) at which the maximum explosion pressure was less than 1.5 bar(g) in three successive tests and the lowest nominal concentration at which the explosion pressure was 1.5 bar(g) or more in one of up to three successive tests.

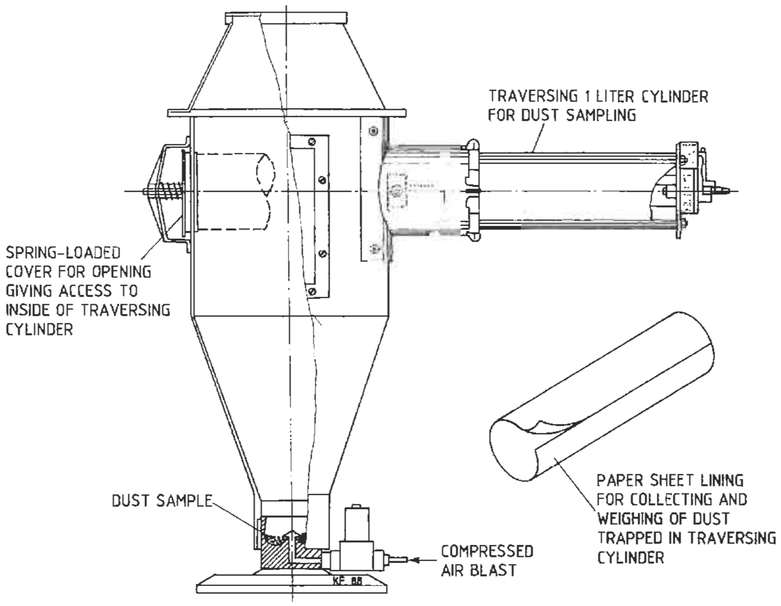


Figure 7.47 *A 15 liter Nordtest Fire 011 vessel equipped with traversing cylinder for measuring local dust concentration in the vicinity of the ignition source (From Nordtest, 1989).*

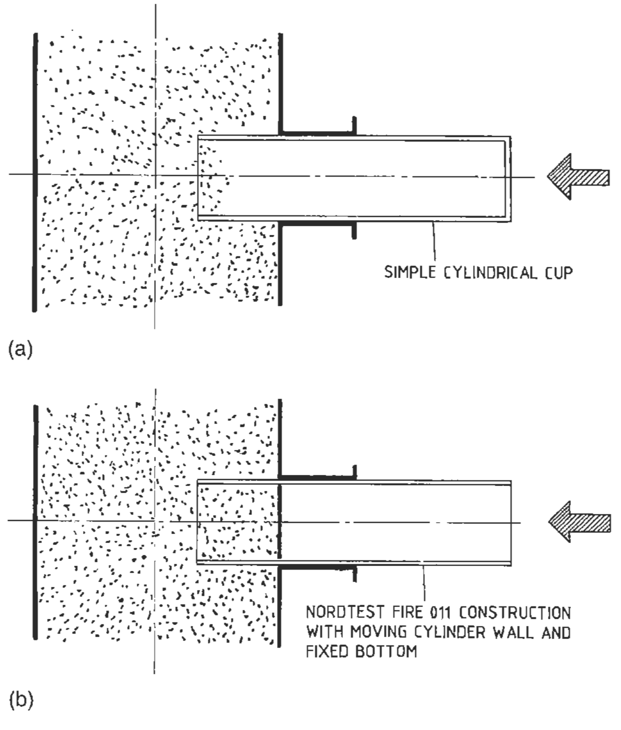


Figure 7.48 *Principle of Nordtest Fire 011 dust cloud sampling cylinder (b) compared with that of a simple cylindrical cup (a).*

As discussed in Section 4.2.6.2 in Chapter 4, there are indications of this test method yielding unexpectedly low minimum explosible dust concentrations for some dusts. This may be due to the use of the very energetic 10 kJ chemical ignition source that may support propagation of flames in dust clouds of lower concentrations than the true minimum explosible concentration.

This problem is avoided when using the ISO (1985a) method, because the vessel of 1 m^3 volume is sufficiently large for ignition-source-independent flame propagation to be necessary to generate significant explosion pressures.

Table 4.9 in Chapter 4 gives comparative data from tests with the three methods, using the same dusts. See also Sections 9.2.4.3 and 9.4.4 in Chapter 9.

7.14
MAXIMUM EXPLOSION PRESSURE AT CONSTANT VOLUME

7.14.1
THE INDUSTRIAL SITUATION

Most process equipment is not strong enough to withstand the typical pressures generated by unvented dust explosions. In principle, strengthening the equipment can prevent it from bursting, but in general, the structures required to achieve sufficient strength have to be so heavy that this approach is generally not recommended, either from the point of view of capital cost or with respect to running and maintaining the plant. Exceptions are cylindrical dust extraction ducting, which can be made pressure resistant with reasonable wall thicknesses, and certain types of equipment, which are heavy anyway, such as some mill types.

Nevertheless, the concept of a fully pressure-resistant process plant is sometimes adopted, such as when the powders are highly toxic and therefore in no circumstances can be allowed outside the equipment. In such cases, it is important to know the highest pressures to be expected, should a dust explosion occur within the equipment. As discussed in Section 1.3.8 in Chapter 1, the maximum explosion pressure (abs) is generally proportional to the initial pressure (abs), which must therefore be specified. In a dust explosion in a fully confined, integrated system of various process items connected by comparatively narrow passages, pressure piling may easily occur, as discussed in Section 1.4.4.1 in Chapter 1. This implies that a local explosion in one process unit may raise the pressure in the unburned dust clouds elsewhere in the interconnected system. Should the flame then propagate into this prepressurized area, a considerably higher maximum pressure can result than if the initial pressure had been atmospheric. Such pressure piling, which may escalate in several stages, can give rise to local transient explosion pressures that are substantially higher than the adiabatic maximum explosion pressure at a constant volume generated from normal atmospheric initial pressure. These possibilities must be considered carefully before adopting laboratory test data for the maximum explosion pressure, which are normally based on atmospheric initial pressure.

7.14.2
LABORATORY TESTS

7.14.2.1
Hartmann Bomb

The Hartmann bomb, described by Dorsett et al. (1960), has been used throughout the world to assess the maximum explosion pressure of dust clouds for nearly half a century. This apparatus, which is illustrated in Figures 7.49 and 7.50, basically consists of a closed vertical 1.2 liter stainless steel cylinder into which a known quantity of dust is dispersed as a cloud by a blast of air and exposed to an ignition source.

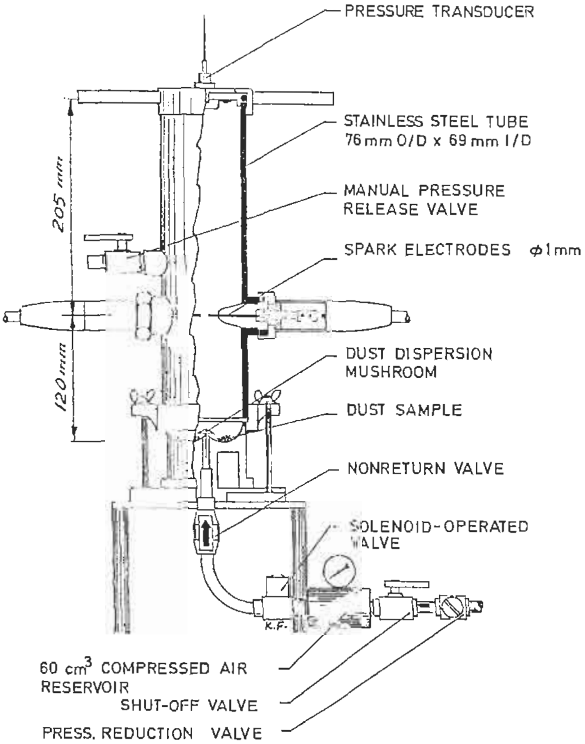


Figure 7.49 *A 1.2 liter Hartmann bomb to determine pressure development in dust explosions at constant volume. This version was developed with multinational cooperation and in all essentials adopted as a standard by the American Society for Testing and Materials (1988b).*

The dispersion mushroom design adopted in a multinational joint effort through the IEC and shown in Figure 7.46 differs slightly from that included in the standard specified by the American Society of Testing and Materials (1988b).

The ignition sources used include continuous trains of electric sparks, single synchronized sparks, synchronized chemical ignitors, and glowing resistance wire coils. Versions of the last two are shown in Figure 7.51. To determine maximum pressure, the

Figure 7.50 *Photograph of the version of the Hartmann bomb shown in Figure 7.49.*

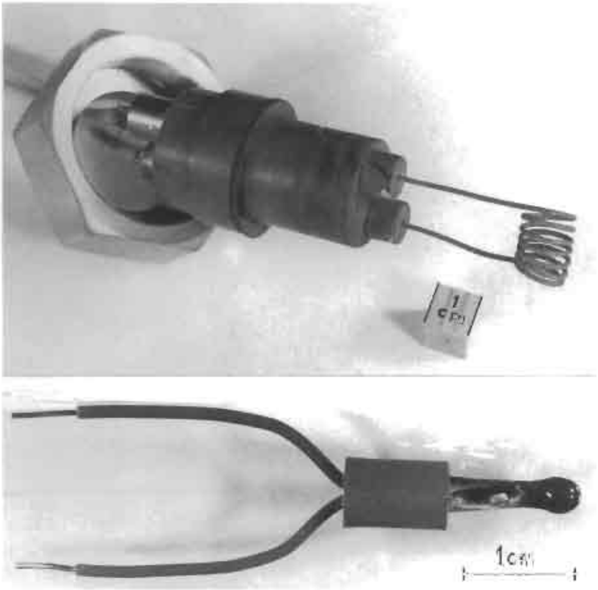


Figure 7.51 *Glowing resistance wire coil (continuous ignition source) (a) and chemical match head (instantaneous source) (b) used in Hartmann bomb tests (From Eckhoff, 1976).*

nature of the ignition source is not decisive, because the maximum pressure is rather insensitive to the turbulence of the dust cloud at the moment of ignition. For the rate of pressure rise, however, turbulence is a key parameter and the moment of ignition must be exactly defined (see Section 7.15).

The development of explosion pressure as a function of time is recorded as illustrated in Figure 7.52 over a range of nominal dust concentrations (dispersed dust mass divided by bomb volume). Due to statistical scatter, several tests have to be determined at each nominal dust concentration. A typical set of results is shown in Figure 7.53. This figure

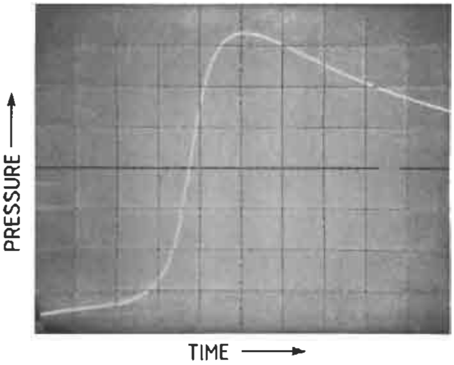


Figure 7.52 *Typical trace of pressure-versus-time during dust explosion in a closed vessel.*

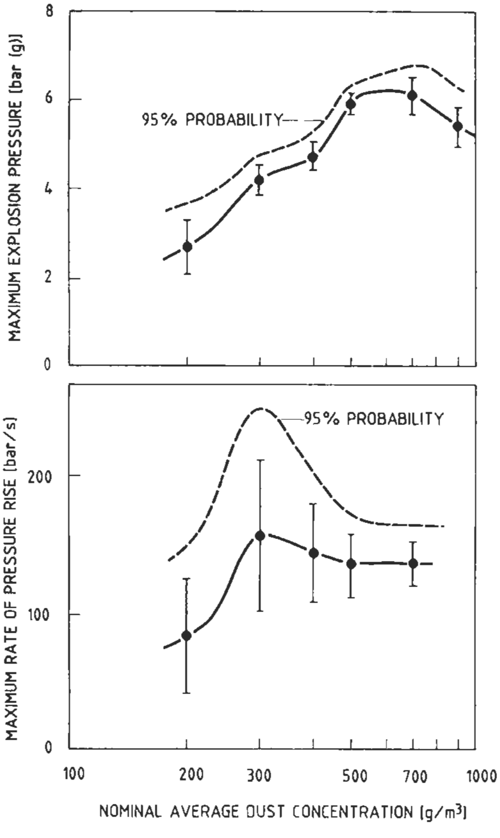


Figure 7.53 *Typical set of results from Hartmann bomb test of a given dust. Bars represent ±1 standard deviation. The dashed line shows the results based on a Gaussian distribution (mean + 1.65 std. dev.).*

also includes the maximum rate of pressure rise (i.e., the maximum value of the slope of the pressure-versus-time curve), which is discussed separately in Section 7.15. In Norway, it has been customary to take the highest 95% probability value as the result of the test. For the example in Figure 7.53, this means a maximum pressure of 6.8 bar(g).

Because of the small volume of the Hartmann bomb and its elongated shape, the heat loss to the vessel wall during the explosion is significant. Therefore, the maximum pressures measured are generally somewhat lower, typically by 25–30%, than those generated with the same dusts in larger vessels, such as the 1 m^3 ISO vessel and various 20 liter vessels. This occurs even though the pressures measured in the Hartmann bomb are not corrected for the increased initial pressure due to the dust dispersion air.

The measurement of maximum constant-volume pressures generated by dust explosions in closed bombs is fairly straightforward. Apart from the wall-cooling effects in small bombs, the results do not depend much on the details of the experiment as long as the dust cloud is reasonably well dispersed and the average nominal dust concentration is varied systematically to identify the worst case.

7.14.2.2
The 1 m^3 Standard ISO Vessel

Side and top views of this apparatus are illustrated in Figure 7.54.

A container of approximately 5 liters capacity and capable of being pressurized with air to 20 bar is attached to the explosion chamber. The container is fitted with a 19 mm Ø opening valve of 10 ms opening time. The container is connected to the explosion chamber via a 19 mm Ø perforated semicircular spray pipe. The diameter of the holes in the pipe should be in the range 4–6 mm. The number of holes is chosen such that their total cross-sectional area is approximately 300 mm^2.

The ignition source is a pyrotechnical ignitor with a total energy of 10 kJ and arranged to fire after a fixed delay of 0.6 s after onset of dust injection. The mass of the pyrotechnical ignition source is 2.4 g, and it consists of 40% zirconium, 30% barium nitrate, and

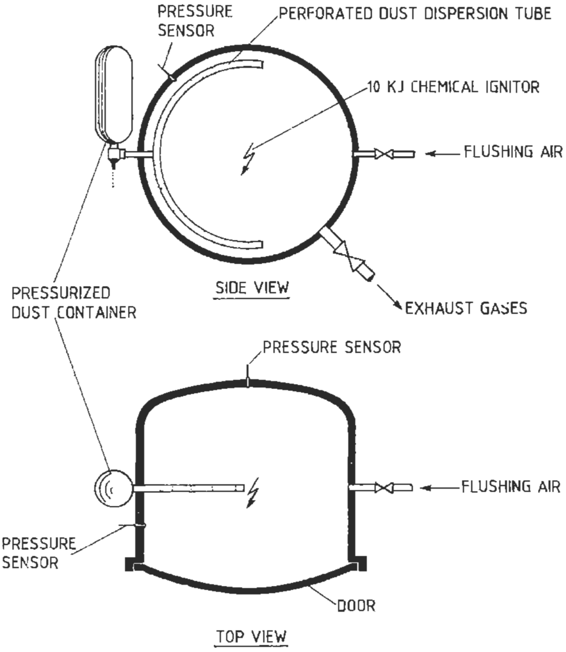


Figure 7.54 *The 1 m^3 closed vessel specified by the International Standards Organization (1985a) to determine maximum explosion pressures and maximum rates of pressure rise of dust clouds in air (From Verein deutscher Ingenieure, 1988).*

30% barium peroxide. It is activated by an electric fuse head. The ignitor is located at the geometric center of the explosion chamber. Two pressure transducers, linked to a recorder, are fitted to measure the explosion chamber pressure development.

The way of determining the maximum explosion pressure is similar to that of the Hartmann bomb test, and Figures 7.52 and 7.53 also apply to the 1 m^3 test. However, due to the comparatively large size of the experiment, the amount of dust and the time required per experiment limit the number of tests that are normally performed.

Maximum explosion pressures measured with this apparatus would be expected to be relatively close to the theoretical maximum adiabatic pressures. Data for a range of dusts are given in Table A.1 in Appendix 1. Figure 7.55 shows a 1 m^3 vessel that would most probably satisfy the ISO-standard requirement, if equipped with appropriate dust dispersion and ignition systems.

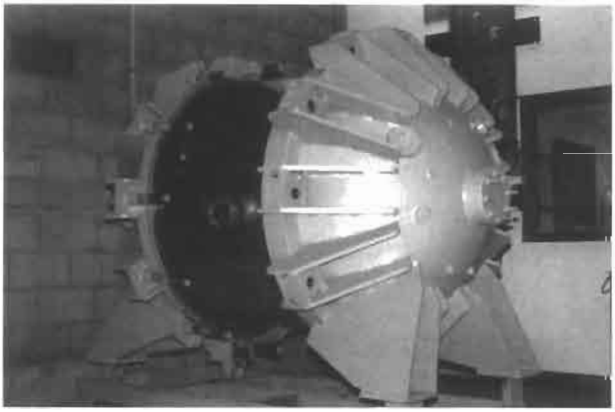


Figure 7.55 *A 1 m^3 spherical explosion vessel composed of two detachable hemispheres (Courtesy of Fike Corporation, United States).*

7.14.2.3
The Siwek 20 Liter Sphere

This vessel was developed by Siwek (1988) primarily with a view to obtain maximum explosion pressures and explosion rates in agreement with data from the 1 m^3 ISO vessel. The Siwek sphere is shown in Figure 7.56.

The sphere essentially is a small-scale version of the 1 m^3 ISO vessel. The original dust dispersion system was of the same type as that of the 1 m^3 ISO vessel, consisting of a pressurized dust reservoir, from which the dust was injected into the main vessel through a perforated tube, as illustrated in Figure 7.54. The experimental conditions required to obtain agreement with the 1 m^3 ISO vessel were specified in a standard issued by the American Society for Testing and Materials (1988c). The ignition source has to be the same type of 10 kJ chemical ignitor as used in the 1 m^3 ISO test. The ignition delay is, however, shorter (60 ms) because of the smaller vessel size. To determine the rate of pressure rise (see Section 7.15), it is important to pay attention even to the design of the capsule containing the pyrotechnical mixture of the ignition source.

Figure 7.56 *A 20 liter Siwek sphere to determine pressure development in dust explosions (Courtesy of R. Siwek, Cuba-Geigy AG, Switzerland).*

Zhu Hailin, Liu Xiangjun, and Li Hongquan (1988) showed that ignitors with metal capsules could give significantly different K_{St} values from those obtained for the same dusts with plastic capsules.

Under these circumstances and testing dusts of small particle size, Siwek obtained quite good correlations between data from the 1 m^3 ISO vessel and that from his 20 liter sphere, as shown in Figure 7.57 (K_{St} is defined in Section 4.4.3.3 in Chapter 4).

Experience in several laboratories disclosed, however, that many cohesive dusts, in particular those of fibrous particles, can easily get packed and trapped inside the perforated dispersion tube of the original dust dispersion system, which is clearly unsatisfactory. This led to the development of an open nozzle system named a *rebound* nozzle, shown in Figure 7.58, which gradually replaced the original perforated ring. According

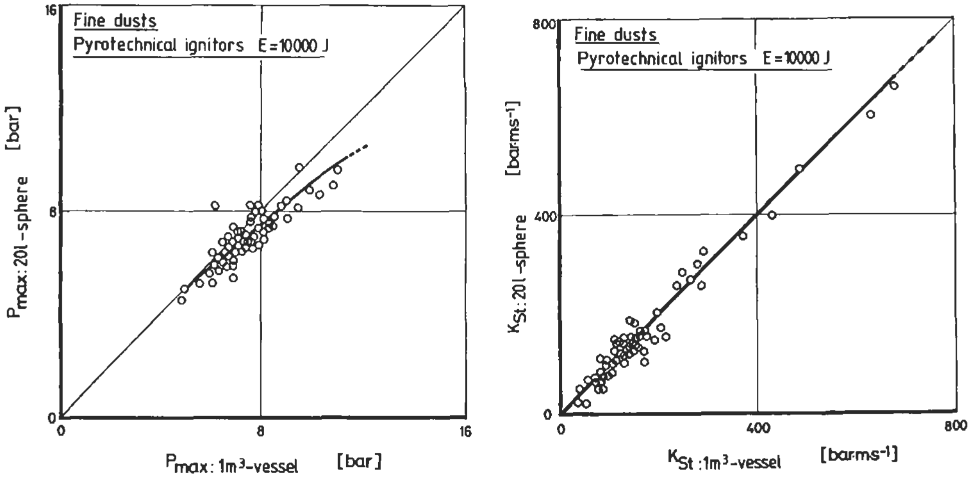


Figure 7.57 *Correlations of maximum explosion pressures and maximum rates of pressure rise from 1 m^3 ISO vessel and 20 liter Siwek sphere (Courtesy of R. Siwek, Cuba-Geigy AG, Switzerland).*

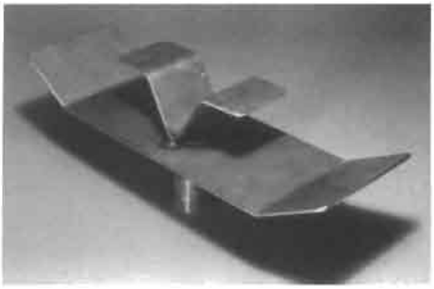


Figure 7.58 *Rebound nozzle for dispersing the dust in the 20 liter Siwek sphere (Courtesy of R. Siwek, Cuba-Geigy AG, Switzerland).*

to Siwek (1988), the new nozzle produces both maximum pressures and K_{St} values in reasonable agreement with those generated by the original perforated-ring system.

7.14.2.4
Other 20 Liter Vessels

The U.S. Bureau of Mines vessel, described by Cashdollar and Hertzberg (1985) and shown in Figure 7.59, is a valid alternative to the Siwek vessel. An advantage, as demonstrated in Figure 7.44, is the large opening, giving easy access to the inside of the vessel for cleaning, inspection, and the like.

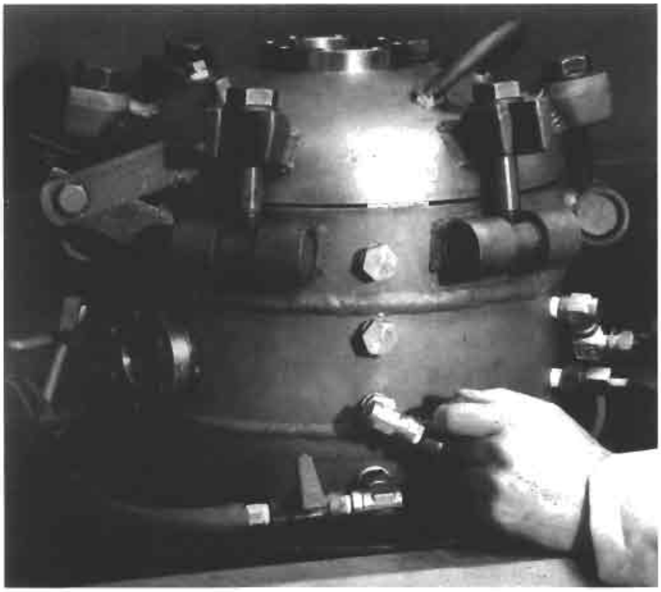


Figure 7.59 *Photo of the 20 liter U.S. Bureau of Mines vessel with the lid on (Courtesy of C. L. Cashdollar, U.S. Bureau of Mines, Pittsburgh, PA).*

It would be expected that the U.S. Bureau of Mines vessel would yield both maximum explosion pressures and rates of pressure rise in agreement with data from the

Siwek sphere provided the dust dispersion and ignition conditions were the same in both vessels.

The 20 liter vessel system described by Burke (1988) was shown to be in accordance with the standard specified by American Society for Testing and Materials (1988c), for determination of both maximum explosion pressures and maximum rates of pressure rise.

Another complete 20 liter vessel test system is illustrated in Figure 7.60.

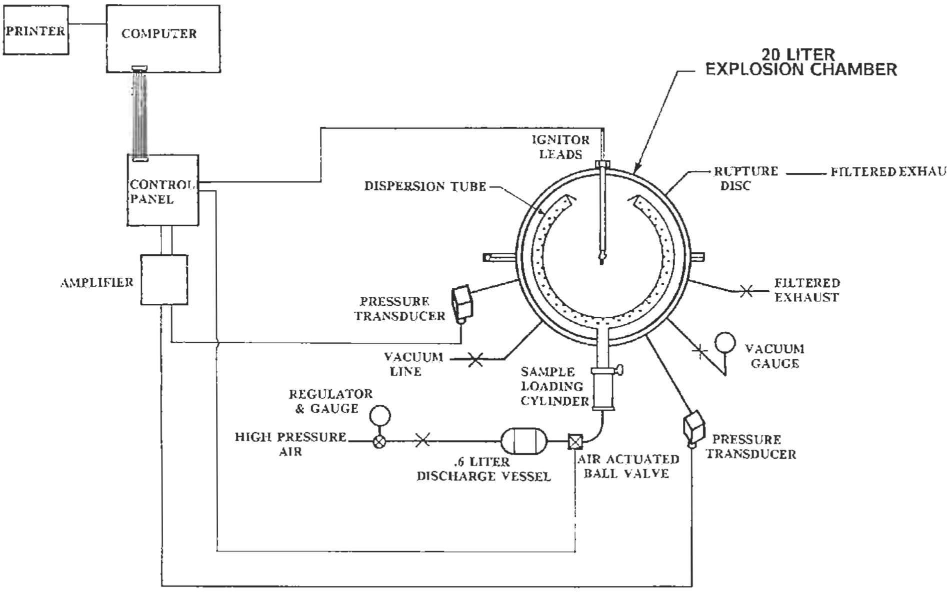


Figure 7.60 *Complete 20 liter sphere system to determine explosibility properties of dusts (Courtesy of Fike Corporation, United States).*

7.15

MAXIMUM RATE OF RISE OF EXPLOSION PRESSURE AT A CONSTANT VOLUME (EXPLOSION VIOLENCE)

7.15.1

THE INDUSTRIAL SITUATION

Industrial enclosures, such as conventional process equipment, are normally far too weak to withstand the pressures exerted even by only partly developed, confined dust explosions. Consequently, a primary objective of fighting an explosion after it has been initiated is to prevent the buildup of destructive overpressures.

At least three techniques for preventing destructive overpressures are in current use in industry. The first and probably most widely used is venting. Another technique is automatic suppression. In case the explosion starts in an enclosure strong enough to withstand the explosion pressure, such as certain types of mills, isolation by high-speed valves to prevent the explosion from propagating to other, weaker enclosures constitutes a third means of protection.

Regardless of which protective technique is adopted, the violence of the dust explosion, that is, the rate of heat generation inside the enclosure where the explosion is initiated, is a deciding factor as to whether a given protective system performs adequately. In view of the fact that the combustion rate can vary substantially from dust cloud to dust cloud, it is important to base the design of industrial equipment on appropriate estimates of the explosion violence or combustion rate that will occur in practice.

7.15.2
LABORATORY TESTS

Maximum rates of pressure rise can be measured in all the closed vessels described in Section 7.14. Section 4.4.3 in Chapter 4 discusses the basic nature of such experiments and shows that the maximum rate of pressure rise in closed bomb apparatuses of the type discussed in Section 7.14 is bound to be arbitrary. This also applies to K_{St} values of dusts (Section 4.4.3.3, equation (4.84)).

The method for determining K_{St} values of dusts specified by the International Standards Organization (1985a) is the same as for measurement of maximum explosion pressure and described in Section 7.14.2.2. Because the standard vessel has a volume of 1 m^3, the K_{St} values in bar m/s are numerically identical with the maximum rate of pressure rise in bar/s.

If smaller vessels, for example, of 20 liters, are used to determine K_{St} values according to the ISO standard, the dust dispersion system, the ignition source strength, and the ignition delay must be tuned in such a way that the products of the maximum rates of pressure rise measured and the cube roots of the vessel volumes equal the K_{St} values that would have been measured for the same dusts in the 1 m^3 ISO standard test (see equation (4.84) in Section 4.4.3.3 in Chapter 4).

Through the years, a considerable number of other nonstandardized closed vessels have been used to assess explosion violence. Nagy et al. (1971) performed experiments in vessel volumes ranging from the 1.2 liters of the Hartmann bomb to 14 m^3. They normalized their results by multiplying all the measured maximum rates of pressure rise by the cube root of the vessel volume, the product being denoted K. With maize starch, all the three smallest vessels, of volumes 1.2 liters, 8 liters, and 28 liters, gave close to identical K values, whereas those of the three larger vessels, of 3 m^3, 6.5 m^3, and 14 m^3, were all about twice as large. With coal dust, nearly identical K values were obtained for the 8 liter and 28 liter vessels, and again these were about half the values for the three larger vessels. However, in this case, the value of the Hartmann bomb was only one-third of that obtained in the 8 liter and 28 liter vessels. Hence, for some dusts, the Hartmann bomb would yield K values very similar to those generated in larger size vessels; whereas for other dusts, the Hartmann bomb values were considerably smaller. A distinct, dust-independent increase of the K value by a factor of 2 was observed when moving from the three laboratory-scale bombs to the closed vessels of industrial scale. This could be due to the use of a different type of dust cloud generation system in the large-scale experiments.

Moore (1979) performed a similar comparison of K values obtained by testing the same dust in four different vessels. These were the Hartmann bomb, a 1.75 liter cylinder with $L/D = 1$, mounted on the standard dust dispersion unit of the Hartmann bomb, a 43 liter sphere, and the standard 1 m^3 ISO vessel. In general, the Hartmann bomb gave the lowest K values, but consistent correlation among values from the various vessels was difficult to establish. Moore interpreted the discrepancies in terms of different degrees of turbulence, different dust concentration distributions, and different ignition source properties in the various tests.

Enright (1984) reported similar comparative experiments in three closed vessels of 1.2 liters, 8 liters, and 20 liters, respectively. The principle of the dust dispersion system was the same for all three vessels, an air blast from a dispersion mushroom impinging on a dust heap placed at the vessel bottom. However, the gap between the dispersion mushroom and the vessel bottom, the volume of the dispersion air reservoir, and the ignition delay all were increased somewhat arbitrarily with vessel volume. For all the three dusts tested—lycopodium, wheat starch, and a "60 μm" aluminum powder—the lowest K values were obtained with the 1.2 liter vessel and the highest with the 20 liter vessel.

This evidence reemphasizes that even the K_{St} concept, as defined by the ISO, remains an arbitrary measure of the explosion violence. K_{St} is not a specific dust constant but clearly also a function of the special test conditions in the ISO standard test.

On the other hand, the K_{St}, as defined by the ISO, seems to provide a reasonable relative measure for ranking the explosion violence to be expected from various dusts in industrial dust explosions. However, the resolution must not be overrated. As shown in Chapter 6, four dusts of very similar K_{St} values in the narrow range 115–125 bar m/s produced maximum explosion pressures in a filter with a given vent, which varied by a factor of 2–3.

It is important to keep in mind the various factors that influence the explosion rate of a dust cloud (see Chapters 4 and 6 and Eckhoff, 1987) and to consider the extent to which they are the same in the standard test and the industrial situation of concern.

It is felt that other test methods for maximum rates of pressure rise, not complying with the ISO standard, may also yield a reasonable relative ranking of dusts with respect to their explosion violence in practice. This includes the Hartmann bomb as standardized by the American Society for Testing and Materials (1988b).

7.15.3
FURTHER DEVELOPMENT OF ADEQUATE TEST METHODS FOR DUST EXPLOSION VIOLENCE ASSESSMENT

As already pointed out, the violence with which clouds of a given dust will explode in an industrial plant is not a specific dust property but indeed also depends on the state of the dust cloud in the actual industrial situation. Test methods that would allow differentiation in test conditions could be designed by following at least three lines of approach (Eckhoff, 1987):

1. The first would be to retain one of the existing standard closed-bomb methods and add to it a differentiated procedure for interpreting results. For example, the measured $(dP/dt)_{max}$ or K_{St} value could be multiplied by one of a range of empirical correlation factors to match the particular industrial situation in question. This would allow existing nomograms for vent area assessment to be maintained. No matter which standard test method is chosen, it would be necessary to standardize extremely

carefully both apparatus and experimental procedures. One could also make active use of the dependence of $(dP/dt)_{\max}$ on dust concentration, which is in fact currently measured in the existing standard tests, as illustrated in Figure 7.53. In most cases, it would seem justified to assume that worst-case concentration throughout the cloud is rather unlikely.
2. A second possibility would be to retain one of the existing bombs but change the experimental program of the test. By including the ignition delay as a parameter, the reaction rate as a function of the relative turbulence level could be assessed experimentally (see also Section 4.4.3 in Chapter 4). This would correspond to varying the turbulence index T_u defined by the International Standards Organization (1985a). The value of $(dP/dt)_{\max}$ at various ignition delays would then represent the respective reaction rates corresponding to various situations in industry. One could then perform tests at the turbulence level that would correspond to the actual industrial situation concerned. It could also be of interest to supplement the explosion test with a dust dispersibility test (see Section 7.4.2) to assess the degree of dust dispersion expected from the dispersion process operating in the specific industrial situation of interest.
3. A third strategy would be to retain one of the existing bombs but design a range of "plug-in" dust dispersion units to allow tests to be carried out with the unit producing the degree of dust dispersion and level of turbulence expected in practice. This would yield different correlations of $(dP/dt)_{\max}$ versus ignition delay, depending on the intensity of the dispersion process (see Figure 4.40 in Chapter 4).

No matter which of these possibilities is pursued, it is necessary to conduct realistic full-scale dust explosion experiments to establish credible correlations between predicted dust cloud combustion rates and those that actually occur in the wide spectrum of situations in which dust clouds may burn in industry.

In the future the maximum pressure rise measurement is likely to be replaced by more basic parameters, such as the induction time of the dust cloud combustion reaction, which will be used as input to advanced computer simulation models for turbulent dust explosions (Eckhoff, 1987).

7.16

EFFICACY OF EXPLOSION SUPPRESSION SYSTEMS

Explosion suppression is discussed in Section 1.4.7 in Chapter 1. The International Standards Organization (1985b) specified a test method for evaluating the effectiveness of explosion suppression systems against defined explosions in closed, or essentially closed, vessels. The test does not cover explosions at elevated initial pressures. The method gives design criteria for apparatus for explosion suppression efficacy tests and criteria for defining the safe operating regime of an explosion suppression system.

The basic test apparatus is the 1 m^3 closed vessel described in Section 7.14.2.2 and shown in Figure 7.54, but other vessels may also be used, provided the volume is sufficiently large and the length-to-diameter ratio is less than 2.

A complete test arrangement, with the suppression system to be tested mounted on the test vessel, is illustrated in Figure 7.61. Figure 7.62 illustrates the type of pressure development observed during a standard test.

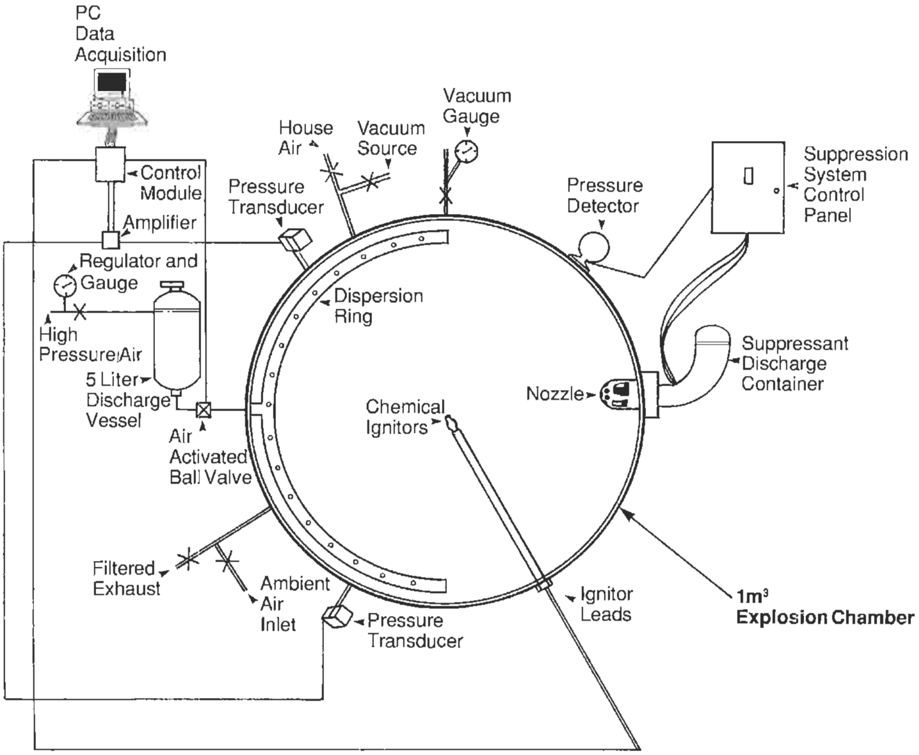


Figure 7.61 *Complete system for testing the efficacy of explosion suppression systems according to the International Standards Organization (1985b) (Courtesy of Fike Corporation, United States).*

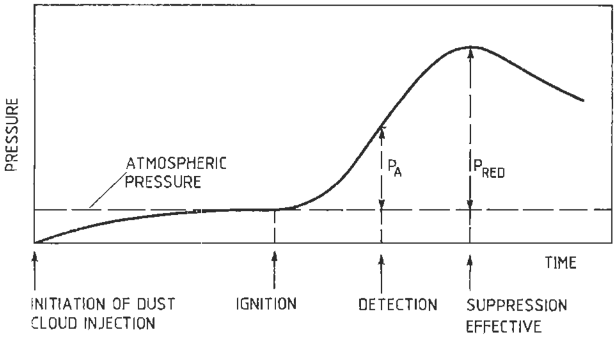


Figure 7.62 *Typical pressure-versus-time trace during a dust explosion suppression test in the standard 1 m^3 ISO apparatus.*

Prior to initiation of the fully automated test, the 1 m^3 vessel is partially evacuated to compensate for the supply of air during the dust injection process, which constitutes the first step of the automatic test sequence. When all the explosible dust has been injected into the test vessel and atmospheric pressure restored, the explosible dust cloud is ignited after a predetermined delay. The pressure detector of the suppression system under test has been preset at a given trigger level P_A, and when this explosion pressure is reached, suppressant injection starts. The efficacy of the suppression is reflected by the magnitude of the peak pressure P_{red}.

By varying the trigger level P_A of the pressure detector and the K_{St} value of the dust, the efficacy of the specific suppression system under test can be assessed for a range of explosible cloud conditions.

The standard test method is unsuitable for predicting the performance of suppression systems if the industrial enclosure to be protected has one or more of the following features:

- Vessel aspect ratio greater than 2:1.
- Partially vented vessels.
- Container fitted with fixed or mobile apparatus that could impede the distribution of suppressant.
- Operating pressures and temperatures substantially higher or lower than normal atmospheric conditions.
- High levels of turbulence or dust or powder throughput.
- Vessel volumes substantially greater or smaller than those used in the efficacy test.

Figure 7.63 shows a test arrangement relevant for testing suppression of volumes larger than 1 m^3. Design methods for systems for suppression of volumes of up to 250 m^3 is discussed in Section 1.4.7.

Figure 7.63 *A 10 m^3 test vessel for assessing the efficacy of suppression systems for volumes larger than 1 m^3 (Courtesy of Fike Corporation, United States).*

7.17
MAXIMUM EXPLOSION PRESSURE AND EXPLOSION VIOLENCE OF HYBRID MIXTURES OF DUST AND GAS IN AIR

The ignitability and explosibility of hybrid mixtures is discussed in Section 1.3.9 in Chapter 1. Such mixtures may be generated in industry in a number of ways, for example, during the drying of explosible dust containing organic solvents.

The International Standards Organization (1985c) designed a test method to assess the explosibility properties of explosible clouds other than dust/air and gas/air, based on the apparatus illustrated in Figure 7.64.

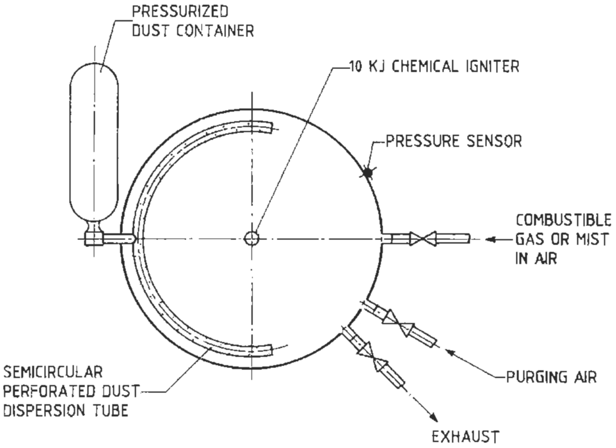


Figure 7.64 *A 1 m^3 closed vessel specified by the International Standards Organization (1985c) to determine maximum explosion pressures and rates of pressure rise of explosible clouds other than dust/air and gas/air.*

The method is intended primarily for hybrid mixtures of combustible dusts and gases in air and mists of combustible liquids in air. However, it also seems to be suitable for investigating the explosibility of dusts in oxidizer gases of other oxygen contents than in air, as mentioned in Section 7.19.

The procedure for testing hybrid gas/dust/air mixtures is as follows:

- The gas/air mixture in the 1 m^3 chamber is prepared by the method of partial pressures or another suitable technique. It is important to ensure that the composition and homogeneity of the gas/air mixture is as required.
- Then the dust sample, of the mass required to obtain the appropriate cloud concentration, is placed in the 5 liter container, which is subsequently pressurized with air to 20 bar. The pressure recorder is activated followed by activation of the dust sample container valve and the ignition source.

- The flow of compressed dust/air suspension into the explosion chamber induces turbulence in the gas/air mixture. Therefore, choosing an appropriate ignition delay (turbulence level) is important. The influence of the compressed air from the dust reservoir on the final explosible gas concentration should be taken into account.
- Tests are conducted for the range of total fuel concentrations and combustible gas/combustible dust ratios required.

7.18

TESTS OF DUST CLOUDS AT INITIAL PRESSURES AND TEMPERATURES OTHER THAN NORMAL ATMOSPHERIC CONDITIONS

Industrial processes are sometimes operated at initial pressures, temperatures, or both higher than normal ambient conditions. In such cases, results from tests of ignitability and explosibility at normal ambient initial conditions may not be relevant. The general trends of the influences of initial pressure and temperature are outlined in Sections 1.3.7 and 1.3.8 in Chapter 1.

Tests to elucidate specific problems are most conveniently conducted in closed bombs of the types described in Section 7.14, fitted with adequate provisions for heating and prepressurization and of sufficient strength. This applies both to ignition sensitivity tests and explosibility tests. The proportional increase of the maximum explosion pressure with initial pressure (Section 1.3.8) requires very strong bombs if the initial pressure is appreciable. Bombs of the type in Figure 7.64 may be used if the gas phase differs from pure air.

7.19

INFLUENCE OF OXYGEN CONTENT IN THE OXIDIZING GAS ON THE IGNITABILITY AND EXPLOSIBILITY OF DUST CLOUDS

7.19.1

THE INDUSTRIAL SITUATION

Full and partial inerting is discussed in Sections 1.3.6 and 1.4.3 in Chapter 1.

The possibility of dust explosions in process equipment can, in principle, be effectively eliminated by substituting the air by a gas that prevents flame propagation in the dust cloud. Since the use of large quantities of inert gas in a plant can be expensive, it is important to limit the inert gas consumption to the extent possible. For most dusts, it is not necessary to substitute the entire atmosphere in the actual area by, for example, nitrogen, carbon dioxide, or other inert gas to obtain inerting. Hence, it is essential to know the critical gas composition for inerting the dust in question. In some cases, it may even be of interest to use smaller fractions of inert gas than required for completing inerting, because this reduces both the ignition sensitivity of the dust cloud and the maximum pressure and rate of pressure rise at constant volume.

7.19.2
LABORATORY TESTS

In the United States, as described by Dorsett et al. (1960), two standard test methods were traditionally used. In both tests, the dust was dispersed in the appropriate gas mixture, from above, into a fairly narrow vertical tube of internal diameter 38 mm and exposed to an ignition source. The apparatus is similar to the Godbert-Greenwald furnace described in Section 7.8. In the first test, the ignition source was an electric spark; in the second test, the hot tube wall. Usually, the limiting gas compositions for flame propagation obtained for the same dust from the two tests differed significantly, the hot surface test yielding lower critical permissible oxygen contents than the spark test.

Figure 7.65 shows a type of apparatus used by some laboratories to determine the maximum permissible oxygen content in the atmosphere for inerting dust clouds.

An experimental procedure applicable to this apparatus is as follows: Compressed air and inert gas are first mixed in the desired proportions in a mixing vessel by the partial pressure method. Once the powder to be tested has been placed in the dispersion cup, a quantity of 3 liters of the gas mixture is admitted gently into the explosion tube via the small reservoir and the thin flushing tube, with the filter paper in position at the top of the Perspex cylinder. During this process, the air that was originally in the Perspex cylinder leaks to the atmosphere. The small reservoir is now pressurized with the appropriate

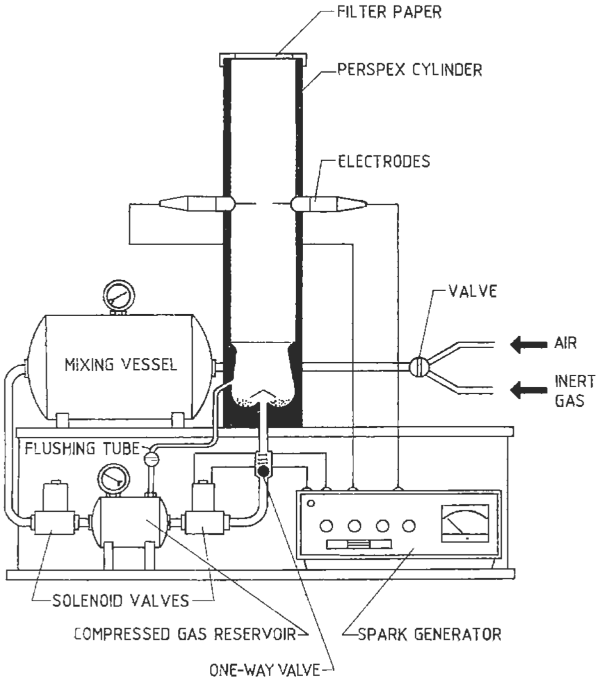


Figure 7.65 *Open 1.2 liter Hartmann tube apparatus for determining the influence of the oxygen content in the atmosphere on the ignitability of dust clouds.*

gas mixture to a predetermined level, found in earlier trials to give the best dust dispersion conditions for ignition and flame propagation in air.

To initiate the test sequence, a pushbutton on the electric spark generator opens the solenoid valve to disperse the powder. After a preset delay, a soft spark of approximately 3 J is discharged across the spark gap in the dust cloud in the tube. It is then observed whether ignition occurs. *Ignition* is defined as visual observation of a dust flame that is clearly detached from the spark. For each particular oxygen concentration, 20 trials are carried out and the results plotted as a frequency-of-ignition versus oxygen-concentration graph. The maximum permissible oxygen content for inerting is then defined as lying between the lowest concentration at which at least 1 trial in 20 gave ignition and the highest concentration at which no ignition occurred in 20 trials.

When applying the test result in industrial plant design, an appropriate safety margin must be incorporated. The method can be refined by actually measuring the oxygen concentration in the Perspex tube prior to each test. This may be necessary at low oxygen contents, of a few percent and lower.

It is important that the ignition source is not the limiting factor for ignition. The situation in this respect is the same as for the minimum explosible dust concentration test. If the ignition source is too weak, apparently inert conditions will be found for oxygen concentrations, which would in fact allow flame propagation once ignition had been accomplished by a sufficiently strong source. For some dusts, a 3 J soft spark source may be too weak to identify the true oxygen limit.

The apparatus in Figure 7.65 is also well suited to measure the minimum electric spark ignition energy as a function of oxygen concentration, which may be useful information for assessing the gain in safety obtained if partial inerting is used.

The apparatus in Figure 7.64 may be used to measure maximum explosion pressure and rate of pressure rise as functions of the oxygen content in the atmosphere, which provide further information about the effect gained by partial inerting. The inlet for combustible gas/air would then instead be used for the mixture of inert gas and air.

7.20

INFLUENCE OF ADDING INERT DUST TO THE COMBUSTIBLE DUST ON THE IGNITABILITY AND EXPLOSIBILITY OF DUST CLOUDS

Section 1.4.3.3 outlines the industrial situation. When required, all the test methods described in this chapter can be applied to mixtures of combustible and inert dust. One problem that could arise, however, is segregation of the two components during dust dispersion because of differences in particle properties (size, shape, density). If such segregation occurs, misleading results could arise because the ratio of inert to combustible dust in the region of the ignition source is either significantly above or below the assumed nominal average.

7.21
HAZARD CLASSIFICATION OF EXPLOSIBLE DUSTS

Attempts have been made in the past at classifying ignitability and explosibility of dusts by one or two dimensionless figures. Experience has shown that the usefulness of such indices is limited, because specific ignitability and explosibility properties are not necessarily correlated.

A hazard classification system for combustible dusts was proposed to the International Electrotechnical Commission (1990b). However, the proposal was not accepted. The system was concerned primarily with the fire and explosion hazard if ignitable dusts are in contact with various kinds of electrical apparatus.

The system uses three symbols:

- + indicates that there is a need for special attention in respect to the combustion property of the dust.
- – indicates that special attention is not required in respect to the combustion property of the dust or that the property cannot be measured by the test specified. (For example, the minimum ignition temperature of a layer of the dust cannot be measured because it melts and runs off the hot surface of the test apparatus.)
- ? indicates that information on the property is not available.

The plus (+) symbol is applied to the following four specific tests, using the sensitivity thresholds indicated:

• Electrical resistivity	$<10^3\ \Omega\text{m}$
• Minimum ignition temperature of dust cloud	<400°C
• Minimum ignition temperature of dust layer of 5 mm thickness	<300°C
• Minimum ignition energy of dust cloud	<15 mJ

The minus (–) symbol is used for all data that equal or exceed these critical thresholds.

The thresholds chosen are bound to be arbitrary. On the other hand, the classification system allows a quick preliminary screening to identify dusts that are definitely hazardous. The system does not imply, however, that the hazard of dusts that appear with a negative sign for all four tests can be neglected.

The National Material Advisory Board (1988) discussed the specification of an explosion hazard classification system of dusts in relation to use of electrical equipment, with reference to the situation in the United States. Two basic questions were considered essential:

- Is the dust combustible?
- Is the electrical resistivity of deposited dust higher or lower than $10^3\ \Omega\text{m}$?

No final conclusions as to the details of a revised classification system were drawn, but some indications were given. The need for further research and international cooperation was emphasized.

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Chapter 8

Electrical Apparatuses for Areas Containing Combustible Dusts

8.1
INTRODUCTION

8.1.1
BACKGROUND AND OBJECTIVES OF CHAPTER

Since the publication of the first edition of this book in 1991, the author has had the opportunity to become more closely acquainted with the specific topic of electrical apparatuses for use in areas containing combustible dusts. This topic was mentioned only very briefly in the two first editions of the book, and the time is ripe for it to be covered more extensively.

Layers and clouds of combustible dusts can be ignited by a variety of ignition sources. An overview is given in Section 1.1.4 in Chapter 1, and in Chapter 5, some ignition processes are discussed in greater detail. Chapter 7 describes laboratory methods for assessing the ignition sensitivity of dust layers and clouds when exposed to different types of ignition sources. Ignition sources that can be generated by electrical apparatuses include electrical sparks and arcs, electrostatic discharges, hot surfaces, and burning metal particles from mechanical impacts. Therefore, careful standardization is required of electrical apparatuses intended for use in the presence of combustible dust. International standards are produced by the International Electrotechnical Commission (IEC) and the European standardization organizations European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC). Corresponding national standards are produced in a number of countries throughout the world.

Greiner (2002) has a useful overview of the status on dust standards within the IEC and CENELEC domains, with regard to both the basic principles of protection and the systems of standards developed. He emphasized that keeping potential electrical ignition sources inside enclosures that prevent ingress of hazardous quantities of dust remains the main, well-proven method of protection.

Greiner did not discuss the new philosophy of standardization in this area, which has gradually emerged during the last decade and given rise to considerable concern. The core of this new philosophy, which has already been put into practice by IEC, is to "harmonize" the standards for combustible dusts with those for combustible gases. A central source of inspiration has been a directive issued by the European Communities in 1994, most often named the *Atex 100a Directive* (1994). (Note: This directive has also been given other names. A useful review of the origins of the names of various European "Atex" directives was by Zeeuwen, 2000). As is discussed in detail in Section 8.1.3, unfortunately, this important directive suffers from insufficient differentiation between combustible dusts and combustible gases and vapors. Such differentiation is essential, because the processes by which explosive dust clouds are generated and sustained are very different from the processes producing explosive gas clouds, as is discussed in detail in Section 8.3. These differences should result in corresponding substantial differences in the technical concepts adopted for design of nonigniting electrical apparatuses.

It may seem as if the push for "harmonization" of a gas and dust standards is not only a result of technical considerations but also of a commercial drive toward facilitating the use of essentially the same apparatuses as manufactured for explosive gas atmospheres in areas containing combustible dusts. Ideally, the European Union (CEN, CENELEC) will give this matter thorough consideration before deciding whether to adopt the new series of "harmonized" IEC dust standards. It is important to promote development of standards that, in an adequate manner, reflect the substantial differences between dusts and gases.

In view of this situation, I have had two main incentives for writing this chapter. First, it was considered appropriate to provide a general overview of the basic principles adopted in design of electrical apparatuses for areas containing combustible dusts. Technical details have been included only if required to elucidate these principles or found to be missing in current standards. Hence, the chapter is not by any means a substitute for the considerably more comprehensive and detailed texts of the numerous international and national standards. Second, certain problems arise from insufficient differentiation between gases or vapors and dusts in the "Atex 100a" directive and "harmonized" standards based on this directive, and alternative approaches are proposed where required. Because of this dual objective, the chapter contains more critical discussion than the other chapters of this book.

8.1.2
BASIC SIMILARITIES AND DIFFERENCES BETWEEN DUSTS AND GASES

As discussed by Eckhoff (2000), explosive gas mixtures and explosive dust clouds, once existing, exhibit very similar ignition and combustion properties, such as

- Flammability and explosibility limits.
- Laminar burning velocities and quenching distances.
- The response of the burning velocity to cloud turbulence.
- Detonation phenomena.
- Adiabatic constant-volume explosion pressures of similar magnitudes.
- Well-defined minimum ignition energies.
- Minimum ignition temperatures for given experimental conditions.

Recognition of these similarities may have contributed to the development of the gas/dust "harmonization" concept. However, dusts differ from gases in two fundamental ways, and both should have a major impact on the ways that electrical apparatuses are constructed to prevent them from becoming potential initiators of dust explosions and fires.

The first difference is in the ranges of hazardous fuel concentrations. For combustible gases and vapors, flame propagation is possible only when the fuel/air mixing ratios lie between the lower and the upper flammability limits. Dust flame propagation, however, is not limited to the flammable dust concentration range of clouds. The state of settled layers or deposits constitutes an additional singular regime of flame propagation. This is because, contrary to combustible gases and liquids, settled powders and dusts in air always have some air trapped in the voids between the particles, which makes it possible for sustained, although often very slow, combustion to propagate throughout the deposit. (See Figure 1.3 in Chapter 1.)

The second basic difference between dusts and gases is in the generation and sustainment of explosive clouds. The paramount question is whether there will be an explosive dust cloud at all. The physics of generation and sustainment of dust clouds and premixed gas clouds are so substantially different that explosive dust clouds are highly unlikely to be generated in a variety of situations where explosive gas clouds may form quite readily. The implications of this is discussed in greater detail in Section 8.3.

8.1.3

THE "ATEX 100a" DIRECTIVE GIVES UNCLEAR SIGNALS WITH REGARD TO DUSTS

The "Atex 100a" Directive (1994), constitutes the philosophical basis of the entire new generation of European apparatus standards for prevention and mitigation of accidental gas, vapor, mist, and dust explosions. It has also had a major impact on the IEC effort to "harmonize" dust standards with gas standards.

However, this directive seems to have been produced largely with reference to gas and vapor explosions, paying only modest attention to the very different physical and chemical properties of dusts clouds and layers. This is evident right from the definition of *explosive atmosphere* in Article 1, item 3: An explosive atmosphere is a "mixture with air, under atmospheric conditions, of flammable substances in the form of gases, vapours, mists or dusts, in which, after ignition has occurred, combustion spreads to the entire unburnt mixture." It seems clear from the context that this definition addresses explosive clouds only, but as pointed out in Section 8.1.2, flame propagation in dusts is not limited to the flammable dust concentration range of clouds. The state of stagnant, settled layers and deposits constitutes an additional singular regime of flame propagation. The "Atex 100a" definition of *explosive atmosphere* in fact also embraces dust layers and deposits, which are also mixtures of air and dust, in which combustion can spread to the entire unburned mixture. But, normally, this process is far from explosive, and smoldering combustion in large dust volumes may develop over weeks, months, and even years.

A further example of the lack of differentiation between gases and dusts occurs in Annex I of the directive, where gases, mists, and dusts are again regarded as a uniform class of "explosive atmospheres" with reference to the definition in Article 1, item 3 quoted previously. Consequently, the discussion in Annex II, item 1.2.9, of the concept of "flameproof" enclosure systems, referring to "explosive atmospheres" at large, also includes dust clouds. The directive defines the flameproofing concept as follows: "If parts which can ignite an explosive atmosphere, are placed in an enclosure, measures must be taken to ensure that the enclosure withstands the pressure developed during an internal explosion of an explosive mixture and prevents the transmission of the explosion to the explosive mixture surrounding the enclosure." This statement clearly addresses the "flameproof" (Ex d) design concept for gases. As discussed in Section 8.4.7, applying this principle of electrical equipment protection to dusts makes little sense.

The "Atex 100a" Directive needs to be revised to expose very clearly the marked differences between combustible gases and combustible dusts. Two main differences are of prime importance in the present context and should be reflected clearly in a revised directive:

- As indicated in Section 8.1.2 and discussed in greater detail in Section 8.3, the mechanisms by which explosive dust clouds are generated and sustained are substantially different from the mechanisms of generation and sustainment of explosive gas clouds. Because of these differences, the optimal ways to design and construct electrical apparatuses for use in the two kinds of explosive atmosphere should be substantially different. A revised directive should reflect these differences.
- Furthermore, a revised directive should make it clear that dust flame propagation is not limited to the flammable dust concentration range of clouds. The state of stagnant, settled layers and deposits constitutes an additional singular regime of flame propagation. Therefore, smoldering and open fires in layers and deposits of combustible dusts are to be regarded as a hazard in its own right, irrespective of whether the layers and deposits may become transformed into explosive dust clouds, or a burning layer may ignite a dust cloud.

8.1.4

SCOPE OF THE IEC STANDARDS ON DUSTS

The IEC (2001a) subscope for "standardization of uniform practices in areas where combustible dusts are present" contains the following two points specifying the basic objectives, which are to

- Address situations where the presence of dust presents a risk of fire or explosion with respect to use of electrical apparatus.
- Test the properties of dusts relating to the risk of fire or explosion.

However, the revised global scope of IEC's (2002a) Ex-standardization work is as follows: "To prepare and maintain international standards relating to electrical apparatus for use where there is a hazard due to the possible presence of explosive atmospheres of gases, vapours, mists or combustible dusts." Here, fires are not included, only explosions.

Hence, there is significant discrepancy between the two scopes. This confusing situation can be resolved in a satisfactory way only by including dust fires even in the global scope.

8.2

CLASSIFICATION OF AREAS CONTAINING COMBUSTIBLE DUSTS

8.2.1

WHAT IS AREA CLASSIFICATION?

The area classification concept applies to both combustible gases and vapors, mists, and sprays of combustible liquids, explosives, and combustible dusts; and it has been in use for many years. It is essentially a systematic method of sub-dividing, in three dimensions, an industrial plant into zones of different categories according to the probability of occurrence of explosive atmospheres.

The ultimate objective of this exercise is to keep the likelihood of accidental ignition of explosive atmospheres at a minimum throughout the plant. This is achieved by differentiating the ignition-preventive measures required for electrical apparatuses to be used in the various zones. Hence, the measures required for apparatuses to be used in a zone of high likelihood of explosive atmosphere are more severe than those required of apparatuses to be used in a zone where this likelihood is low.

From the point of view of comprehensive quantitative risk analysis (see Section 1.5.1.3 in Chapter 1), it has been pointed out that the philosophy of classical hazardous area classification does not account for the consequences of possible ignition. In other words, the approach of classical hazardous area classification does not reflect whether an ignition is likely to lead to a major catastrophe or produce only a minor incident. In the area classification approach, the objective is to minimize the risk of ignition and not to minimize the overall explosion risk.

Central organizations producing area classification standards include the IEC, CEN, and CENELEC of the European Union and the NFPA in the United States. Lloyd (1993) and Laar (1994) reported the state of the art at that time on international standards on classification of areas containing combustible dust and guidelines for selection of electrical equipment for such areas.

8.2.2

DEFINITION OF ZONES ACCORDING TO THE THREE-ZONE CONCEPT

Many countries, including the United States (see NFPA, 1997), Germany, and Norway, have traditionally used a dust zone classification system based on only two hazardous zones. However, in many countries, this system is gradually being replaced by a three-zone concept. Blob et al. (2001) discussed the transfer in Germany from the previous national two-zone concept to the internationally accepted (IEC, CENELEC) three-zone concept. They concluded that the three zones offer greater possibility for differentiation and thus more precise classification, which facilitates the zoning process.

The "Atex 118a" directive (1999) defines the three hazardous zone categories that have to be identified in areas containing combustible dusts, in the context of European standards. These definitions, which have also been adopted by IEC, are

Zone 20. A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is present continuously, for long periods, or frequently.

Zone 21. A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is likely to occur occasionally in normal operation.

Zone 22. A place in which an explosive atmosphere in the form of a cloud of combustible dust in air is unlikely to occur in normal operation but, if it does occur, persist for only a short period.

In accordance with the philosophy of the "Atex 100a" Directive (1994), layers or deposits of combustible dusts are not considered hazardous in themselves. They are taken into account only if they are considered possible sources of generation of explosive dust clouds or if they can give rise to dust fires that can ignite dust clouds (see Section 8.1.3).

Beck (2002) summarized the main philosophy of the "Atex 118" and "Atex 100a" Directives, with regard to dusts. Electrical apparatuses are classified in three categories. Category 1 apparatuses can be used in all three zones, category 2 apparatuses can be used in zones 21 and 22 but not in 20, whereas category 3 apparatuses can be used only in zone 22.

8.2.3

INTERNATIONAL STANDARDS

The CENELEC (2002) and draft IEC (2002b) standards for classification of areas containing combustible dusts are practically identical, and both define the hazardous zones 20, 21, and 22 in accordance with the definitions given in Section 8.2.2. The term *source of release for explosive atmosphere* is central in both standards. The term has been adopted from the corresponding gas standards, which to a large extent focus on explosive gas clouds generated by intentional or accidental releases and leaks of combustible gas into the atmosphere. In the case of dust clouds, *point of dust cloud generation* or *area of dust cloud generation* would seem more appropriate.

The way in which the three zones are to be marked on hazardous area classification drawings according to the CENELEC (2002) and draft IEC (2002b) standards is shown in Figure 8.1, and examples to illustrate the use in practice are given in Figures 8.2 and 8.3.

The interior of the hopper in Figure 8.2 is classified as zone 20, because explosive dust clouds are generated there during the quite frequent emptying of bags into the hopper. Because of the dust extraction system, explosive dust clouds are not expected to extend outside the hopper in normal operation. However, abnormal situations may arise in which this may occur, such as if a bag bursts during being emptied or the dust extraction system fails. Therefore, a zone 22 classification is assigned to a limited area just outside the hopper opening.

The interior of the cyclone in Figure 8.3 is classified as zone 20 because of the presence of an explosive dust cloud frequently, or even continuously, for long periods. However, the dust concentration in the gas leaving the cyclone and entering the dusty side of the filter is normally below the minimum explosive concentration, except for short

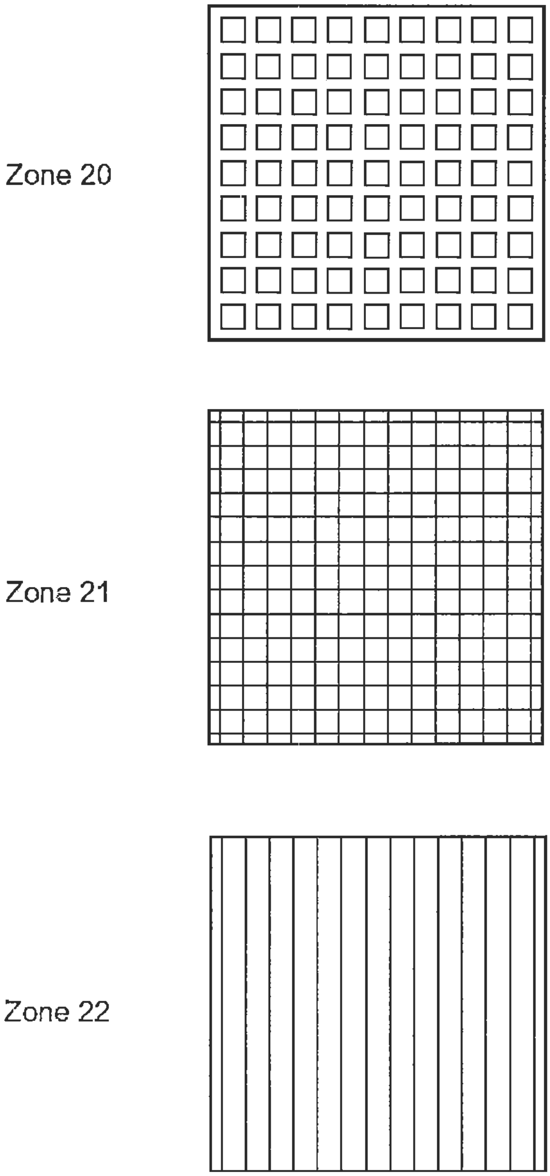

Figure 8.1 *Standardized system for marking zones 20, 21, and 22 on hazardous area classification maps of an industrial plant (From CENELEC, 2002).*

periods when the bags are blown or shaken to release accumulated dust. Hence, the dusty side of the filter is classified as zone 21. The clean side of the filter normally has only negligible quantities of dust. However, filter bags may burst or other abnormal situations may arise causing explosive dust clouds to be generated on the clean side of the filter, which is therefore classified as zone 22.

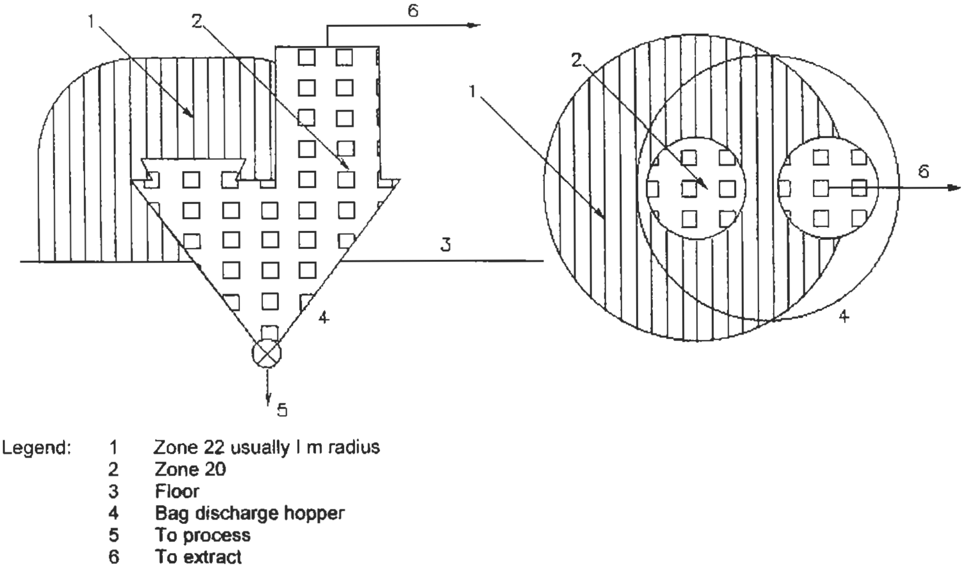

Figure 8.2 *Marking of zones 20 and 22 on a hazardous area classification map of a station for emptying bags containing combustible powder into a hopper equipped with dust extraction (From CENELEC, 2002).*

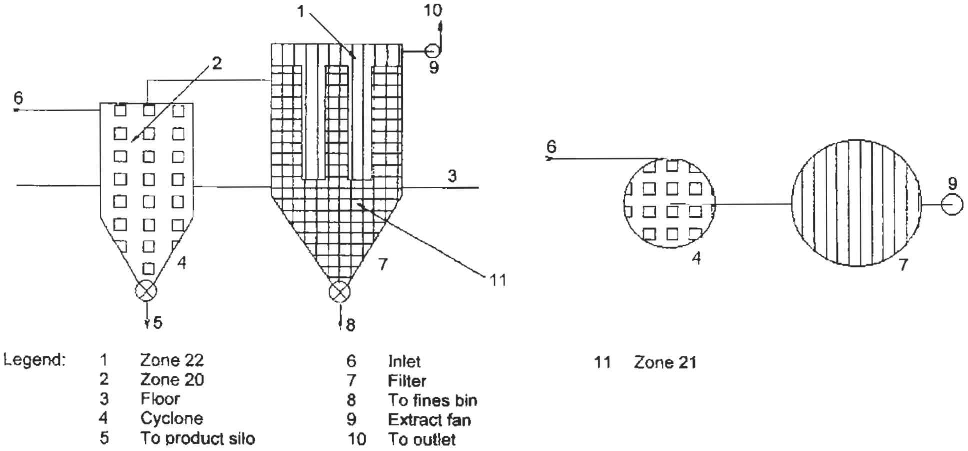

Figure 8.3 *Marking of zones 20, 21, and 22 on hazardous area classification map of a dust collection plant comprising a cyclone and a filter in series (From CENELEC, 2002).*

8.2.4

NEED TO REVISE AREA CLASSIFICATION STANDARDS TO INCLUDE DUST FIRES AS A HAZARD IN ITS OWN RIGHT

In areas containing combustible dusts, as indicated in Section 8.1.2 and discussed in more detail in Section 8.3, dust fires must be considered as a potential hazard in its own right, irrespective of any additional risk of dust explosions. As discussed in Sections 2.6–2.8 in Chapter 2, smoldering fires in large storage silos have given rise to major accidents, without dust explosions playing a significant role. This is one good reason why combustible dust layers and deposits should be included in the definition of hazardous areas in the area classification standards for combustible dusts, irrespective of whether the layers and deposits may become transformed into explosive dust clouds or a burning layer may ignite a dust cloud.

8.3

WHY DIFFERENT ELECTRICAL APPARATUS DESIGN CRITERIA ARE NEEDED FOR AREAS WITH COMBUSTIBLE DUST AND EXPLOSIVE GAS ATMOSPHERES

8.3.1

INFLUENCE OF INERTIAL FORCES ON THE MOVEMENT OF DUST PARTICLES

8.3.1.1

Origin and Lifetime of Explosive Dust Clouds in Industrial Practice

Once a combustible gas has been homogeneously mixed with air, the mixture, for most practical purposes, stays homogeneous, due to random molecular motion. In dust clouds, however, the fuel particles are generally so much larger than the molecules of the air (mostly in the range 1–100 μm) that their movement within the air is controlled by inertial forces, including gravity, rather than by random molecular motion. The role of inertial forces increases systematically with increasing particle size and increasing density of the particle material. Turbulence and other convective movement of the air can prolong the time over which the particles stay in suspension.

Inside certain types of industrial process equipment, the dust is kept in suspension more or less continually by rotation of the whole unit, movement of inserts, or airflow. Therefore, explosive dust clouds may exist more or less continually in normal operation due to the basic nature of the operation (zone 20). Such equipment include mills, some types of powder mixers and dryers, dust collectors and connected ducts, pneumatic powder transportation pipes, and bucket elevators.

Dust clouds of significant size (the order of at least 1 m^3) may also, intentionally or unintentionally, be generated outside process equipment. However, the duration of the process of cloud generation is then normally very short (e.g., pouring or discharging operations, accidental bursting of sacks and bags). The dust particles start to settle out of suspension as soon as the cloud generation process terminates, and typical total lifetimes of explosive clouds outside process equipment is on the order of fractions of a minute. One exception is long-duration minor dust leaks from, say, flanges in pneumatic transport lines, but the dust cloud volumes produced in such cases normally are quite small.

8.3.1.2
Migration of Dust Particles through Narrow Holes and Gaps in Enclosure Walls

Because dust particles are so much bigger than gas molecules, they do not travel through narrow holes and slots on the order of 1 mm diameter and smaller in the same way as gas molecules. In principle, dust particles may be carried through narrow passages by the airflow generated by a moderate pressure difference across the passage. However, dust particles may easily adhere to the area around the passage entrance and the passage walls and eventually block the passage.

Furthermore, dust particles that have been able to pass through narrow holes or gaps in this way settle out of suspension as soon as they have passed the hole or gap and the air velocities dropped to negligible values. Therefore, dust particles entering enclosures in this way do not remain suspended in the air and eventually form explosive dust clouds but settle out as layers on the internal surfaces of the enclosure. It seems difficult to envisage that any foreseeable mechanical process inside typical electrical apparatus enclosures could redisperse such dust layers into explosive dust clouds within the enclosure.

The NFPA (1997) contains a paragraph that, in an excellent way, using practical terms, clarifies the basic difference between gases and dusts with regard to their abilities to migrate through narrow passages. In a slightly modified form, this paragraph says:

> Walls are much more important in separating hazardous and non-hazardous zones in the case of combustible dusts than in the case of combustible gases. Only completely non-perforated solid walls make satisfactory barriers in the case of gases, whereas closed doors, light-weight partitions, and even partial partitions could make satisfactory barriers between hazardous and non-hazardous zones in the case of dusts.

For the context of electrical apparatuses, this paragraph may be slightly rephrased by replacing the first word, *walls*, by *enclosures*.

8.3.2
THERMAL HAZARDS ASSOCIATED WITH ACCUMULATION OF DUST LAYERS INSIDE ELECTRICAL APPARATUS ENCLOSURES

8.3.2.1
Combustible, Electrically Nonconductive Dusts

If the surface temperature of a heat-producing component inside an enclosure reaches the ignition temperature of the dust layer under the prevailing conditions, the layer starts to burn or glow. Then the temperature of the component on which the dust layer rests may become considerably higher than had the dust been noncombustible, and the component may fail and give rise to problems that may or may not be related to fire and explosion hazards.

In principle, heated layers of some organic dusts might decompose and develop combustible gases that do not burn directly but mix with the air over time by convection and molecular diffusion and eventually form a premixed explosive gas atmosphere inside the enclosure. This may not be a very likely scenario in general, but in special cases where such a chain of events cannot be excluded, the electrical components inside the enclosure may have to satisfy the requirements for areas containing explosive mixtures of combustible gases and vapors.

8.3.2.2
Combustible, Electrically Conductive Dusts

In general, electrically conductive dusts are metal dusts, and hence layers of such dusts also normally are comparatively good heat conductors. Overheating heat-producing components due to thermal insulation by the dust layer therefore seems less likely with metal dusts than with organic dusts. Also, layer ignition temperatures as measured in laboratory tests (see Chapter 7) are generally higher for metal dusts than organic dusts. Hence, short-circuiting of electrical components, printed circuits, and the like, on which the dust settles, constitutes the main hazard presented by electrically conducting dusts. This is not a genuine fire or explosion risk and should, strictly speaking, be treated separately in other contexts, such as together with problems arising from corrosive and abrasive dusts (see Section 8.4.1 on protection by enclosures).

8.3.3
THERMAL HAZARDS ASSOCIATED WITH ACCUMULATION OF DUST LAYERS ON EXTERNAL SURFACES OF ELECTRICAL APPARATUS ENCLOSURES

As long as the minimum ignition temperature of the dust (for layer or cloud, depending on circumstances) is higher than the maximum temperature of the external enclosure surface, the dust will not be ignited by the surface. This is definitely true if the enclosure surface is entirely free of dust deposits, that is, if the hazard is limited to direct ignition of an explosive dust cloud by the clean hot surface. It is also true if just a small part of the enclosure surface is covered by a dust layer, so that this does not significantly hamper the heat transfer from the interior of the enclosure, via the surface, and into the surroundings. For these cases, the maximum permissible enclosure surface temperatures can be specified on the basis of relatively simple standard laboratory tests for minimum ignition temperatures (see Section 8.4.2).

However, the situation is different if a substantial part of the enclosure surface is covered by a thick dust layer. In this case, the surface temperature of the enclosure may increase to a value significantly higher than that attained in the absence of dust. This is because the surface temperature of a temperature-classed enclosure is seldom a constant inherent property of the enclosure but a result of the temperature distribution along the heat transfer path between the heat generating component(s) inside the enclosure and the atmosphere surrounding the enclosure. The electrical power generated inside the enclosure is a more typical inherent constant property. Then, if the enclosure surface is covered by a dust layer providing significant thermal insulation, the temperature distribution along the heat transfer path toward the surroundings will change, and the surface temperature of the enclosure may significantly exceed the maximum value attained in the absence of dust. This, in turn, may lead to ignition of the dust layer, even if its minimum hot-plate ignition temperature, determined by, for example, the standard IEC hot-plate test, is significantly higher than the maximum nominal temperature of the enclosure surface under dust-free conditions.

Existing comprehensive numerical simulation models can predict whether smoldering combustion in dust layers or deposits may develop in given practical scenarios, such as when specific dusts are in defined contact with specified electrical apparatuses. In future safety standards for industry, numerical simulation may become mandatory in assessing the possibility of smoldering combustion in given scenarios. Published work related to this problem is reviewed in Sections 9.2.3 and 9.3.5 in Chapter 9.

8.4

ENCLOSING POTENTIAL IGNITION SOURCES TO PREVENT HAZARDOUS INGRESS OF DUST

8.4.1

THE IP CODE FOR PREVENTION OF DUST INGRESS

The use of suitable enclosures to keep dust away from delicate electrical and mechanical components has a long tradition. Irrespective of specific hazardous effects, the presence of dusts is generally incompatible with delicate equipment and components, if only from the point of view of cleanliness and tidiness. However, a number of more specific reasons for applying this concept have been put forward:

- Combustible dust can form an explosive dust cloud inside the enclosure and cause a dust explosion.
- Combustible dust can form a combustible dust layer inside the enclosure and cause a dust fire.
- Electrically conductive dust can cause short-circuiting inside the enclosure.
- Abrasive or corrosive dusts can damage delicate mechanical components inside the enclosure.

In the context of preventing ignition of combustible dusts, only the first and second reasons are relevant. Furthermore, when considering that formation of explosive dust clouds inside enclosures of a reasonable standard, by ingress of dust from the outside, is highly unlikely (see Section 8.3), the possibility of dust fire is in fact the only hazard that has some relevance in the present context.

The IEC (2001c) produced a standard, the IP (International Protection) code, that defines various "degrees of protection" against ingress of solid objects, including dust particles and water. According to Greiner (2001), the current code is the result of an evolution initiated by the production of a national German standard in 1934.

According to IEC (2001c), the degrees of protection offered by a given enclosure are specified by two digits, the first referring to ingress of solid objects, the second to ingress of water. For solid objects six levels of protection are defined, ranging from objects larger than 50 mm (digit 1) to dusts (digits 5 and 6). For water, the corresponding range is from gentle dripping (digit 1) to continuous complete immersion (digit 8). The code also specifies the test methods by which enclosures can be checked for compliance with the requirements of the various degrees of protection.

It is important to note that the IEC (2001c) IP code, does not cover protection against ingress of explosive gases. As discussed in Section 8.3.1, satisfactory protection against the ingress of gas is very difficult to achieve using normal enclosure technology, such as flanges with gaskets, because gas molecules migrate though even very tiny openings, in particular if there is a pressure drop across the opening. For this reason, it has been necessary to introduce a number of additional technologies to prevent either ingress of explosive gases into enclosures (oil-filled, pressurized, and molded enclosures), ignition of explosive gas that has entered the enclosure (enclosures filled with glass beads or sand, elimination of potential ignition sources inside enclosure), or transmission of an explosion inside the enclosure to a possible external explosive atmosphere ("flameproof" enclosures).

However, in the case of dusts, none of these additional measures are required to prevent formation of explosive dust clouds inside enclosures. Common enclosure technology, such as flanges with gaskets, provides the protection required.

The IEC IP code specifies two levels of prevention of ingress of dust into enclosures, "dust protected" (digit 5) and "dusttight" (digit 6), which are defined as follows:

- *Dust protected.* A limited quantity of dust is allowed to penetrate into the enclosure under certain conditions (IP 5X).
- *Dust tight.* No dust is allowed to penetrate into the enclosure (IP 6X).

IEC (2001c) also specifies the tests to which enclosures of categories IP 5X and IP 6X must be subjected. The test apparatus used should incorporate the same basic features as illustrated in Figure 8.4.

The enclosure to be tested is placed inside a test chamber where a very dense cloud of fine talcum powder is maintained continuously during the test period, either by a powder circulation pump, as illustrated in Figure 8.4, or by some other means. Depending on the practical circumstances in the industry in which the enclosure to be tested is to operate, tests can be conducted either with a slight negative pressure inside the enclosure to be tested, as illustrated in Figure 8.4, or with no pressure difference across the enclosure wall.

CENELEC (1998b) specifies the IP requirements for combustible dusts as follows:

- Zones 20 and 21: IP 6X
- Zone 22: IP 6X for electrically conductive dusts and IP 5X for electrically nonconductive dusts.

CENELEC (1998b) also specifies marking codes to be used to identify the degree of protection offered by a given enclosure.

Greiner (2001) illustrated the use of IP enclosures to prevent ingress of dust into various electrical apparatuses, such as electrical motors and terminal boxes. With adequate design of the flange/gasket arrangement, IP 6X could be obtained quite readily.

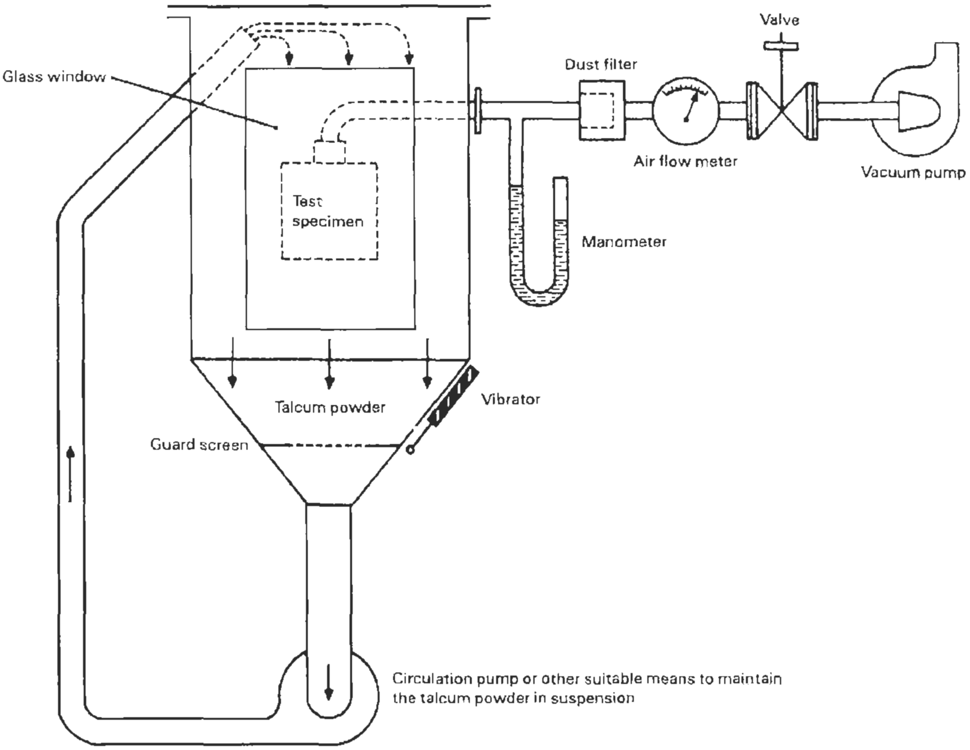

Figure 8.4 *Apparatus used to test the ability of enclosures to prevent ingress of dust (From IEC, 2001c).*

8.4.2
DESIGN OF APPARATUS TO PREVENT IGNITION OF DUST CLOUDS AND DUST LAYERS BY HOT ENCLOSURE SURFACES

8.4.2.1
Ignition of Dust Clouds by Hot Surfaces

This topic is discussed in Section 5.5 of Chapter 5 and Section 7.8 of Chapter 7. Although it is known that the minimum ignition temperature of a given dust cloud is not a true inherent constant of the cloud, results from the laboratory-scale tests described in Section 7.8.2 of Chapter 7 are regarded as representative of the dust tested. The specific test method prescribed by CENELEC and IEC is illustrated in Figure 7.24 in Chapter 7 and described in detail in CENELEC (1998c) and IEC (1994b). The variation in the minimum ignition temperature with variations in the practical conditions of ignition is accounted for by requiring a substantial safety margin. Hence, both CENELEC (1998b) and IEC (2002c) require that the maximum temperature of the dust-free enclosure surface does not exceed two-thirds the minimum ignition temperature for dust clouds, in °C, measured in the standard test.

8.4.2.2
Ignition of Dust Layers by Hot Surfaces

The topic of self-heating and self-ignition in dust layers is discussed in Section 5.2 of Chapter 5 and Section 7.7 of Chapter 7. The specific test method prescribed by CENELEC and IEC to determine minimum ignition temperatures of a dust layer on a hot surface of constant temperature is illustrated in Figure 7.17 in Chapter 7 and described in detail in CENELEC (1998c) and IEC (1994b). Tests with a given dust, varying the thickness of the dust layer, show that the minimum ignition temperature decreases systematically with increasing layer thickness. Both CENELEC (1998b) and IEC (2002c) require that the maximum temperature of the enclosure surface be at least 75°C lower than the minimum ignition temperature determined in the test. Figure 8.5 indicates how the maximum permissible enclosure surface temperature decreases systematically with increasing dust layer thickness, for three different dusts having minimum hot surface ignition temperatures of 250°C, 320°C, and 400°C, respectively, for 5 mm layer thickness. However, if a large part of the hot surface is covered by a comparatively thick dust layer, the surface temperature of the enclosure may increase to a value significantly higher than that attained in the absence of dust, as discussed in Section 8.3.3. In that case, Figure 8.5 does not apply and special assessment is required. This may imply both special tests and mathematical model simulations, as also discussed in Section 8.3.3.

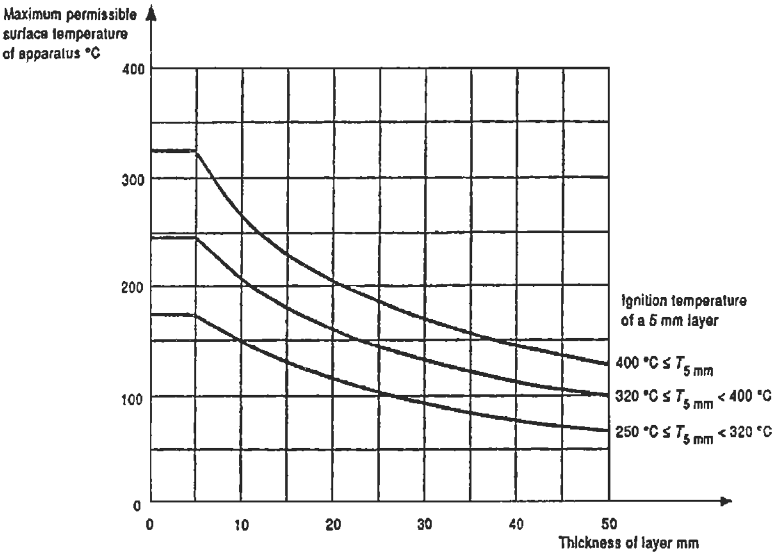

Figure 8.5 *Graph of maximum permissible temperatures of enclosure surfaces as functions of the thickness of a layer of combustible dust on the surface. It is assumed that the dust layer on the enclosure surface does not significantly increase the temperature of the surface over that attained without a dust layer (From CENELEC, 1998b).*

8.4.3
OTHER REQUIREMENTS TO IP ENCLOSURES

International standards (see Section 8.4.4), such as CENELEC (1998a, 1998b), require that enclosures satisfy some further requirements in addition to the ability to prevent ingress of dust and maintain a surface temperature below a prescribed upper limit:

- *Thermal endurance.* Enclosures made of plastic materials must be able to withstand certain specified thermal load tests, both in the range of low and high temperatures. This also applies to any plastic materials used for cementing.
- *Mechanical strength.* Enclosures must be able to withstand relevant tests for mechanical strength.
- *Grounding and bonding of metallic parts.* All metal parts, which by becoming electrostatically charged can give rise to electrostatic discharges that can ignite clouds or layers of the dust in question, must be properly grounded and bonded.
- *Antistatic properties.* To avoid propagating brush discharges (see Section 1.1.4.6 in Chapter 1) enclosures made of plastic materials must satisfy certain requirements to the maximum permissible insulation resistance to ground, the maximum permissible breakdown voltage across the thickness of the plastic wall, or the minimum permissible thickness of external plastic insulation on metal.
- *Protection against incendiary metal particle sparks.* Exposed parts of enclosures must not contain metals able to generate impact sparks that can ignite clouds or layers of the actual dust (see Section 1.1.4.5 in Chapter 1, Section 5.4 in Chapter 5, and Section 7.12 in Chapter 7).

8.4.4
INTERNATIONAL STANDARDS FOR DESIGN OF ENCLOSURES FOR ELECTRICAL APPARATUSES FOR AREAS CONTAINING COMBUSTIBLE DUSTS: AN OVERVIEW

The IEC (1992) suggested that safe design of equipment for areas containing combustible dusts be based essentially on two basic principles: isolation of potential ignition sources by means of enclosures that keep the dust out to the required extent (IP 5X or 6X) and prevention of ignition of the actual dust (layer or cloud) by the enclosure surface. This philosophy has been adopted in current European standards, as expressed in the two standards CENELEC (1998a, 1998b): "The ignition protection is based on the limitation of the maximum surface temperature of the enclosure, and on the restriction of dust ingress into the enclosure by the use of 'dust tight' or 'dust protected' enclosures." In addition, the points mentioned in Section 8.4.3 are accounted for. There seems to be no valid reason for departing from this simple, sound philosophy as the basis in international standards work also in the future. The philosophy also seems to be largely in agreement with prevailing standards and philosophy of standardization in the United States.

The IEC (1999a, 1999b) seriously considered adopting the two CENELEC (1998a, 1998b) standards. However, as discussed in Sections 8.1.1 and 8.1.3, it eventually decided to depart from this approach. Instead, it developed a series of new standards with the objective to obtain as much "harmonization" as possible with the existing series of standards for explosive gases. The resulting series of standards is IEC (2001b, 2002c, 2002d, 2002e, 2002f, and 2002h). Two of these, the "pressurization" standard (IEC, 2001b) and the "molding" standard (IEC, 2002f), are discussed in Sections 8.4.5 and 8.4.6. The reasons why the concept of "flameproof" enclosures for gases is not applicable to dusts (see discussion of "Atex 100a" in Section 8.1.3) are given in Section 8.4.7. The "intrinsic safety" standard (IEC, 2002h) is discussed in Section 8.5.

8.4.5
THE IEC STANDARD FOR PRESSURIZED ELECTRICAL EQUIPMENT ENCLOSURES FOR AREAS CONTAINING COMBUSTIBLE DUST

8.4.5.1
Background

The controversy presented by this standard is discussed more extensively by Eckhoff (2002a). The Ex"pD" standard (IEC, 2001b) was the first of the new "harmonized" dust standards issued by IEC. The self-contradictions contained in this standard can be traced back to deficiencies in the European Union "Atex 100a" Directive (see Section 8.1.3) and the corresponding deficiencies in the "Atex 118a" Directive and current standards for classification of areas containing combustible dusts, building on "Atex 118a" (see Section 8.2).

8.4.5.2
The Ex"p" Concept for Gases and Vapors

The basic idea of the Ex"p" standard for gases (IEC, 2001d) is to locate electrical components that contain potential ignition sources, like hot surfaces and electric sparks, within an enclosure supplied with a sufficient internal overpressure to prevent any explosive gas atmosphere that might appear outside the enclosure from entering it through minor gaps and holes in the enclosure walls. Ex"p" equipment for gases is generally quite expensive, not in the least because of the automatic control and interlocking system that constitutes an essential, integral part of such equipment. This can be justified for larger enclosures, such as instrument cabinets and large electrical motors.

8.4.5.3
The Situation with Dusts

The interior of electrical apparatus enclosures must be kept entirely free of dust particles in some special cases. For example, dusts of abrasive or corrosive materials cannot be admitted to the interior of delicate machinery, and accumulation of layers of electrically conductive dusts on open electric or electronic circuitry is clearly undesirable. A well-designed pressurization system prevents dust from entering enclosures in such cases. However, these considerations are outside the scope of preventing dust explosions or fires and can be taken care of by modifying the IP standard by adding pressurization as an option (see the discussion of IP in Section 8.4.1).

As discussed in Section 8.3, dust particles that enter an enclosure through narrow unintentional holes and gaps do not accumulate as an explosive cloud of particles suspended in the air but settle out as dust layers on the internal surfaces of the enclosure. Furthermore, it does not normally represent great difficulties to design dusttight enclosures to satisfy the requirements of the enclosure standard IP 6X, as defined in Section 8.4.1. In comparatively large apparatus enclosures, such as instrument cabinet, with doors and windows fitted with rubber gaskets and locking arrangements, it may be difficult to completely prevent ingress of dust. However, the transmission of explosive dust clouds from the outside the enclosure to its interior, through possible narrow gaps and holes, can be excluded.

A further consideration is that any such larger enclosure that is embraced by an explosive dust cloud becomes covered by dust very soon after the appearance of the cloud, and regular dust removal from the exterior is required. Therefore, one hesitates to locate such enclosures in zones 20 and 21 in the first place, just from the point of view of keeping the workplace clean and tidy.

A related concern is that with dusts, as opposed to gases, it is impossible for humans to perform any installation, maintenance, or repair work inside the explosive atmosphere, that is, inside a dust cloud having dust concentrations in the explosive range.

The IEC (2001b) Ex"pD" standard for dusts seems, to a large extent, to be an edited copy of the IEC (2001d) Ex"p" pressurization standard for gases and vapors. This is evident from the scope of the dust standard, which defines the purpose of pressurization as "to prevent the entry of dust which might otherwise lead to the formation of a 'combustible mixture' within the enclosure." In the context of this standard, the term *combustible mixture* means an explosive dust cloud. Furthermore, in Section 6 of the standard, dealing with temperature limits of hot surfaces inside the enclosure, the overall task is said to be "to ensure that, if pressurization ceases, any explosive dust atmosphere which may exist [inside the enclosure], is prevented from making contact with that surface before . . ." A final example is found in the introduction to Section 7.5 in the standard, which is concerned with guarding "against the possibility that electrical apparatus protected by pressurization may cause an explosion (inside the enclosure) in the case of failure of the protective gas supply."

8.4.5.4
The Self-Contradiction of the Dust Pressurization Standard

IEC Ex"pD" standard is self-contradictory because it rests on the erratic assumption that dust particles in a dust cloud embracing an enclosure, by entering it though unintentional narrow holes and gaps, can accumulate as an explosive dust cloud inside the enclosure. As discussed in Section 8.3, if significant quantities of dust particles enter an enclosure at all, they accumulate as a layer not as an explosive cloud. According to the philosophy of the current international area classification standards (see Section 8.2), the interior of a reasonably dusttight nonpressurized enclosure is therefore to be regarded as a nonhazardous (safe) area.

If the self-contradiction inherent in the new standard is to be resolved, focus must be shifted from the hazard of dust explosions to the hazard of smoldering or open dust fires, which can occur in layers and are also clearly undesirable. But, within the context of the "Atex 100a" Directive and the current area classification standards (see Sections 8.1.3

and 8.2), dust fires are not regarded as a hazard in their own right. Therefore, areas containing layers of combustible dust that are unlikely to become dispersed into dust clouds are not regarded as hazardous areas.

8.4.6
ENCAPSULATION BY MOLDING

As part of the effort to "harmonize" dust standards with gas standards, IEC (2002f) produced a new standard for encapsulation of electrical equipment for combustible dust atmospheres by molding. In this type of protection, electrical parts that can ignite an explosive atmosphere are molded into a compound material in such a way that the atmosphere cannot make contact with these parts. The compounds can be thermosetting, thermoplastic, epoxy resins, elastomers, and the like, with or without fillers.

It is difficult to see that this comprehensive Ex"pD" standard for dusts, which is to a large extent an edited copy of the corresponding gas standard IEC (2002g), is very helpful. As discussed in Section 8.3, the issue of preventing the formation of an explosive atmosphere inside enclosures is not relevant for dusts. A relevant specific issue with dusts would rather be to make sure that molded components embedded in dust deposits do not give rise to self-heating or self-ignition of the dust layer or deposit. The basic European enclosure standard for dusts (CENELEC, 1998a), discussed in Section 8.4.4, contains a paragraph on "materials used for cementing," which may be expanded to cover additional aspects of encapsulation by molding that may be relevant for dusts. If necessary, a reference could be made to gas standards (e.g., IEC, 2002g).

8.4.7
WHY THE CONCEPT OF FLAMEPROOF ENCLOSURES IS NOT RELEVANT FOR COMBUSTIBLE DUSTS

8.4.7.1
The Original Flameproof Concept for Gases and Vapors

This section is included mainly to support the discussion of the "Atex 100a" Directive in Section 8.1.3. The basic concept of "flameproof" enclosure design is to confine possible gas or vapor explosions inside enclosures containing potential ignition sources to the volume of the enclosure only. It is then assumed that combustible gas that appears on the outside of an enclosure may give rise to formation of an explosive gas mixture inside the enclosure by entering it through narrow holes and gaps, such as during "thermal breathing." Confinement of the explosion to the interior of the enclosure is achieved by fulfillment of three basic requirements. First, the enclosure must have sufficient strength to withstand the maximum possible internal explosion pressure. Second, any gaps or holes in the enclosure wall must be narrow and long enough to prevent hot combustion gases produced by the internal explosion, which are expelled from these openings, from igniting any explosive gas mixture outside the enclosure. Finally, the external enclosure wall temperature must be lower than the minimum ignition temperature of the explosive mixture of the gas or vapor in question.

8.4.7.2
The Situation with Dusts

The fundamental assumption on which the flameproof concept rests (i.e., that an explosive cloud can accumulate inside enclosures by transfer of fuel from the outside) does not apply to dusts (see Section 8.3). By using "dust-protected" or "dusttight" enclosures (IP 5X or 6X), generation of explosive dust clouds inside the enclosure, such as by "thermal breathing" processes, can be effectively excluded. Dust particles that get into an enclosure through narrow gaps or holes at all accumulate as a layer, not as a cloud.

In addition to considering the improbable event of an explosive dust cloud being formed inside the enclosure, one must also consider that the explosive mixture outside the enclosure, into which explosion transmission is to be prevented, is not a gas but a transient dust cloud of short duration (zone 21).

The maximum experimental safe gap concept was adopted successfully by Schuber (see Section 4.4.6 in Chapter 4) to prevent dust explosion transmission through rotary locks between process units in powder processing plants. However, this application is in no way related to the design of electrical equipment according to the Ex"p" concept for explosive gas mixtures.

It should finally be mentioned that a most unusual dust version of the maximum experimental safe gap (MESG) concept was proposed by Harper, Plain, and Wilton (1997). In this case, the concern was to prevent smoldering combustion in dust layers inside enclosures from propagating to the outside through holes and gaps in the enclosure wall. It seems that the use of the term *flameproof* and the designation Ex"d" for equipment designed according to this idea would cause much confusion, and a completely different notation should be sought.

8.5
INTRINSICALLY SAFE ELECTRICAL APPARATUSES

8.5.1
THE ORIGINAL CONCEPT FOR GASES AND VAPORS

In essence, *intrinsically safe* design means that all electrical components are designed in such a way that generation of electrical sparks or hot surfaces capable of igniting the premixed gas in question is effectively prohibited. This means that the maximum electrical energies that can become stored in the various parts of the electrical system, such as in capacitances and inductances, must be very low. Ex"i," therefore, is applicable only to apparatuses demanding very low power or energy to operate. This design concept, in contrast to others, implies that electric circuitry can be in direct contact with the explosive gas or vapor atmosphere without any ignition hazard.

8.5.2
THE SITUATION WITH DUSTS

In practice, electrical circuits, switches, and so forth to be used in areas containing combustible or electrically conductive dusts should, for reasons discussed in Section 8.4, always be kept inside enclosures. This will prevent significant quantities of dust from coming in contact with electrical components in general, including components that may generate electric sparks or hot surfaces. Hence, direct adoption of the entire concept of "intrinsically safe design" from the gas/vapor domain into the domain of combustible dusts does not seem to be an optimal approach.

However, in some highly special applications, there is a genuine need for intrinsically safe apparatus in environments containing combustible powders or dusts. One example is capacitive level indicators for solid bulk materials stored in silos and bins. In this case, a live capacitor "plate," in the form of a bare metal rope carrying a voltage to ground, is directly exposed to the combustible powder and dust inside the silo or bin. According to Klotz-Engmann (private communication, 2001, 2002), an ignition risk could arise from electrical sparks generated by direct contact between the energized bare metal rope and any grounded metal part of the silo. This possibility has to be considered in zones 20 and 21, at least when taking into account possible faults. Figure 8.6 illustrates the application of this type of level indicator; and Figure 8.7 shows three models, one with a metal rope, for powders in bins and silos, and two with metal rods, for liquids in tanks. The basic principle of measurement is as follows: A short electric pulse (ns wave package) is emitted from the sensor head at the top of the silo and travels down the vertical metal rod or rope. At the point where the rod or rope becomes immersed in the powder, its impedance changes abruptly, which causes a partial reflection of the electrical pulse from this point backward to the sensor head at the top. The distance d from the sensor head at the silo top to the powder or liquid surface is then $d = {}^{1}/_{2}ct$. Here, c is the speed of the electromagnetic wave pulse passing along the metal rope or rod and t is the time from the emission of the pulse from the sensor head to the

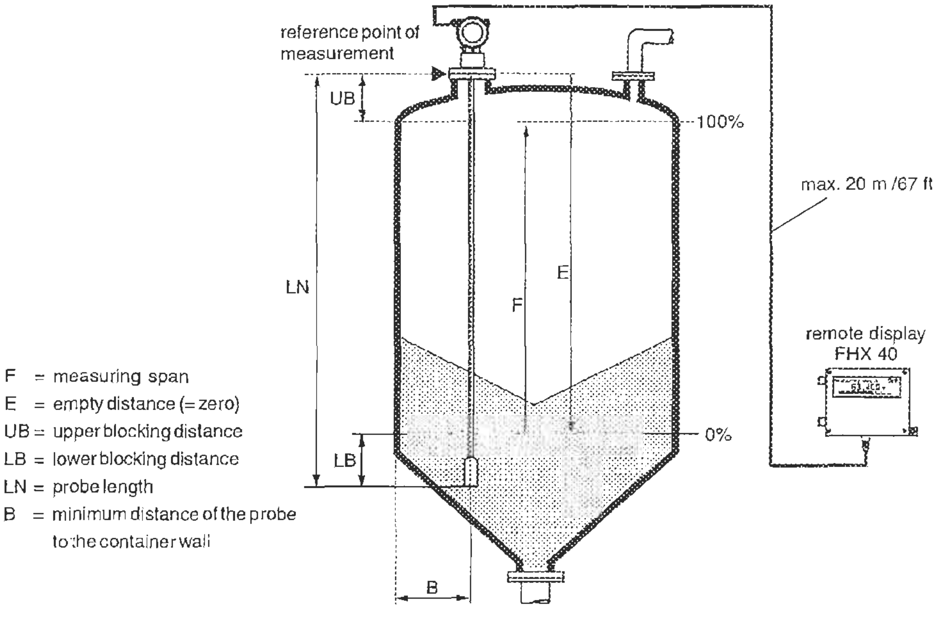

Figure 8.6 *The use of a capacitive level indicator for powders in silos (Courtesy of G. Klotz-Engmann, Endress + Hauser, Germany).*

Figure 8.7 *Three models of a capacitive surface level indicator. The model to the left, with a metal rope carrying a weight at the end, is for powders and granulates in silos. The two other models, with coaxial and plain metal rods respectively, are for liquids in tanks (Courtesy of G. Klotz-Engmann, Endress + Hauser, Germany).*

return of the reflected pulse from the point where the rod or rope becomes immersed in the powder.

8.5.3
THE NEW IEC EX"iD" STANDARD FOR DUSTS

The voluminous, detailed draft Ex"iD" standard for dusts, produced by IEC (2002h), is to a large extent based on the corresponding IEC (1999c) and CENELEC (2001) standards for gases. In view of the very limited applications for intrinsically safe electrical apparatuses in areas containing dusts, the proposed draft standard does not seem an optimal solution. Furthermore, in spite of entering into minute details on a number of aspects, the draft standard provides no guidance for differentiating between dusts of different ignition sensitivities, such as by introducing dust groups corresponding to the gas groups in the gas standards. Instead, the gas group IIB requirements are imposed on all dusts. One argument in favor of this approach is that the same electrical apparatuses can be used for almost all combustible gases and vapors and for all dusts. However, whereas this approach clearly simplifies production, stocking, and sale of electrical apparatuses, it is not an acceptable basis for a safety standard. The basic objective of any safety standard should be to define borderlines between safe and unsafe conditions, with reasonable safety margins.

In view of this, the possibility of producing a completely independent, intrinsic safety standard for dusts should be given careful consideration. Such a standard should focus directly on the very limited segment of intrinsic safety technology relevant to combustible dusts and provide proper guidance for differentiation based on ignition sensitivity. In the following, a simple, but nevertheless comprehensive, solution to the differentiation problem is given.

8.5.4
MINIMUM IGNITION ENERGY, A UNIVERSAL IGNITION SENSITIVITY PARAMETER FOR THE DESIGN OF ELECTRICAL APPARATUSES THAT ARE INTRINSICALLY SAFE IN THE PRESENCE OF EXPLOSIVE DUST CLOUDS

8.5.4.1
Basic Approach

In essence, the concept is to use conservative first-order ignition curves, estimated from the experimental minimum ignition energy (MIE) value of clouds in air of the actual dust. Internationally standardized test methods (e.g., IEC, 1994; CEN, 2002), allow MIE for clouds of any dust to be readily determined down to the range of 2–3 mJ.

8.5.4.2
Range of MIEs for Dust Clouds

In the past, it was thought that the absolute lower limit for MIEs of dust clouds in air was on the order of 10 mJ, that is, about 2 orders of magnitude above the values of IIA gases. For example, Dorsett and Nagy (1968) reported a figure of 15 mJ for a very fine sulfur powder of average particle size 4 μm. However, Eckhoff (1975) showed that the true MIEs for very sensitive dusts were considerably lower, by at least 1 order of magnitude, than the values published in the 1960s. More recently, Bartknecht (1993) indicated an extreme lower limit, by reporting a MIE value of very fine sulfur powder of only 0.01 mJ, practically identical with MIE of carbon disulphide.

As documented by Bartknecht (1993) and extensively by Beck, Glienke, and Möhlmann (1997), MIEs of clouds of various dusts in air span over at least eight decades, from perhaps as low as 0.01 mJ to beyond 1 kJ at the upper end. Hence, there is an obvious need to establish a system for differentiating the maximum permissible spark energy requirements to Ex“iD” equipment for dusts.

8.5.4.3
Experimental Assessment of MIEs of Dust Clouds

The strong influence of the spark discharge time on the MIE for dust clouds was first indicated by the results of Boyle and Llewellyn (1950) and Line, Rhodes, and Gilmer (1959). Experiments by Eckhoff and Enstad (1976) gave further support to the validity of the observation by Line et al. that the shock wave produced by sparks of very short duration can in fact prohibit ignition by blowing the dust away from the spark before the ignition process gets underway.

Section 5.3 in Chapter 5 provides a more recent summary of the state of the art on electric spark ignition of dust clouds. An important conclusion is that conservative experimental determination of the MIE of dust clouds requires the use of electric sparks of sufficiently long discharge times to prevent significant disturbance of the dust cloud by the shock wave generated by the spark discharge. This is achieved by introducing a 1–2 mH inductance in the discharge circuit, and this feature is compulsory in the IEC (1994) and CEN (2002) standard methods for MIE determination for dust clouds. (This inductance is removed when the purpose of the test is to assess the sensitivity to ignition by electrostatic spark discharges.)

A major limitation of the test apparatuses commonly used is that they cannot generate sparks of energies significantly lower than 2–3 mJ. Efforts should be made, therefore, to develop generators for synchronized sparks of energies down to 0.1 mJ or even 0.01 mJ. Research to meet this need is in progress in Norway.

8.5.4.4

Relationship between MIE and Ignition Curves for Gases

In the Ex"i" standards for gases (such as IEC, 1999c; CENELEC, 2001), the ignition curves play a central role. These are empirical borderlines separating the combinations of circuit parameters that cannot produce incendiary electric spark discharges from those that can. The curves are determined experimentally by a special ignition apparatus specified in the same standards. In this apparatus, the explosive gas atmosphere is exposed to electrical sparks generated by breaking or closing electrical circuits. Three different types of ignition curves are determined: capacitive, inductive, and resistive. The dependence of the ignition curves on the ignition sensitivity of the gas is taken care of by having complete sets of such curves for the four different standard gases: methane, propane, ethylene, and hydrogen. All other gases and vapors are then grouped in four corresponding categories, according to their standard "minimum ignition current," determined in a closely specified way.

The relationship between the MIE and ignition curves for gases was investigated by Eckhoff (2002b). He showed that the simple basic equation $0.5CU^2$ = MIE defines an "ultimate," conservative capacitive ignition curve, when MIE is determined experimentally under optimal conditions for ignition. The capacitance C is in °F, the voltage U in V, and MIE in J. Similarly, it was demonstrated that the equation $0.5LI^2$ = MIE defines an "ultimate," conservative inductive ignition curve. Here, the inductance L is in H and the current I is in A. The latter equation is valid only as long as $L > 1$ mH. For $L < 1$ mH, the electrical circuits used to determine the ignition curves behave essentially as purely resistive circuits. However, for resistive ignition curves, a simple theoretical basis is lacking, and one must rely on an empirical correlation of experimental data. Eckhoff (2002b) showed that existing experimental resistive ignition curves for the four "gas groups," as well as a unique resistive ignition curve for lycopodium dust clouds reported by Lunn (2001) and Bennett et al. (2003), can be represented by the conservative equation $I = 15{,}000\ \text{MIE}^{0.45}/U^2$, where the current I is in A, MIE is in J, and the voltage U is in V.

8.5.4.5

Conservative Ignition Curves for Dusts Clouds Based on MIE

For capacitive circuits, conservative ignition curves are obtained directly from the equation $0.5CU^2$ = MIE. A chart showing this graphically, for a range of MIE values, is given in Figure 8.8. In the case of inductive circuits, conservative ignition curves

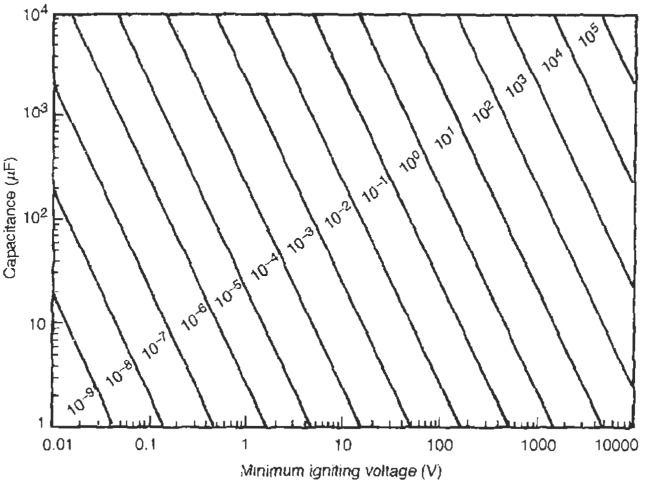

Figure 8.8 *Theoretical conservative capacitive ignition curves for dust clouds based on the equation* $0.5CU^2 = MIE$. *The numbers attached to the straight lines are the respective MIE values in J.*

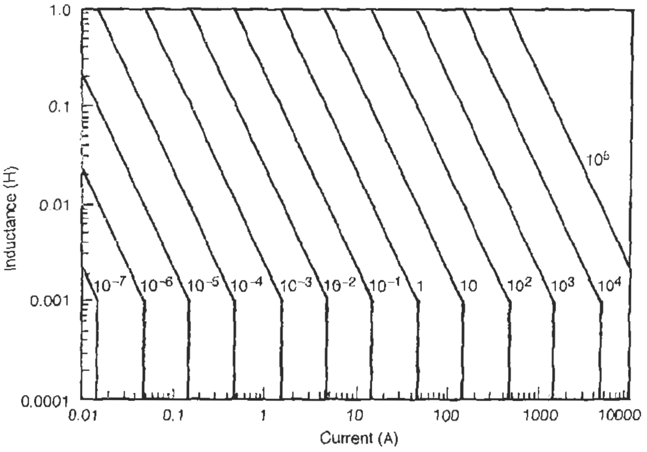

Figure 8.9 *Theoretical conservative inductive ignition curves for dust clouds based on the equation* $0.5LI^2 = MIE$, *valid for* $L > 1$ *mH. The numbers attached to the straight lines are the respective MIE values in J.*

are obtained directly from the equation $0.5LI^2 = \text{MIE}$ for $L > 1$ mH. For smaller L, the ignition current is independent of L and t essentially resistive. A chart showing conservative ignition curves for inductive circuits, for a range of MIE values, is given in Figure 8.9. For resistive ignition circuits, the equation $I = 15{,}000\ \text{MIE}^{0.45}/U^2$ provides a first-order conservative estimate based on existing experimental ignition curves for gases and dust clouds. A graph representing this equation for a range of MIE values is given in Figure 8.10. However, considerable uncertainty is involved in extensive extrapolation of this equation into the regions of higher MIE. Therefore, more research is needed to establish more-reliable resistive circuit ignition data in the range of higher MIEs.

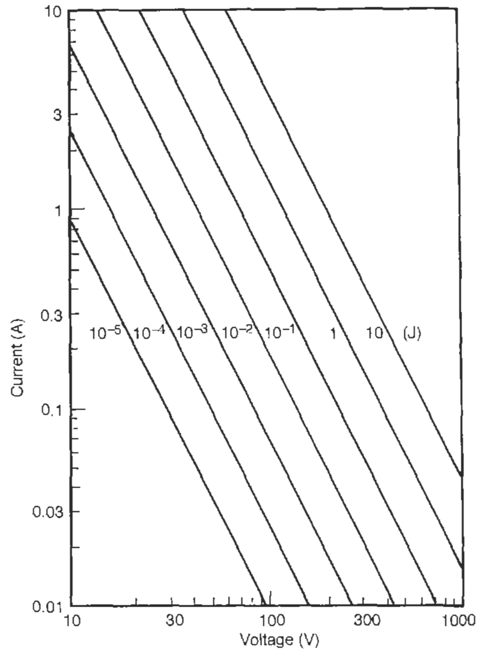

Figure 8.10 *Theoretical resistive ignition curves based on the empirical equation* $I = 15{,}000\ MIE^{0.45}\ 1/U^2$ *obtained by correlating resistive ignition data for combustible gases and lycopodium dust. The numbers attached to the straight lines are the respective MIE values in J.*

8.6
SUMMARY AND CONCLUSIONS

8.6.1
"ATEX 100a" DIRECTIVE

Revision of the current European "Atex 100a" Directive constitutes a first important step toward an improved approach for the standardization of electrical apparatuses to be used in areas containing combustible dusts. The revised directive must differentiate clearly between the way in which gas clouds, on the one hand, and dust clouds, on the other, are generated and sustained in industrial practice; and it must include open and smoldering dust fires as hazards in their own right, in addition to dust explosions.

A revised "Atex 100a" Directive will prevent excessive "harmonization" of standards for electrical apparatuses for combustible dusts, with established standards for gases and vapors.

8.6.2
AREA CLASSIFICATION

International and European area classification standards, as well as the European "Atex 118a" Directive, must be revised to include combustible dust layers and deposits that can give rise to open or smoldering fires in the definition of *hazardous areas*, irrespective of whether the layers or deposits may become dispersed into explosive dust clouds.

The term *source of release*, which is indeed appropriate for gases, is not useful in the context of dusts and should be replaced by a more relevant term, such as *area of dust cloud generation*.

8.6.3
PROTECTION BY ENCLOSURES

8.6.3.1
IP Enclosures

At least four reasons for using dust tight or dust protected enclosures have been put forward. To avoid ingress of

- Combustible dust that can form an explosive dust cloud inside the enclosure.
- Combustible dust that can form a combustible dust layer inside the enclosure.
- Electrically conductive dust that can cause electrical short-circuiting inside the enclosure.
- Abrasive or corrosive dust that can damage delicate mechanical and electrical components inside the enclosure.

Only ingress of dust that can form explosive dust clouds is within the "Atex" domain for dusts as presently defined by the existing European directives. However, ingress of dust that can form explosive dust clouds can be effectively prevented by IP 5X or 6X enclosures.

Safe design of electrical equipment for areas containing combustible dusts should, with very few exceptions, be based on two simple concepts: The first is use of enclosures that prevent ingress of dust to the required extent; the second is adoption of measures that keep the temperature of any surface in contact with dust clouds or layers sufficiently low to effectively prevent ignition. This sound philosophy is expressed clearly in current European standards. For example, in CENELEC (1998a, 1998b), "The ignition protection is based on the limitation of the maximum surface temperature of the enclosure, and on the restriction of dust ingress into the enclosure by the use of 'dust tight' or 'dust protected' enclosures."

8.6.3.2
Pressurized Enclosures

The new "pressurization" standard for dusts (IEC, 2001b) is self-contradictory because it rests on a fundamentally wrong assumption. This assumption is that combustible dust that enters the interior of an electrical apparatus or component enclosure through unintentional tiny holes and gaps in the enclosure wall can accumulate as an explosive dust cloud inside the enclosure. In reality, only dust layers can be generated by this kind of dust ingress. Hence, for the new standard to have some relevance, terms like *explosive dust clouds, explosive dust air mixtures, combustible dust atmospheres*, and *explosive concentrations of combustible dust mixed with air* must be replaced by *layers of combustible dust* throughout the standard.

As a rule, enclosures designed according to the IP 6X or 5X requirements are fully satisfactory for preventing hazardous ingress of dust.

8.6.3.3
Molding

A special dust standard for enclosures sealed by molding seems unnecessary. The standard proposed by the IEC (2002f) is, to a large extent, an edited copy of the corresponding gas standard, IEC (2002g). The basic European enclosure standard for dusts (CENELEC, 1998a) contains a paragraph on "materials used for cementing," which may be expanded to cover any additional aspects of encapsulation by molding that may be relevant for dusts.

8.6.3.4
Flameproof Enclosures

This concept, as understood in the context of explosive gases, is not applicable to dusts.

8.6.4
INTRINSIC SAFETY

In some very special cases, there is a genuine need for intrinsically safe apparatus even in environments containing combustible dusts. Electric spark ignition sensitivities of dust clouds, expressed in terms of their minimum ignition energies, vary substantially, across at least 8 orders of magnitude. Therefore, substantial differentiation of current and voltage limitation requirements for intrinsically safe apparatuses is essential in an intrinsic safety standard for dusts. Such differentiation is missing in the current IEC (2002h) draft standard. However, experimental conservative MIEs for dusts, obtained by current standard test methods, constitute an obvious basis for adequate differentiation.

Conservative "ignition curves" can be estimated from the MIE using only simple theory or empirical correlation. Hence, for capacitive circuits, conservative safe combinations of circuit parameters are obtained by satisfying the criterion $0.5CU^2 < \mathrm{MIE}$. For inductive circuits, corresponding conservative safe combinations are given by the criterion $0.5LI^2 < \mathrm{MIE}$, as long as $L > 1$ mH. For resistive circuits, the simple empirical relation $I < 15{,}000\ \mathrm{MIE}^{0.45}\ 1/U^2$ was shown to apply to the available data.

There is a need for a standard method for experimental determination of the MIE for dust clouds in the important energy range below 1 mJ, which is not covered by typical standard test apparatuses. A research program aimed at developing such a method is currently being conducted in Norway.

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Chapter 9

Research and Development, 1990–2002

9.1
INTRODUCTION

9.1.1
BACKGROUND AND OBJECTIVE OF CHAPTER

This review chapter is the result of a continuous literature survey process starting in 1992, just after the release of this book's first edition. Early versions of the chapter were presented at three consecutive IBC courses in the United Kingdom and at a conference in Poland. The first published paper version was Eckhoff (1993a). A subsequent intermediate version was presented in the Peoples Republic of China (Eckhoff, 1994). The latest intermediate paper version, just before appearing as Chapter 8 in the second edition of this book in 1997, was Eckhoff (1996a). In the present, third edition of the book, the review chapter has been updated by adding a substantial amount of more-recent material, published in the period 1996–2002, mainly papers in internationally recognized journals and proceedings of internationally recognized conferences and symposiums.

The purpose of the chapter is twofold. First is a wish to update the book by summarizing, within a structured framework, the results of some of the extensive research and development that has taken place worldwide since the completion of the manuscript for the first edition (Chapters 1 to 7 plus appendices) in 1990. Second is the need to emphasize even more strongly some significant features of a new philosophy of dust explosion prevention and mitigation that seems to have gained strength over the last decade. *Increased differentiation* and *tailor-making* are key words.

In the first part of the chapter, new knowledge on the fundamental aspects are reviewed. Such insight is becoming steadily more important as more and more practical problems are being approached by developing comprehensive mathematical models. New, more directly applicable knowledge on preventing and mitigating dust explosions in industrial practice are addressed specifically in the second part of the chapter. The final third part is devoted to the important area of test methods to assess ignitability and explosibility of dusts.

9.1.2
BOOKS AND CONFERENCE PROCEEDINGS PUBLISHED AFTER 1990

Bartknecht (1993) produced a comprehensive revised, updated, and extended unified version of his two previous books, the one on dust and gas explosions from 1978 and the one on dust explosions only from 1987 (see Chapter 1). The new unified volume, published in the German language, covers the results of the total amount of Bartknecht's extensive experimental research and development in the fields of dust and gas explosion prevention and control. These were acquired partly during his time at the Safety in Mines Research Establishment at Dortmund, Germany, and partly during his years with Ciba-Geigy AG in Switzerland. In addition to the extensive coverage of Bartknecht's own work, the volume contains material from other workers.

Steen (2000) edited a comprehensive handbook on explosion protection, also in German, which covers a wide range of topics relevant in the present context, from the basics of ignition and flame propagation processes in dust clouds and layers to explosion prevention and mitigation in practice. The book succeeds the classical *Handbuch der Raumexplosionen* edited by Freytag. Sections of the book are written by 25 internationally recognized experts, mostly from Germany.

The hazard of dust cloud ignition by electrostatic discharges of various kinds has been briefly outlined in Sections 1.1.4.6 and 1.4.2.7 of this book, with reference to more extensive accounts. The useful books by Glor (1988) and Lüttgens and Glor (1989) again should be mentioned specifically here. More recently, Lüttgens and Wilson (1997) produced an excellent addition to the technical literature on this problem, of which analyses of a unique selection of practical case histories constitute a major and most useful part.

The data on ignitability and explosibility of dust given in Appendix A1 were, with kind permission, selected and translated from a unique collection of test data published in German by BIA in 1987. A few years ago, Beck, Glienke, and Möhlmann (1997) from BIA produced a complete English translation of their updated, extended, and unique collection of data.

IBC (main office, London) arranged a series of consecutive summer schools on dust explosion prevention and mitigation at Cambridge, UK, in 1992, 1993, and 1994. Some of the papers presented remained unchanged during the 3-year period, others were revised annually. Most of the papers from these events are referred to individually in this chapter. The Australian branch of IBC (Sydney) arranged two special "Dust Explosion Summits" for Australia in February 1996 and March 1997, but the papers are not referred to specifically here.

The proceedings of the second and third World Seminar on the Explosion Phenomenon and on the Application of Explosion Protection Techniques in Practice, held in Ghent, Belgium, March 1996 and February 1999, contain about 20 papers each that are related more or less directly to the dust explosion problem. The proceedings were published by EuropEx, Kontich, Belgium. Again, a wide range of topics were treated, from broad reviews and general risk considerations to specific technical papers addressing recent development in research and design of protective and mitigating measures. Relevant papers from both conferences are referred to individually here.

A series of five International Colloquiums on Dust Explosions were arranged more or less biannually in Poland, starting in 1984. The sixth colloquium was arranged in the Peoples Republic of China. All the papers from the last colloquium in Poland (1993) and the one in the Peoples Republic of China (1994) are referred to individually in the present review. The Seventh International Colloquium on Dust Explosions was held in Bergen, Norway, June 1996. The proceedings, published by Christian Michelsen Research (CMR), Bergen, contain about 40 papers, on a wide range of topics related to dust explosions and dust fires. The eighth event in this series was held in Schaumburg, IL, September

1998, and the proceedings, published by Safety Consulting Engineers Inc., Schaumburg, contain 26 full papers, again covering a wide range of topics. Most of the papers from these two events are referred to individually in the chapter. The subsequent ninth colloquium was held in Tsukuba, Japan, October 2000, and about 30 full papers were presented. The most important ones were subsequently published in a special issue of the *Journal of Loss Prevention in the Process Industry*, and each of these papers is referred to in the present review. The last event in this series covered here, the 10th, was held in Bourges, France, October 2002. All the papers on dust explosions presented there are referred to individually in this review.

VDI (Verein deutscher Ingenieùre) in Düsseldorf, Germany has, since 1977 if not earlier, arranged a series of consecutive symposiums on the Safe Handling of Combustible Dusts, in Nuremberg. The proceedings were published by VDI. Most of the large number of papers from the three symposiums held in 1992, 1996, and 2001 are referred to individually in this chapter. Time did not permit inclusion of the papers from the most recent event in this series, in October 2002. However, the event was devoted entirely to various aspects of the implementation of the Atex directive in practice, which was also covered extensively in the 2001 event.

The proceedings of the Third International Seminar on Fire and Explosion Hazards, April 2000, in Windermere, UK, arranged by the Centre for Research in Fire and Explosion Studies, University of Central Lancashire, Preston, UK, contains 11 papers on various aspects of the dust explosion problem, some of which are referred to in the present review.

9.2
STATUS AND OUTSTANDING PROBLEMS IN FUNDAMENTAL RESEARCH ON DUST EXPLOSIONS

9.2.1
THE MAIN TOPICS COVERED

The fundamental aspects of dust explosion research may be grouped under four main headings, as shown in Table 9.1. The first column deals with the problem area discussed extensively in Chapter 3 of this book. Aspects of some important items in the second column are discussed in Chapter 5, and the topics of the third column are treated in Chapter 4. However, the blast wave problem has not been discussed at length in any of the preceding chapters.

As pointed out by Ronney (1999) it is well known that gravity influences many types of combustion processes, particularly where buoyancy is a central mechanism in the transportation of heat and matter. To resolve the complex interaction of the various mechanisms involved in the initiation and propagation of dust explosions, experiments to an increasing extent are conducted at zero or very low gravity. This eliminates the influence of the factors caused by gravity, such as buoyancy. Nongravity, or microgravity, experiments are most often performed in drop towers, diving aircraft, or space stations. The review that follows also includes some investigations of this type.

Table 9.1 Fundamental aspects of dust explosions

Dust cloud formation processes	**Dust cloud ignition processes**	**Flame propagation processes in dust clouds**	**Blast waves generated by burning dust clouds**
Interparticle forces in dust deposits (cohesion)	General ignition theory	Single-particle ignition and combustion in a hot oxidizer gas	Blast wave properties as a function of burning dust cloud properties
Entrainment of particles from dust deposits by shock waves passing across the deposit surface	Ignition of single particles and clouds	Laminar and turbulent flames in dust clouds	Effects of blast waves on humans and mechanical structures
Entrainment of particles from dust deposits by turbulent gas flows	Ignition by smoldering combustion in dust layers and deposits	Mechanisms of heat transfer: conduction, convection, radiation	Ability of blast waves to transform dust layers into dust clouds (coupled to first column)
Transport of dust particles in turbulent gas flows	Hot surfaces	Limit conditions for flame propagation through dust clouds: particle properties, dust concentration, oxygen concentration, geometry	
Measurement and characterization of state of turbulence in dust clouds	Flying burning metal particles	Acceleration of dust cloud flames by turbulence	
Measurement and characterization of distribution of particles in dust clouds	Electric sparks and arcs	Detonation of dust clouds	
	Electrostatic discharges		
	Hot gas jets		
	Shock waves		
	Focused light-beam hot spots		
	Influences on ignition sensitivity of dust cloud properties: composition, size and shape of particles, turbulence, dust concentration, gas phase composition		

9.2.2
GENERATION OF PRIMARY DUST CLOUDS AND RESULTING DUST CLOUD STRUCTURES

9.2.2.1
Background

The important role of the way in which dust clouds are generated is sometimes overlooked when discussing dust explosions. Work published up to 1990 is discussed in Chapter 3. It is well established experimentally that the initial state of a cloud of a given dust in a given gas (dust concentration, degree of dispersion into individual particles, dynamic state) has a strong influence on both the ease with which the dust cloud ignites and the rate at which it burns.

9.2.2.2
Generation of Dust Clouds in Industrial Processes

Little fundamental, quantitative knowledge exists about the ways in which *primary dust clouds* are generated in industrial processes. Some work has been done on entrainment of dust particles by turbulent gas flows passing over dust layers and ridges in wind tunnels. However, mathematical models connecting essential parameters of dust cloud generation processes and the states of the resulting dust clouds are scarce. Lightstone and Raithby (1998) presented a mathematical model that predicts the motion of particles in a turbulent flow. The model solves for the probability density function (pdf) of particle velocity and treats the impact of the velocity pdf as a diffusion process. Particle concentrations are, in turn, found from the velocity distributions. Good agreement was found between model predictions and experimental data.

When designing experiments for fundamental studies, one should select configurations that can be related to industrial practice. Examples are bulk dust dropped into an airflow and entrainment of dust layers by airflows in channels and galleries with and without flow-obstructing obstacles. Valuable impulses for further studies can probably be obtained from the extensive research carried out worldwide on pneumatic transport of powders.

Armour-Celu, Woodhead, and Barnes (1998) developed an electrostatic measurement technique by which the charging trends during pneumatic transport of powders in pipelines could be inferred. However, processing the measured signals also seemed to reveal information about the *flow pattern of the particles* in the pipeline. It was indicated that the velocity of the particles closest to the pipe wall might be derived from power spectral densities. Also, for a constant suspension density, any variation in particle size is reflected in the power spectral density.

9.2.2.3
Characterizing Dust Cloud Structures: What Is the "Turbulence" of a Dust Cloud?

Comprehensive characterization of turbulence in homogeneous fluids is an extremely demanding task. So, comprehensive characterization of particle-laden turbulent flows may seem close to the impossible. Nevertheless, much valuable research work in this challenging and technologically important field has been conducted, and further significant work is in progress. Elghobashi (1994) reviewed the progress made and the challenges remaining in numerical modeling of particle-laden turbulent flows. Shirolkar et al. (1996) discussed some fundamental issues involved in such modeling, such as the key characteristics of turbulent flow and the nature of the interaction between turbulence and an individual particle. They also discussed some key issues involved in comprehensive numerical models of pulverized-coal combustion. Gouesbet and Berlemont (1999) reviewed the work carried out, since about 1980 by a research group in France, on Eulerian and Lagrangian approaches for predicting the behavior of discrete particles in turbulent flows.

Zhang and Reese (2001) presented a new two-fluid model for gas/solids flows, which accounts for the influence of the gas turbulence on the random motion of the particles. The model comprises a generalized kinetic theory as well as a new gas turbulence modulation model. Simulation results showed that the influence of gas turbulence on the microscopic particle motion is significant in relatively dilute flows of small particles and, therefore, should be accounted for.

A considerable amount of experimental work has also been conducted. Hauert, Vogl, and Radandt (1994) measured rms (root mean square) turbulent velocities, global velocities, and dust concentrations in experimental dust clouds in the standard 1 m^3 ISO (International Standards Organization) vessel and in a 12 m^3 silo. In the latter case, the dust was either blown into the silo via a pneumatic transport pipe or dropped into it from a screw conveyor at the silo top. This kind of work is essential, for example, for testing (validating) the performance of numerical codes for simulating dust cloud formation in real industrial situations. Such codes, in turn, constitute an essential element in future comprehensive codes for simulating dust explosion propagation in industrial situations.

Hauert et al. (1994) applied laser-doppler anemometry (LDA) for measuring the "turbulence" in their experimental clouds of maize starch. As tracer particles, they simply used the starch grains of the experimental cloud itself. It has been argued against this procedure that such comparatively large particles are unable to follow the rapid turbulent movement of the gas phase, and therefore the measurements performed do not represent the real turbulence of the cloud.

However, this argument raises a basic question: *What is the "turbulence" of a dust cloud in the context of flame propagation and dust explosion?* This question is addressed in Section 9.2.4 when discussing new basic experimental evidence related to turbulent frame propagation in dust clouds.

Hauert et al. (1996), again using LDA, measured particle velocities and turbulence intensities in clouds of maize starch in a 12 m^3 experimental silo, generated by pneumatic injection. Independent measurements of dust concentrations were also undertaken. Results from numerical modeling of the experimental system were in good agreement with the measurements. Some experiments in which the dust clouds in the silo were ignited were also conducted. Büter et al. (1996) investigated the extent to which application of LDA to the comparatively large particles in clouds of corn and wheat starch in air can provide information on the turbulence intensity of the dust clouds. It was concluded that the fluctuating movement of the comparatively large wheat starch particles did not reflect the true turbulence intensity of the air, because the particles are unable to follow the rapid turbulent fluctuations in the air.

Mercer et al. (2001) and Dahoe et al. (2001) discussed the results of a comprehensive experimental investigation of the turbulence decay in a spherical 20 liter closed vessel, following the injection of the compressed air, used to produce explosive dust clouds. LDA was used to characterize the decay of the turbulent, transient flow field. The three different nozzle systems used—the "rebound" nozzle, a perforated annular nozzle, and the circular "Dahoe" nozzle—produced different transient flow fields, in accordance with the features of the nozzles.

Schneider and Eisenreich (2001) described a new *system to generate transient, predictable dust clouds for research purposes.*

The dynamic state of a dust cloud that influences the ignition sensitivity of the cloud clearly is the state at the moment of ignition (initial state). When it comes to flame propagation, however, the picture is complicated further by the strong coupling between the flame propagation process and the instantaneous dynamic state of the unburned cloud just ahead of the flame. Therefore, the initial state of the dust cloud, at the moment of ignition, is only one of several factors deciding the course of flame propagation.

9.2.2.4
Generation of Secondary Dust Clouds by Entrainment of Dust from Layers and Deposits

As soon as a significant blast wave has been generated by the primary dust flame, this blast may generate secondary explosive clouds ahead of the flame by entraining dust deposits and layers (see Section 3.6 in Chapter 3). Lebecki et al. (1990) investigated such processes in a 100 m long gallery of cross section 3 m^2. To establish an improved understanding of these processes, further experimental and theoretical studies of the interaction of blast waves with dust clouds and dust layers and deposits need to be conducted. Work on this problem has also been performed by Ural (1992), Gelfand and Tsyganov (personal communication at the Semenov Institute of Chemical Physics, Moscow, 1992), and others. Gelfand and Tsyganov (personal communication, 1992) showed that the presence of dust layers on solid surfaces exposed to blast waves changed the blast wave characteristics as compared with the characteristics in the case of dust-free surfaces. Kauffman, Sichel, and Wolanski (1992) and Austin et al. (1993) summarized their extensive research on the entrainment of dust layers in long tubes by the blast wave heading a dust explosion propagating along the tube. Tamanini and Ural (1992) summarized their work on characterizing the dispersibility of dust layers when exposed to air blasts. Geng, Tang, and Grönig (1993) studied the influence of clouds of maize starch in oxygen on the peak pressures of incident shock waves of Mach 5.4 and 6.0.

Increased emphasis should be put on investigating the connection between the parameters of dust cloud generation processes and the structures of the resulting dust clouds. The structures of the clouds produced must be defined in terms of distribution of dust concentration, quality of dust dispersion (deagglomeration), turbulence level, and global velocities. Kosinski et al. (2001) presented a numerical simulation study of the structure of the flow of dust clouds in branched channels.

Various *test methods* have been proposed for evaluating the ease with which dust clouds can be produced from deposits and layers of powders and dusts (see Section 7.4.2 in Chapter 7). Breum (1999) investigated systematically the parameters influencing the “dustiness” results produced by a rotary drum tester. A general definition of the *dustiness* of a material is “the tendency of a sample of the material to liberate dispersed dust particles into the air.” In the rotary drum test, the material to be tested is placed inside the drum and air is passed through the drum. The mass of dispersed dust particles collected on a filter at the drum exit during the test period is taken as a measure of the dustiness of the material tested. The materials studied by Beum were bentonite, barium sulphate, talc, Aloxite, carbon black, and coal. Except for coal, dustiness was in general positively correlated to the mass of the powder sample tested. A three-parameter multiplicative model for the dustiness potential was developed for two of the materials tested.

Fundamental theoretical studies have been performed on the generation of dust clouds behind shock waves sweeping across a dust layer at 90° to the layer surface. Frolov, Mack, and Roth (1993) developed a mathematical diffusion model describing such a process. A similar model was developed by Lu et al. (1993). This kind of work is indeed relevant in the context of the propagation of secondary dust explosions. Nikolova (1993) developed a source code for numerical models for the simulation of dust cloud flow. The code can be used for cold flows as well as flows with combustion. Medvedev et al. (1993) conducted experimental studies of the entrainment of dust from dust layers by the short-duration flow generated by the rarefaction wave in a shock tube. Dushin et al. (1993) developed a mathematical model of the evolution of a cloud of entrained dust in the atmosphere, following a huge explosion on the ground. Nikitin et al. (1994) performed a theoretical numerical study of the evolution of a dust cloud in a turbulent atmosphere. The cloud could be generated instantaneously, as a result of a sudden explosion blast, or continuously, from multiple moving sources. Schumann and Rastogi (1995) presented some results from numerical modeling of dust cloud generation inside a 1 m^3 vessel, following release of dust from a pressurized bottle, using the BASSIM computer simulation code developed by the Battelle Institute in Germany.

Boiko and Papyrin (1994) studied dust dispersion behind a shock wave, using an advanced laser visualization method. In subsequent experiments, Boiko and Poplavski (1996) studied the effect of the dust concentration in a dust cloud behind a shock wave on the acceleration of the cloud. Data from this kind of work are important in the development of comprehensive dust explosion codes, in particular for modeling the influence of the blast ahead of the propagating dust cloud flame on the structure of the unburned cloud into which the flame is about to propagate.

Klemens, Wolanski, and Klammer (1998b) presented a mathematical model for simulating the process of entrainment of dust particles from a dust layer, by the gas flow behind a shock wave passing across the layer. In their later studies, Klemens et al. (2000b) presented a numerical study of flow-induced dust entrainment in a channel with obstacles, followed by a study by Klemens, Gieras, and Szatan (2002a) on numerical modeling of dust layer dispersion by a rarefaction wave. Fedorov and Gosteau (2002) presented a mathematical model describing the initial stage of the entrainment of single dust particles from a dust layer by a gas flow passing across the layer. The model was verified against experimental data. Fedorov and Fedorova (2002) performed numerical simulations of the entrainment of dust particles from a near-wall dust layer by a shock wave propagating across the layer.

To guide fundamental research in this area in the direction of maximum practical relevance, further information about dust cloud structures typical to industrial operation is required. This means not only the cloud structures in normal plant operation but, perhaps even more important, the structures existing during abnormal transient phases, including plant startup and closedown. The occurrence of dust explosions may sometimes seem more likely during such periods than under normal steady-state conditions.

9.2.3
IGNITION AND COMBUSTION OF SINGLE PARTICLES AND DUST DEPOSITS: IGNITION OF DUST CLOUDS

9.2.3.1
General

The concept of *thermal runaway*, or *thermal explosion*, is a common basis for understanding and describing ignition processes. An outline of the basics concepts is given in Section 5.1 in Chapter 5. Theories have been developed even for the complex cases with reactant consumption during the process leading to ignition. It does not seem realistic for the time being to foresee the development of a single unified theory, usable in practice, that covers all types of ignition sources. It is rather expected that separate theories, in terms of dynamic computer models, will be developed for various categories of ignition sources, such as hot surfaces and electric sparks. Work conducted on ignition of premixed gases should be studied to see whether elements of gas ignition theory can be applied to ignition of dust clouds. However, development of such theories needs to be backed by careful experimentation. The theories must consider many variables, related partly to the nature of the potential ignition source itself and partly to the combustible dust layer or cloud exposed to the source.

In their theoretical analysis of ignition, Zolotko et al. (2001) considered ignition of single particles, particle clouds, and particle deposits. The particle materials comprised a group of metals differing both with regard to phase transformation temperatures and oxide film structures. A thermal description of ignition was adopted, and it was shown that the ignition temperature of the systems studied is inversely related to their reaction activity, which is, in turn, determined by the ratio of the specific reaction surface of the particles to the specific surface of the heat exchange.

9.2.3.2

Ignition and Combustion of Single Particles

Work published up to 1990 is discussed in Section 4.1 in Chapter 4.

Backreedy et al. (1999) presented an extended model for the combustion of *coal* particles, based on detailed experimental investigation. Devolatilization and char burnout were central issues covered. Rybak et al. (1996) conducted a comprehensive experimental mathematical and numerical study of the ignition of single coal and char particles and coal particle clouds.

Rosenband and Gany (2001) investigated the influence of particle agglomeration on the behavior of *aluminum* particles under gradual heating in an inert or oxidizing gaseous flow field. Rosenband and Gany (2002) described the experimental methods used in this kind of studies. In the long term, results from such basic studies may contribute to the fundamental understanding of combustion of single particles and their agglomerates during actual dust explosions and thus contribute to the development of more refined combustion models. Dreizin (1999a, 1999b) studied the microscopic processes of combustion of single aluminum particles, under both normal and negligible gravity, and in various atmospheres, including air. During particle combustion, oxygen is dissolved in the molten particle core, which is surrounded by a solid oxide cap, and the flame develops asymmetry. Tao (2002) studied the ignition of aluminum particles behind a shock wave. Details of the microscopic mechanisms of particle ignition and combustion were resolved. This type of study, for different categories of particles, can provide valuable detailed information to be used in mathematical models of dust cloud combustion.

Dreizin, Berman, and Vicenzi (2000) conducted a similar investigation of the combustion of single *magnesium* particles and proposed a combustion model by which the oxygen that approaches the burning particle gets dissolved in the molten metal core. The heterogeneous oxidation of the Mg-O solution proceeds simultaneously with the combustion of the magnesium vapor given off from the molten metal core. However, as soon as all the metal vapor has been oxidized, the heterogeneous oxidation of the Mg-O solution becomes the essential combustion mechanism. During this process, a solid magnesium oxide cap is gradually built up around the liquid particle core. This model deviates somewhat from the classic Cassel model (see Section 4.1.2 in Chapter 4).

Fedorov and Gosteev (1996) combined the classic thermal explosion theory and the catastrophe theory in their mathematical analysis of ignition of single magnesium particles. In their basic study, Rosenband, Gany, and Timnat (1998) investigated the combustion of *magnesium and boron* particles in a hot steam flow, whereas Foelsche, Burton, and Krier (1999) and Zhou et al. (1999) studied the ignition and combustion of single *boron* particles.

Zevenbergen (2002) conducted a series of experiments in which he ignited single magnesium particles by a continuous light beam from a carbon dioxide laser. The single particle was kept suspended in air in a fixed position by means of an acoustic levitator. This made it possible to heat the particle in a controlled manner by the laser beam and monitor the particle temperature continuously during the heating process, using an optical multiwavelength thermometer, right up to the sudden very steep temperature rise at the point of ignition. For this particular setup, Zevenbergen found that the critical particle temperature for ignition was independent of the particle diameter over the diameter range 150–750 μm investigated. This means that the minimum radiated energy that had to be absorbed by a particle for the particle to ignite, assuming negligible heat loss from the particle during the heating period, was proportional to the particle volume. This, in turn, means that a constant minimum radiated energy per unit particle volume had to be absorbed by a particle for the particle to ignite, irrespective of particle size. As discussed in Section 1.3.2 of Chapter 1 and illustrated in Figure 1.30, previous experimental and theoretical work indicate that the minimum ignition energies of clouds of some dusts in air are also proportional to the particle volume. However, the absence of any observed influence of particle size on the critical particle temperature for ignition cannot be expected to hold as the particle size increases far beyond the maximum size investigated by Zevenbergen.

Panagiotou, Levendis, and Delichatsios (1996) used a three-color near-infrared optical pyrometer for monitoring the combustion of single spherical *polystyrene* particles of diameters in the range 47–355 μm, whereas Joutsenoja et al. (1999) applied a two-color optical pyrometer for nonintrusive in situ measurement of the dependence between the temperature and size of burning coal particles.

Experiments under *close-to-zero gravity conditions* have been used to study the detailed mechanisms of combustion of single particles for quite some time (see Figures 4.4 and 4.5 in Chapter 4). More recently Yang, Hamins, and Donnelly (2000) used this method to study zero-gravity combustion of supported thermoplastic particles of *PMMA, polypropylene*, and *polystyrene*. Although the particle sizes used, 2–6.5 mm, were comparatively large from the point of view of dust explosions, the basic combustion mechanisms found are probably also qualitatively valid for smaller particles.

Zhang and Bar-Ziv (1997) presented a new method for determining *thermal conductivities* of single μm-sized particles. This parameter is important when modeling the microscopic mechanisms of flame propagation in dust clouds.

9.2.3.3
Initiation and Propagation of Fires in Dust Layers and Deposits

Work on this problem up to 1990 is discussed in Section 5.2 in Chapter 5 and Section 7.7 in Chapter 7. An overview of research on self-heating and self-ignition in dust deposits was given by Crowhurst (1993a). Hensel and John (1992, 1993) provided further insight into the important relationship between the conditions required for initiating smoldering combustion in a *dust layer on a hot plate* and the layer thickness. Hensel et al. (1994) presented a mathematical model for numerical simulation of temperature development in powder deposits enclosing a heat source of constant power. The model was tested against experiments in which a metal sphere, heated by a constant power source, was embedded in the powder sample. Further promising work along this line, focusing on the critical heat flux for ignition rather than on the critical surface temperature, was reported by Krause and Hensel (1994). It was pointed out that *critical heat flux* relates more to situations encountered in practice than critical constant surface temperature. Krause and Hensel (1996) presented a numerical method by which nonsteady temperature fields in dust deposits can be computed. This enables numerical analysis of a number of practical cases that cannot be treated using the classic thermal explosion theory of Frank-Kamenetzki, including nonsteady thermal processes and heat transfer under any physically feasible boundary conditions. Krause and Schmidt (1997, 1998a, 1998b, 2000, 2001) investigated experimentally critical thermal conditions that may lead to initiation of smoldering processes or further development of such processes, once initiated. A typical critical condition can be either the critical minimum temperature of an embedded hot body or the critical minimum size of an initial glowing nest. Krause and Schmidt also studied the dependence of the propagation velocity of a smoldering front inside a bulk powder on the size of the powder sample investigated, the calorific properties of the powder, and the rate of supply of oxygen to the reaction zone, for different organic powders, including cork dust, wood dust, and cocoa powder. Schmidt, Lohrer, and Krause (2003) investigated self-ignition processes in dust deposits when surrounded by heated oxygen/nitrogen mixtures of oxygen contents down to 1.3 vol.%

Zhang and Deng (1993) studied the *combustion rate* of coal dust layers on constant-temperature hot surfaces. Influences on the oxidation rate of hot surface temperature, oxygen content in the atmosphere, and flow rate of air across the layer were investigated. Vance, Chen, and Scott (1996) investigated the effect of moisture content and drying procedure on the rate of temperature rise in a sample of subbituminous coal during self-heating and ignition in oxygen under adiabatic conditions. Coal that originally had 20 wt% moisture showed the highest self-heating rate when partially dried to a moisture content of 7 wt%.

Kauffman et al. (1992) summarized their quite extensive research on smoldering combustion of dust heaps and dust layers. Chernenko, Alfanasyeva, and Lebedeva (1993) investigated flame propagation along the surface of layers of metal powders and mixtures of metal powders and metal oxides. The influence of the chemical composition of the powder layer, and to some extent also of the particle size, on the burning velocity along the surface of the layer was determined experimentally. Matyukhina and Babushok (1993) developed a mathematical model for self-heating in coal deposits, taking into account the effect of diffusion of air into the deposit. Sobolev (1993) developed a discrete, two-temperature mathematical model for heat conduction in a dust deposit. Itagaki and Matsuda (1994) used both differential scanning calorimetry and accelerating rate calorimetry to measure the exothermic reactivity of activated carbon dusts. Adsorbed nitrogen oxides or fluorine on the coal surface increased the exothermic reactivity markedly, the onset temperature of exothermic reactions being as low as 30–40°C.

Schecker (1996) investigated *theoretically* the critical conditions and induction times for initiation of smoldering combustion in large deposits of combustible bulk material, with particular reference to coal. Nakajima and Tanaka (1996) performed *model calculations* of spontaneous ignition in an *auto-oxidative powder bed* and found that the critical state for ignition could be classified into two categories: the Frank-Kamenetskii and the oxygen-deficient types. The first implies an irreversible transient process at the critical point, leading to ignition. Its thermal stability is rather frail against the changes in ambient conditions. In the second type, oxygen diffusion controls the rate of heat generation in the bed, and the thermal stability is comparatively robust. The two types can be largely discriminated by considering the nature of the combustible material and the porosity of the bed.

Scheidemann and Adomeit (1996) presented a mathematical analysis of the *transformation of a slow smoldering fire inside a heap of carbon dust into an open fire*, by the impact of an airflow on the side of the heap. The model does not consider the transformation of the fire into a dust explosion should a sufficiently strong airflow disperse the dust in the heap into an explosive dust cloud. In their studies of the *effect of admixed inert material* on the minimum hot-plate ignition temperature of coal dust, Reddy, Amyotte, and Pegg (1998) successfully applied the classic ignition model developed by Thomas and Bowes.

Li and Xiao (1999) developed a mathematical and numerical simulation model to predict the self-heating behavior of *milk powder* deposits of low moisture contents. The numerical scheme solves the mass and energy balances simultaneously. Model predictions agreed well with experimental data, and it was foreseen that the model could also be applied to other exothermally reactive solids. In a subsequent investigation Li, Xiao, and Mackereth (1999) studied the effect of aging of milk powders and their fat content on the self-heating and smoldering properties. It was found that the kinetic parameters changed with the aging temperature and the tendency to self-heat or smolder increased with the fat content.

Arisoy and Akgün (2000) developed a non-steady-state mathematical model for predicting the *safe storage height of coal stockpiles*, below which significant self-heating is not initiated during the finite storage time of the stockpile. The numerical solution provided by the model is in terms of the maximum temperature within the stockpile as a function of time.

Anderson, Sleight, and Torero (2000), in their experimental investigation, identified specific "ignition signatures" that indicate the *onset of a self-sustained downward smoldering* process in a porous material. Polyurethane foam was used as the porous material, but the findings are probably valid also for powder and dust deposits prone to smoldering. The test samples were exposed to a constant heat flux imposed by a cone heater for different periods of time. Three stages were observed during the ignition process: (1) warming up and (2) unsteady smoldering, both controlled by the heat flux supplied from the outside, and (3) self-sustained smoldering, supported by the heat generated by the smoldering process itself. Each stage was characterized by specific changes in temperature and mass loss rates (ignition signatures).

Glinka, Klemens, and Wolanski (1993) conducted an experimental, theoretical study of *ignition of dust layers by thermal radiation*. Important features of the ignition process were resolved in detail by means of high-speed Mach-Zehnder interferometry.

In a series of unique experiments carried out in a space shuttle, Walther et al. (1999) studied smoldering combustion processes under *microgravity conditions*. The objective of the study was to achieve a better understanding of the various mechanisms that control smoldering processes, to provide improved means to prevent and control such processes. The data from the microgravity experiments were compared with corresponding experiments under normal gravity to resolve the specific influence of gravity, and a significant effect of gravity was indicated by some results.

Tse et al. (1999) developed and used an *ultrasonic tomographic* imaging technique to examine smoldering combustion processes in a permeable medium. The method provides information about the local permeability variations within a smoldering sample, which can, in turn, be converted to information on the propagation of the smoldering reaction. Results from studies of two-dimensional smoldering processes were reported.

Peters (1999) studied the combustion of *coal* particles in a packed bed and identified four distinct combustion regimes, characterized by certain values of the dimensionless Damköhler number and Thiele modus. Two of the regimes resembled a well-stirred reactor, and the two others were characterized by a conversion front propagating with a characteristic velocity through the packed bed.

A question asked by many is whether combustion in dust layers and deposits can be *initiated by metal particle sparks*. Hesby (2000) conducted a series of experiments in which layers of a wide range of dusts were exposed to showers of burning steel particles generated by forcing rods of various steel types against a grinding wheel. The experimental parameters included rod/wheel contact pressure and contact time and distance between the rod/wheel contact point and the dust surface. The minimum numbers of particles required for ignition were estimated for various experimental conditions. A main conclusion was that the number of steel sparks from single accidental impacts would be all too low to cause ignition of the dust layers studied.

9.2.3.4
Ignition of Dust Clouds

A brief introduction to this topic is given Section 1.1.4 in Chapter 1. In dust explosion statistics, the frequency data for the occurrence of various ignition sources sometimes contain categories that are not entirely unambiguous. The categories "friction sparks," "friction heating," or just "friction," constitute one example. Sometimes hot surfaces, generated either by repeated impacts on the same spot or by sliding friction, are included in the "friction spark" or "mechanical spark" category. The perception of the basic mechanisms causing ignition in these cases is not always clear. Ignition may have been caused by either the burning metal particles or the hot surface produced at the object being ground, cut, or hit by repeated impacts. Furthermore, one does not always distinguish between the comparatively scattered transient showers of burning metal particles from single accidental impacts and the dense semi-stationary spark showers of such particles produced by grinding and cutting equipment. A central objective of research in the area of dust cloud ignition is to identify the details of the various ignition mechanisms.

Wel (1993) conducted a series of experiments in which laminar dust clouds were ignited by a short *focused laser light pulse* (100 μs or 10 ns) from a Nd-YAG laser (1064 nm wavelength). This kind of experiment can provide basic information about dust cloud ignition processes and flame propagation processes in dust clouds. Wel et al. (1994) used a simple, modified Semenov theory for autoignition (no temperature gradients inside the initially heated volume) to transform the experimental laser-light-pulse ignition data to predicted minimum ignition temperatures and energies. The predicted values were in approximate agreement with minimum temperatures and energies for the ignition actually measured. Proust (2002), also using a Nd-YAG CW laser, determined experimentally the minimum laser beam power required for igniting dust clouds by the heat absorbed by a solid target heated by the laser beam. The variable parameters included the laser beam diameter, the duration of the irradiation, the target material (combustible or noncombustible), and the type of dust (starch, lycopodium, lignite, sulphur, ABS, and aluminum).

Gieras and Klemens (1994) studied the critical conditions for ignition of single coal particles in air and in air-containing methane. They also investigated the critical conditions for ignition of clouds of coal dust in air and methane/air.

In the past, the *minimum hot-surface temperature for ignition of a dust cloud* has often been regarded as if it were a universal constant for a given cloud. Consequently, results from small-scale laboratory tests were often applied directly to industrial plant design. However, it has been known for some time (see Section 5.5 in Chapter 5) that minimum ignition temperatures of dust clouds vary significantly with scale. This was confirmed by Wolanski (1992).

Ignition of dust clouds by *small burning metal particles* (impact sparks, metal sparks) generated by mechanical impact has been discussed in Section 5.4 in Chapter 5. This is a complex process, and comprehensive, practically useful theories do not seem to be within sight. Such theories must comprise several complex subprocesses. The first is the generation and initial heating of the metal particle by the impact. The second is the ignition of the flying hot particle and the subsequent burning process. The third is the heat transfer to the dust cloud, which ultimately determines whether ignition occurs or not.

Ignition of dust clouds by *electric and electrostatic spark discharges* between two metal electrodes is another complex topic. Such sparks can be generated in a number of ways, such as in switches, by various failures in electric circuits, and by discharge of static electricity. Some approximate theories for ignition of dust clouds by electric sparks are reviewed in Section 5.3 in Chapter 5. The variables of the electric spark ignition problem include voltage and current characteristics across the spark gap, spark gap geometry, and electrode material, as well as dust cloud variables. The variables include particle material and particle size and shape distributions, dust moisture content, dust concentration, and the dynamic state of the dust cloud with respect to the spark gap.

Xu and Lin (1993) performed a semi-quantitative theoretical analysis of electric spark ignition of dust clouds. They proposed a strategy for calculating minimum ignition energies, in terms of the lowest energy capable of establishing self-sustained laminar flame propagation in the dust cloud. This strategy is the same as the one proposed previously by Klemens and Wojcicki (see Chapter 5). Bobkov et al. (1996) analyzed electrostatic discharge processes and ignition of dust clouds by electrostatic discharges theoretically, by means of mathematical catastrophe theory. Although the analysis confirmed measured trends qualitatively, it also confirmed the substantial complexity of these kinds of processes and that one most probably has to rely on experimental investigation in the foreseeable future. Dahn, Reyes, and Kashani (1993) reviewed some published work on electric spark ignition of dust clouds and confirmed the dramatic influence of the combination of capacitance and resistance of the experimental discharge circuit on the minimum capacitor energy required for ignition. Wieczorek and Zalosh (1998) confirmed the earlier important findings (see Chapter 5 and Figure 1.40 in Chapter 1) that the minimum ignition energy (MIE) of dust clouds depends strongly on the discharge time of the electric sparks used and the movement or turbulence of the dust cloud in the spark region.

Lorenz and Schiebler (2001a) presented the results from a comprehensive, detailed experimental and theoretical investigation of the energy transfer processes taking place during an electrostatic spark discharge. The temperature and pressure development in the spark channel during its formation and subsequent expansion were investigated. This also included cooling the channel by thermal radiation. Lorenz and Schiebler emphasized the dependence of the ability of a given discharged electrical energy to ignite a dust cloud on these basic physical spark characteristics. Some aspects of this problem are discussed in Section 5.3 of Chapter 5. Further experimental evidence was provided by Nifuku and Katoh (2001).

Seplyarskii (2001a, 2001b) performed a mathematical analysis of the critical conditions for ignition of a cloud of combustible dust by either a small heated solid body (2001a) or an electric spark (2001b). In the analysis, it was assumed that the role of the ignition source was to heat the gas phase, which then, heated the dust particles.

As discussed in Section 1.3.7 in Chapter 1 and illustrated in Figure 1.49, it is generally found that the minimum ignition energy of clouds of a given dust in air decreases systematically with increasing temperature of the dust cloud prior to ignition. However, Pellmont (1997) reported a singular, distinct exception from this rule with a specific nicotinic acid product having a melting point of about 235°C and subliming at higher temperatures. In this case, the MIE increased markedly with the dust cloud temperature, from less than 10 mJ at 20°C via 125 mJ at 80°C to more than 10 kJ at 140°C. In general terms, the probable reason for this is that the physical and chemical properties of this particular dust changes with increasing initial cloud temperature, in the direction of lower ignitability. Pellomont suggested that the complex molecular structure of the material tested changed with increasing cloud temperature.

With respect to the ever more-complex *one-electrode discharge types* (corona, brush, propagating brush, etc.), valuable experimental insight has been gained during the past years, but so far no attempt at developing dust cloud ignition theories seems to have been made. Glor (1993) gave an informative overview of the status on both theoretical and experimental work. Research on possible incendiary discharges from powders poured into a heap was discussed by Glor and Maurer (1992), whereas Glor (personal communication with G. Glor, Ciba-Geigy AG, Basle, Switzerland, 1993) presented results from continued work on whether incendiary brush discharges can occur in dust clouds in air. No conclusive answer was obtained. The same question was addressed later in the experimental investigation by Larsen, Hagen, and Wingerden (2001a) and Larsen et al. (2002b), who were in fact able to ignite clouds of sulfur dust in oxygen-enriched air by true brush discharges. However, ignition in air alone was never observed. Because of the very low minimum ignition energy of clouds of sulfur dust in air, this indicates that ignition of even the most sensitive dust clouds by brush discharges in air is unlikely.

Armour-Celu et al. (1998) developed a measurement technique by which the *electrostatic charging trends during pneumatic transport* of powders in pipes can be inferred.

In the context of gas explosion-proof electrical equipment enclosures, where the maximum experimental safe gap (MESG) is a central concept, the basic problem is ignition of an explosible gas cloud by a *jet of hot combustion products*. In dust clouds, this may not be as obvious a problem as for gases, but the concept of MESG has some relevance in relation to explosion isolation (see Section 9.3.5). Pioneering performed in this area work was by Schuber (see Section 4.4.6).

Schumann and Rastogi (1995) studied the secondary explosion in a free dust cloud ejected from a pressurized vented vessel without internal combustion, when the free cloud was ignited by a 10 kJ chemical ignitor. Only quite low overpressures, not exceeding

50 mbar, were found. From this they concluded that the significant secondary explosion pressures that can occur in the external cloud outside a vented enclosure, as a result of primary explosions inside the enclosure, is due to very powerful *flame jet ignition* of the external cloud.

Initiation of dust explosions by *shock waves* has been studied by several workers, and valuable insight has been gained. One practical future application of this knowledge could be to use induction times for shock wave ignition in models of flame propagation in turbulent dust clouds (see Section 9.2.4). An informative analysis of shock wave ignition of dust clouds was given by Wolanski (1990) and research at University of Michigan, United States, was reported by Kauffman et al. (1992). Geng, Tang, and Grönig (1993b) measured the ignition delay behind an incident shock wave of Mach 4–6 passing through a cloud of maize starch in oxygen. Ural (personal communication from E. A. Ural, Factory Mutual Research, Norwood, MA, 1992) emphasized that different induction times are observed with incident and reflected shock waves, due to different ignition mechanisms. Boiko, Papyrin, and Poplavski (1993) measured ignition delays for coal dust clouds exposed to reflected and incident shock waves. Boiko and Papyrin (1994) estimated ignition delays of various dusts in incident and reflected shock waves. Geng, Lao, and Tang (1994a) performed a numerical study of the fluid-dynamic effects of an incident shock wave passing through a dust cloud on the delay for igniting the dust behind the shock. Geng et al. (1994b) used a vertical shock tube to measure ignition delays of dust clouds behind an incident shock.

Lu and Fan (1994) developed a comprehensive analytical model allowing prediction of ignition delay times of dust clouds exposed to shock waves. Good agreement between predictions and experimental data was obtained. Hu and Sun (1994) studied the development of aluminum dust explosions initiated by shock waves from gas explosions, whereas Hu et al. (1994) investigated the fast ignition and combustion of wheat flour behind a shock wave in a shock tube. Similar experiments were conducted by Elkotb et al. (1996) with wheat flour and provender dust. Klemens et al. (1998b) presented a mathematical model for simulating the ignition and burning of a cloud of coal particles in air behind a shock wave passing through the cloud. The moving cloud was treated as a two-phase, two-velocity, and two-temperature continuum, with both mechanical and thermal interaction between the phases.

9.2.4
FLAME PROPAGATION PROCESSES IN DUST CLOUDS

9.2.4.1
General

Work up to 1990 is discussed in Chapter 4. Some central topics are the same as for flame propagation in premixed gases:

- Laminar flames.
- Flame acceleration mechanisms.
- Turbulent flames.
- Detonation.

In the case of dust clouds, ignition and combustion of single dust particles is an additional fundamental research area, which has already been reviewed in Section 9.2.3.

An important difference between dust clouds and premixed gases is that, in dust clouds, inertial forces can produce fuel concentration gradients (displacement of particles in relation to gas phase). Furthermore, thermal radiation may contribute significantly to the heat transfer from the flame to the unburned cloud, depending on the type of particles (e.g., light metals). Shevchuk, Zolotko, and Eckhoff (2001) investigated theoretically various possible flame propagation regimes in clouds of dusts of five different metals. They concluded that the mechanism of heat transfer from the flame front to the unburned cloud is essentially conductive, the radiative contribution amounting to only about 5%. However, in some cases, an appreciable fraction of the power generated in the flame front is radiated backward into the reaction products. Whereas this power fraction is regarded as lost when focusing just on forward isobaric flame propagation, it indeed contributes to the temperature and pressure increase in the reaction products and, hence, is of prime importance when focusing on the potential violence and destructive effect of a dust explosion. More work is needed to explore the role of thermal radiation in the propagation of dust explosions.

Lee, Zhang, and Knystrautas (1992) showed that theoretical equilibrium properties of dust cloud combustion (constant-pressure adiabatic flame temperatures and maximum constant-volume explosion pressures) calculated by standard computer codes are in good agreement with experimental data obtained by various workers. Wolanski (1990) reviewed the problems involved in determining flame structures, laminar or quasi-laminar burning velocities, lower flammability limits, and conditions required for flame acceleration and transition to detonation in dust clouds. The influences of added inert particles were also considered. Deng et al. (1993a) proposed that the *burning velocity of a dust layer* under "specific laminar conditions" be regarded as the fundamental combustion property of a dust. They did not, however, elaborate the idea to the extent needed to resolve the implications of the proposal with respect to dust cloud combustion.

It should be mentioned very briefly that much research work has been done on various aspects of combustion of liquid sprays and mists (Eckhoff, 1991), which is in part also relevant in the context of dust explosions. A more recent example is the detailed investigation by Karpetis and Gomez (2000) of well-defined, nonpremixed turbulent methanol spray flames. A comprehensive description of the structure of such flames was obtained by applying a variety of advanced complementary diagnostic techniques, including broadband chemiluminescence imaging, CH radical emission imaging, doppler interferometric techniques, and spontaneous Raman spectroscopy.

The experimental investigations of flame propagation processes in dust clouds are reviewed next, followed by works to develop mathematical models and numerical codes of such processes. Experimental as well as theoretical studies of dust cloud detonation are covered in a separate section.

9.2.4.2
Laminar Flames in Dust Clouds

Experimental and theoretical work on this topic up to 1990 is discussed in Sections 4.2.3–4.2.5 in Chapter 4. Knowledge about laminar flame propagation processes in dust clouds is essential for understanding dust explosion propagation in general. Research in this area comprises both experimental work and mathematical modeling.

On the modeling side, Krainov (1996) analyzed plane laminar flame propagation in dust clouds mathematically, whereas Krishenik and Shkadinskii (1993) developed a *mathematical model* for laminar flame propagation in dust clouds of mixtures of two monosized particle fractions. Both conductive and radiative heat transfer were incorporated in the model. Krishenik and Shkadinski (1996) performed a mathematical analysis of the effect of gravity on flame propagation in dust clouds, accounting for radiative, conductive, and convective heat transfer. Tunik (1996) presented a mathematical model for low-speed combustion of hybrid clouds of coal dust in methane/air mixtures.

When it comes to *experimental work*, Mazurkiewicz and Jarosinski (1993) analyzed the gas composition just upstream of a stationary, stabilized maize starch/air flame front in a burner. It was found that CO, CO_2, H_2, and CH_4 were the main components produced during the initial pyrolysis stage. The CO_2 content increased with decreasing temperature. In the gas phase oxidation reaction, burning of CO was most important. Mazurkiewicz and Jarosinski (1994) described an experimental burner for conical dust flames in air and measured *laminar burning velocities* and flame temperatures for maize starch/air as a function of dust concentration. The average flow velocities of unburned dust cloud through the burner were in the range 0.61–0.65 m/s, but these values were reduced by the ratio of the burner cross-section area and flame surface area to comparatively low estimates of laminar burning velocity, in the range 0.15–0.05 m/s. Proust (1993) described other experimental studies of laminar burning velocities and maximum flame temperatures in clouds of starch, lycopodium, and sulfur in air, whereas Seshadri, Berlad, and Tangirala (1992) studied the inherent structure of laminar dust flames. Bradley et al. (1994) investigated the burning of clouds of fine graphite dust (4 μm) in premixed methane/air in a flat laminar flame. The experiments gave further support to the hypothesis that active radicals in the gas phase catalyze the char oxidation. This work provides a basis for developing a mathematical model for laminar combustion of clouds of ultrafine coal dust. Gieras and Klemens (1994) compared flame propagation in clouds of coal dust in air and in methane/air at normal and microgravity conditions. This made it possible to isolate the influence of buoyancy. In the absence of gravity, flame propagation occurred at velocities very close to the corresponding fundamental laminar burning velocities.

Wingerden (personal communication with K. van Wingerden, Chr. Michelsen Institute, Bergen, Norway, 1993), based on his own experiments, discussed the need for reconsidering the phenomena involved in steady-state upward laminar flame propagation in vertical tubes. Wingerden and Stavseng (1996) investigated experimentally upward quasi-laminar flame propagation in dust clouds in a vertical tube with a closed top and open bottom. The dusts used were lycopodium, maize starch, lignite dust, and dust of hard coal. Their reported values of laminar burning velocities were obtained by multiplying the measured upward flame speed of the parabolic flame front by the ratio of the area of the tube cross section and the surface area of the parabolic flame front. (See the discussion of the work of Proust and Veyssiere in Section 4.2.3.3 in Chapter 4.) However, this method of calculation may seem to contain an inherent paradox, because the observed constant parabolic flame shape of the upward propagating flame is not consistent with the assumption of a uniform laminar burning velocity perpendicular to any point on this flame surface. The flame propagation process, Han et al. (2000, 2001) presented a more-detailed analysis of upward propagation laminar lycopodium/air flames in a vertical duct. At 170 g/m^3 a global approximately steady upward flame speed of about 0.50 m/s was observed, and global flame thickness of about 20 mm could be estimated. However, the global faint parabolic flame front contained a complex microstructure of small, more luminous flamelets, and a complex flow pattern in the unburned dust cloud ahead of the flame was resolved. This suggests that the determination of fundamental burning velocities of dust clouds in vertical tube experiments is far from straightforward. In addition to flow ahead of the flame, it is also likely that the parabolic flame front is subjected to the flame stretch phenomena.

In their experimental investigation, Krause, Kasch, and Gebauer (1996) studied the effects of flow velocity and dust concentration on the apparent measured laminar dust cloud burning velocity in vertical tubes. Similar experimental studies were conducted by Glinka et al. (1996). Ju, Dobashi, and Hirano (1998a) studied the *detailed structure of flames* propagating through clouds of stearic acid particles. The reaction zone was explored by means of an electrostatic microprobe and Schlieren photography. Klemens, Szatan, and Wolanski (1998a) studied flames in clouds of stearic acid particles in air in a vertical duct of square cross section. Schlieren photography was used to record flame structure and flame development.

Extensive experimental research in Japan on the detailed structure of flames propagating through clouds of 1-octadecanol, stearic acid, and iron particles in air is described in a series of papers by Chen, Dobashi, and Hirano (1996); Ju, Dobashi, and Hirano (1998a, 1998b, 1998c); J.-H. Sun, Dobashi, and Hirano (1998, 2000, 2001); Dobashi, Sun, and Hirano (2000); and Dobashi (2001). Global flame propagation velocities were measured by direct and Schlieren high-speed photomicrography, whereas laser MIE-scattering techniques were used to study the behavior of individual particles. The structure of the ionized reaction zone was studied using a micro-scale electrostatic probe, whereas *temperature profiles across the flame fronts* were measured by means of thermocouples. Similar detailed experimental studies of pulverized coal flames, comprising chemical species concentrations (CO, CO_2, NO, and O_2), flame velocities, and flame temperatures were performed by Nazeer, Pickett, and Tree (1999) and Pickett, Jackson, and Tree (1999). Special attention was paid to the effect of swirl on the flame structure. Klemens et al. (2000a) studied details of the structures of flames in quasi-laminar clouds of coal, lignite, and stearic acid in air in various apparatus. The diagnostics included Mach-Zehnder interferometry and Schlieren and other photographic techniques. (Similar earlier work by Klemens and coworkers is described in Section 4.3 in Chapter 4.)

In their experimental and theoretical investigation Goroshin, Bidabadi, and Lee (1996) studied the combustion of well-dispersed, laminar clouds of fine atomized aluminum particles of Sauter mean diameter about 5 μm. The *quenching distance* in air was measured to be about 5 mm, which yielded an estimated *flame thickness* of about 2.8 mm. The downward laminar flame front velocity in air was on the order of 80 cm/s. The experimental data did not permit estimation of the corresponding fundamental laminar burning velocity. The mathematical analysis of the problem at hand yielded calculated quenching distances in good agreement with those determined experimentally. Colver, Kim, and Yu (1995), using an *electrostatic method for generating homogeneous experimental dust clouds*, found that the minimum quenching distances for laminar dust clouds in air was in excess of 5 mm for 17.5 μm diameter aluminum particles and about 14 mm for an American coal.

An excellent contribution to improved understanding of the *nature of laminar dust flames* was given by Dahoe, Hanjalic, and Scarlett (2002). They used a burner apparatus to produce stable cornstarch flames in air, and the laminar burning velocity was measured by laser-doppler anemometry. It was found that the laminar burning velocity varied with flame shape, and this was accounted for by introducing the "Markstein length" of a dust/air flame. This parameter is specific for any given dust cloud. It has a magnitude on the order of the laminar flame thickness of that specific dust cloud and serves as a measure of the sensitivity of the laminar burning velocity to changes in the flame shape. Dahoe et al. emphasized that neither the theoretical derivation nor the experimental determination of the *Markstein length* is trivial and much remains to be learned about its precise dependence on the chemical and physical properties of the specific combustible mixture being investigated. In the light of this work, time seems ripe for reconsidering some conclusions drawn from earlier work to determine laminar burning velocities of dust clouds in vertical tube experiments (see Section 4.2.3 in Chapter 4). As pointed out by Dahoe et al., buoyancy may have contributed significantly to the upward movement of the flame front in these tubes. Also, the observation of a constant shape (often about hemispherical) of the upward propagating flame seems to contradict the assumption of a constant burning velocity perpendicular to the flame surface implied in the mathematical correction formula frequently used to transform the observed flame velocity into the corresponding velocity of a plane laminar flame.

9.2.4.3
Limiting Dust Cloud Compositions for Flame Propagation

This is an important fundamental research topic for at least three different practical applications. The first is assessment of *explosive or nonexplosive*; the second, assessment of *minimum explosive dust concentration*; and the third, assessment of *maximum permissible oxygen concentration for inerting*. Work up to 1990 is discussed in Section 4.2.6 in Chapter 4 and Section 7.13 in Chapter 7. Recent work on some aspects of experimental determination of limiting cloud compositions for flame propagation is reviewed in Section 9.4.4.

Mintz (1993) found evidence for the existence of a *maximum explosive dust concentration* for dust clouds under certain circumstances. For a narrow size fraction (106–125 μm) of maize starch, a reasonably well-defined limit of 800–1000 g/m^3 was found. The results were interpreted in terms of a simple "oxygen depletion" model.

The influence of particle size distribution on the *minimum explosive dust concentration* was investigated by Poletaev and Korolchenko (1993), using data from experiments with polysized polyethylene dusts. Promising agreement between theory and experiments was obtained. Hanai et al. (1996) measured the minimum explosive dust concentration for PMMA particles in air under microgravity conditions. In the absence of buoyancy, using a point ignition source, spherical flame ball development was obtained. In the range of particle diameters studied, the minimum explosive dust concentration increased systematically with the particle diameter. Results from comparative experiments at normal gravity differed only modestly from the corresponding microgravity results.

Hertzberg, Zlochower, and Cashdollar (1992a) measured minimum explosive concentrations, maximum explosion pressures and maximum rates of pressure rise at constant volume, and maximum flame temperatures for clouds in air of dusts of 14 metals.

They found that, for some metals, flame propagation appears to occur in a mixture of metal vapor and air, similar to the gas phase flame propagation mechanism in clouds of organic dusts.

It is well known that pulverized coal and coal dust in mines do not represent a dust explosion hazard unless the *content of volatiles* exceeds 7–8%. However, this does not apply to carbon dusts of specific surface areas exceeding the order of 100 m^2/g (N_2 adsorption). Wiemann (1992) showed that dusts of such materials (active carbon/active coke) of considerably lower volatile content than 7–8% could produce fully developed dust explosions in the standard 1 m^3 ISO vessel.

The influence of particle size on the flammability limits of clouds of stearic acid in air was investigated by Ju et al. (1998b). They found that the lower flammability limit was defined mainly by the mass concentration of particles of diameters smaller than 60 μm.

Horstmann et al. (1996) found that the minimum air pressure, below which clouds of a given dust can no longer propagate a flame, decreases with increasing volume of the test apparatus. The underlying reason for this is that the quenching distance of clouds of a given dust increases with decreasing air pressure.

9.2.4.4
Turbulent Flame Propagation in Dust Clouds

This important topic has been studied *experimentally* and *theoretically* by a number of investigators. Work up to 1990 is discussed in Section 4.4 in Chapter 4. Eckhoff (1992) summarized some work on the influence of initial and explosion-induced turbulence, on dust explosions in closed and vented vessels. Wel et al. (1992, 1993) reemphasized the important role played by turbulence in dust explosion propagation in closed vessels. Kauffman et al. (1992) and Austin et al. (1993) summarized their quite extensive research on turbulent combustion of dust clouds, whereas Tamanini and Ural (1992) outlined their work on the effect of the initial turbulence of the dust cloud on the flame propagation in closed and vented systems.

Scheuermann (1994) also investigated the influence of the initial dust cloud turbulence on the development of dust explosions in vented enclosures. Rzal-Rebière and Veyssière (1992) addressed some central basic aspects of turbulent dust flames. Veyssière (1992) summarized all the fundamental studies on flame propagation in dust clouds conducted at LED in Poitiers, comprising laminar flame propagation in dust clouds, the role of turbulence in flame acceleration, and the conditions for propagation of detonationlike, but nonideal, combustion waves. Rzal-Rebière and Veyssière (1994) in their basic studies investigated the interaction of a laminar maize starch/air flame with an obstacle: a sphere, a disk, or a vortex ring. With the ring, flame quenching phenomena were observed, which were attributed to centrifugal separation of dust particles and air in the turbulent eddies. This is a very important observation, indicating that the burning rate of a dust cloud may not respond to turbulence in the same way as the burning rate of a premixed gas.

Further work toward improved understanding of the relation between the dynamic state of a dust cloud and its combustion rate is needed. The basic microscopic turbulence mechanisms that promote the combustion process must be identified. The investigation by Mitgau (1996) and Mitgau, Wagner, and Klemens (1997) seem to be highly significant in this respect. These workers determined correlations between *normalized turbulence intensities* of dust clouds and their normalized burning velocities for four combustible dusts. For the three of these requiring oxygen from the air for their combustion—lycopodium, maize starch, and PMMA—positive correlations were found, as would be expected from experience (see Figure 4.47 in Chapter 4). However, Mitgau and Mitgau et al. also tested a *dust* of a special chemical compound *having the required oxygen for its combustion within itself.* In this case, when the supply of oxygen from the atmosphere was not required for combustion of the particles, the effect of increased turbulence was in fact to decrease the burning velocity. One mechanism that could cause such a decrease is increased cooling of the burning particles due to increased relative velocity between each particle and the air surrounding it with increasing turbulence of the dust cloud. Apparently, the mechanism of increased turbulent mixing of combustion products and burning particles with unburned particles, which would be expected to enhance combustion, was not sufficiently strong to counteract the combustion-retarding mechanism by increased cooling of the preheated and burning particles due to increased turbulence.

Therefore, enhanced turbulent replacement of gaseous reaction products by fresh air around each particle is perhaps a more important basic combustion enhancement mechanism in clouds of particles requiring oxygen from the air for their combustion than turbulent mixing of combustion products and burning particles with unburned particles. In other words, for these types of particles, which are normally encountered in dust explosions, it seems as if the velocity difference between an individual particle and the air surrounding it on a microscopic scale is a basic key factor causing the burning velocity to increase with increasing "turbulence."

In the development of *comprehensive models* to be used in practice, some pragmatism is still required. For example, an induction time for ignition may be taken as a global characteristic of the combustion chemistry (shock tube or stirred reactor; see the review of shock wave ignition in Section 9.2.3). An alternative approach is to consider the laminar burning velocity as the fundamental parameter, as suggested by Bradley, Chen, and Swithenbank (1988). Empirical relationships between *turbulent burning velocity* and *turbulence intensity* are then established, using the laminar burning velocity as a normalizing parameter. Numerical "*flame libraries*" can then be established and used for closing the positive-feedback loop of *combustion-expansion-flow-turbulence-combustion* in numerical dust explosion simulation codes. The ongoing research and debate on numerical modeling of premixed gas combustion should be watched carefully to ensure that any elements that may contribute to solving the dust explosion modeling problem be explored. Korobeinikov and Vorobiev (1996) showed how *catastrophe theory* may be applied in the mathematical analysis of the complex ignition and extinction processes involved, for example, in the propagation of flames in dust clouds and premixed gases.

Understanding *flame acceleration* due to flame distortion and turbulence produced by the propagating explosion itself is central for understanding both dust and gas explosions in practice. Extensive experimental research programs have been conducted to study these phenomena for gas explosions in obstructed geometries, as discussed, for example, by Moen et al. (1982); Hjertager, Fuhre, and Bjoerkhaug (1988); and Bakke and Wingerden (1992). By employing the experimental facilities used in these experiments and repeating the experiments in the various vessels, using dust clouds instead of premixed gas, valuable insight could be gained. Systematic comparison of results with previous data from gas explosions would yield an overview of similarities and discrepancies, which would help focus basic research efforts on important areas where dust cloud combustion may differ significantly from combustion of premixed gases. Chen, Fan et al. (1996) conducted turbulent dust and gas explosions in a 12 m long horizontal, one end open tube of internal diameter 0.14 m. The gases used were pentane and epoxy propane, and the dust was aluminum. Ignition was performed at the closed tube end. Both with the gases and the dust, a continuously accelerating flame, headed by a shock wave, was observed in the tube. Numerical analysis confirmed that the shock wave was a result of the flame acceleration in the tube, caused by the friction between the flowing unburned cloud and the tube wall.

Shi, Zhu, and Radandt (2001) investigated the relationship between chaos theory and *dust-dispersion-induced turbulence* in different test vessels. They found that dust-dispersion-induced turbulence exhibits chaotic features, and they suggested that the use of chaos theory in mathematical models of turbulent dust cloud combustion processes will contribute significantly to improved description and understanding of these processes.

The role of thermal radiation in the propagation of turbulent dust flames remains partly unresolved. The dust type and particle size are probably important parameters. Gui and Cho (1999) investigated the radiant heat transfer in a circulating fluidized bed coal combustor and found that the contribution of thermal radiation to the total heat flux was in the range 15–36%.

9.2.4.5
Dust Flames in Closed Vessels

Constant-volume dust explosions in closed bombs is another important field of research on dust flame propagation. Some work up to 1990 is discussed in Section 4.4.3 in Chapter 4 and Sections 7.14 and 7.15 in Chapter 7. Pu et al. (1991) concluded that the turbulence structure of experimental dust clouds in the commonly used 20 liter spherical dust explosion test bomb had little resemblance to *turbulence structures* in dust clouds in accidental dust explosions in industry. Mercer et al. (1998) described a joint effort to characterize the *turbulent flow field* inside the 20 liter bomb. Mintz (1995) discussed some further problems with 20 liter bomb experiments.

Wlodarczyk et al. (1993) conducted experiments in a 5 liter spherical explosion bomb to determine the influence of the dust concentration in exploding aluminum dust/air clouds, on the content of aluminum oxide in the reaction products. Fan, Ding, and Tang (1993) developed a *dynamic numerical simulation model* for the propagation of spherical Al-dust explosions in closed vessels. Good agreement was found between experiments and theoretical predictions for the influence of particle size on the pressure development in the vessel.

Dahoe et al. (1995) constructed a 20 liter spherical dust explosion vessel allowing variation of the initial pressure between atmospheric and 14 bar overpressure and initial temperatures between below 0°C and 250°C. Experiments could also be conducted in *enriched oxygen atmospheres*, up to pure oxygen. The problem of ensuring constant turbulence of the dust cloud at the moment of ignition, with varying dust concentration and pressure and temperature of the gas phase, was investigated. Further development of this vessel was discussed by Dahoe et al. (1996c), and the reinforced 20 liter vessel was then capable of withstanding internal overpressures of up to 150 bar and providing initial dust cloud temperatures of up to 450°C. Special experimental procedures had to be developed for extreme test conditions.

In a later contribution, Dahoe et al. (2001a) investigated the *influence of initial turbulence* of the dust cloud on the maximum pressure produced in closed-bomb dust explosion experiments. For cornstarch, they found that the maximum pressure increased by a factor of 1.6 with a given, significant increase in turbulence. As they pointed out, this effect had also been reported by earlier workers. However, the point made is that this increase would not have been expected if the maximum explosion pressure had been just a straightforward thermodynamic function of the nominal chemical composition of the burning cloud, as is essentially the case with premixed gases. On the other hand, an increase by a factor of 1.6 is modest compared to the corresponding substantially larger increase of the maximum rate of pressure rise by a factor of about 25. Therefore, it may still be argued that, compared to the maximum rate of pressure rise, which certainly contains a strong kinetic element, the maximum pressure is essentially a thermodynamic property. Nevertheless, the analysis by Dahoe et al. is timely and interesting, because it stresses that a dust cloud can never be really "premixed" in the same sense as a homogeneous gas cloud. The influence of turbulence on the maximum explosion pressure is then basically to modify the chemical composition during the combustion process and hence the combustion thermodynamics. Transport and mixing processes by turbulent mechanisms then play a central role. From the point of view of design of process enclosures in practice, as emphasized by Dahoe et al., a factor on the order 1.5 in expected maximum explosion pressure is significant and should be accounted for.

Gieras, Klemens, and Wolanski (1996a) determined *turbulent dust cloud burning velocities* from dust explosion experiments on a 1.25 m^3 closed spherical chamber. Dahoe et al. (1996a, 1996b) conducted similar experiments in closed spherical vessels 1 m^3 and 20 liters. These workers also developed a comprehensive mathematical three-zone model for constant-volume dust explosions in spherical vessels. In the model, the intermediate third zone (i.e., the reaction zone), separating the zone of combustion products from that of still unburned dust cloud, was assumed to possess a final thickness. The analysis revealed that the so-called cube root law breaks down if the ratio of reaction zone thickness to vessel radius exceeds 1%. For relatively small vessels, this is the case for most dusts. Formal *cube root law* agreement with larger vessel experiments can then be accomplished only by tuning the initial turbulence of the dust cloud in the smaller vessel.

Zhen and Leuckel (1996, 1997) investigated the influence of the characteristics of *pyrotechnical ignition sources* on the development of dust explosions in a standard (ISO) 1 m^3 closed vessel. Such ignition sources may increase the violence of the explosion, due to having large volumes and multipoint properties.

In their experimental study, Pu, Podfilipski, and Jarosinski (1998) compared *effective burning velocities* in clouds of fine aluminum dust and cornstarch in a 7 liter closed bomb, under micro gravity (drop tower) and normal gravity conditions. The dust clouds were produced by a short blast of air, and the time interval between dust dispersion and ignition was varied. The pressure development with time was recorded. Turbulence properties of the unburned cloud, as a function of the time elapsed after dust dispersion, were measured using hot-film anemometry. The results indicated that, under *microgravity*, the dust cloud remained well dispersed and homogeneous, even at long ignition delays, when the turbulence had decayed to a level where the cloud was essentially laminar. Hence, microgravity experiments may offer a means of detailed studies of genuinely laminar dust flames.

9.2.4.6
Dust Flame Propagation in Long Tubes and Pipelines

Some work up to 1990 is discussed in Section 4.4.7 in Chapter 4. In a comprehensive 5-year research program, Lebecki et al. (1995) investigated the propagation of grain dust explosions in a large-scale experimental gallery. The main conclusions were these: The minimum nominal dust concentration for flame propagation was 50 g/m^3; for dust concentrations higher than 100 g/m^3, flame acceleration right up to *detonation* was observed; and strong grain dust explosions could be suppressed using passive water barriers, whereas use of active barriers were necessary for weak ones.

Proust (1996) reviewed the state of the art on propagation of dust explosions in pipelines in relation to gas explosion propagation in pipelines.

Hu and Sun (1994) investigated the mechanisms of fast combustion of Al-powder, suspended in atmospheres of different oxygen contents, using an explosion shock tube technique, whereas Pu et al. (1993) studied experimentally the acceleration of an Al-dust/air flame in a one end open, horizontal tube of diameter 140 mm and length 5 m. With ignition at the closed end, maximum flame speeds at the open exit end amounted to 1200 m/s. Al-dust was also used in the experiments by Chen, Dobashi, and Hirano (1996), Liu and Bai (1998), and Pu et al. (2001) for studying the mechanisms of acceleration of dust explosions in long tubes. Liu and Bai and Pu et al. investigated the entire range of flame velocities, from the weak initial flames right up to detonation (1500 m/s). Turbulence played a key role in the flame acceleration process.

9.2.4.7
Comprehensive Mathematical Models of Turbulent Flame Propagation in Dust Clouds

Comprehensive mathematical models for simulation of turbulent dust flame propagation processes are being developed at great pace. Some work up to 1990 is reviewed in Section 4.4.8 in Chapter 4. Kjäldman (1992), one of the pioneers in this field, summarized his early work on applying computational fluid dynamics (CFD) to turbulent dust explosion propagation. The application of the numerical model to peat dust explosions in a closed 20 liter vessel showed promising agreement with experiments. Smirnov et al. (1996) outlined a mathematical analytical scheme with numerical software comprising both ignition and flame propagation in turbulent dust clouds, whereas Smirnov et al. (1997, 2000) described comprehensive mathematical models of turbulent combustion of dust/air mixtures in depth. Rose et al. (1997, 1999) applied a Lagrangian approach to the modeling two-phase turbulent reactive flows, whereas Wörsdörfer et al. (2001) outlined various possible routes for comprehensive numerical modeling of dust and gas explosions. Kosinski, Klemens, and Wolanski (2002) discussed the potential of CFD-based mathematical modeling of large-scale dust explosions. The vast number of control volumes required to obtain adequate resolution has been a major obstacle.

Kosinski et al. presented a new, efficient combustion model. The model, which is based on the Arntzen model for gas explosions, was found to possess considerable advantages compared with the standard chemical kinetics models.

Wingerden (1996a, 1996b) reviewed the role of turbulence, preignition turbulence as well as explosion-induced turbulence in deciding the course of gas and dust explosions in industrial process environments. In general, combustion rates increase considerably with increasing turbulence, but excessive turbulence may quench combustion. He also presented some of the first comprehensive, validated CFD-simulations of flame and pressure development in a large-scale vented dust explosion. The experiments simulated were a series of maize starch explosions in a vented 20 m^3 chamber in the United Kingdom. This version of the numerical model, based on the well-known FLACS code for gas explosions, represented an important first step, but comparison with simulations and experiments revealed a clear need for improved dust cloud combustion models. Wingerden et al. (2001) presented further work on developing such a model.

Krause (1993) presented a comparatively simple two-dimensional model for numerical simulation of explosions in vented enclosures. The turbulence submodel was empirical, and the explosive cloud was regarded as a homogeneous, premixed gas. Comparison with more complex models gave reasonable agreement. Comparison with dust explosion experimental data was not reported. Krause (1994) used this simulation model to predict the maximum explosion pressure in a vented explosion as a function of the vent area and the turbulence intensity in the dust cloud just prior to ignition. The model was able to reproduce the earlier experimental finding of Tamanini et al. (see Chapter 6, Section 6.4) that the maximum explosion pressure in the vented vessel increases with increasing initial turbulence intensity in the exploding cloud. Krause and Kasch (1998a, 1998b, 2001) investigated experimentally the influence of dust concentration and flow velocity on flame propagation processes in dust clouds in vertical tubes of various diameters. They also developed numerical models for both laminar and turbulent flame propagation and discussed computed predictions of the course of a dust explosion in a real silo.

Poletaev (1995) studied the possibility of applying a "relay" model to flame propagation in dust clouds. According to this model, any particle will ignite, with a given delay, if the distance to the nearest burning particle does not exceed a given "maximum radius for heat interaction."

Korobeinikov et al. (1996) performed a mathematical analysis of unsteady dust explosion propagation in tubes, using coal dust and corn starch as specific model dusts. They also analyzed the dispersion of a dust layer on the tube bottom by an airflow in the tube. Korobeinikov et al. (2002) formulated a comprehensive mathematical model describing the sequence of unsteady processes that can take place behind a shock wave propagating along a dust layer. Special cases that were simulated by the model included dust entrainment and dispersion from a dense dust layer by a shock wave passing across the layer and dispersion, ignition, and combustion of coal dust in a long tube, initiated by a local gas explosion in the tube.

Schumann, Rastogi, and Friehmelt (1996) compared pressure-versus-time traces obtained by numerical simulation of dust explosions in closed and vented vessels, of volumes ranging from 1 m^3 to 250 m^3, with results from corresponding real experiments. The comprehensive numerical CFD-based BASSIM code was used for the dynamic simulations. Comparisons were also made with results computed using a simple empirical correlation equation based on experimental results. A main conclusion was that there was room for considerable improvement of the combustion submodel in the code to account for the pyrolysis of organic dust particles and the effect of turbulence on the combustion rate.

Detkovskii et al. (1996) developed a numerical model describing transient flame propagation following ignition of a free turbulent jet of combustible dust in premixed methane/air. Different secondary combustion-induced flow patterns can result, depending on the initial jet parameters. The predicted courses of events were found to be in satisfactory agreement with results from careful experimental investigation of the same process.

Zhong, Deng, and Li (1998); Zhong et al. (2001); and Zhong and Deng (2000) developed a comprehensive numerical CFD-based code for explosions of clouds of *cornstarch* in air. The scheme comprises the gas phase flow, including the k-ϵ model, the movement of dust particles in the gas flow, evaporation of water from the particles, flux of combustible vapors from the particles, combustion of the vapor phase, and combustion of carbon residue of particles. The effect on the combustion rate of incomplete dust dispersion, that is, particle agglomerates, was accounted for. Numerical simulation of maize starch explosions in the essentially closed 12 m^3 silo, in which Hauert, Vogl, and Radandt (1994) had carried out concentration and turbulence measurements, were performed, adopting the dust cloud structures measured by these workers as preignition or initial conditions. Unfortunately no experimental explosion data were available for validating the simulations.

Zhong et al. (2002) developed a CFD-based Eulerian/Lagrangian model for *coal dust* explosions comprising the following features: a nonelemental Arrhenius model and eddy breakup model for the chemical reactions, detailed models of water vaporization, volatile decomposition, and surface oxidation of carbon, and the k-ϵ turbulence model for the gas phase, and a random trajectory model for the particle phase. The model was tested against results from coal dust explosions in closed vessels.

Bielert and Sichel (1999, 2001) developed a numerical model for simulation dust explosions in *pneumatic conveyors*. The model combines a front-tracking method with a solver for the Euler equations. The combined effects of chemical reactions and flow turbulence were represented by the turbulent burning velocity of the dust cloud.

Pascaud and Brossard (2000) presented a mathematical model for the combustion of *hybrid systems* (e.g., cornstach/propane/air) in closed vessels.

9.2.4.8
Simplified Approximate Models

Having first emphasized the central role that turbulence must play in any relevant dust explosion model, Tamanini (1996b, 1998a, 2001, 2002) suggested that scientifically based approximate design tools, which also account for turbulence effects, can be readily obtained by adopting *lumped-parameter descriptions* of the system of concern, as is done in dimensional analysis. His main argument is that comprehensive models handling the entire reactive flow field in complex geometries may not be generally accessible for some time, and when available, they will be expensive and time consuming to use. Tamanini (1995a, 1995b) used a lumped-parameter approach to establish a correlation for predicting the effect of vent ducts on the venting efficiency, whereas Tamanini (1996a) used it for sizing dust explosion vents in spray dryers, where the explosive cloud only occupies part of the dryer volume. Tamanini (1996c) also presented a simplified model of the *effect of the inertia of vent covers* on the efficiency of the venting process. Tamanini (1998b, 2002) proposed that this kind of simplified, but still scientifically based, models be used in future revised vent design guidelines to replace the entirely empirical statistical correlations used up to now. It seems clear that Tamanini's approach represents a great step forward compared to entirely empirical formulas and correlations. It is regrettable that his important contribution has not been included in the recent European Union design guidelines for dust explosion venting arrangements, CEN (2002).

On the other hand, the accessibility of user-friendly comprehensive CFD-based computer codes for dust explosion simulation is expected to increase at great pace, and only time can show how long the need for simplified, intermediate lumped-parameter models, as proposed by Tamanini, will persist. It must also be pointed out that the lumped-parameter approach can handle only comparatively simple problems, such as venting simple, single process units. Only comprehensive computer codes can handle the complex explosion scenarios often encountered in the process industries. There, process units of varying complexity are interconnected by ducts and conveyor lines, and the propagation of a dust explosion in such an integrated system can be performed only by powerful computer codes. However, development of and confidence in comprehensive computer codes have to be built on extensive validation against full-scale dust explosion experiments, covering a wide range of dusts, initial dust clouds states, and geometrical configurations.

9.2.4.9

Detonations and 'Quasi'-Detonations in Dust Clouds

Some work up to 1990 is reviewed in Section 4.5 in Chapter 4. It is now generally accepted that detonations can occur even in dust clouds. A review of the state of the art and remaining problems in dust cloud detonation research at that time was given by Kauffman, Sichel, and Wolanski (1991). The current status on dust cloud detonations was also summarized by Alexander et al. (1993). Kauffman et al. (1992) and Austin et al. (1993) summarized their extensive work on how detonations can develop from *accelerating turbulent combustion* in dust clouds in long tubes. Sichel and Kauffmann (1994) studied the transition from deflagration to detonation (DDT) during dust explosions in long ducts. The dust was initially deposited as a layer along the duct floor, and the dust cloud was generated by the entrainment of the dust layer by the blast wave propagating ahead of the flame.

Khomik, Gelfand, and Knyazev (1993, 1994) determined experimentally the *minimum critical tube diameter* for detonation propagation in suspensions of a fine aluminum flake dust in air. The critical value found was in the range 0.040–0.055 m. Korobeinikov (1993) conducted a theoretical study of the propagation of detonation waves in dust clouds. The problem of establishing adequate *scaling rules* was given particular attention. Markov (1993) presented a new method for numerical simulation of nonsteady detonations in dust clouds. Two-dimensional computations yielded a multiwave structure of the detonation process. Ding and Huang (1994) analyzed the mathematical theory for the reaction zone in a detonation wave passing through a dust cloud and proposed a new numerical criterion describing the C–J condition.

Tulis et al. (1993) conducted detailed experimental studies of the structures of detonation processes in clouds of aluminum in air. The influence of particle size and shape was studied, and various detonation wave structures were identified. Paplinski and Wlodarczyk (1994) analyzed the critical conditions for direct initiation of detonations in dust clouds of infinite size. Klemens et al. (1993) performed experiments in which detonation waves in *hybrid mixtures* of methane, air, and oats dust were studied. Tulis et al. (1996), Carvel et al. (1996), and Ven, Olivier, and Grönig (1996) presented experimental results from different studies of multiple or double fronts in dust cloud detonations and the dynamic structural response of a tube during dust cloud detonation inside the tube. Fedorov, Fomin, and Khmel (1996) analyzed real detonation waves in aluminum/oxygen mixtures mathematically, whereas Fedorov et al. (1998) developed a mathematical model for steady, self-sustained nonideal detonation of clouds of aluminum particles in air. These last workers were able to confirm the existence of steady *Chapman-Jouguet detonation regimes*. Klammer et al. (1999) applied the viscous laminar Navier-Stokes model in their model of generating a dust cloud quasi-detonation inside a plane channel by two different mechanisms. In the first case, the dust was initially deposited as a layer on the channel floor, and dust dispersion and cloud ignition occurred via a supersonic flow into the channel. In the second case, the dust was predispersed throughout the channel volume, and ignition occurred at the heated closed end of the channel. In their theoretical study of detonation processes in clouds of starch particles in nitrogen/oxygen and hydrogen/oxygen atmospheres, Veyssière et al. (1999) applied a model based on the same main assumptions as had been used previously to model nonideal detonations of aluminum dust dispersed in explosive gas/oxygen atmospheres. It was assumed that the starch particles are gasified by pyrolysis after the temperature has reached some critical value and that the burning rate is controlled by the gasification rate. The model predictions suggested that discrepancies between some earlier experimental results were caused by different particle sizes of the starches and different lengths and diameters of the shock tubes used in the various experiments.

Klemens et al. (2001b) used similar numerical models to simulate central processes related to dust explosions in *coal mines*, including dust layer entrainment behind a shock wave and initiation of dust cloud deflagration and detonation by alternative mechanisms.

Zhang, Grönig, and Ven (2001) summarized the extensive work on DDT and stable detonation waves in dust clouds in air conducted in the Stosswellenlabor of RWTH Aachen in Germany. The DDT process in long tubes is composed of a reaction compression stage followed by a reaction shock stage as the predetonation process. The transverse waves that couple the shock wave and the chemical energy release are responsible for the propagation of a stable dust/air detonation. The minimum tube diameters for DDT and subsequent propagation of stable detonation waves in clouds of most industrial and agricultural dusts in air are in the range 0.1–1.0 m and minimum length-to-diameter ratios for DDT to occur are larger than 100, even when a quite strong ignition source is used.

9.2.4.10
Miscellaneous

Huang, Pu, and Ding (1994) observed that *burning clouds of aluminum dust in air are electrically conductive*. They attributed this effect to generation of metal vapor by evaporation of the particles prior to combustion. In addition to being of fundamental interest, the observed effect also has implications with respect to industrial safety.

Zuikov and Zemsky (1997) presented experimental data for the kinetics of release of hydrogen when silicon powder makes contact with water or some aqueous solutions. It was shown that the released hydrogen can form explosive mixtures with the air into which it is released. Zemsky, Zuikov, and Devlicanov (1997) suggested that the formation and ignition of *hybrid mixtures* of silicon dust, hydrogen, and air could well have been the cause of several explosions in silicon powder production plants.

9.2.5
BLAST WAVES GENERATED BY BURNING DUST CLOUDS

A useful condensed introduction to the complex field of the properties and effects of blast waves from explosions was given by Harmanny (1992).

One case of practical interest is blast waves from explosions in partly confined geometries, for example, deliberately vented or bursting process equipment and workrooms. The strength and shape of blast waves from dust explosions depend on the way in which the dust clouds burn. For example, Wirkner-Bott, Schumann, and Stock (1992) conducted a fairly detailed study of the nature of the "secondary explosion," that is, the explosion of unburned dust cloud outside the vent opening. This phenomenon was discussed further by Schumann and Wirkner-Bott (1993). Central variables influencing blast wave generation, in addition to the type of dust and geometry of system, include the dynamic state of the dust cloud at the moment of ignition, the ignition point in relation to the vent, the vent size, and the vent-cover opening pressure. Wingerden (1993) presented an informative overview of pressure and flame effects in the direct surroundings of installations protected by dust explosion venting.

Some basic studies of shock wave emission from burning dust clouds were performed by Gelfand et al. (1990).

Medvedev, Polenov, and Gelfand (1994a) studied, experimentally as well as theoretically, the blast wave generated by sudden expansion of a dust-filled enclosure, such as a hopper or a pipe. The same authors (1994b) also studied the interaction between blast waves and dust deposits, using a specially developed shock tube technique. The experiments revealed a strong dependence of the pressure amplitude transmitted through the dust on the duration of the compression phase of the primary air shock wave. Smirnov, Kuksenko, and Chen Dongqing (1994) presented a new mathematical model of shock wave propagation in dust clouds, comprising a range of different particle sizes within the same cloud. Interparticle collision was not considered. An experimental and numerical study of the supersonic flow behind a shock wave passing through a dust cloud was performed by Boiko et al. (1994). Gelfand et al. (1994) investigated experimentally the attenuation of shock waves propagating through dust clouds in a 50 mm diameter shock tube. Reasonable agreement between the experimental data and analytical and numerical predictions was found for incident shock waves of Mach < 3.

The effect of a given blast wave on humans, buildings, and process equipment is an important area where more research is needed. Valuable reviews were given by Mercx (1992) and L'Abbé (1992). Britan et al. (1994a) studied the interaction of shock waves with layers of water-based foam used in fire fighting. Induction times and time constants for foam layer destruction were determined. Britan et al. (1994b) analyzed the features of the transmitted shock wave and the waves reflected from the air/foam boundary and the walls of the experimental channel.

9.3

STATUS AND OUTSTANDING PROBLEMS IN PREVENTING AND MITIGATING DUST EXPLOSIONS IN INDUSTRY

9.3.1

THE ROLE OF FUNDAMENTAL KNOWLEDGE IN ASSESSING HAZARDS IN PRACTICE

The various aspects of applied dust explosion research and development may be systematized as shown in Table 1.9 in Chapter 1. A number of fundamental research topics are listed in Table 9.1. The two are intimately related because fundamental knowledge is essential for proper understanding of practical aspects. Experience has shown that the development of good practical solutions may be hampered by not accounting for relevant fundamental knowledge. In recent years, the appreciation of the benefits that can be harvested from cross fertilization between fundamental research and applied research and development has been increasing.

Deng and He (1994) pointed out the need for using thermodynamics, chemical reaction kinetics, and fluid dynamics for the proper description of ignition and flame propagation phenomena in dust clouds and layers. These topics constitute central elements of classic chemical reaction engineering, and Deng and He proposed a corresponding concept, dust explosion reaction engineering (DERE) for the dust explosion domain.

Siwek (1994) presented a concentrated overview of current methods for dust explosion prevention and mitigation in the process industries, based mainly on pragmatic experimental research and development performed within the Swiss/German domain. Siwek's paper reflects the important fact that industry needs practical solutions for today. It cannot wait for more ideal solutions that may become available in some distant future. However, industrial pragmatism must not, on the other hand, block the constant striving for better solutions based on improved basic understanding of the phenomena involved. It seems as if the mutual understanding and respect between the two parties, the industry and the researchers, is growing.

The point is illustrated by Eckhoff (1995), who reviewed the state of the art on preventing and mitigating dust explosions in ferroalloy crushing and grinding plants. Silicon crushing and grinding was considered specifically by Eckhoff (1996b). In general, both electric spark ignition sensitivity and explosion violence (K_{St}) of metal dusts increase markedly with decreasing particle size, right down to the 1 μm. In the past, this was seldom taken into account. Often particle size was just pragmatically specified in terms of "less than 74 μm" or "less than 63 μm," but this is by no means satisfactory. More systematic research is needed, in particular on alloys, where the most hazardous components may sometimes accumulate in the fine tail of the particle size distribution. The specific roles of the chemistry and particle size of the various components in ferroalloy dusts at large in determining both ignition sensitivity and explosion violence need to be investigated more closely. Cashdollar (1998) discussed various central aspects of dust explosion research, prevention, and mitigation.

9.3.2

INHERENTLY SAFE PROCESS DESIGN

Kletz (1999) outlined his important message of adopting the concept of inherently safe process design whenever possible. Traditionally, industry has tried to prevent accidental explosions mostly by adding preventive and mitigatory equipment and enforcing safe procedures. But such equipment is often expensive, and procedures may fail. Inherent safety implies that the process design itself is such that no explosion hazard exists. Kletz gives some examples of inherently safe process design in practice.

Amyotte and Khan (2002) proposed a framework for directing the concept of inherently safe process design specifically toward reducing the dust explosion hazard in industry. One hopes this contribution will stimulate to further work in this important area.

9.3.3

PAPERS COVERING SEVERAL METHODS AND SPECIFIC APPLICATIONS

An overview of preventive and mitigatory techniques in use is given in Section 1.4 in Chapter 1.

In the late 1970s and early 1980s, a significant fire and explosion problem existed in the U.S. grain handling and grain related industry. Because of investigations initiated by the federal government and research undertaken by government and the industry, federal safety regulations were issued and an educational program initiated by the industry and affiliated labor unions, as reviewed by Kauffman et al. (1996). As a result, the frequency and severity of these accidents decreased significantly.

Siwek (1992) described experiments where a *combination of explosion venting and automatic suppression* was adopted for mitigating or controlling dust explosions in various enclosures. Sliz, Lebecki, and Dyduch (1993) investigated the performance of such a combined system for mitigating grain dust explosions in an 8 m^3 experimental vessel. Different types of vent covers and suppressors were tested.

Zeeuwen (1996) discussed alternative *strategies for protecting process installations* against dust explosions—full containment, explosion venting, automatic explosion suppression, and explosion isolation—using a grinding installation as an example. Hoppe, Jaeger, and Terry (1998, 2000) discussed strategies and specific measures for preventing and mitigating dust explosions, developed and implemented in a major international chemical process company. Stevenson (1998) gave a broad overview of available methods for dust explosion prevention and mitigation. Jaeger (2001) used a practical example to illustrate a strategy for minimizing the dust explosion hazard in the process industries. The two main elements form the strategy, relevant ignitability and explosibility characteristics of the dusts in question and adequate methods for performing risk analyses.

Beck and Kleinhans (1996) reviewed possible measures for preventing and mitigating dust explosions in *silo vehicles* for transportation of combustible powders and bulk materials. Preventing ignition by eliminating potential ignition sources is a primary objective.

Scholl (1996) discussed methods for protecting *particle board production plants* against dust explosions. Such plants typically comprise wood cutting and grinding equipment, dryers, mechanical and pneumatic conveyors, classifiers and sieves, and storage containers. Grosskopf and Li (1998) and Grosskopf (2002) discussed possible methods, and called for standards, for preventing and mitigating dust explosions in coal grinding plants.

Siwek (1999) considered the specific problem of protecting *fluidized bed process units* against damaging dust explosions. The approach to be chosen depends on the thermal stability and burning properties of the actual powder as a layer or deposit, the ignition and explosion properties of the powder as a dust cloud, and the possible presence of organic solvents (hybrid mixtures). Siwek (2000) presented a similar analysis for *spray dryer installations.*

Barth et al. (1996) and Kubainsky et al.(1996) discussed means of adequate mitigation of dust explosions in *small-scale milling and granulation plants*, respectively. In the milling plants, the possibility of ignition in the mill cannot be fully eliminated, and adequate mitigatory measures must be taken. These include isolation measures and stopping the supply of material to the mill should an explosion occur. Special venting arrangements were not considered necessary. In the small-scale granulation plant without organic solvents, measures to eliminate potential ignition sources were considered sufficient. With solvents present, this would not be the case and additional protective measures must be taken.

Hungerbach (1996) discussed possible measures for mitigating dust explosions in *fluidized bed process* equipment. One possibility is venting, with bursting panels and vent ducts. Further possibilities include automatic explosion suppression and full explosion confinement.

Wilen (1998) summarized the results of a joint European experimental research program on safe handling of *renewable fuels* and *fuel mixtures*: wood fuels and wood wastes, agricultural residues and energy crops, low-rank coals, and mixtures of wood and barley dusts with lignite. The program comprised an extensive series of tests at atmospheric and elevated initial pressures up to 18 bar, including *inerting* and *automatic suppression tests.*

Faber (2001) suggested suitable means for preventing and mitigating dust explosions during finishing and *electrostatic dry painting* of aluminum automobile bodies.

Cashdollar (1998, 2000) gave a comprehensive overview of the chemical and physical dust characteristics that determine the potential explosion hazard posed by a given dust and how these characteristics influence the choice of adequate methods for prevention and effective mitigation of dust explosions in practice.

Zeeuwen (2000) reviewed the dust explosion hazard in powder handling and processing at large, as well as available methods for prevention and mitigation. The new particular challenges presented by the European Union "Atex" directives were also discussed.

Rabenstein (2001) presented a set of guidelines, produced by a German working group, to protect *dust extraction systems* in various industries against accidental dust explosions. Depending on the fire and explosion characteristics of the dust, such systems can present a comparatively high dust explosion risk, and corresponding measures have to be taken to reduce the risk to an acceptable level.

Bunse (2001) described the design of a system for cost-effective protection of *bucket elevators* against destructive dust explosions. *Quenching tubes* (see Section 1.4.6.6 in

Chapter 1) for venting in-house dust explosions at the top and boot of the elevator were used in combination with flame-triggered water mist injection along the elevator legs.

Going and Snoeys (2002) discussed suitable methods for mitigating *metal dust* explosions based on experimental investigation. In particular, isolation, venting, and automatic suppression were considered.

9.3.4

GENERATION AND PROPERTIES OF EXPLOSIVE DUST CLOUDS IN INDUSTRY

The challenge is to characterize typical dust cloud structures in terms of spatial distributions of particle size, dust concentration, turbulence, and global flow generated in typical process units, like mills, dryers, mixers, bucket elevators and other conveyors, silos, filters, cyclones, and connecting ducts. These cloud structures define the initial cloud properties at the location of the primary dust explosion and may have a major impact on the course of development of the explosion. It is well known that the dynamic state of a dust cloud dramatically influences both its ignition sensitivity and its combustion rate.

Comparatively little new quantitative knowledge of practical use has been traced. Therefore, experimental investigation of typical processes of the generation of dust clouds and the resulting cloud structures in various types of process equipment and operation modes should be encouraged. This is an area where close interaction of fundamental and applied research can be highly beneficial. The work of Hauert et al. (1994), discussed in Section 9.2.2, constitutes an important step in this direction.

Jong et al. (1999), in their useful review of methods for determining powder "flowability," mentioned two methods for determining the dispersibility, or "dustability," of powders that are of interest in the present context (see also Chapter 3 and Section 7.4.2 in Chapter 7). Dahmann and Möcklinghoff (2000), in the context of industrial hygiene, also described a method for testing the "dustability" of industrial powders.

9.3.5

PREVENTING IGNITION SOURCES

9.3.5.1

Introductory Remarks

Reference is made to the first column of Table 1.9 in Chapter 1. A considerable amount of fundamental knowledge is available, as discussed in Section 9.2 with reference to the second column of Table 9.1. Generally any "ignition" process comprises a range of very complex subprocesses. Simple parameters, such as a minimum ignition energy or temperature, are not true constants for a given dust but vary significantly with the geometry and other properties of the ignition source as well as with the state of the dust cloud.

Maurer and Glor (1996) discussed the extent to which the minimum ignition energy of a dust, determined in a standard test, can be used as a basic criterion for selecting an appropriate means to prevent accidental ignition of explosive dust clouds in industry. Schacke, Viard, and Walther (1996) proposed some basic concepts to facilitate dust explosion prevention and control when designing and running a chemical process plant. Identifying, knowing, and eliminating possible ignition sources is of prime concern. Maximum benefit is obtained if this concern is taken into account from the early design phase, during which it can also be decided whether further measures, such as inerting and venting, are required. Klais and Niemitz (1996) addressed the special problems arising, and the precautions to be taken, when semi-stable chemical substances capable of reacting or decomposing exothermally, even in the absence of oxygen from the air, are exposed to thermal or mechanical loads in drying and grinding operations. Substances that may show this behavior include azide, azo, and di-azo compounds; hydrazine; peroxides; nitro and nitroso compounds; epoxides; and some nitrates.

9.3.5.2

Self-Heating, Spontaneous Combustion, and Smoldering Combustion in Dust Layers and Deposits

Some research work up to 1990 is discussed in Section 5.2 in Chapter 5. Test methods are reviewed in Section 7.7 in Chapter 7.

Gibson (1993a) gave a summary of methods for preventing ignition of powders and dusts in drying operations. Zockoll (1994a, 1996a, 1996b) described the development of a new system for early detection of self-heating and self-ignition in deposits of organic powders in spray dryers, based on detection of low concentrations of CO, in the 1–10 ppm range, with particular reference to drying plants for milk powder production. It is important that the system supplier and the user work closely together to ensure an optimal system design for any given application. Loebel (1996) described the design and installation of, and first experience with, a smoldering coal fire detection system, based on a semiconductor gas sensor. A multisensor system for detection of gases developed by slow smoldering fires in lignite was described by Kohl and Kelleter (1996). H_2 and CO were monitored continuously, using electrochemical sensors, and it was found that the ratio of the measured concentrations of the two gases could provide information about the state of development of the smoldering fire.

Zeeuwen (1999) outlined how critical conditions for self-heating in stored bulk powders in industrial situations can be determined by employing suitable laboratory-scale test methods.

Carson (1996) presented a systematic approach for characterizing the tendency of combustible dusts to self-heat and start burning spontaneously, comprising various laboratory-scale tests and mathematical models. The experimental methods included differential thermal analysis (DTA), thermogravimetric analysis (TGA), isothermal oven tests, and adiabatic calorimetry. By means of this methodology, the critical conditions at which the actual dust begins to pose a threat of spontaneous combustion can be determined. Matyukhina (1996) studied the self-heating and onset of spontaneous combustion in coal deposits, taking into account both air penetration due to the pressure exerted by strong winds and the kinetics of slow coal consumption.

Krause and Schmidt (1997) reported experimental studies of critical thermal conditions for the onset and sustained propagation of smoldering processes. Particular attention was paid to the critical initial temperature of an embedded hot solid body and the critical size of an intial smoldering nest (see also Section 9.2.3). Krause and Schmidt (2002) studied self-ignition in deposits of five dusts in oxygen/nitrogen atmospheres containing less oxygen than air. They found that self-ignition could occur even with oxygen contents as low as 3–6 vol%. This is in agreement with the findings of Walther shown in Figure 1.67 in Chapter 1.

Sweis (1998) and Reddy et al. (1998) studied the effect of admixed inert material on the minimum ignition temperatures of oil shale and tar sand (Sweis) and coal dust (Reddy et al.). The hot-plate configurations used in the two investigations were different. El-Sayed and Abdel-Latif (2000) investigated the critical hot-plate temperature as well as the critical heat flux for ignition of layers of corn flour and a 80/20 mixture of wheat flour and corn flour. The effect of sample diameter and height was studied. Empirical correlations of the critical temperature for ignition, time to ignition, thermal properties, and geometrical dimensions of the powder sample, were given. Lebecki et al. (2002) investigated the influence of the thickness of the dust layer on the minimum hot-plate temperature for ignition. Experiments with both constant hot-plate temperature and constant heat flux were conducted.

Tuomisaari, Baroudi, and Latva (1998) investigated suitable methods for fighting smoldering fires in silos, both experimentally and theoretically. By means of the relevant heat and mass balance equations, combined with dimensional analysis, critical parameters were identified, including particle size and moisture content, but the theoretical analysis also revealed the great complexity of the problem. Some qualitative guidelines for fighting smoldering silo fires were given. To obtain quantitative guidelines, further studies would be required.

Based on practical experience, Broeckmann (2001) discussed the limitations of infrared radiation detectors and low-concentration CO monitoring systems for detecting "sparks" and open or smoldering fires in the process industries. Aspects to be taken into acount to ensure adequate performance of such systems were outlined.

Carvalho, Gurgel-Veras, and Carvalho (2002) presented the results of an experimental study of smoldering processes in wood logs, both on a laboratory scale and in prescribed forest burns. The main objective was to analyze the parameters that control initiation and sustained propagation of the smoldering process.

Xu, Cui, and Xu (1993) found that very weak electric spark discharges, in the range 0.1–1.0 mJ, can probably initiate smoldering combustion in layers of linen flax. Hesby (2000) ignited layers of combustible dusts by showers of metal sparks generated by forcing rods of various metals against a grinding wheel. Parameters controlling the number and size of the sparks impacting on the dust layer included the contact pressure between metal rod and grinding wheel and the duration of the contact. A conclusion was that it seems highly unlikely that steel spark showers from single accidental impacts can initate smoldering combustion in layers of dusts of natural organic materials.

9.3.5.3
Ignition of Dust Clouds by Hot Surfaces and Smoldering and Flaming Nests

Work up to 1990 is reviewed in Section 7.8 in Chapter 7.

Zockoll and Wiemann (1996) found that minimum ignition temperatures of dust clouds determined in the standard Godbert-Greenwald furnace were systematically about 100 K lower than those determined with plane hot surfaces of areas up to 144 cm^2. Therefore, current requirements for maximum permissible surface temperatures of apparatus in industry may seem unnecessarily conservative. Gummer and Lunn (2003) found that smoldering dust nests were poor ignition sources for most dust clouds, whereas flaming nests caused ignition more readily.

9.3.5.4
Ignition of Dust Clouds by Electrostatic Discharges

A brief review of the various types of electrostatic discharges is given in Section 1.1.4.6 in Chapter 1. The book by Lüttgens and Wilson (1997) is an excellent addition to the technical literature on the electrostatic discharge ignition problem in practice. Analyses of a unique selection of practical case histories constitute a major and most useful part of the book.

Wang and Lou (1994) discussed the electrostatic hazards in *powder handling and storage* in general and proposed methods for preventing or reducing this hazard. Rogers (1996a, 1999) summarized some guidelines for assessing electrostatic discharge ignition hazards in plants containing explosible dusts and hybrid mixtures. Glor (1997) reviewed the electrostatic hazards in powder handling at large, and Glor (2001a) reviewed recent results from testing and research that should be accounted for when assessing the electrostatic ignition hazard in industry. More recently, CENELEC (2002) issued a comprehensive "Code of Practice" for avoiding hazards due to static electricity, which contains specific sections dealing with explosible dust and powder systems and hybrid systems comprising both explosible dusts or powders and explosible gases.

Hesener, Krause, and Schecker (1998) and Kraus, Lüttgens, and Schecker (2001) developed an *expert system* to be used to identify hazards due to the possible occurrence of various types of electrostatic discharges in various process situations. The system, using CENELEC report R044-001 (the 1999 ed. of CENELEC, 2002) as the technical basis, covers explosive gases and vapors and mists, as well as explosible dusts. In the first phase of system development, available knowledge was collected and structured systematically. In the second phase, the development the systematized knowledge was implemented in the expert system. The system supplies references to existing guidelines and regulations.

Sun (1994) constructed a new type of *electrostatic charge eliminator* for charged powders pneumatically conveyed in pipes. The method was tested successfully in industrial practice over a period of 1 year.

Pratt (1994) presented three case histories in which electrostatic spark discharges were generated during *pneumatic transport of powders*. Dahn (1996) reviewed the electrostatic hazards involved in various systems for pneumatic transport of powders and dusts, including dilute phase, negative pressure systems and dense phase, positive pressure systems. Taking adequate measures to reduce the dust explosion hazard requires knowledge of relevant process features and relevant physical and chemical properties of the powders and dusts. Gajewski (1997) determined the net electrostatic charge accumulated in granulated polypropylene when being conveyed pneumatically in pipes, using an electrostatic, inductive noncontact measurement method. Laar (2001) discussed the practical circumstances under which various kinds of electrostatic discharges can be generated during transport of combustible dust in permanent ducts and flexible hoses. Particular emphasis was put on circumstances leading to incendiary propagation brush discharges. Nifuku and Enemoto (2001) investigated the possibility of initiation of a malt dust explosion in a silo by an electrostatic discharge generated during pneumatic transportation of malt into the silo. They concluded that the charge accumulation may, under certain circumstances, be sufficient to produce an incendiary electrostatic spark discharge.

Glor (1996) discussed experiments in which electrostatic *cone discharges* were generated during pneumatic filling of a 50 m^3 silo with powders and granules. The results indicated that the upper limit of the equivalent discharge energy of such discharges increases with the silo diameter to the power of 3.4 and the median particle/granule diameter to the power of 1.5. For a silo of diameter 3 m and granules of 3 mm diameter, the maximum expected equivalent discharge energy amounts to 1 J. For a silo diameter of 1 m and particles of 0.1 mm diameter, the corresponding value is only 0.1 mJ. Glor and Maurer (1996) and Glor and Schwenzfeuer (1997) discussed further evidence elucidating the conditions under which incendiary electrostatic discharges can be generated when bulk material is discharged into, say, a silo, forming a conical heap. Glor (2001b) gave a more recent review of the state of the art on the cone discharge hazard.

Xu et al. (1996) found that clouds of fibrous organic dusts in air, such as of linen flax dust, could be ignited directly by electrical sparks from electrostatically charged nongrounded metal plates of area at least 100 cm^2, whereas charged plates of areas in the range 10–100 cm^2 may initiate combustion in deposited fibers. Electrostatic discharges from the dust itself does not give rise to ignition.

The question of whether *brush discharges* can ignite dust clouds has been raised frequently. Schwenzfeuer and Glor (1996) studied the incendivity of electrostatic brush discharges indirectly, by discharging them to ground via a spark gap located in the dust cloud to be ignited. But, observation of ignition in this kind of experiment does not imply that the brush discharge used would have been able to ignite the dust cloud in question directly. As a result of this argument, Schwenzfeuer and Glor (1997) developed an alternative experimental method for generating brush discharges, which made it possible to expose the explosive dust cloud to the brush discharge directly. In a later paper, Schwenzfeuer and Glor (2001b) reported that they had not been able to ignite dust clouds directly with brush discharges, but these findings were not conclusive. However, the experimental investigation by Larsen et al. (2001a, 2001b) provided the missing evidence. These workers were, in fact, able to ignite clouds of sulfur dust in oxygen-enriched air by true brush discharges, which demonstrates for the first time that brush discharges can, in principle, ignite dust clouds. However, Larsen et al. were unable to ignite clouds of sulfur in air only, despite numerous attempts. Because of the very low minimum ignition energy of clouds of sulfur dust in air, this may suggest that brush discharge ignition of clouds in air of even the most ignition-sensitive dusts is unlikely.

Dahn and Dastidar (2002) developed a new test method for investigating the ability of *propagating brush discharges* to stir up and ignite a layer of fine combustible dust on a electrically charged insulating surface backed by a grounded conductor.

The special problem of electrostatic discharge hazards in connection with industrial use of *flexible intermediate bulk containers (FIBC)*, often named *big bags*, was discussed by Rogers (1994) and by Dahn, Reyes, and Kashini (1994). Glor, Mauer, and Rogers (1995) and Glor (1998) discussed further developments in assessing the electrostatic dust explosion hazards associated with powder-dust handling and packaging. New results from tests during filling flexible big bags were presented. This information allows the implementation of a systematic procedure for evaluating potential electrostatic hazards with various products and under various operational conditions. Blum et al. (2001) discussed appropriate labeling of FIBSs to be used in areas where explosive atmospheres can be generated. Glor and Schwenzfeuer (2001) and Schewenzfeuer and Glor (2001a) discussed further evidence facilitating the assessment of the hazard of electrostatic discharges igniting explosive dust clouds at large, and particular attention was paid to brush and cone discharges in powder storage systems including silos and FIBCs.

9.3.5.5
Ignition of Dust Clouds by Glowing or Burning Particles

A brief review is given in Section 1.1.4.5 in Chapter 1. Some research work up to 1990 is discussed in Section 5.4 in Chapter 5.

Jansson et al. (1998) emphasized the dust explosion hazard presented in some industries, such as the wood working industries, by burning and glowing particles. An example of commercially available equipment to prevent ignition in industrial plants by this category of potential ignition sources was given by Kleinschmidt (personal communication with H.-P. Kleinschmidt, Fagus-GreCon Greten GmbH. and Co., Alfeld-Hannover, Germany, 1992), who presented a system for detection and extinction of "sparks" in terms of flying burning or glowing particles. Jansson (personal communication with L. Jansson, Firefly AB, Huddinge, Sweden, 1993) presented an alternative system that offers an adjustable lower particle temperature limit of detection, down to 150°C. A multizone checkpoint system prevents false alarms and indicates the size of the hot object (single particle, several particles, or extensive flame). Depending on the detection temperature and the nature of the industrial process, detection of a hot object may give rise to either activation of an extinction system, closedown of the plant, or simply adjustment of plant running conditions to prevent further hot object generation. Other "spark" detection and extinguishing systems have also been described, such as by T & B Electronic (1994).

The interior of a turbo mill, a cross beater mill, a pin mill, a pinned disk mill, and the like can become an effective ignition source when a *foreign body enters the mill* together with the material to be milled and causes a dust explosion. This problem was addressed by Barth et al. (1995), with particular reference to small laboratory-scale mills. Such mills are normally naturally vented and sufficiently strong to withstand the modest overpressures to be expected, should a dust explosion occur inside the mill. The problem is to eliminate the dust flame hazards associated with the venting of the system. Barth et al. proposed several solutions to solve this problem.

9.3.5.6
Miscellaneous Ignition Sources

Proust (1996b) investigated experimentally the extent to which *a beam of laser light* is able to ignite an explosive dust cloud. He found no generally valid correlation between the ease with which a dust cloud could be ignited directly by a laser beam and the minimum electrical spark ignition energy of the same dust cloud. He also found that the probability of a given laser beam igniting a given dust cloud increased markedly if ignition occurred indirectly, via a small solid target inside the dust cloud that was heated by the laser beam. Zevenbergen et al. (1996) tried to determine the actual minimum amount of energy that had to be transferred to an explosive dust cloud from a laser beam to cause ignition. For clouds of lycopodium in air, the laser energy required, obtained by calculation (280 mJ), was considerably higher than the minimum ignition energy obtained by direct experimentation using electric sparks (3–7 mJ).

9.3.5.7
Design of Electrical Apparatus for Areas Containing Combustible Dusts, to Prevent Ignition by Such Apparatus

This topic was addressed only very briefly in the two preceding editions of this book. Therefore, in this edition, an updated comprehensive discussion is given in the new Chapter 8.

9.3.6
PREVENTING EXPLOSIVE DUST CLOUDS

9.3.6.1
Inerting by Adding Inert Gas

This can be accomplished by adding inert gases such as nitrogen or carbon dioxide to reduce the volume percentage of oxygen in the atmosphere to a level at which the dust cloud can no longer propagate a self-sustained flame. Discussion of alternative techniques adopted in practice is given in Section 1.4.3.1 in Chapter 1. A fair amount of data exists on the maximum permissible oxygen content in the atmosphere for inerting (see Table A.2, Section 1.3.6 in Chapter 1, and Section 7.19 in Chapter 7). However, there is room for improving the test methods by which such data are obtained.

Glor and Schwenzfeuer (1996) determined the *limiting oxygen content* in the atmosphere, below which a cloud of a given material suspended in that atmosphere is not ignited, as a *function of the energy of the ignition source*. It was found that the limiting oxygen contents with electrostatic discharges or impact sparks as ignition sources are significantly higher than the absolute limit (LOC) determined in standard tests, using a very strong pyrotechnical ignition source. Schwenzfeuer, Glor, and Gitzi (2001) extended these studies to cover a much wider ignition energy range than in the previous studies, from 1 mJ to 10 kJ, and a total of nine dusts. All the data could be represented by a single equation expressing the critical concentration of oxygen for inerting the actual dust cloud, as a function of the actual ignition energy (IE) and the MIE of the actual dust in air determined in the standard test.

Most LOC data are for atmospheric pressure and normal temperature. Data for other conditions, in particular for elevated temperatures and pressures, are sometimes required, and adequate test methods should be developed. Glor (personal communication with M. Glor, Ciba-Geigy AG, Basle, Switzerland, 1993) determined maximum permissible O_2 contents for inerting clouds of coal dusts at elevated temperatures and pressures. Wolinski and Hayashi (1993) determined standard explosibility parameters of dusts of various rare metal alloys in air containing halon-1301 and additional nitrogen. Theories for flame propagation limits (see previous discussion with reference to the third column of Table 9.1) would be useful even in this context, and their development should be encouraged. Krause, Weinert, and Wohrn (1993) proposed a simplified, quite approximate method for first-order estimation of the minimum oxygen concentration for flame propagation in dust clouds. Maddison (1993) summarized some important aspects of inerting powder-handling plants using nitrogen, carbon dioxide, and other inert gases.

Gao et al. (1994) described a new system for injection of pulverized bituminous coal into a blast furnace for steel production, of which nitrogen inerting constitutes a central safety measure. Full or partial (see Section 9.3.7) inerting by inert gas also constitutes a primary element in the strategy for reducing the coal dust explosion hazard in melted slag reduction furnaces, as outlined by Wang, Zhang, and Liu (1994).

While reducing the oxygen content in the atmosphere prevents dust explosions, it can introduce a suffocation hazard. However, research has shown that adding a few vol% CO_2 to the gas mixture reduces the critical oxygen threshold for suffocation considerably. An inert gas mixture (INERGEN) utilizing this effect has been marketed by Dansk Fire Eater A/S (1992). Further work to identify gas mixtures that keep the dust cloud inert without presenting a suffocation hazard would be welcomed.

Pellmont (2001) presented a cost-effective solution for protecting a solvent-free sewage sludge drying plant against dust explosions, based on inerting by means of nitrogen.

Wilen et al. (1998) conducted gas inerting experiments with biomass dust clouds at elevated initial pressures, ranging from 5 to 18 bar. Contrary to what was found with coals, these experiments revealed an increase of the limiting oxygen concentration (LOC) for inerting with increasing initial pressure.

9.3.6.2
Inerting by Adding Noncombustible Dust

This method is not generally applicable, because the inert dust in most cases causes unacceptable contamination. However, there are cases where the dust or powder processed is already a mixture of combustible and noncombustible dusts and control of the composition ensures that dust clouds are nonflammable. It is then essential to avoid segregation of combustible and noncombustible components, throughout the process (see Section 1.4.3.3 in Chapter 1, Section 7.20 in Chapter 7, and Table A.3).

Zhang, Zhao, and Shi (1994) studied the possibility of preventing grain dust explosions in grain storage facilities by adding talc powder to the grain stream. The method works, as far as explosion prevention is concerned, but the health and hygiene aspects require careful consideration. Mintz et al. (1996) were concerned with inerting of clouds of metal dust in a particular application where this inerting method is, in fact, applicable. Tests were carried out using mixtures of 50:50 Al-Mg dust, Al dust, and 70:30 Mg-Ca dust, respectively, and MgO dust, which was the inertant. The results indicated that between 70 and 75% of fine MgO dust was required to completely inert the 50:50 Al-Mg dust. This is in the same range as the levels of rock dust needed for coal dust inerting. Use of a coarser MgO dust raised the fraction of MgO required for inerting.

Amyotte, Mintz, and Pegg (1995); Dastidar, Amyotte, and Pegg (1997); Dastidar et al. (1998); Dastidar and Amyotte (1999); and Chatrathi and Going (2000) determined experimentally critical mass ratios and dust concentrations in mixtures of combustible dusts, mostly coal and solid pulverized suppressants, for rendering clouds in air of the mixtures nonflammable. Various factors that might influence the test results were subject to special investigation. For example, Dastidar et al. (1998) encountered some disagreement between results from a 20 liter and a 1 m^3 test chamber. Further work to resolve this problem was undertaken by Dastidar et al. (2001). Dastidar and Amyotte (2002) conducted experiments in a 20 liter closed bomb to determine the minimum fraction of fly ash that had to be added to a 36% volatiles Pittsburgh coal dust to render clouds of the mixtures nonexplosive. The results showed that the minimum fraction required decreased with increasing fineness (decreasing particle size) of the fly ash. Hamdan and Qubbaj (1998) investigated the effect of calcium carbonate, stone dust, and clay dust for inerting oil shale dust.

9.3.6.3
Dust Concentration Below the Minimum Explosive Concentration

Keeping the concentration of dust in the cloud below the minimum explosive concentration is a third means of maintaining dust clouds nonexplosive. The practical use of this method is discussed in Section 1.4.3.2 in Chapter 1. The method requires *reliable monitoring of the actual dust concentration.* The work by Hauert et al. (1994) is important even in this context. Zockoll (1994b) described an apparatus, based on infrared light attenuation, for determining dust concentrations of clouds generated in various industrial situations. Typical measurement results were reported, demonstrating the feasibility of the method. Shao Fuqun and Wang Shi (1994) reviewed some nonintrusive methods for measuring the dust concentration in dust clouds, primarily in pipes and ducts. Xu et al. (1994) proposed a systematic method for estimating the dust explosion hazards in industrial plants based on estimating the *expected dust concentration.* The method implies an empirical relation between local dust concentration and the local rate of dust deposition from the cloud (mass/(time·area)). The properties of the dust emission source must be known. It is also necessary to know the minimum mass of dust deposit per unit of surface area required to maintain self-sustained dust cloud combustion along the surface. Furthermore, the assumption that entrained dust will become distributed evenly throughout the available space may not always hold. For example, a thin dust layer on a floor may be dispersed into just a shallow, dense dust cloud close to the floor, through which the flame can sweep along the floor. The conditions required for producing this kind of self-sustained shallow sweeping flames need to be investigated further in the context outlined in the first column of Table 9.1.

Xu, Zheng, and Xu (1993b) found that the minimum explosive concentration (MEC) of *linen flax dust* in air was independent of particle size up to about 100 μm. For larger particles, a systematic increase of MEC with increasing particle size was found. Mittal (1993) discussed various mathematical models for calculating minimum explosive concentrations of dust clouds.

9.3.6.4
Minimum Hazardous Mass of Dust

Wolanski (1994) suggested that the concept of "minimum hazardous mass of dust" be introduced in the evaluation of dust explosion hazards in practice. This parameter is defined as the minimum mass of the actual dust that can generate a dust explosion of destructive strength. The parameter is not a constant for a given dust but depends also on the characteristics of the actual enclosure in which the explosion takes place. The basic idea is as follows: A quantity of dust, unable to generate a cloud of concentration above the minimum explosive value, when being dispersed evenly throughout the entire enclosure volume, can present a significant explosion hazard when being dispersed in the enclosure as a smaller, and correspondingly denser, cloud.

9.3.7
PROTECTIVE AND MITIGATORY MEASURES

9.3.7.1
Various Measures

Lunn (1999) and Lunn et al. (2001) discussed important additional aspects requiring consideration when implementing various concepts for dust explosion protection in practice. Examples are the use of *deflector plates* for guiding blasts and flames expelled from dust explosion vents in a safe direction, accounting for *vent cover inertia* and *pressure losses in vent ducts* when assessing required vent areas, and essential considerations when *complex systems* of process equipment connected by pipelines or ducts are to be protected. Siwek (2001) presented new German guidelines for dust explosion venting at large and special guidelines for protecting fluidized bed installations.

9.3.7.2
Full Confinement by Using Explosion-Pressure-Resistant Process Equipment

An outline of this concept is given in Section 1.4.5 in Chapter 1. The applicability of the concept is limited due to high equipment costs. However, the method is used in some special cases, for example, when the powder or dust is highly toxic and reliable confinement is absolutely necessary. Current experimental methods allow sufficiently accurate prediction of maximum explosion pressures in simple vessels with point source ignition. It should be pointed out that closed-bomb explosion test data for elevated initial pressures may be of limited value for predicting maximum explosion pressures in the case of complex dynamic pressure development, such as in *pressure-piling* situations.

There is considerable room for further improvement in the design of pressure-resistant process equipment, with respect to minimizing its heaviness. The German concept of pressure-shock-resistant design should be developed further. Crowhurst (1993b) has a useful overview of the state of the art on design of equipment to withstand a given internal overpressure caused by a fully confined or vented explosion. Bartenev, Gelfand, and Frolov (1993) developed a mathematical model for the failure of a process vessel subjected to an internal exothermic, comparatively slow, process creating an overpressure by which the maximum initial velocities of fragments or vent covers may be estimated. Bartenev et al. (1994) extended this work to the case where the pressurized vessel is filled with dust. Experiments revealed that the presence of dust can have a significant effect on the pressure development inside the bursting vessel and on the kinematic parameters of the ejected fragments.

Design of protective measures to handle dust explosions at elevated initial pressures requires special consideration. Garcia-Torrent and Menéndez (1993) found that the proportionality between initial and final pressure found previously in small laboratory-scale vessels (see Section 1.3.8 in Chapter 1) also holds in vessels of 1 m^3 volume, at least up to 12 bar initial pressure. In later investigations with various coals, Dennison et al. (1995) and Conde-Lazaro and Garcia-Torrent (1998, 2000) confirmed the proportionality between initial pressure and maximum explosion pressure in closed vessels up to 20 bar initial pressure. This proportionality was also confirmed for biomass dusts by Rautalin and Wilen (1996) and Garcia-Torrent et al. (1998). Pilao, Ramalho, and Pinho (2002) studied the influence of the initial pressure of clouds of cork dust in air on the maximum explosion pressure and the maximum rate of pressure rise generated in a closed 23 liter explosion bomb. It was found that both parameters increased linearly with the initial pressure. Pilao et al. also found that the minimum explosive dust concentration increased linearly with the initial pressure.

9.3.7.3
Explosions in Systems of Interconnected Process Units: Explosion Isolation

The objective of explosion isolation is to prevent dust explosions from spreading from the primary explosion site to other process units, workrooms, and the like. An outline of the explosion isolation concept is given in Section 1.4.4 in Chapter 1. A basic understanding of flame propagation and pressure build-up in coupled process equipment ("interconnected vessels") is required for specification of performance criteria of various types of active and passive isolation equipment. Wingerden and Alfert (1992), Wingerden et al. (1994), and Wingerden, Pedersen, and Eckhoff (1995) reported on dust explosion experiments in a system of two vented vessels connected by a duct. They found that the passage of flame from the primary ignition vessel through the duct and into the second vessel could result in substantially higher explosion pressures there than would have occurred in a single vented vessel of the same size and vent area. The combined reasons for this were pressure piling, jet-initiated high initial turbulence, and turbulent jet ignition in the second vessel.

Further extensive and most valuable large-scale experimental work in this area was reported by Lunn (1992a, 1996), Lunn et al. (1996), and Holbrow, Andrews, and Lunn (1996). These investigations comprised dust explosion experiments in various systems of interconnected vessels of volumes ranging from 2 to 20 m^3. Both vented and fully enclosed systems were studied. The experiments confirmed the findings of Wingerden and Alfert (1992) and Wingerden et al. (1995). In fully enclosed systems, significant pressure piling effects, yielding maximum explosion pressures approaching 20 bar(g), were observed in some experiments. It was also found that the pressure in the primary vessel could rise to higher values than expected for single vessels, but to a lesser degree than in the secondary vessel. The combined effects depended on the connecting pipe diameter, the pipe length, the vessel volumes and their ratio, in which of the two vessels the explosion was initiated, the explosibility of the dust, and the vent areas of the two vessels.

Holbrow, Lunn, and Tydesley (1999) summarized the status on this problem and presented coherent quantitative guidance for design of interconnected process equipment, focusing on the two protection technologies—explosion containment and explosion venting.

Vogl (1994) presented further results from a comprehensive experimental program in Germany on propagation of dust explosions in interconnected process systems (see Section 4.4.7 and Figure 4.66 in Chapter). Pipe lengths up to 48 m and pipe diameters up to 200 mm were used. The influences of a range of experimental parameters on the flame speed and explosion pressure were studied: initial air velocity in pipe, pipe diameter, ignition source location, dust concentration in pipe, and the K_{St} value of the dust. Vogl (1996) presented results from further experimental studies of the propagation of dust explosions in a system consisting of a 9.4 m^3 vented vessel into which powder or dust was conveyed pneumatically at up to 30 m/s through a 25 m long pipeline and immediately extracted pneumatically from the vessel and conveyed further, through another 20 m of pipe, to a cyclone collector. The test dusts were corn starch and wheat flour. With corn starch, flame speeds of 600 m/s were observed in the pipeline. Further aspects of this research program, in particular the prediction of flame speeds in pipes and ducts, were discussed by Roser et al. (1999), whereas Vogl and Radandt (2001, 2002) presented new experimental data on minimum pipe diameters for transmission of dust explosions from one process unit to another. It was found that dust flame transmission could occur in pipes of surprisingly small diameters. For example, with a wheat flour of $K_{St} = 100$ bar·m/s, the dust flame was able to propagate through a 27 mm diameter pipe of at least 12 m length. Based on another extensive series of experiments, Roser et al. (2001) developed empirical correlations for predicting the time that a dust explosion in a process unit of a given volume would need to propagate through a given distance of a duct of a given diameter connecting the process unit to another, neighboring unit. Knowing this time is critical in the design of effective explosion isolation systems to be installed in pipes and ducts connecting to process units in which dust explosions can occur.

Wiemann and Faber (1996) studied experimentally the propagation of dust explosions in a fully closed, coupled system consisting of a 1 m^3 vessel and a 5 m^3 vessel connected by a 10 m long straight pipe of internal diameter 400, 200, or 100 mm. Considerable pressure piling effects were observed, and with maize starch, with ignition in the 5 m^3 vessel, a maximum pressure of nearly 18 bar was observed in the 1 m^3 vessel. Kubainsky et al. (2001) presented results from a series of full-scale experiments, which showed that a dust explosion in a vented filter enclosure can give rise to substantial dust flame propagation back into the upstream raw gas duct, in the direction opposite that of the normal raw gas flow into the filter. It was concluded, therefore, that, in such systems, the installation of effective explosion isolation equipment in the upstream raw gas duct is required.

Various passive and active techniques for interrupting explosions in pipelines have been developed, but there is room for further improvement. If adequate performance can be achieved, passive techniques are clearly more attractive than active ones. Zellweger (personal communication with J. Zellweger, Rico-Sicherheitstechnik, St. Gallen, Switzerland, 1992) described work to improve passive and active isolation valves of the VENTEX type. Closing times (from sensing of the explosion to valve is fully closed) down to 12 ms were obtained for active valves. A simplified VENTEX valve, operating in one direction only, has also been developed. Passive explosion interrupters and diverters based on venting at a 180° bend have been in use for some time. However, there is a need for further exploration of the potential and limitations of this attractive, simple principle of explosion isolation. A new low-pressure-drop design of this kind of diverter was described by Alfert and Fuhre (1992) and Wingerden and Alfert (1992). Glor (personal communication with M. Glor, Ciba-Geigy AG, Basle, Switzerland, 1993) reported on work on the performance of explosion barriers in ducts connected to vessels with venting or automatic explosion suppression. Klincewicz and Kordylewski (1993) described a new design of an active explosion diverter for interrupting explosions in pipelines. The new design avoids the pressure drop created in normal operation by passive diverters but requires active triggering. Moore and Siwek (1996) investigated experimentally the performance of automatic explosion suppression systems for interrupting explosions in pipelines and ducting between process units. Some quantitative design guidelines were given.

Cybulski et al. (1994b), Lebecki et al. (1998, 2000, 2001), developing systems for interrupting coal dust explosions in coal mine galleries, used solar panels for automatic detection of the coal dust flame and simultaneous actuation of water barriers. The water was contained in plastic bags or containers, opened by a detonating cord or charge triggered by the flame-generated power from the solar panel.

Siwek (1996c), in a comprehensive paper covering both dust and gas explosions, reviewed the wide range of isolation techniques available for preventing dust explosions from propagation from one process unit to neighboring units (see Section 1.4.4 in Chapter 1). The paper also provided some quantitative design guidance. Faber (1999) discussed the various types of active and passive explosion isolation technologies in use. These can be grouped in three main categories: complete isolation devices, pressure wave interrupters, and flame interrupters. For some applications, the different concepts can be combined. Xu et al. (1996) investigated experimentally constructive measures, that is, vents in the pipe wall and flame arrestors inside the pipe, for mitigating or interrupting dust explosions in pipelines for pneumatic transport of coal powders.

9.3.7.4
Partial Inerting by Inert Gas

This relatively new, promising concept for mitigating dust explosions deserves further attention. The idea is that, as the oxygen content in the atmosphere is decreased, there is a systematic decrease of both ignition sensitivity and combustion rate of the dust cloud. Some data illustrating this are given in Section 1.3.6 in Chapter 1. In some cases, the explosion hazard may be reduced substantially by only a moderate reduction in the oxygen content. Section 6.6 in Chapter 6 provides a philosophical basis for reducing explosion vent areas by partial inerting. More research seems necessary to establish correlations between the oxygen content in the gas phase and ignitability and explosibility parameters of dust clouds. Some data were produced in the joint European research program CREDIT (1995), focusing on the influence of oxygen content of the atmosphere on the minimum spark energy and hot-surface temperature for ignition of dust clouds.

Zeeuwen et al. (1996) confirmed experimentally that even modest reductions in the oxygen concentration in the atmosphere by partial inerting can increase the minimum ignition energies of dust clouds substantially. The minimum ignition temperatures of clouds and layers were found to be less sensitive to reductions in the oxygen content. The effect of partial inerting on the explosion violence (important for full confinement, venting, suppression, and isolation) was not investigated in this study. Glor and Schwenzfeuer (1996, 1999) provided further information on the influence of the oxygen content in the atmosphere on the minimum ignition energy of dust clouds. Devlikanov, Kuzmenko, and Poletaev (1995) found that, for clouds of nutrient yeast dust in mixtures of air and nitrogen, the explosion violence index k_{St} was a linear function of the percentage of oxygen in the gas phase.

Schacke and Walther (1998) suggested that partial inerting may, in fact, also be a useful concept in preventing gas and vapor explosions. In some cases, it may be possible, by using only modest quantities of inert gas, to reduce the ignition sensitivity of the explosive atmosphere to a level at which marginal potential ignition sources, like electrostatic brush discharges and single metal sparks, are no longer able to cause ignition. Conde-Lazaro and Garcia-Torrent (1998, 2000) carried out a series of partial inerting experiments at 12 bar initial pressure, in a demonstration PFBC pulverized coal power plant. The effects of adding inert gas and inert dust (see below) were investigated.

9.3.7.5
Explosion Venting

This widely used protective method is explained and discussed in Section 1.4.6 in Chapter 1 and in Chapter 6.

In spite of extensive research and development, dust explosion venting remains a complex and in part controversial subject. The key issue in explosion vent arrangement design is *vent area sizing*, and a thorough understanding of flame propagation processes in dust clouds is essential for proper appreciation of the challenges encountered in designing optimal venting arrangements for industry.

Useful reviews of various aspects of dust explosion venting in practice were given by Scholl (1992), Lunn (1992b, 1992c), Siwek (1996b), and Grosskopf (2002). Siwek (1996d, 1998), covering gas explosion venting as well, reviewed material that has in part been the basis of the most recent draft edition of the German VDI 3673 guideline. This guideline, in turn, has been a major input to the dust part of the venting guideline issued by the European Union technical committee TC 305.

The basic understanding of flame propagation processes inside and outside vented enclosures is still unsatisfactory. This implies that neither the processes by which dust clouds in vented enclosures are generated nor the way in which the clouds burn are sufficiently well understood. Consequently, adequate venting theories do not exist, and one must rely on experiments. However, during the last two decades, the *need for a differentiated approach* to assessment of vent area requirements, in view of the different turbulence levels, degrees of dust dispersion, and concentration distributions of dust clouds that occur in practice, has gradually become accepted. Eckhoff (1993b) discussed this problem with particular reference to venting of large silo cells. Deng et al. (1993b) conducted vented maize starch explosions in a 95 m^3 vertical experimental silo of $L/D = 3$. The vent was located in the silo roof. The vent area required for keeping the maximum explosion pressure below a predetermined value was considerably smaller than that predicted by the 1979 VDI venting code. Hoechst, Leuckel, and Eibl (1993) conducted systematic maize starch/air explosion experiments in a top-vented silo of volume 50 m^3 and $L/D = 4$. Both dust concentration and initial turbulence (prior to ignition) were monitored. Both the dust injection process and the ignition point location were varied. Flame propagation and pressure buildup during the vented explosion were measured. Comparative experiments with methane/air in the silo were also performed. Hauert (1996), Arnold et al. (2001), and Hauert et al. (2001) presented the results of a series of large-scale wheat and maize dust explosion experiments in a vertical 12 m^3 top vented silo of $L/D = 3$. They found that horizontal pneumatic dust injection tangentially at the silo top gave considerably lower maximum pressures for a given vent size, than both pneumatic dust injection vertically downward, and dust injection by the traditional VDI pressurized-nozzle technique. Both turbulence intensities and dust concentrations in the experimental dust clouds were measured.

A similar trend was found by Zockoll et al. (2001), who performed controlled vented dust explosion experiments in a hammer mill grinding plant, as used in the animal feed industries. Their overall conclusion was that, in a real plant, the vent areas required to ensure given maximum reduced explosion pressures were substantially smaller, typically by a factor 3–4, than those specified by the VDI-3673 guideline. This is not surprising in view of the extensive discussion of these effects given in Chapter 6. Holbrow, Lunn, and Tyldesley (2002) reported results from a comprehensive experimental program on venting of dust explosions in full-scale bucket elevators. Both a single-leg elevator (total height about 25 m) and a twin-leg elevator (total height about 18 m) were used in the experiments. A number of vent openings were distributed along the length of the elevators. The dusts used were a milk powder and three different types of corn flour. On the basis of the results obtained recommendations were given for design of vent arrangements for bucket elevators in industrial practice.

Tamanini and Valiulis (1996) presented an improved version of the VDI and NFPA (National Fire Protection Association, United States) guidelines for sizing of dust explosion vents. The improvement was achieved by systematizing the data in the context of a simplified physical model of the vented explosion. In this way, it was possible to obtain approximate predictions of the effects on the required vent area, of elevated initial pressure, deflagrations in only part of the enclosure volume, vent ducts, and inertia of the vent cover (panel).

A similar, more recent contribution was made by Ural (2001), who developed a unified formula for vent sizing covering all cases within a restricted domain. The restrictions were *L/D* close to 1, the entire volume filled with turbulent explosive dust cloud, atmospheric initial pressure, vent cover opening pressure much greater than the maximum pressure in vented explosion, and negligible inertia of the vent cover. For these conditions, Ural was able to correlate available data, using two basic dust parameters: the burning velocity of the turbulent dust cloud under the prevailing conditions and the constant-pressure expansion ratio for combustion of the dust cloud in question. For a given dust, the two parameters were derived from the pressure-versus-time data obtained in closed-bomb tests with that dust.

CEN (2002) prepared a new standard for design of dust explosion venting systems, which, in principle, opens up a diffentiated approach to vent sizing that accounts for the variations in dust cloud structures encountered in practice in industry. In most practical cases, this will result in more liberal vent area requirements than those of some previous rigorous standards, as discussed by Eckhoff (2003).

In CEN (2002) this is expressed (slightly modified) as:

> In situations of moderate or low cloud turbulence, and in situations where non-homogeneous dust clouds or low dust concentrations are the norm, the standard procedure for assessing the explosion violence of the dust is likely to overstate the explosion hazard. In such circumstances a reduced vent area can be used, based on either published or new experimental data obtained form representative vented explosion trials.

A main conclusion from an experimental study on venting of gas explosions by Alexiou, Andrews, and Phylaktou (1996) is no doubt also applicable to dust explosion venting: From the point of view of minimizing the pressures from accidental explosions in vented elongated enclosures, the vent area should be distributed on several vent openings, spread out throughout the length of the enclosure. A main issue is then to minimize the distance from any possible point of ignition to the nearest vent opening.

Molkov et al. (1993) studied experimentally the *influence of the inertia of the vent cover*, on the gas dynamics of the venting process. Good agreement was obtained between pressure-versus-time traces from experiments, and corresponding traces obtained using the numerical simulation code DYNAMICS. Fan Xisheng and Li Li Wu Jianxing (1994) studied, theoretically as well as experimentally, the influences of details of the mounting flange arrangement on the static bursting pressure of bursting panels and membranes. They observed two distinctly different bursting patterns, bursting of the membrane in its central region and bursting along the edge. Based on the results from their large-scale experiments Hoechst and Leuckel (1996) reported that increasing the mass/inertia of the vent cover does not necessarily cause an increase of the maximum explosion pressure in vented enclosure. Complex interactions of increased flow rates causing increased turbulence and combustion rates, and hence increased rates of pressure rise, inside the vented enclosure can explain this. Faber (1996) also discussed the influence of deviations from ideal performance of vent covers (immediate complete opening of vent at P_{stat}) on the required vent area. By introducing a vent opening efficiency factor $0 < E_F < 1$, Faber defined the relation between the vent area for ideal covers, A_E, and the area actually required, A_N, as $A_N = A_E/E_F$. Tamanini (1996c) presented a model of the effect of the inertia of vent covers, on the efficiency of the venting process, based on a simplified lumped-parameter approach.

A further dimension of complexity is added to the venting problem if the initial pressure (or temperature) deviates from atmospheric. Results from *venting of dust explosions in air of elevated initial pressure* were reported by Siwek, Glor, and Torreggiani (1992).

In dust explosion venting, maintaining the integrity of the enclosure is not the only concern. Venting implies that both *pressure waves and flames are emitted into the surroundings*; and this may present a hazard, depending on the size of the emitted flame and the magnitude of the blast wave. Crowhurst, Colwell, and Hoare (1994) and Crowhurst et al. (1995) reported from a series of large-scale venting experiments (40 m^3 and 20 m^3) where external blast waves and flame lengths were determined and compared with existing empirical correlations. Schumann and Rastogi (1995) presented further data of lengths and velocities of the flames expelled from the vent of a 1 m^3 vessel in the case of dust explosions in the vessel. Peng et al. (1994) developed a labyrinth-type flame arrester for mitigating flame and pressure and pressure effects from dust explosion venting. Experiments with a 2.7 m^3 vented enclosure suggested that this arrester concept works satisfactorily for St1 dusts. The maximum explosion pressures in the vented enclosure, with the arrester mounted in the vent, were only a few percent higher than the pressures without the arrester, whereas both flame and pressure effects were substantially reduced. As a part of an extensive program of large-scale vented dust explosion experiments, Crowhurst et al. (1996) investigated the characteristics of explosion pressures measured around complex structures near the vented explosions. They were able to suggest some empirical equations for estimating expected pressures in various locations relative to the vented enclosure.

Forcier and Zalosh (2000) reviewed various correlations of experimental data that have been developed for estimating *external pressures* to be expected from vented dust and gas explosions. In addition, they explored the possibility of applying approximate spherically symmetric and elipsoidal blast wave models. The results indicate that the simplified models can produce predictions in good agreement with the more complex data correlations.

Harmanny (2001) reexamined some existing guidance on *blast emission* into the surroundings by vented dust explosions, by taking into account a well-established relationship predicting blasts from vented underground ammunition storage explosions. Existing guidance tends to overestimate the near-field blast effects and underestimate the far-field effects. The predictions according to the revised approach are in considerably better agreement with experimental data than predictions by the existing guidance.

Holbrow, Hawksworth, and Tyldesley (2000) described a research project studying the effects of *thermal radiation* from vented dust explosion flames. The objective was to establish critical borderlines around a dust cloud fireball, beyond which the thermal radiation would no longer be a risk to people. Dust explosions were created in a large vented vessel, using six dusts and a range of different experimental conditions, and the thermal radiation pulse from the fireball expelled from the vessel was measured at various distances from the fireball.

Li et al. (1994) presented a new version of the *Q-pipe*, which was first developed in Norway (see Section 1.4.6.6 in Chapter 1), in which the conventional bursting diaphragm had been replaced by a reusable vent cover. This solution is of interest in situations where the expected frequency of explosions is comparatively high. Emde and Penno (1996) discussed further improvements of the design of Q-pipes for flame-free dust explosion venting, allowing a significant reduction of the size of the Q-pipe, for maintaining a given P_{red} with a given vent area, compared to the Q-pipe size required with the previous design concept.

The influence of *vent ducts* on the maximum explosion pressure in the vented vessel has been studied experimentally by several workers. Ural (1993) presented a theoretical model for vented gas explosions by which he was able to calculate pressure-versus-time characteristics in the vented vessel that agreed well with corresponding experimental data. It remains to be investigated, however, whether this theory can reproduce existing experimental data for dust explosions. Tamanini (1995a, 1995b) formulated a set of model equations of the dynamics of the processes taking part in the duct during venting. The equations rested on the assumption that inertia and friction in the duct are the main flow controlling processes. By analyzing the equations Tamanini identified three dimensionless groups of variables that characterize the venting process. Finally, he fitted his model to the experimental data of Lunn et al. (1988) (see Section 1.4.6.5 in Chapter 1). Good agreement was found between theoretical predictions and the conservative envelopes of experimental data, over a range of vented-enclosure volumes from 0.2 m^3 to 20 m^3. Griesche (1996) discussed the special case where the vent cover is placed at the duct exit, as opposed to the more common location at the duct entrance. By correlating data from lignite dust explosion experiments in 1.2 and 10 m^3 vessels fitted with ducts of various lengths and diameters, he found an empirical relationship for estimating reduced explosion pressures for cases where the vent cover is located at the vent duct exit. Lunn et al. (1998) discussed the effects of vent ducts on the maximum pressures generated in vented dust explosions in dust collectors, whereas Lunn (2001) used the U.K. Institution of Chemical Engineers guidance for design of vent ducts to illustrate the increase of the reduced explosion pressure that inclusion of bends in a vent duct can produce. He also suggested a consistent method for quantifying this effect in the context of the current European standard for design of venting systems.

Ponizy and Leyer (1999a, 1999b) conducted an in-depth experimental study of the flame dynamics in a vented vessel connected to a duct, using propane/air as the explosive mixture. A main conclusion was that the change of the combustion regime inside the vessel that causes the increased maximum explosion pressure experienced with ducts is driven by an impulse generated in the initial part of the duct shortly after the flame front has entered it.

Tamanini and Valiulis (1998a, 2000) presented a new theoretical approach for predicting the resultant *reaction impulse* acting on a process structure during a vented explosion. This applies to situations where the peak of the explosion pressure pulse cannot be regarded as quasi-static with respect to the response of the actual vented structure. The equations obtained by Tamanini and Valiulis were extensively validated by comparison with data from actual vented dust explosion experiments in vessels of volumes ranging from 0.64 m^3 to 95 m^3. It was concluded that some previously published methods grossly overestimate the expected resultant impulse.

Nasr and Eibl (2001) described a complete system for predicting the course as well as the consequences of vented *dust explosions in silos*, comprising both a numerical dust explosion model and a finite-element-based model for the structural response. The model predictions were supported by results from experiments in a 50 m^3 reinforced concrete silo.

Venting of industrial buildings requires special considerations. A useful overview was given by Crowhurst (1993c). Höppner (1996) discussed the design of dust explosion venting arrangements for rooms and buildings of volumes >5000 m^3, with walls that can withstand overpressures of only <0.2 bar. In a dust explosion, only part of such large volumes are filled with the explosive dust cloud.

Improvement of current *dust explosion venting guidelines* is still needed. The German draft VDI-3673 venting guideline, issued in 1992, encountered some objections in other countries. This applies, in particular, to the concept of "heterogeneous" dust clouds. Nevertheless, computer-based "software" for easier use of this draft guideline was presented by Alfert (1993). Hattwig and Hensel (1993) discussed deficiencies in the new VDI draft guideline on the basis of dust explosion experiments in 45 m^3 ($L/D = 2$) and 85 m^3 ($L/D = 4$) vented silos of square cross sections. Eckhoff (2003) reviewed experimental evidence in support of a more relaxed approach to vent sizing.

As discussed in Section 9.2.4.8, Tamanini (1996b, 1998a, 2001) suggested that scientifically based approximate vent design tools, which also account for turbulence effects, can be readily obtained by adopting lumped-parameter descriptions of the actual systems. Tamanini (1998b) proposed that this kind of simplified scientific model be used in future revised vent design guidelines to replace the entirely empirical statistical correlations used so far. Tamanini (2002) summarized his valuable effort of correlating existing experimental dust explosion venting data by applying the classical method of dimensional analysis. It is regrettable that this important work has not been included in the recent European Union guideline for design dust explosion venting arrangements, CEN (2002).

However, the ultimate long-term solution for the design of explosion venting arrangements will be *comprehensive computer models*, capable of predicting propagation of dust explosions in variety of complex coupled process systems encountered in the process industries. Such models are being developed worldwide at great pace and are likely to become the answer in practical design in a not too distant future (see Section 9.2.4.)

9.3.7.6
Automatic Explosion Suppression

This active method for dust explosion mitigation, described in Section 1.4.7 in Chapter 1, is comparatively complex and expensive. It is used when simpler, less expensive methods cannot be applied. Although automatic dust explosion suppression has been in use for several decades, improvements are made continuously through research and development. Moore (1992a) reported that the *number of suppressant bottles* of a given size required for suppressing explosions of a given dust in a given vessel was reduced by a factor of 0.2–0.3 when the dust clouds were generated by industrial pneumatic injection rather than the VDI method used in previous experiments. Glor (personal communication with M. Glor, Ciba-Geigy AG, Basle, Switzerland, 1993) and Moore (1992b) reported on work on the possibility of applying automatic explosion suppression even in the case of highly explosible organic dusts of $K_{St} > 200$ bar·m/s. In the case of aluminum powders, satisfactory suppression has not yet been achieved for powders of K_{St} > 200 bar·m/s, which means that only dust explosions in clouds of relatively coarse aluminum powders can be suppressed. The influence of the dynamic state of the dust cloud at the moment of suppressant injection, the influence of the suppressant injection on this state, and development of improved suppressants are some areas for further research.

Experiments have indicated that *water can be an effective suppressant,* if injected at a temperature >180°C. According to Tyldesley (personal communication, November 1993), optimum suppression requires about 0.5 liters of water per m^3 of vessel volume. Of the superheated water, 16–18% is flashed to steam, the remainder forms very small droplets. Reduced maximum explosion pressures of 0.3–0.4 bar(g) were obtained in experiments in a 28 m^3 experimental vessel, using a dust of K_{St} = 150 bar·m/s. Moore (1996a) considered the various types of suppressants employed in automatic dust explosion suppression systems. After the use of "halons" became highly restricted due to the environmental problems caused by these substances, the chemical industry identified a range of alternative agents that are environmentally acceptable and at the same time have good fire-extinguishing properties. Moore discussed the *desired properties of an explosion suppressant* in general and compared the effectiveness of available suppressants. Dastidar et al. (1998) determined the minimum concentrations of inert powder/powdered suppressant (MIC) required to effectively prohibit flame propagation at any concentration of the explosible powder or dust. Knowing this parameter can facilitate the design of optimal explosion suppression systems. Moore and Dunster (2001) discussed the influence of various key parameters on the performance of automatic explosion suppression systems, with reference to results from experiments and modeling. Tailoring, accounting for the intimate relation between hardware design and suppressant properties, is essential to ensure optimal system performance.

Gieras et al. (1994) conducted a series of experiments to optimize the shape and mass of the *explosive charge used for automatic release* of suppressant (powder) for suppressing dust explosions. The overall aim of the research was to minimize the powder ejection time after the onset of the dust explosion had been detected. Gieras, Klemens, and Wolanski (1996b) and Klemens et al. (1998a, 2000a) developed and tested this system further and reported that the exit seals of their pressurized suppressant containers could be blown open within a fraction of a ms. In a subsequent experimental study, Gieras and Klemens (2002) compared the effectiveness of water spray, inert dusts, and common pulverized suppressants for suppressing explosions of organic dusts in a closed 1.25 m^3 chamber.

Siwek and Moore (1995) and Moore and Siwek (1998) summarized their extensive work on suppression of dust explosions and added some further data that filled significant gaps in previous knowledge and enabled thorough revision of some commonly used *design nomographs.* The papers provide useful updated guidance to engineers having to specify suppression system requirements for specific industrial applications. Moore (1996b) paid particular attention to the choice of suppressant and the close interaction between the chemical and physical properties of the suppressant and the optimal design of the system for injecting the suppressant into the flame to be suppressed. Chatrathi and Going (1998) compared the effectiveness of three different suppressants—sodium bicarbonate, monoammonium phosphate, and rock dust—for suppressing dust explosions. The dusts used in the tests were of coal, maize starch, polyethylene, anthraquinone, and aluminum. It was concluded that specific heat, thermal conductivity, particle size and shape, and the mechanism of particle decomposition were important parameters deciding the effectiveness of the suppressants tested.

Lebecki et al. (1998, 2000) investigated the possibility of using solar panels as flame detectors for activating triggered barriers of water or stone dust for suppressing coal mine explosions. The yellow light emitted by the burning coal dust particles is an effective activator of the solar panels. It seems reasonable to anticipate that this flame detection method may also be suitable for some applications of explosion suppression in the process industries.

Chatrathi (1996) and Chatrathi and Going (2000) gave overviews of the current technology and philosophy for implementing automatic explosion suppression systems in practice, whereas Moore and Siwek (1999) outlined the content of the new European Union CEN TC 305 standard for design of systems for automatic suppression of accidental explosions in the process industries. The standard also covers the methodology to determine the efficacy of designed systems.

Siwek and Moore (1996), after discussing results from both gas and dust explosion suppression experiments, presented experimental results from suppression of explosions in *hybrid mixtures* of propane and an organic dust in air. It was found that both the maximum reduced explosion pressure and the maximum rate of pressure rise increased approximately linearly with the propane content in the range 0–4 vol%.

Brehm (1996) investigated experimentally the influence of *elevated initial temperature* of the explosive dust cloud on the efficacy of an automatic explosion suppression system. The test dust was maize starch and the two initial temperatures used were 20 and 150°C. It was found that the maximum reduced explosion pressures both increased and decreased with increasing initial dust cloud temperature, depending on other experimental conditions.

The European standards organization CEN (2001) produced a draft standard for explosion suppression systems, which seems to open up for greater flexibility than the traditional, mostly very conservative approach outlined in Section 1.4.7.2 in Chapter 1. For example, if the turbulence level or degree of homogeneity of the cloud of a given dust in the actual process situation is lower than produced by the rather conservative traditional standard VDI-method of dust cloud generation, this can be accounted for in the process design. In the new standard, this is expressed as follows (slightly edited):

> In situations of moderate or low turbulence, and/or in situations where non-homogeneous dust clouds is the norm, the standard procedure for assessing the explosion violence of the dust is likely to overstate the explosion hazard. In such specific circumstances, explosibility characteristics obtained from systematic representative explosion trials at the actual process conditions may be used as a basis for designing the suppression systems.

Comprehensive numerical modeling of the complex explosion suppression process, based on computational fluid dynamics, is likely to become a useful tool for analyzing and optimizing the performance of explosion suppression systems. Morgan (2000) assessed the suitability of commercially available CFD software for modeling the types of flows encountered in explosion suppression processes. Using results from his model simulations, he was able to design a novel suppressant injection nozzle, which was shown to be more effective than the standard nozzles currently used.

9.3.7.7

Design of Process Equipment for Specified Internal Explosion Loads

This problem is always a central concern when designing explosion protection systems, whether they are for full explosion confinement, explosion isolation, explosion venting, or automatic explosion suppression. Crowhurst (1993b) discussed the general design of enclosures to withstand a given maximum explosion pressure, whereas Harmanny (1993) presented a new formula for predicting the duration of vented dust explosions in enclosures of volumes from 10–60 m^3. This is useful for evaluating whether static pressure considerations or impulse considerations apply when predicting the response of the enclosure structure to the explosion load.

Harmanny (1996, 1999) revisited the problem of assessing the structural response of a given process equipment to explosion loads. With regard to dust explosions in the process industries, he concluded that most often they are sufficiently slow for the load to be regarded as quasi-static. However, there are certain cases where dynamic effects play a significant role. There are, so far, no established design methods for structures responding nonlinearly to the explosion loads. Often accurate determination of the explosion pressure resistance of structures, such as various process equipment, is very difficult, because of their complex shapes and lack of essential detailed information on materials and methods of manufacture. Comprehensive finite-element-based computer codes for determining detailed stress/strain analysis of complex structures subjected to defined static and dynamic loads have been available for some time. It is foreseen that the use of such tools in assessing the explosion strength of complex structures, such as various process equipment, will increase in the years to come.

Li et al. (2002) studied experimentally the *plastic deformation* generated in a 1100 mm × 1100 mm square steel plate with a 440 mm × 440 mm square central hole, by pressure pulses typical of those produced by dust explosions in process equipment. The pressure pulses were generated by suddenly releasing large amounts of precompressed air from a pressure tank fitted with an outlet of large diameter and a fast-opening valve. It was found that existing finite-element-based computer software, assuming quasi-static pressure loading, predicted the observed deformations in the test plate well, also for plastic deformation, if this was not excessive. Mavrot et al. (2003) investigated the ability of large concrete silos to withstand transient internal loads from dust explosions.

9.3.7.8
Preventing Secondary Explosions Outside Process Equipment

This remains a very important issue in any effort to fight the dust explosion hazard. Adequate housekeeping is an essential means of achieving this aim. A brief introduction to this concept is given in Section 1.4.9 in Chapter 1. However, there are still unanswered questions concerning the level of cleanliness required, and further work is needed for assessment of the maximum acceptable mass of deposited dust per unit area of surface to prevent secondary dust flame propagation under various conditions. Cybulski et al. (1993) showed that comparatively weak secondary dust explosions in short, narrow tunnels in grain elevators can be extinguished by properly designed, actively triggered water barriers. Cybulski et al. (1994) presented results of experiments with propagation of weak coal dust explosions in a network of full-scale mine galleries. A main conclusion was that, under the conditions prevailing, the possibility of flame penetration into blind gallery branches was small. This kind of work may also be of relevance to the analysis of flame propagation in large industrial systems, such as in grain storage and handling plants.

Gieras, Klemens, and Wolanski (1993) studied the development of combustible gases (H_2, CO, and CH_4) during combustion of fuel-rich clouds (up to 5 kg/m^3) of grain dust in air. This is an important aspect in the context of industrial safety, because mixtures of combustible gases and air can give rise to severe secondary gas explosions following comparatively slow primary fires in fuel-rich dust clouds.

9.3.7.9
Miscellaneous

Michelis (1996) investigated the influence of different underground roadway configurations on the course of coal dust explosions in underground coal mines. Lorenz and Radandt (1996) presented a method for calculating trajectories and flying distances of fragments of solid materials emitted from exploding silos, other process equipment, and buildings. Calculated results were compared with experimental data and data from actual dust explosions. Loock et al. (1996) presented a systematic approach for assessing the hazard impact that potential dust explosions in industrial plant handling various natural organic dusts have on the near neighborhood.

9.3.8
RISK, SAFETY, AND HAZARDS ANALYSIS

A brief introduction to this topic is given in Section 1.5.1.3 in Chapter 1. Quantitative risk analysis (QRA) receives increasing attention as a potential means of controlling explosion risks in the process industries. This also applies to the dust explosion hazard. The subject is complex and in part controversial, not least because of lack of relevant quantitative failure rate data. Nevertheless, attempts have been made at applying QRA to the dust explosion problem, as demonstrated by Wagner (1994). Mittal (1994) discussed the risk of dust explosions in pneumatic powder transportation systems. Potential sources of ignition were identified, with the main focus on electrostatic discharges. A systematic risk evaluation and risk reduction approach was outlined. Liu and Wang (1994) proposed a quantitative, computer-based "decision support system" for assessing the explosion hazard and taking appropriate actions to prevent and mitigate coal dust explosions in metal production plants. Moore and Freehill (1994) outlined a philosophy for systematic analysis of the risks of dust explosions in industrial plants. Specific technical solutions for preventing and mitigating explosions for some typical cases were proposed. Radandt (1996b) outlined the philosophy of risk identification and risk reduction in relation to prevention and mitigation of industrial explosion hazards, on which the European Union "Atex 118a" Directive is based. This directive applies to gas and vapor explosions as well as to dust explosions. In a subsequent paper, Radandt (1999) emphasized the importance of having adequate process knowledge when identifying process risks and suitable measures for risk reduction.

9.3.9
HUMAN AND ADMINISTRATIVE RISK AND HAZARD FACTORS: RISK AND SAFETY MANAGEMENT

This book primarily covers the chemistry, physics, and technology of dust explosion prevention and mitigation. However, human hazard factors also play a very important role and have to be controlled, as discussed by Fernando (1993). A brief introduction to this important, but complex topic is given in Section 1.4.12 in Chapter 1.

Brascamp (1996) pointed out that industrial disasters, such as dust explosions, are often not simply a consequence of direct technical failure or operators not executing their tasks correctly. Quite frequently, the basic, underlying reason turns out to be lack of adequate formal safety management systems. Various aspects of safety management were discussed in a series of papers presented at an international symposium organized by the European Safety Management Group (2001). Barth (2001) emphasized the importance of companies establishing systems for explosion risk management control to ensure effective, long-lasting explosion protection of their plants. He outlined possible structures of such systems. With particular reference to the pharmaceutical industry, Hesener, Barth, and Dyrba (2001) underlined the need for having adequate systems for explosion risk management and control even in small and medium-size plants.

9.3.10
COSTS OF EXPLOSION PREVENTION AND MITIGATION

Alfert (1996) addressed the issue of the bottom-line costs of various dust explosion protection systems offered on the market. Considerable gains can result if measures to increase the inherent safety of the process plant are combined with traditional measures for dust explosion prevention and mitigation. However, this requires that the specific expertise covering traditional explosion prevention and protection be combined with intimate knowledge of the process to be protected.

Janssens (2001) pointed out that the investment required to achieve proper prevention and control of the explosion hazard in a given plant is not necessarily excessive. By combining thorough knowledge of the processes to be protected, ignition and flame propagation phenomena, and the principles and technologies available for explosion control, good solutions can be obtained at an acceptable cost.

9.3.11
NEW EUROPEAN UNION LEGISLATION TO PREVENT AND MITIGATE ACCIDENTAL EXPLOSIONS

Radandt (1996a) outlined the new European Union (EU) framework of directives for protection against accidental explosions, based on the Articles 100a (minimum requirements to products and equipment) and 118a (minimum requirements to the use of products and equipment at work) of the European Union Treaty. Radandt (1996c) discussed the structure of the new European Union system of standards for preventing and mitigating dust explosions, based on the EU Directives 89/392 and 94/9. Grass (1999a) outlined the implications of the European Union Directive 94/9/EC ("Atex 100a") on apparatus design standards for preventing and mitigating accidental dust explosions. Grass (1999b) described the European Union Directive "Atex 118a" as the "social counterpart" to the "Atex 100a" Directive. "Atex 118a" lays down minimum requirements for the safety and health of workers potentially at risk from explosive atmospheres, including explosive dust clouds. Central issues include area classification, written instructions and permits to work, and programs for training workers. Ehlers (1996) summarized the positive and negative impacts of the new European Union system of standards and guidelines for preventing and mitigating dust explosions in the process industries, as observed from a food producing company. Hattwig (1996) summarized the work performed to develop new standards for dust explosion prevention and mitigation in the process industries, by the three independent technical committees: CEN/TC 114, CEN/TC 305, and CENLEC/TC 31. Rogers (1996b) outlined the work performed by the European Union working group CEN/TC 305/WG 2 on developing standards for nonelectrical apparatus to be used in explosive atmospheres, including explosive dust clouds.

Makin (1999) described the essential features of the European Union Machinery Directive, with particular emphasis on the links to the "Atex 100a" Directive in matters related to accidental explosion risks. Wingerden (1999) described the basis and philosophy underlying the development of the new explosion venting standard produced by the European Union CEN/TC 305.

Various aspects of the Atex approach adopted by the European Union were discussed by Radandt (2001), Grass (2001), Carruthers (2001), Dyrba (2001), Uth (2001), Ott (2001), Rogers (2001), Wingerden (2001), Pineau (2001), Fuchs (2001), and Dill (2001). These included superior legal issues such as the relationship between national and European Union law, various Atex directives, and a range of specific technical standards.

Feitenhansl (1996) outlined the new European Union system of standards and guidelines for testing, certifying, and control related to prevention and mitigation of dust explosions in the process industries. Griesche (2001) and Fritsch (2001) discussed the procedures required by the European Union for testing and certifying specific commercial apparatus to be used in dust explosion protection in the process industries. Jockers (2001) and Unruh (2001) focused on the problem that, in the new European Union system, a given apparatus has to comply with several different standards.

9.4

STATUS AND OUTSTANDING PROBLEMS IN TESTING DUST IGNITABILITY AND EXPLOSIBILITY

9.4.1

HISTORICAL BACKGROUND AND INTRODUCTION

The testing philosophy and test methods are discussed extensively in Chapter 7. When some of the older test methods were designed, the ambition was, in fact, quite modest. The original intention was just to establish some relative measures of properties of practical relevance to preventing and controlling or mitigating dust explosions. Later, some of these methods were adopted as official standards, and test data were sometimes treated as basic physical constants for a given dust to an extent far beyond the original purpose of the test. As more knowledge from systematic research became available, the lack of justification for this use of these test data was pointed out and the arbitrary, relative nature of the various test methods was brought to light again.

The current situation is complex. It is realized that only a few of the dust parameters currently being used to characterize the ignition sensitivity and explosibility of dusts can be regarded even as approximate "physical or chemical constants" for a given dust. In most cases, a great number of variables are involved and a differentiated view is required.

In general, measurements or testing may be conducted on various levels of resolution, ranging from pragmatic full-sale testing to highly detailed microscopic measurements. However, all the way through, twin sets of measurable parameters and matching theory can be envisaged. Sometimes, the test result is applied directly to industrial practice, with no transformation, which implies the assumption that the "theory" is just a factor of 1. This may apply to minimum ignition energies, minimum ignition temperatures, and flame propagation limits. However, most often, some transformation of the test result ought to be performed to obtain parameters relevant to the actual practical situation. But adequate transformation theories are scarce.

A number of standard test methods have been developed through the years, for example, by the IEC (International Electrotechnical Commission) and ISO (International Standards Organization). In the United States, the ASTM (American Society for Testing and Materials) issued a number of standards in this area. The standards organization of the European Union, CEN, in the early 1990s, launched a multiyear program to produce a series of standard methods for testing of explosion propagation limits, ignition sensitivity, and explosion violence of combustible dust clouds.

Siwek (1996a) reviewed of a variety of test methods in use within the Swiss/German domain, and Cashdollar (1996) reviewed extensive work by U.S. Bureau of Mines to predict ignitability and explosibility properties of coal dusts from laboratory-scale tests. Nifuku, Matsua, and Enemoto (1998, 2000) described a series of standardized test methods used in Japan to determine the ignitability and explosibility parameters of combustible dusts. Some specific concerns when applying these test methods to metal dusts were discussed by Matsuda et al. (2001). Dahn and Dastidar (2002) developed a new test method to investigate the ability of propagating brush discharges to stir up and ignite layers of fine combustible dust on a electrically charged insulating surface backed by a grounded conductor.

Beck (2001) announced that the unique BIA collection of ignitability and explosibility test data for more than 4000 dust samples, given in Beck et al. (1997), had been made accessible on Internet.

9.4.2
TWO APPROACHES FOR ACHIEVING DIFFERENTIATION

One approach for handling the increasing requirement for differentiation is to have several test methods for any given parameter, allowing for test conditions to be selected according to the practical use of the test result. In the case of minimum ignition energy, such an approach has been incorporated in the new IEC standard, issued in 1994. Whereas an appreciable inductance is to be included in the capacitive discharge circuit in standard testing, to obtain the most incendiary sparks, this is not considered relevant if the test result is to be used for assessing the electrostatic spark ignition sensitivity of dust clouds.

A similar approach would be possible when testing for explosion violence. It is now widely accepted that the standard ISO K_{St} value of a given dust reflects a rather extreme combustion rate in the conservative direction, because the turbulence level and the degree of dust dispersion in the test are rather extreme. If K_{St} values are still to be used for sizing explosion vents, differentiation may be obtained by varying the intensity of the dust cloud formation process in the test to fit the practical situation of interest. The work by Liu et al. (1994) is relevant in this context. They described introductory studies of the turbulence structure in experimental dust clouds in the 1.2 liter Hartmann bomb under various conditions of dust injection. The Hartmann bomb was traditionally used to characterize the explosion violence to be expected from various dusts, but because of its small size, it has been replaced by larger test vessels.

In an alternative approach for obtaining the required differentiation, the measured dust ignitability or explosibility parameter is of a more basic nature. Differentiation to meet various practical situations in industry is then obtained via suitable theories, using the measured basic parameter as input.

In explosion violence assessment, the K_{St} parameter would then be replaced by, for example, the laminar burning velocity of the dust cloud. The dust cloud combustion process in the actual industrial situation could then be computed by means of a suitable theory. However, theories for transforming such basic parameters to flame propagation rates in practice must imply complex fluid dynamic computer simulation codes, as discussed earlier in this chapter.

In the minimum ignition energy, the basic approach would imply that the basic energy value obtained in the test be converted to minimum energies for ignition of the same dust cloud by various kinds of specific discharges, such as direct electrostatic two-electrode sparks, break flashes (e.g., live wire rupture), and various electrostatic one-electrode discharges. But adequate theories are scarce and time may not be ripe to fully adopt this approach yet. However, Eckhoff (2002) proposed a way in which the MIE of a dust, by means of simple classic theory, can be transformed to conservative estimates of the complete capacitive and the inductive "ignition curves" required for designing intrinsically safe electrical equipment that can be used in the presence of explosive clouds of that dust. (A comprehensive discussion of this topic is given in Chapter 8.)

9.4.3
NEW TEST METHODS

Breum (1999) investigated systematically the parameters influencing the "dustiness" of a range of powders as measured by a rotary drum tester.

Siwek and Cesana (1994) presented a new test apparatus to determine the minimum electric spark ignition energies of dust clouds down to below 1 mJ spark energy. The measurements in the low-energy range are demanding and require carefully designed equipment and skilled personnel. Zhou, Tan, and Yu (1994a) discussed the features of an apparatus for determining the minimum electric spark energy for igniting very sensitive explosives such as lead azide. Spark energies as low as 1 μJ were attainable using a traveling-electrode system.

Choi et al. (2001) attempted to use the vibrating-sieve method to generate the explosive clouds in minimum electric spark ignition energy tests. For readily dispersible powders, this worked satisfactorily. However, in the case of fine, cohesive powders, it was not possible to obtain adequate dispersion of the particles, and the apparent MIE obtained for such a powder was much higher, by a factor of about 10, than the value found when the dust cloud was generated by an air blast.

In their useful review of methods for determining powder "flowability" properties at large, Jong et al. (1999) mentioned two methods for determining the dispersibility, or "dustability," of powders. (See also Chapter 3 and Section 7.4.2 in Chapter 7). Dahmann and Möcklinghoff (2000), in the context of industrial hygiene, also described a methodology for testing the "dustability" of industrial powders, which may be of interest in the present context.

The European standardization organization CEN has issued a series of new standards for testing dust ignitability and explosibility (CEN, April 2001, 2003a, 2003b, 2003c, 2003d). ASTM (2001) in the United States is annually bringing an updated review of their standards.

9.4.4
DETERMINING THE LIMITS OF FLAME PROPAGATION: A PROBLEM OF THE SCALE OF THE EXPERIMENT

Reliable assessment of whether or not a given dust cloud can propagate a self-sustained flame constitutes the basic test objective in the assessment of both introductory dust explosibility/nonexplosibility and the minimum explosive dust concentration (MEC) and limiting oxygen concentration for inerting (LOC). However, great care must be exercised in designing such tests. A basic inherent problem is that, near the limits, self-sustained flame propagation cannot be established unless a considerable amount of energy is supplied to initiate flame propagation. Hence, if the volume of the experimental dust cloud is too small, it is difficult to assess whether observed flame propagation is truly independent of the ignition source. Some results by Cashdollar et al. (1992) and Cashdollar and Chatrathi (1992) are of fundamental significance in this context. They found that clouds in air, at normal ambient conditions, of an anthracite coal dust of 8% volatile matter did not show self-sustained flame propagation in a 1 m^3 test chamber, even when exposed to a 30 kJ chemical ignitor. However, in a 20 liter chamber, fully developed explosions were generated even with a 5 kJ chemical ignitor. The reason for this could be that, in the smaller chamber, the initial combustion and expansion of the dust cloud was directly supported by the ignition source. The pressure and temperature in the unburned cloud ahead of the flame would then have increased significantly above ambient when the flame eventually propagated without support from the ignition source. Consequently, the self-sustained flame propagation, if any, would then occur in an adiabatically precompressed dust cloud, rather than in a cloud of normal ambient temperature and pressure. These results suggest that great care must be exercised whenever comparatively small chambers, in particular, closed ones, are used to determine any explosion limit. Going, Chatrathi, and Cashdollar (1998, 2000) carried out a further parallel experimental determination of MEC and LOC in a 20 liter spherical vessel and the standard (ISO) 1 m^3 vessel. The results confirmed that the limits determined in the 20 liter vessel vary significantly with the energy of the pyrotechnical ignition source used. A 2.5 kJ ignition source gave the closest match to the data obtained in the 1 m^3 vessel.

Wiemann (1996) reported on controlled real-plant-condition dust explosion experiments in a jet mill in a coal power plant. The overall conclusion was that borderlines drawn between conditions of dust concentration, dust moisture, oxygen concentration of the atmosphere, ignition energy, and so forth that produce and do not produce explosions are generally more liberal than corresponding borderlines based on laboratory experiments. In particular, the LOC was significantly higher in the actual mill explosion experiments than in closed-bomb laboratory experiments.

Matsuda and Itagaki (1994) compared dust explosions in a 30 liter explosion bomb with explosions in a 1 m^3 vessel. They found that the range of explosive concentrations in the 30 liter vessel were considerably wider than those in the 1 m^3 vessel for the same dust.

A marked increase of the explosive range was found in the 30 liter bomb when increasing the ignition energy from 1 to 10 kJ. This effect was practically absent in the 1 m^3 vessel in the ignition energy range 4–20 kJ. Tian, He, and Zhang (1994), using a 20 liter explosion bomb, found that the minimum explosive concentrations of coal dusts decreased by a factor of 2 or more when the ignition energy was increased from 2.5 to 10 kJ. Xu et al. (1994) also arrived at the conclusion that the apparent MEC determined in a 20 liter bomb depends markedly on the ignition energy. It was found that 10 kJ would be too high to yield realistic results.

All this suggests that, ideally, limiting conditions for flame propagation should be determined in apparatuses of sufficient volume to prevent a significant influence of even quite strong ignition sources on the main phase of flame propagation. In Europe, the standards organization CEN adopted the standard (ISO) 1 m^3 bomb for this kind of tests.

Zhou, Zhang, and Yu (1994b) proposed an alternative procedure for determining the MEC in closed-bomb explosion experiments. Their experimental evidence indicated that, at MEC, the time interval from ignition to the pressure peak has its highest value. They suggested that this criterion be used instead of some arbitrary pressure rise criterion of explosion.

Chawla, Amyotte, and Pegg (1996) compared two different procedures (ASTM and IEC) to determine the MEC in closed 20 liter bomb tests. Because of an excessive ignition energy of 10 kJ, the IEC procedure gave unrealistically low MEC values, whereas the ASTM procedure, using 2.5 kJ ignition energy, produced MEC values in good agreement with those found in experiments at a larger scale.

Sapko et al. (2000) found that tests in a 20 liter closed bomb gave quite good predictions of the MEC values actually found in large-scale mine gallery dust explosion experiments with dusts of bituminous coals, gilsonite, oil shales, and sulphide ores. The ignition source in the 20 liter tests was a 2.5 or 5 kJ pyrotechnical ignitor.

9.4.5
MISCELLANEOUS

Tian et al. (1994), using a 20 liter explosion bomb, found that, when using a 2.5 kJ ignitor, and adding 2 vol% methane to the air, the minimum explosive dust concentration dropped by at least a factor of 2 compared with the values for dust in air. This "hybrid" effect had been studied previously by several other workers (see Chapter 1).

Hertzberg et al. (1992b) determined a range of dust explosibility parameters for nine dusts of solid explosives when dispersed as clouds in air in a closed bomb. In the low-concentration range (≤ 400 g/m^3), the dusts behaved as dusts of normal carbonaceous and plastic materials. At higher concentrations, they became more hazardous, starting to exhibit genuine explosives properties.

Cashdollar (1994) measured the explosibility parameters of clouds in air of a range of metal dusts, silicon, boron, and carbon, using the ASTM 20 liter bomb. The measured parameters were the minimum explosive dust concentration (both 2.5 and 5 kJ ignition energy), P_{max} and $(dP/dt)_{max}$. In addition, nominal stoichiometric dust concentrations and nominal adiabatic flame temperatures were calulated.

Wang and Zhang (1994) determined the minimum ignition energy, minimum explosive concentration, and maximum explosion pressure for clouds of TNT dusts in air.

The values are similar to those of natural organic materials. The results confirm that dilute clouds of dusts of explosives do not exhibit explosive properties but behave as clouds of ordinary combustible dusts. Similar conclusions were drawn by Li, Wang, and Ou (1994), who studied the dust explosion properties of dry "powder emulsion explosive" powders.

Matsuda (1996) measured the minimum ignition temperature and explosion violence properties of clouds of magnesium and various magnesium alloys in air and carbon dioxide. The magnesium dust tested did not ignite (10 kJ pyrotechnical ignitor) when dispersed in nitrogen.

Pegg and Amyotte (1996) and Pegg et al. (1997) determined the ignitability and explosibility characteristics of some azide-based powders used as gas generants. None of the powders tested represents a severe dust explosion hazard. Soundararajan, Amyotte, and Pegg (1996) investigated the explosibility characteristics of iron sulphide dusts as a function of particle size.

In an experimental investigation, Gieras and Wolanski (1998) determined the constant-volume explosion behavior (maximum pressure and maximum rate of pressure rise) of clouds of rare earth metal dusts in atmospheres of mixtures of nitrogen and water vapor.

Jong et al. (1999) gave a useful review of methods for determining the "flowability" properties of powders at large, including two methods for determining the dispersibility of powders (see also Section 7.4.2 in Chapter 7).

Conde-Lazaro and Carcia-Torrent (1998, 2000) studied experimentally the influence of high initial pressures, up to 15 bar(abs), on constant volume maximum explosion pressures and rates of pressure rise. For the dusts tested, the maximum explosion pressure was approximately proportional to the initial pressure. The relationship between the initial pressure and maximum rate of pressure rise was less straightforward, with the turbulence of the dust cloud playing a main role (see Section 1.3.8 in Chapter 1).

Lucas (2001) investigated the ignitability and explosibility characteristics of dusts produced at very low pressures (vacuum) during the growing of single silicon crystals. These dusts are very reactive and can present a significant dust explosion hazard when brought in contact with air at atmospheric pressure. However, by controlled flushing of the dusts with air, controlled surface oxidation of the particles is obtained, which reduces the dust explosion hazard.

Nifuku et al. (2002) investigated the ignitability and explosibility of dusts generated in processes for recycling electrical appliances. Dusts of polyurethane and other plastics produced in shredding processes were subjected to a comprehensive testing program. Amyotte et al. (2003) determined the minimum ignition temperatures of clouds of iron sulfide particles in the BAM furnace.

9.5
DUST EXPLOSION STATISTICS AND CASE HISTORIES

This section adds to the case histories described in Chapter 2 of this book.

Beck and Jeske (1996) presented statistical data for recorded dust explosions in the German process industries by BIA up to 1995. Sugar dust explosions in Germany are treated specifically in a separate section of the paper. This includes a detailed analysis of a major sugar dust explosion in a sieving plant. Schoeff (1999a) reviewed the dust explosions that occurred in the U.S. grain, feed, and flour industries over the years, with special emphasis on the decade 1988–1997. The statistics showed that, on average, significant progress had been made during that decade in reducing both the annual number of explosions and the severity of each explosion. In another paper, Schoeff (1999b) discussed the grain dust explosion catastrophe in Haysville, Kansas, in June 1998, in which 7 men were killed and 10 injured and that caused substantial material damage. The whole event comprised a series of perhaps five successive distinct explosions.

A step-by-step account of successful extinction of a smoldering fire in a silo, using nitrogen, was provided by Hoischen (1996). Fortunately, the extent of the fire, when the extinction process was initiated, was limited to the part of the stored bulk material close to its free upper surface. This may explain why extinction by applying nitrogen was comparatively straightforward in this case (see also Section 2.8 in Chapter 2). Hoischen also gave some general recommendations for advance inerting of silos by applying nitrogen.

Masson (1999) discussed the cereal dust explosion catastrophe at Blaye near Bordeaux on August 20, 1997. The explosion occurred when barley was transferred from a silo cell to an open storage room. Seven workers lost their lives. The plant, comprising a total storage capacity of about 50,000 m^3, suffered extensive damage. Of the 44 silo cells, 28 were completely demolished. The ignition source was probably either a smoldering fire in a dust collector bin (self-heating) or a hot surface (friction heating) somewhere in the headhouse.

Laar (1996, 1999) emphasized the necessity of basing the design of measures to prevent and mitigate dust explosions on dust safety characteristics relevant for the actual industrial situation. The point was illustrated by analyzing the explosion hazard in a plant for pneumatic transportation of a plastic granulate into a silo, which contrary to a priori expectations, suffered a catastrophic dust explosion.

Mniszewski (1998) reviewed analytical techniques that have proven to be useful in practical explosion accident investigation. Although the main focus of the paper is on gas and vapor cloud explosions, much of the material covered also applies to dust explosion investigation.

Broeckmann (1999) investigated an explosion case that occurred with a powder found unable to produce dust explosions in standard tests. This special material gave rise to an explosion in a mill via exothermal decomposition initiated by friction or impact, which occurred even though the oxygen concentration in the atmosphere in the mill had been reduced substantially by adding nitrogen.

Matsuda and Yamaguma (2000) analyzed a tantalum dust explosion that occurred in a tantalum production plant in Japan in Spring 1997. One worker was killed and another seriously injured. The explosion occurred while the two workers were discharging fine tantalum dust, collected in a bag filter unit of volume about 10 m^3, from the hopper at the bottom of the filter unit. Matsuda and Yamaguma conducted a comprehensive investigation to identify possible ignition sources, and it was concluded that the explosion was most probably initiated by an electrostatic discharge.

Alfert and Pistauer (2001) described a method used successfully to control and mitigate a fire in sugar residue pellets stored in a 30,000 m^3 silo. The novel element was the application of a jelly layer on top of the burning pellets in the silo. In addition to reducing the convection inside the burning pellets mass, this cover also had a direct quenching effect on the fire and a filtering effect on the smoke expelled from the silo into the surroundings. However, the jelly layer did not prevent continued slow smoldering inside the pellets mass, which persisted for about 8 weeks. Eventually, the smoldering terminated by itself, after which 15 tonnes of carbonized pellets were removed and the silo torn down.

Stiegler (2001) discussed a sulfur dust explosion in Germany in 2000. The explosion, which occurred during loading of bulk sulfur, was probably initiated by an electrostatic discharge. The explosion also initiated a subsequent fire, causing further damage to the plant. No persons were injured. The cause of a series of sulfur dust explosions and fires in the Shanghai Sulphur Factory, China, was investigated by K. Sun et al. (2001). High specific charges on the sulfur powder and high voltages of 25–60 kV were measured in the plant. Therefore, electrostatic discharges, either spark or "cone" (discharge along the surface of a heap of charged coarse particles), caused by charge buildup during pneumatic transport of sulfur in the plant, were found to be the likely ignition sources. Effective means for reducing the charge buildup were suggested (see Sections 1.1.4.6 and 1.4.2.7 in Chapter 1).

Wassenhoven (2001) presented a series of case histories in which chips, powders, or dusts of magnesium, aluminum, or titanium gave rise to explosions or fires. Kremers (2001) was concerned with the dust fire and explosion hazards in the wood processing industries. Statistical data for the occurrence of different types of ignition sources and for the different types of process equipment involved in the explosions were presented, together with a case history of a dust explosion in a factory making wood furniture.

The essential features and consequences of a major dust explosion catastrophe in a port grain storage facility at Blaye, France, in 1997 were discussed by Pineau (2001b). Eleven persons lost their lives and one was injured. The material damage to the large silo complex of the plant was extensive. Other industrial installations in the near neighborhood were affected as well.

Amyotte and Oehmen (2002) analyzed the various circumstances that led to a severe underground mine explosion in Canada in 1992, in which 26 miners were killed. Multiple layers of accident causation were resolved by the systematic application of a loss causation model. Both the immediately visible causes and hidden basic causes, having their origin in lack of management control, were identified. The two most important lessons to be learned are the need for a rigorous loss management system and an appropriate attitude toward industrial safety throughout the entire organization.

A severe dust explosion that occurred in the silo area of an acrylonitrile-butadiene-styrene (ABS) plant in Taiwan was investigated by Kao and Duh (2002). Six silos containing fine powders exploded sequentially. All the top plates and bag filter installations of the six silos, each of 330 m^3, were blown away. The explosion was probably initiated by a cone discharge ("Maurer" discharge) in one of the silos. The flame transfer to the other five silos occurred through ducts connecting the silos.

9.6
EXPERT SYSTEMS: FRIENDS OR ENEMIES?

Expert systems are computer-based decision-making tools that make relevant expert knowledge accessible to nonspecialist users by means of "if-then" rules and "class/object" structures.

During the last few years, there has been increasing interest in developing sophisticated computer-based expert systems to evaluate dust explosion hazards and assess the optimal safety design features. Haefen and Schecker (1993) presented such a system to assess dust explosion hazards in industry and select appropriate means of prevention and mitigation. The system is, in all essentials, based on the German protection philosophy. Wach (1993) presented another expert system designed for the same purpose, but the technical and philosophical basis was not explicitly stated. A comprehensive expert system, Dust Expert, developed in the United Kingdom, was presented by Tyldesley (1993), and the need for quality assurance of such systems was emphasized. Vadera, Meziane, and Huang (2001) reported on the experience of using the "mural" system for specifying Dust Expert with regard to the users' expectations concerning (1) spotting any inconsistencies; (2) helping manage and organize specifications, including provisions of easy access to and procedures for updating, adding, and deleting specifications; (3) helping manage and carry out the refinement process; (4) helping manage and organize theories; and (5) helping manage and carry out proof.

Hesener and Schecker (1995) developed the expert system ExTrA to facilitate safety analysis of drying plants. The systematic procedure implied in the system consists of four steps: hazard identification, hazard assessment, development of a protection concept, and selection of specific protection methods and technology. Hesener and Schecker (1996) gave a more-general presentation of ExTrA, which was developed for basic training, advanced knowledge retrieval, and hazard assessment in industry. The system presented was regarded as a prototype rather than a final product.

Hesener et al. (1998) and Kraus et al. (2001) developed an expert system to be used to identify hazards due to the possible occurrence of various types of electrostatic discharges in various process situations. The system, using the very comprehensive CENELEC report R044-001 as its technical basis, covers explosive gases and vapors and mists as well as explosible dusts. In the first phase of system development, available knowledge was collected and structured systematically. In the second phase, the development of the systematized knowledge was implemented in the expert system. The system gives references to existing guidelines and regulations.

Lorenz (1999) presented an expert system for the design of explosion venting arrangements. The system is based on the VDI 3673 venting code, which is very close to the new European Union code produced by CEN TC 305. The system accounts for the inertia of vent covers and doors and assesses forces acting on these covers and doors. The extent to which debris is ejected into the surroundings by destructive explosions is also accounted for. Lorenz and Schiebler (2001b) presented an expert system incorporating the four programs—SIMEK, STS, Vent, and Vessel—dealing with the design of explosion doors and lids, ejection of debris, venting assuming "zero mass" vent covers, and the stability of pressurized enclosures, respectively.

Siwek and Cesana (2001) described the two expert systems WinVent 3.0 and ExTools. The first provides the information required for designing dust and gas explosion venting systems according to the National Fire Protection Association (1998) and the Verein deutscher Ingenieure (2000); the second deals with safety related to gases and liquids only.

The development of this kind of expert system is a natural consequence of two main factors. The first is the almost explosive development of the performance of personal computers. The second is the steadily increasing knowledge about ignition and explosion phenomena, which demands a steadily more differentiated and complex approach for solving the practical design problems.

As long as this development is conducted by people who are experts not only on computers but also on the physics and chemistry of the phenomena treated, expert systems should indeed be welcomed. However, the possibility exists that, in the future, software may be put on the market that is not up to acceptable standards with respect to the physics and chemistry. As long as the interior of the system is not fully exposed, deficiencies in the basics may not be obvious to the user. A need may emerge for establishing some internationally recognized body of experts that can ensure that expert systems offered in the area of dust explosion prevention and mitigation are up to acceptable standards.

Adequate maintenance is another key in the evaluation of the usefulness of expert systems. Unless such systems are updated continually along with the appearance of new knowledge in the fields covered by the systems, they may soon become outdated and unreliable.

9.7

JOINT RESEARCH EFFORTS IN EUROPE

During the early 1990s, the potential for organizing joint European research efforts emerged within the EU/EFTA/EUREKA system. This also applied to dust explosion research. British Materials Handling Board (BMHB) in the United Kingdom played a central role in this process (personal communication with P. G. Middleton, BMHB, 1992). A number of parallel research programs were conducted within the European Union's CREDIT Project. The following areas were covered by the project:

- Combustion processes in dust clouds (experiments, theoretical models).
- Identification and control of ignition sources.
- Design of methods to prevent and protect against dust explosions.

The results of this important research effort were published as conference proceedings (CREDIT, 1995), containing about 10 papers covering a wide range of topics, such as initiation of smoldering combustion in powder deposits by localized heat sources, measurement of dust cloud characteristics in industrial plants, measurement of laminar burning velocities of dust clouds, partial inerting of dust clouds, measurement of dust flame structures, measurement of blast effects and fireball sizes from vented dust explosions, and last but not least, a start on a development of a comprehensive CFD-based (computational fluid dynamics) numerical computer code for simulating the development of dust explosions in complex industial powder processing and handling systems. An overview was given by Gibson (1996).

In 2002, the European Union launched another 3-year dust explosion research program, DESC. The participants include companies, institutes, and universities from the United Kingdom, Norway, the Netherlands, Germany, Poland, and Sweden. A central objective of this program is the further development of a CFD-based computer code for simulating dust explosions in real industrial process plants. The code, capable of being run on a PC, is being developed from general-purpose software and data from extensive measurements of burning velocities and other basic properties of explosive dust clouds. The code will be validated and tested against data from a wide spectrum of dust explosion experiments.

9.8
RESEARCH AND DEVELOPMENT IN THE PEOPLES REPUBLIC OF CHINA

Wang (1994), characterizing the Peoples Republic of China as a developing country, emphasized the need for increasing the efforts to prevent dust explosion accidents in China's rapidly growing industry. Of the number of dust explosions recorded in this country during the decade 1980–1989, 65% were in the grain industry, 17% in the textile industry, 12% in the coal industry, and 6% in the metallurgical industry. With the rapid development of the chemical and metallurgical industries, the annual number of explosions can easily rise, if adequate precautions are not taken. There is a strong need for education and training on all levels and for adequate safety technology.

The Sixth International Colloquium on Dust Explosions in Shenyang, Peoples Republic of China, in August/September 1994 (see Section 9.1.2), demonstrated that research and development on dust explosion prevention and protection in this enormous country is growing at great pace.

Deng, Gang, and Zong (1996) and Deng (1999) outlined various methods to prevent and mitigate accidental explosions in industry and the efforts in the Peoples Republic of China to introduce safety standards to promote further reduction of the accidental explosion risks in the Chinese industry.

9.9
CONCLUSIONS

Initiation and propagation of industrial dust explosions are, from a fundamental scientific point of view, extremely complex phenomena. Comprehensive mathematical theories to predict ignition and combustion of dust clouds in industrial environments from fundamental physical and chemical principles in general are, at present, beyond reach.

It is not surprising, therefore, that the vast amount of existing knowledge on dust explosion-related phenomena is to a large extent fragmented. It is believed, however, that more and more fragments will, step by step, become tied together and steadily increasing domains of coherence will emerge. Comprehensive mathematical models and powerful computers are invaluable tools in this process. But, experiments remain indispensable in the calibration of the mathematical models, because such models will remain approximate and require careful tuning in the foreseeable future. It is necessary to continue the execution of realistic industrial-scale experiments. At the same time, more basic research and mathematical modeling should continue at full pace.

Much of the research that needs to be undertaken is very demanding, and international cooperation in joint research programs should be encouraged.

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Appendix

Ignitability and Explosibility Data for Dusts from Laboratory Tests

A.1

TABLES A.1, A.2, AND A.3 AND COMMENTS FROM THE BIA (1987)

A.1.1

LIMITATIONS TO THE APPLICABILITY OF THE DATA

A.1.1.1

Particle Size and Moisture Content

The applicability of the data in Tables A.1, A.2, and A.3 to other dusts of apparently identical materials is limited. In practice, dusts of a given overall chemistry may differ widely in particle size, particle shape, and sometimes also in particle surface reactivity. Furthermore, most ignitability and explosibility parameters are influenced by inherent features of the test method. Therefore, as a general rule, the tabulated data should be used only as indications and not as the ultimate basis for design of actual safety measures in industry. On the other hand, data obtained using the same test method allows relative comparison of ignitability and explosibility of various dusts. It is always necessary, however, to account for any significant differences between the particle size distributions and particle shape of the actual dust of interest and those in Tables A.1, A.2, and A.3.

For a given dust material, the maximum explosion pressure (P_{max}) and the maximum rate of pressure rise (K_{St}) increase systematically with decreasing particle size and moisture content. The minimum ignition energy (MIE) generally decreases with decreasing particle size and moisture content. Decreasing the moisture content and particle size can also cause a decrease in both the minimum explosible dust concentration (C_{min}) and the minimum ignition temperature of a dust cloud (T_{min}). The dusts were tested "as received," and general lack of information on the moisture content presents a further uncertainty concerning the specific applicability of the data. This applies, in particular, to the data for wood and cellulose and food and feedstuffs. Such dusts often contain considerable fractions of moisture in the "as received" state.

It is generally advisable to have the actual dust of interest tested in a professional laboratory.

A.1.1.2
Initial State and Composition of the Gas in Which the Dust Is Dispersed or Deposited

The data in Table A.1 apply to

- Atmospheric pressure (from −0.2 to +0.2 bar(g)).
- Oxygen content of air (from 18 to 22 vol% O_2).
- Normal ambient temperature (from 0 to 40°C).

In general, P_{max}, and under certain conditions also $(dP/dt)_{max}$ or K_{St}, increase proportionally with the absolute initial pressure. Increased oxygen fraction in the atmosphere increases both the ignitability and the explosibility, whereas a lower oxygen content than in air reduces the hazard correspondingly. Increased initial temperature increases the ignition sensitivity (reduces MIE). Normally, data for conditions that deviate significantly from the standard test conditions have to be determined specifically in each case.

If the gas phase contains some combustible gas or vapor, even in concentrations considerably below the lower explosibility limit for the gas or vapor, hybrid effects can give rise to considerable increase of both ignition sensitivity and explosibility. In such cases, specific tests definitely have to be conducted.

A.1.2
COMMENTS ON THE VARIOUS ITEMS IN TABLE A.1

A.1.2.1
Selection and Identification of Dusts

The original table, published in German by the BIA (1987), contains nearly 1900 dusts. Therefore, the selection of about 375 dusts in Table A.1 constitutes about 20% of those in the original tables. When making the selection, the samples of a given dust material that gave the most severe test data were normally preferred. In addition, sequences for some given dust materials showing systematic effects of, for example. moisture content or particle size were included. Examples of this are data for peat and aluminum.

In the original German table, the dusts are identified by a code number, which has been omitted here. However, the sequence of the dusts in the condensed table is identical to that in the original table. If required, the dusts in the condensed table can be easily identified in the original German table by means of the particle size data and the ignitability and explosibility data.

A.1.2.2
Particle Size Distribution

Most of the dusts were tested as received. However, in some cases, fractions passing a 63 μm sieve were tested.

A.1.2.3
Minimum Explosible Dust Concentration (C_{min})

Most of the tabulated data were determined in the standard closed 1 m^3 ISO (1985) vessel or in the closed 20 liter Siwek sphere. Experience has shown that the latter apparatus tends to give lower values than the 1 m^3 vessel, often by a factor of 2. (Note: Another standard small-scale method, approved by Nordtest, 1989, seems to give data in somewhat closer agreement with those from the 1 m^3 ISO vessel.) The C_{min} values in brackets were determined in the modified 1.2 liter Hartmann apparatus in terms of the smallest dispersed dust quantity that propagated flame, divided by the vessel volume. These values are sometimes higher than the true C_{min} because of the comparatively weak ignition source used.

A.1.2.4
Maximum Explosion Pressure (P_{max})

The maximum explosion pressures were obtained either in the standard 1 m^3 ISO vessel or in the 20 liter Siwek sphere. The data in brackets were obtained in the 20 liter sphere using a simplified test procedure due to limited amounts of dust for testing. The standard procedure requires at least three replicated tests at each dust concentration over a range of different concentrations.

A.1.2.5
Explosion Violence (K_{St}, St class)

K_{St} is defined as the maximum rate of pressure rise during a dust explosion in an equidimensional vessel, times the cube root of the vessel volume. K_{St} (bar m/s) is numerically equal to the maximum rate of pressure rise (bar/s) in the 1 m^3 standard ISO (1985) test. The K_{St} data in the table were obtained either in the standard ISO test or in the 20 liter Siwek sphere, adopted by ASTM (1988), which has been calibrated to yield comparable K_{St} values.

The St class was determined using the modified Hartmann tube with a hinged lid at the top. Brackets indicate that this test method is not considered adequate in the Federal Republic of Germany for conclusive classification of St2 and St3 dusts (St2 means that 200 bar m/s $\leq K_{St} <$ 300 bar m/s, and St3 that $K_{St} \geq$ 300 bar m/s).

A.1.2.6
Minimum Ignition Temperature of Dust Clouds

These data were acquired using either the Godbert-Greenwald furnace or the BAM furnace. The data in brackets were obtained using a modified, elongated version of the Godbert-Greenwald furnace, yielding somewhat lower values than the version proposed as an IEC (International Electrotechnical Commission) standard.

A.1.2.7
Minimum Ignition Energy (MIE)

In the original BIA (1987) publication, the MIE values appear in a separate table. However, because the dusts could be identified by their reference numbers, it was possible to incorporate the MIE values in Table A.1. These values are determined using soft sparks (long discharge times) in agreement with the VDI method described by Berthold (1987). Down to net spark energies of about 1 mJ, this method is in complete accordance with the CMI method described by Eckhoff (1975). The VDI and the CMI methods are the basis of the method for measuring MIE that is being evaluated by the IEC. The VDI and CMI methods differ from the earlier U.S. Bureau of Mines (USBM) method, in which an appreciable fraction of the $\frac{1}{2}CV^2$ quoted as MIE was lost in a transformer and never got to the spark. Therefore, the USBM MIE values are generally higher than those determined by the new method. A tentative correlation for transforming USBM data to equivalent VDI/CMI data is given in Figure A.1 (see also Section A.2.4).

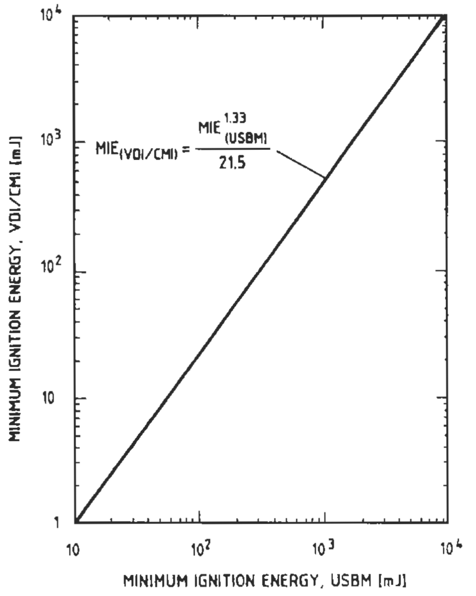

Figure A.1 *Approximate empirical correlation between the minimum ignition energies measured by the earlier USBM method described by Dorsett et al. (1960), and values generated by the more recent methods described by Eckhoff (1975) and Berthold (1987), and the method being evaluated by the IEC (see Chapter 7). Note: The correlation must be used as an indication only and must not be extrapolated*

A.1.2.8
Glow Temperature

These data were obtained with a 5 mm thick layer of dust resting on a hot plate of known, controllable temperature (equivalent to proposed standard IEC method for determining the minimum ignition temperature of a dust layer on a hot surface).

A.1.2.9
Flammability

The dusts are classified according to their ability to propagate a combustion wave when deposited in a layer. Ignition is accomplished using either a gas flame or a glowing platinum wire at 1000°C. The test sample is a 2 cm wide and 4 cm long dust ridge resting on a ceramic plate. Ignition is performed at one end. The classifications are

- Class 1. No self-sustained combustion.
- Class 2. Local combustion of short duration.
- Class 3. Local sustained combustion but no propagation.
- Class 4. Propagating smoldering combustion.
- Class 5. Propagating an open flame.
- Class 6. Explosive combustion.

The numbers in brackets refer to a modified test procedure according to which 20 weight% diatomaceous earth is mixed with the powder or dust to be tested. By this means, some materials that otherwise would not propagate a flame because they melt may show sustained flame propagation.

A.2
APPLICABILITY OF EARLIER USBM TEST DATA

A.2.1
BACKGROUND

The U.S. Bureau of Mines in Pittsburgh, PA, developed a comprehensive set of laboratory test methods for characterizing ignitability and explosibility of dusts, and published a large number of test data, which have been widely used throughout the world. The test apparatuses and procedures were described by Dorsett et al. (1960). Test data for 220 agricultural dusts were reported by Jacobson et al. (1961); for 314 dusts in the plastics industry, by Jacobson, Nagy, and Cooper (1962); for 314 metal powders, by Jacobson, Cooper, and Nagy (1964); for 241 carbonaceous dusts, by Nagy, Dorsett, and Cooper (1965); for 175 chemicals, drugs, dyes, and pesticides, by Dorsett and Nagy (1968); and for 181 miscellaneous dusts, by Nagy, Cooper, and Dorsett (1968); that is, for 1445 dusts altogether.

In more recent years, alternative test methods have been developed, and there is a need to indicate the extent to which the substantial amount of the earlier USBM data are compatible with more recent data, as for example those in Tables A.1, A.2, and A.3.

A.2.2
MINIMUM IGNITION TEMPERATURE OF THE DUST CLOUD

The apparatus used was the original Godbert-Greenwald furnace, which is essentially the same apparatus as the Godbert-Greenwald furnace used for determining the data in Table A.1. The earlier USBM data should therefore be compatible with those in Table A.1.

Table A.1 Ignitability and explosibility of dusts

	Particle size distribution								Ignitability and explosibility of dust clouds						Dust layers		
	Weight % <Size (μm)							Median	1 m^3 or 20 L vessel			Mod. H. Explos. <63 μm	T_{min} (°C)		VDI	DIN	
Dust type	500	250	125	71	63	32	20	(μm)	C_{min} (g/m^3)	P_{max} (bar(g))	K_{St} (bar · m/s)	(Class)	G.G.	BAM	MIE (mJ)	Glow temp. (°C)	Flam. <250 μm (Class)
Cotton, wood, peat																	
Cotton			98	72		38	25	44	(100)	7.2	24	St. 1	560			350	3
Cellulose			92	71		20	3	51	60	9.3	66		500		250	380	5
Wood dust				90		47	7	33					500		100	320	
Wood dust	58		57	55		43	39	80					480		7	310	
Wood dust (chipboard)				70		30		43	60	9.2	102	St. 2	490			320	3
Wood, cardboard, jute									30	5.8	26		610		245	360	5
Wood, cardboard, jute, resin									30	8.4	67		520		3	350	5
Lignin dust			96	85		66	57	18	15	8.7	208		470			>450	5
Paper dust				91		83	73	<10		5.7	18		580			360	
Paper tissue dust			75	58				54	30	8.6	52	(St. 2)	540			300	4
Paper (phenolresin treated)				100		90	25	23	30	9.8	190		490			310	
Peat (15% moisture)			84	58		26	3	58	60	10.9	157	St. 1	480			320	4
Peat (22% moisture)			82	65		40	15	46	125	8.4	69	St. 1	470			320	4
Peat (31% moisture)			87	76		43	20	38	125	8.1	64		500			320	
Peat (41% moisture)			88	76		40	18	39	No ignition				500			315	
Peat (from bottom of sieve)			78	48		22		74	125	8.3	51	St. 1	490			310	4
Peat (dust deposit)				66		33	11	49	60	9.5	144		(360)			295	
Paper pulp				93		76		29		9.8	168						
Food, feedstuffs																	
Gravy powder (21% starch)					100					5.1	12			500	>1000		
Citrus pellets					100				60	7.7	39			460	250		
Dextrose, ground			100		94	71		22				St. 2					2
Dextrose				38		5	4	80	60	4.3	18	St. 1	500			570	3
Fat/whey mixture	76		11	3				330		7.0	23		450		180	410	5
Fat powder (48% fat)		100	75		24	7		92	30	6.4	20	St. 2					2
Dough					100									430	>100		

Fishmeal	68		23		12			320	125	7.0	35		530				
Fructose (from filter)	99		39	17				150	60	9.0	102		430		<1	Melts	
Fructose	92		15					200	60	7.0	28		440		180	440q	
Fructose	81							400	125	6.4	27		530		>4000	Melts	
Barley grain dust	79	51	25		8	3		240							100		4
Dough					100				125	7.7	83			400			
Oats grain dust	64		24		8			295	750	6.0	14	St. 1				350	3
Wheat grain dust				48		30		80	60	9.3	112	St. 1				290	3
Wheat grain dust	100	81	50		32	25		125				St. 2					3
Coffee (from filter)				100		99	89	<10	60	9.0	90		470			>450	
Coffee (refined)					100					6.8	11			460	>500		4
Cocoa bean shell dust					100				125	8.1	68				>250		4
Cocoa/sugar mixture	53		20					500	125	7.4	43	St. 1	580			460	2
Potato granulate					100					6.4	21			440	>250		3
Potato flour			86	53		26	17	65	125	9.1	69		480			>450	
Lactose (from filter)				83		60	47	22	125	6.9	29		450		80	>450	
Lactose (from cyclone)				97		70	41	23	60	7.7	81	St. 2	520			>450	3
Maize seed waste (9% moisture)	98	67	40		23	16		165	30	8.7	117			440	>10		
Milk powder			34	18				165	60	8.1	90		460		75	330	
Milk powder	98		15	8				235	60	8.2	75		450		80	320	
Milk powder (low fat, spray dried)	100	100	99		60	17		46	30	7.5	109				>100		
Milk powder (full fat, spray dried)				30				88	60	8.6	83	St. 1	520			330	2
Whey fat emulgator	62		7	2				400		7.2	38		450		90	420	5
Olive pellets					100				125	10.4	74			470	>1000		
Rice flour					100				60	7.4	57			360	>100		
Rye flour			94	76		58	15	29		8.9	79		490			>450	
Soy bean flour				85		63	50	20	(200)	9.2	110	St. 1	620			280	2
Potato starch					100				30	7.8	43			420	>1000		
Potato starch				100		50	17	32		(9.4)	(89)		520		>3200	>450	2
Maize starch				99		98	94	<10		10.2	128		520		300	>450	2
Maize starch				94		81	60	16	60	9.7	158	St. 1	520			440	2

Table A.1 continued

	Particle size distribution								Ignitability and explosibility of dust clouds						Dust layers		
	Weight % <Size (μm)							Median (μm)	1 m³ or 20 L vessel			Mod. H. Explos. <63 μm (Class)	T_{min} (°C)		VDI MIE (mJ)	DIN Glow temp. (°C)	Flam. <250 μm (Class)
Dust type	500	250	125	71	63	32	20		C_{min} (g/m³)	P_{max} (bar(g))	K_{St} (bar · m/s)		G.G.	BAM			
Rice starch (hydrolyzed)				29		15		120	60	9.3	190	(St. 2)	480			555	5
Rice starch				99		74	54	18					470		90	390	3
Rice starch				86		62	52	18		10.0	190	(St. 2)	530			420	3
Wheat starch						84	50	20	60	9.8	132	(St. 2)	500			535	3
Tobacco			81	64		29		49		4.8	12		470			280	
Tapioca pellets				61		42		44	125	9.0	53	St. 1	(450)			290	4
Tea (6% moisture)					100				30	8.1	68			510			≥3
Tea (black, from dust collector)			64	48		26	16	76	125	8.2	59	St. 1	510			300	4
Meat flour			69	52		31	21	62	60	8.5	106	St. 1	540			>450	2
Wheat flour								50					500		540	>450	
Wheat flour			97	60		32	25	57	60	8.3	87		430			>450	
Dough					100									400	>100		
Wheat flour 550				60		34	25	56	60	7.4	42		470		400	>450	
Milk sugar				99		92	77	10	60	8.3	75		440		14	Melts	5
Milk sugar				98		64	32	27	60	8.3	82	St. 1	490			460	2
Sugar (icing)				88		70	52	19					470			>450	
Coal, coal products																	
Activated carbon				99		80	55	18	60	8.8	44		790			>450	
Activated carbon				88		64		22	No ignition					670		335	
Activated carbon (16% moisture)			84	65		38		46	125	8.4	67		(630)				
Brown coal			83	69		40	20	41		9.1	123		420		160	230	4
Brown coal (from electrostatic filter)			75	60		27		55	60	9.0	143	St. 1	450			240	4
Brown coal (dust from grinding)			71	56		38	30	60		8.9	107		420		230	230	3
Brown coal/anthracite (80:20)				66		43	24	40	60	8.6	108		440		>4000	230	
Brown coal/anthracite (20:80)				91		85	80	<10		0.4	1		590			280	
Brown coal coke	93		18	13				290	250	8.4	115	St. 1	560			>450	3

Brown coal (graphitized)				82		55	35	28	No ignition					>850		>450	
Char coal				99		88	67	14	60	9.0	10	St. 1	520			320	4
Char coal				95		85	58	19	60	8.5	117		540			270	
Char coal	36							>500	No ignition					>850		>450	
Asphalt				83		54	32	29	15	8.4	117		550			Melts	
Bituminous coal				97		93	85	<10		9.0	55		590			270	
Bituminous coal (Petchora)			76	65		46	37	38	125	8.6	86		610			360	
Anthracite (dust from filter)				99		97	85	<10	No ignition				>850			360	
Bituminous coal (high volat.)							99	4	60	9.1	59		510			260	
Other natural organic products																	
Cotton seed expellers	66		24	10			245	125	7.7	35	St. 1	(480)				350	3
Dextrin				57		26	55		8.8	109	St. 1	490				>450	2
Wheat gluten (after mill)			78		28	13	48	30	8.7	105		540				Melts	
Blood flour			93	61		27	5	57	60	9.4	85		610			>450	1
Hops, malted	52		14	9				490		8.2	90		420			270	
Leather dust (from collector)									(100)			(St. 2)					5
Linen (containing oil)	63		21					300		6.0	17		(440)			230	
Lycopodium					100	91								410		280	
Oil shale dust				99		79	50	20	125	5.2	35		520			290	2
Oil shale dust				71		50	39	32	No ignition				610			>450	
Grass dust	96		26					200	125	8.0	47		470			310	
Walnut shell powder									(100)			St.1					4
Plastics, resin, rubber																	
Acrylnitrile-Butadiene-Styrene-Co-polym.	79	37	24					200	60	9.2	147	(St. 2)	480			>450	5
Epoxy resin (for powder coating)		100	82		58	28		55	(100)			(St. 2)					2
Cellulose-2, 5-acetate				100		89	53	19	30	9.8	180		520			>450	
Polyester resin with glass	92	91	89		80	72		14	(100)			(St. 2)					5
Rubber				93		45		34	(100)	7.4	106	(St. 2)					5
Rubber (dust from grinding)			78	43		12		80	30	8.5	138		500		13	230	5
Resin (from filter)				97		44		40	30	8.7	108		460			Melts	
Epoxy resin (60% resin + 36% TiO_2)				99		67	43	23		7.8	155						

Table A.1 continued

	Particle size distribution								Ignitability and explosibility of dust clouds						Dust layers		
									1 m³ or 20 L vessel			Mod. H. Explos. <63 µm	T_{min} (°C)		VDI	DIN	
	Weight % <Size (µm)							Median (µm)	C_{min} (g/m³)	P_{max} (bar(g))	K_{St} (bar · m/s)	(Class)			MIE (mJ)	Glow temp. (°C)	Flam. <250 µm (Class)
Dust type	500	250	125	71	63	32	20						G.G.	BAM			
Epoxy resin				95		60	36	26	30	7.9	129	St.1	510			Melts	2
Epoxy resin with Al				90		46		34		8.9	208		570			Melts	
Melamin resin				99		84	55	18	125	10.2	110	St. 1	840			>450	2
Melamin resin				66		24	13	57	60	10.5	172	St. 1	470			>450	2
Phenol resin				100		99	94	<10	15	9.3	129	(St. 2)	610			>450	2
Phenol formaldehyde resin	100	98	81		50	30		60	(100)			St.1				4	4
Polyamid resin				95		84		64	15	3.0	8.9	105		450		Melts	
Polymethacrylate	56				100	33			15	8.0	199					(2)	
Silicon resin	91		59	39		20	13	100	60	7.2	80		480			Melts	
Caoutchouc			58	40		20		95	30	9.5	192		450			230	
Synthetical caoutchouc			66	46		18	9	80	15	8.6	145	(St.2)	450			240	5
Methylmethacrylate-Butadiene-Styrene			45	18				135	30	8.6	120		470		11	Melts	5
Methylmethacrylate-Butadiene-Styrene			34	11				150	30	8.4	114		480		30	Melts	5
Polyacrylamide (from filter)				100		95	81	10	250	5.9	12	St. 1	780			410	2
Polyacrylate (from filter)			100	63		11	1	62	125	6.9	38		460		>1800	420	5
Polyacrylnitrile (32% H_2O)			95	47		16		63	60	7.4	41						
Polyamide flock (3.3 dtex 0.5 mm)				100		25	3	37	30	9.8	93	St. 1	520			Melts	2(3)
Polyester								<10		10.1	194		570			Melts	
Polyethylene			91	51		10		72		7.5	67		440			Melts	
Polyethylene	82			8	2				280		6.2	20		470		Melts	
Polyethylene (high pressure)			98	93		65	10	26		8.7	104		490			>450	
Polyethylene (low pressure)						95	86	<10	(30)	8.0	156	(St. 2)	420			Melts	2(5)
Polyethylene (low pressure)			36	10				150	125	7.4	54	St. 1	480			Melts	3(5)
Polyethylene (low pressure)	90		20	9				245	125	7.5	46	St. 1	460			Melts	3(5)
Polymethacrylate (from filter)				90		70	48	21	30	9.4	269	(St. 2)	550			Melts	5
Polymethacrylimide			45	15				105	30	9.6	125	(St. 2)	530			Melts	5

Polypropylene				92		61	40	25	(30)	8.4	101	(St. 2)	410			Melts	3(5)
Polypropylene	100		12					162	(200)	7.7	38	St. 1	440			Melts	2(5)
Polystyrene (copolymer)			32	11				155	30	8.4	110		450			Melts	
Polystyrene (hard foam)	30		10	5				760		8.4	23						
Polyurethane					100	90		3	<30	(7.8)	(156)						5
Polyvinylacetate (copolymer)						83	50	20	60	8.7	86	St. 1	660			Melts	2
Polyvinylalcohol				74		55	44	26	60	8.9	128	(St. 2)	460			Melts	5
Polyvinylalcohol				57		29	9	56	60	8.3	83	St. 1	460			Melts	5
Polyvinylchloride						100		<10	30	8.4	168						
Polyvinylchloride			46	15				125	30	7.7	68		530			340	
Polyvinylchloride (em., 97.5% PVC)				97		73	26	25	125	8.2	42		750		>2000	>450	
Polyvinylchloride (em., 97% PVC)				60		31	14	51	125	8.5	63		790		>2000	350	
Polyvinylchloride (susp.)			66	23				105	125	7.7	45	St. 1	510			>450	2
Polyvinylchloride (susp.)			30					137	No ignition				>800			>450	
Urea-formaldehyde (molded form)				99		91	75	13	60	10.2	136	St. 1	700			390	2
Melamine-formaldehyde (molded form)				93		86	70	14	60	10.2	189	St. 1	800			>440	2
El.stat. coating powder (epoxy)				100		70		29	30	8.9	100	(St. 2)	540			Melts	2(3)
El.stat. coating powder (polyurethane)				100		66	22	29	30	7.8	89	St. 1	490			Melts	2(2)
Shellac					100	33			15	7.6	144	(St. 2)					
Wax (NN ethylene distearamide)					100	95		10	15	8.7	269	(St. 2)					2(2)
Pharmaceuticals, cosmetics, pesticides																	
Acetyl salicylic acid					100				15	7.9	217	(St. 2)		550			2(5)
Amino phenazone						100	98	<10		10.3	238		330			>450	
Ascorbic acid, L(+)-				93		75	61	14	60	6.6	48	(St. 2)	490			Melts	2(2)
Ascorbic acid				92		38	15	39	60	9.0	111	(St. 2)	460			Melts	2(2)
Caffeine					100				30	8.2	165	(St. 2)		>550		Melts	2(5)
Cysteine hydrate				100		98	94	<10	125	7.4	40		420		>2000	Melts	
L-Cystin				100		95	69	15	60	8.5	142		400		40	Melts	

Table A.1 continued

Dust type	Particle size distribution								Ignitability and explosibility of dust clouds						Dust layers		
	Weight % <Size (μm)							Median (μm)	1 m³ or 20 L vessel			Mod. H. Explos. <63 μm (Class)	T_{min} (°C)		VDI MIE (mJ)	DIN Glow temp. (°C)	Flam. <250 μm (Class)
	500	250	125	71	63	32	20		C_{min} (g/m³)	P_{max} (bar(g))	K_{St} (bar · m/s)		G.G.	BAM			
Digitalis leaves				59		42		46	250	8.5	73						
Dimethylaminophenazone						100		<10		10.0	337						
2-Ethoxybenzamide					100				15	8.6	214	(St. 2)		490		Melts	2(5)
Fungicide (Captan)			100		99	93		5	(500)			St. 1					5
Fungicide (org. zinc comp.)						99	96	<10	60	9.0	154		480			300	
Fungicide (Maneb)				98		97	93	<10					380		>2500	200	
Methionine				100		99	95	<10	30	9.4	143		390		9	Melts	5
Methionine				100		98	87	<10	30	8.7	128		390		100	Melts	5
Sodium - L (+) ascorbate				97		67	45	23	60	8.4	119	St. 1	380			380	2
Paracetamole					100				15	7.9	156	(St. 2)		>550		Melts	2(5)
Pesticide				99		98	95	<10	60	8.6	151		410			320	
Intermediate products, auxiliary materials																	
Adipinic acid				98		92	86	<10	60	8.0	97	(St. 2)	580			Melts	2(5)
Aging protective					100	67		<32	15	8.2	256	(St. 2)					2(3)
Anthracene	89		20	7				235	15	8.7	231		600			>450	
Anthrachinone						100		<10		10.6	364						
Anthrachinone				100		90	75	12	30	9.1	91						
Azodicarbonamide						100		<10		12.3	176						
Benzoic acid									(30)			(St. 2)					2(5)
Betaine hydrochloride				93		85	78	<10	60	9.8	114	(St. 2)	400			>450	3
Betaine monohydrate	34		4					710	60	8.2	63	St. 1	510			>450	5
Diphenol ketylene				98		80	60	15		9.0	270						
Calcium acetate			74	41		25	17	92	500	5.2	9	St. 1	730			>460	2
Casein				99		65	40	24	30	8.5	115		560			>450	
Sodium caseinate (from filter)				100		99	77	17	60	8.8	117		560		740	>450	
Carboxy methyl cellulose				97		89		<15		9.2	184						
Carboxy methyl cellulose				50		20	12	71	125	8.9	127	St. 1	390			320	3

Methyl cellulose				96		87	30	22		10.0	157		400		12	380	
Methyl cellulose				100		69	10	29	60	10.0	152		400		105	>450	5
Methyl cellulose				93		37	12	37	30	10.1	209		410		29	450	5
Ethyl cellulose				66		40		40		8.1	162		(330)			275	
Chloroacetamide	98	79	33		13	3		170	(200)			St. 1					2(2)
Cyanoacrylicacid methylester	69		20					260	30	10.1	269	(St. 2)	500			>450	5
Dicyandiamide				99		98	97	<10		3.7	9		> 850			>450	
1.3-Diethyldiphenyl urea				98		93	83	<10	15	8.8	163	(St. 2)	530			Melts	2(5)
1.3-Diethyldiphenyl urea	8							1300	30	8.7	116	(St. 2)	600			Melts	2(5)
Dimethyl terephtalate						60		27	30	9.7	247		460		2	> 450	
Diphenyl urethane	93		49	27				128	30	8.9	218	(St. 2)	660			Melts	2
Diphenyl urethane	31							1100	30	7.6	51	(St. 2)	660			Melts	2
Emulgator (50% CH, 30% fat)			89	50		11		71	30	9.6	167		430		17	390	
Ferrocene			71	33				95	15	8.3	267		500		5	>450	5
Fumaric acid	100	75	24		15	11		215	(100)			(St. 2)					5
Epoxy resin hardener				97		85	60	17	60	10.0	64		>850			Melts	2
Urea	4	2	<1					2900				St. 1					1(2)
Hexamethylene tetramine				100		69	42	27	30	10.5	286						
Hexamethylene tetramine	100		30	9				155		10.0	224		530			Melts	
Cellulose ion exchange resin								<10	60	10.0	91	(St. 2)	410			>450	5
Cellulose ion exchange resin				27		9		112	30	9.4	112		(350)			>465	
Condensation product (phenol)				92		74	50	20	15	8.2	171	(St. 2)	560			Melts	2(5)
D(-)-Mannite				61		24	13	67	60	7.6	54	St. 1	460			Melts	2
Melamine				98		95	88	<10	1000	0.5	1	St. 1	>850			>450	2
Melamine peroxide				61		56	46	24	250	12.2	73	St. 1	>850			380	2
Melamine phosphate					100	79		22				St. 1					2
Melamine phtalate				99		89	65	16	125	8.1	52	St. 1	910			Melts	2
Metal soap (Ba/Pb-stearate)					100	48			15	8.1	180	(St. 2)					2(2)
Metal soap (Zn-behenate)					100	80			15	8.1	119	(St. 2)					2(3)
Methacrylamide	42						580		8.5	113			530		180	>450	
Naphtalene	89		66		35	12		95	15	8.5	178		660		<1	>450	(5)
Naphtalic acid anhydride					97	69	16	60	9.0	90			690		3	Melts	
2-Naphtol				100		96	94	<10		8.4	137		430		5	>450	

Table A.1 continued

	Particle size distribution								Ignitability and explosibility of dust clouds						Dust layers		
												Mod. H.			VDI	DIN	
	Weight % <Size (μm)							Median	1 m³ or 20 L vessel			Explos. <63 μm	T_{min} (°C)		MIE	Glow temp.	Flam. <250 μm
									C_{min} (g/m³)	P_{max} (bar(g))	K_{St} (bar · m/s)						
Dust type	500	250	125	71	63	32	20	(μm)				(Class)	G.G.	BAM	(mJ)	(°C)	(Class)
Sodium amide									(200)			(St. 2)					2
Sodium cyclamate	97	52	13		5	2		260				St. 1					5
Sodium hydrogen cyanamide			95	90		28	8	40	125	7.0	47		460			Melts	
Sodium ligno sulphonate			100		63	20		58	(200)			St. 1					2
Oil absorber (hydrophobic cellulose)			65	51		31	21	65	60	7.2	42		540			>450	
Paraformaldehyde				89		65	41	23	60	9.9	178	(St. 2)	460			>480	5
Paraformaldehyde				86		58	37	27	60	10.7	222		460			>450	
Pectin			86	61		21		59	60	9.5	162		460			300	
Pectinase				91		47	20	34	60	10.6	177		510		180	>450	3
Pentaerythrite				100		98	86	<10	30	9.6	120		470		<1	Melts	2(5)
Pentaerythrite (from filter)		90	33		6	3	85	30	9.1	188			490		6	Melts	5
Pentaerythrite	86		47	36		20	12	135	30	9.0	158				27	Melts	5
Phtalic acid anhydride									(100)			(St. 2)					5
Polyethylene oxide	99	83	53		29	14		115	(30)			(St. 2)					3(5)
Polysaccharide					100	78		23	(500)			St. 1					4
Propyleneglycol alginate			57	24				115	125	8.8	82		440			450	
Salicylic acid									(30)			(St. 2)					2(5)
Saponin				93		77	65	13		9.4	150	St. 1	440			>450	3
Lead stearate			99	96		90	80	<10					480		<1	Melts	
Lead stearate							90	12	30	9.2	152	(St. 2)	630			Melts	5
Calcium stearate				99		92	84	<10					520		9	Melts	
Calcium stearate						92	80	<10	30	9.2	99		580		16	>450	
Calcium stearate	100		43	25				145	30	9.2	155		550		12	>450	
Magnesium stearate									(100)			(St. 2)					2(2)
Sodium stearate				92		67	45	22	30	8.8	123	St. 1	670			Melts	2
Zinc stearate									(100)			(St. 2)					2(5)
Zinc stearate				95		86	72	13					520		5	Melts	
Stearin/lead				99		95	75	15	60	9.1	111		600		3	>450	

Stearin/calcium				100		89	64	16	30	9.3	133		620		25	>450	
Stearic acid	12							1300	8	7.2	34	(St. 2)	500			Melts	1(1)
Terephthalic acid dinitrile					100	78			<30	8.8	260	(St. 2)					5
2.2-Thiodiacetic acid				48		27	18	75	30	6.5	72	St. 1	350			410	2
Thio urea	56		1					460	250	3.5	8	St. 1	440			Melts	2(2)
Trimellitic anhydride	4							1250	30	6.8	33		740		>2500	Melts	2(5)
Trisodium citrate	36	2	1					800				St. 1					2
Tyrosine (final product)	100		99			48		10				(St. 2)					5
Tyrosine (raw product)	99		96		91	74		15				(St. 2)					5
Viscose flock					100	94		13	(100)			St. 1					4
Tartaric acid	100	5	1					480				St. 1					2
Zinc cyanamide				99		96	94	<10	No ignition				>850			>450	3
Zinc cyanamide	47	34			27	14		600		(4.8)	(53)	No ignition					2
Zinc pyridine thione						100			(500)			St. 1					2(5)
Other technical and chemical products																	
Organic dyestuff (blue)				99		98	95	<10		9.0	73		710			360	
Organic dyestuff (khaki)				86		29	11	44					690			450	
Organic dyestuff (red)								<10	50	11.2	249		520			Melts	
Organic dyestuff (red)				65		33	23	52	60	9.8	237	(St.2)	470			>450	5
Organic dyestuff (Azo, yellow)				100		98	95	<10	60	11.0	288	(St.2)	480			Melts	2(5)
Organic dyestuff (disp., brilliant pink)			91	73		25		46					610		>4000	450	
Organic dyestuff (brown)									(200)			St. 1					4
Organic dyestuff (Phthalocyanine)				96		86		<10	(200)	8.8	73	St. 1	770			355	4
Fuchsin base				74		45	26	36		8.4	115		640			Melts	
Bituminous hydrocarbon			23	11			260	30	7.6	63			500			Melts	2
Light protection agent				97		92	83	<10		8.9	214		530			>450	
Light protection agent				100		93		<15		10.0	310						
Soap								65	30	9.1	111		580			Melts	
Surfacer (epoxy based)					100	77		24	(200)			St. 1					2
Surfacer (polyester based)					100	85		19	(500)			St. 1					2
Washing agent (Na-sulphate)	88			14				275	30	9.0	287	(St. 2)	330			Melts	5

Table A.1 continued

Dust type	Particle size distribution								Ignitability and explosibility of dust clouds						Dust layers		
	Weight % <Size (μm)							Median	1 m³ or 20 L vessel			Mod. H. Explos. <63 μm	T_{min} (°C)		VDI	DIN	Flam. <250 μm
	500	250	125	71	63	32	20	(μm)	C_{min} (g/m³)	P_{max} (bar(g))	K_{St} (bar · m/s)	(Class)	G.G.	BAM	MIE (mJ)	Glow temp. (°C)	(Class)
Wax raw material (Alkylaryl sulphonate)												St. 1					5
Wax raw material (olefin sulphonate)			60	28			105	30	8.6	115			390			>590	
Metal alloys																	
Aluminum powder				94		88	79	<10	60	11.2	515		560			430	
Aluminum powder				98		70	45	22		12.5	400		650			270	
Aluminum powder				99		64	47	22	30	11.5	1100		500			>450	
Aluminum powder				94		60	17	29	30	12.4	415	(St.3)	710			>450	
Aluminum grit				100		96		23	30	11.0	320		850			>450	
Aluminum grit				99		16	2	41	60	10.2	100		>850			>450	
Aluminum grit	92		26	6				170	No ignition				>850			>450	1
Aluminum shavings	80		35	20				190					620		>1800	>450	
Aluminum shavings	79		29	17				240	No ignition				>850			>450	
Aluminum/iron (50:50)				93		68	48	21	250	9.4	230		760			>450	
Aluminum/magnesium			47					130		10.4	52	St.1	>850			>450	
Aluminum/nickel				95		86		<10		11.4	300						
Aluminum/nickel (50:50)				37		18		90	No ignition				>850			>450	
Bronze powder						97	60	18	750	4.1	31	St.1	390			260	4
Calcium/aluminum (30:70)						68	46	22		11.2	420		600			>450	6
Calcium/silicon (from cyclone)				94		75	48	21	60	9.8	200	(St.2)	770			>440	1
Calcium/silicon				87		55		28					770		145	>450	
Iron (from dry filter)				98		82	67	12	500	5.2	50		580			>450	
Iron carbonyl							96	<10	125	6.1	111	(St.2)	310			300	3
Ferrochromium				96		82	73	<10	500	6.4	86		>850			>450	
Ferromanganese				99		97	90	<10		6.8	84		730			>450	
FeSiMg (22:45:26)				99		77	57	17		9.4	169		670		210	>450	
Ferrosilicon (22:78)				97		70	47	21	125	9.2	87		>850			>450	

Hard metal (TiC, TiN, WC, VC, Mo)		100	95		68	40		43	(200)			St.1					4
Co-Al-Ti (62:18:20)				92		61	41	25	500	7.4	134		730			>450	
Magnesium				100		70		28	30	17.5	508						
Magnesium	99		1					240	500	7.0	12	(St. 2)	760			>450	5
FeSiMg(24:47:17)				99		70	47	21		9.9	267		560		35	>450	
Manganese (electrolyt.)				82		70	57	16		6.3	157		(330)			285	
Manganese (electrolyt.)				70		41		33		6.6	69						
Molybdenum				100		96	92	<10	No ignition				>850			390	
Niobium (6% Al)	87	44	24		9	3		250	(200)			St.1					2
Silicon				99		98	97	<10	125	10.2	126		>850		54	>450	3
Silicon (from filter)					100	99	<10	60	9.5	116			>850		250	>450	1
Silicon (from dust extr.)				90		70	57	16	60	9.4	100		800			>450	
Steel (100 Cr6) dust					100	74	(30)	(4.0)	(82)			(St. 2)					2
Titanium				98		55	24	30					450			>450	
Titanium (preoxidized)				77		46	26	35					380			400	
Ti/TiO$_2$ (dust deposit)	61	40	28		12	6		310	(100)			(St.3)					5
Zinc (from zinc coating)				91		72	53	19		6.0	85	St.1	800			>450	2
Zinc (from zinc coating)				93		70		21	250	6.8	93		790			>450	
Zinc (dust from collector)							99	<10	250	6.7	125	(St.2)	570			440	3
Zinc (dust from collector)				97		91	72	10	125	7.3	176	St.1					2
Other inorganic products																	
NH$_4$NO$_3$/Dicyanamide (66:34)				60		42	35	50	250	7.0	21		390			>450	
Graphite (99.5% C)					100	97		7	<30	5.9	71			>600		680	1
Carbon fibers (99% C)									(100)			St. 1					2
Molybdenum disulphide				92		75	53	19	250	5.6	37	St. 1	520			320	4
Petroleum coke				93		75	59	15	125	7.6	47	St. 1	690			280	4
Petroleum coke			83	51		22	14	71	125	3.8	3		750			>450	3
Petroleum coke (calcinated)			94	86		64	47	22	250	6.8	14		>850			>450	3
Phosphorus (red)				100		92	59	18		7.9	526		400			340	5
Soot							99	5	60	9.2	85		760			590	
Soot (from filter)								<10	30	8.8	88		840			570	
Sulfur				97		85	71	12					240		<1	250	
Sulfur				96		70	51	20	30	6.8	151	(St. 2)	280				5

Table A.1 continued

	Particle size distribution								Ignitability and explosibility of dust clouds							Dust layers	
	Weight % <Size (μm)							Median (μm)	1 m³ or 20 L vessel			Mod. H. Explos. <63 μm (Class)	T_{min} (°C)		VDI MIE (mJ)	DIN Glow temp. (°C)	Flam. <250 μm (Class)
Dust type	500	250	125	71	63	32	20		C_{min} (g/m³)	P_{max} (bar(g))	K_{St} (bar · m/s)		G.G.	BAM			
Sulfur				86		23		40					330		3	270	
Sulfur			53			7		120					370		5	270	
Titanium carbide									(100)			(St. 2)					4
Titanium hydride									(200)			St. 1					2
Titanium monoxide									(200)			(St. 2)					4
Other materials																	
Fly ash (from electrofilter)			100		99	92		6	125	1.9	35	No ignition					1
Ash concentrate				87		61	48	21	60	8.6	91		580			260	
Bentonite/asphalt/coal/org. (15:45:35:5)		90			55			54	(100)			St. 1					2
Bentonite/coal (50:50)		98	86		69	41		42	(100)			St. 1					2
Bentonite der. + org. comp.				89		45	23	35	60	7.4	123		430			>450	3
Pb and Ca stearate mixture		98			70			35	(100)			(St. 2)					2(2)
Break liner (grinding dust)				98		95	89	<10	250	6.9	71		530			310	
Brush dust (Al brushes)				99		74	30	25	30	11.4	360		590		<1	450	
CaC/diamide lime/Mg (72:18:10)		99		93		87	80	8	125	5.8	30						4
Mud from setting chamber			99	91		62	45	23	60	7.7	96		430			260	5
Dust from polishing (Al)			44	26				150		5.0	18		440			320	5
Dust from polishing (Zn)		60	35		15	2		190	(200)			St. 1		400		350	2
Dust from polishing (brass)									(100)			St. 1					4
Dust from grinding (Al)					100	85			(30)	(5.7)	(214)	(St. 2)					4
Dust from grinding (Zn)					100	67			(500)	(2.3)	(24)	St. 1		480			1
Dust from grinding (cardboard)	70	64	44		25	10		160	(100)			St. 1					5
Dust from grinding (polyester)				98		95	93	<10	30	9.5	153		500			>450	5
Dust from grinding (polyester)			97	84		60	41	25		9.4	237		550			>450	5
Dust from grinding (Ti)	89	64	37		18	4		170	(100)			(St. 2)					2
Dust from grinding + polish. (polyester)				99		96	91	<10					530		<1	>450	

Blasting dust (light metals)					100	82			15	7.6	242	(St. 2)		370		280	4
Immersion polishing agent	46							600	(30)	6.2	11	St. 1	580			340	2
Textile fibers (nat. + synth.)									(30)			St. 1					5
Toner							100	<10	60	8.9	196			520	4	Melts	
Toner							100	<10	30	8.7	137			530	<1	Melts	5
Toner				100		96	48	21	60	8.8	134			530	<1	Melts	(3)
Toner				100		95	30	23	60	8.8	145			530	8	Melts	(3)
Toner/iron powder				58		37		60	60	8.2	169			570		>450	
Toner resin				98		78	55	18						580	<1	>450	(5)
Zinc stearate/Bentonite (90:10)									(100)			(St. 2)					3
Zinc stearate/Bentonite (20:80)												(St. 1)					2

Source: BIA (1987).

Table A.2 Maximum permissible O_2 concentration for inerting dust clouds in atmospheres of $O_2 + N_2$

Dust type	Median particle diameter by mass (μm)	Maximum O_2 concentration for inerting by N_2 (vol%)
Cellulosic materials		
Cellulose	22	9
Cellulose	51	11
Waste from wood cutting	130	14
Wood	27	10
Food and feedstuffs		
Pea flour	25	15
Maize starch	17	9
Waste from malted barley	25	11
Rye flour 1150	29	13
Starch derivative	24	14
Wheat flour 550	60	11
Coals		
Brown coal	42	12
Brown coal	63	12
Brown coal	66	12
Brown coal briquette dust	51	15
Bituminous coal	17	14
Other materials		
Ground hops	500	17
Hops draff	490	18
Plastics, resins, rubber		
Resin	<63	10
Rubber powder	95	11
Polyacrylnitril	26	11
Polyacrylnitril	26	10
Polyethylene, h.p.	26	10
Pharmaceuticals, pesticides, etc.		
Aminopheenazone	<10	9
Herbizide	10	12
Methionine	<10	12
Intermediate products, additives		
Barium stearate	<63	13
Benzoyl peroxide	59	10
Bisphenol A	34	9
Cadmium laurate	<63	14
Cadmium stearate	<63	12
Calcium stearate	<63	12
Methyl cellulose	29	15
Methyl cellulose	49	14
Methyl cellulose	70	10
Dimethyl terephtalate	27	9
Ferrocene	95	7
Bistrimethylcilyl-urea	65	9
Naphthalic acid anhydride	16	12
2-Naphthol	<10	9

Table A.2 continued

Dust type	Median particle diameter by mass (μm)	Maximum O_2 concentration for inerting by N_2 (vol%)
2-Naphthol	<30	9
Sodium methallyl sulphonate	280	15
Paraformaldehyde	23	6
Paraformaldehyde	27	7
Pentaerythrite	<10	11
Pentaerythrite	<10	11
Other technical and chemical products		
Blue dye	<10	13
Organic pigment	<10	12
Metals, alloys		
Aluminum	22	5
Aluminum	22	6
Calcium/aluminum alloy	22	6
Ferrosilicon	17	7
Ferrosilicon	21	12
Magnesium alloy	21	3
Other inorganic products		
Soot	<10	12
Soot	<10	12
Soot	13	12
Soot	16	12
Soot desorbed from acetylene	86	16
Soot desorbed from acetylene	120	16
Others		
Bentonite derivative	43	12

Source: BIA (1987).

Table A.3 Inerting of dust clouds by mixing the combustible dust with inert dust (1 m^3 standard ISO (1985) vessel, 10 kJ chemical ignitor)

Combustible dust		Inert dust		
Type of dust	Median particle size by mass (μm)	Type of dust	Median particle size by mass (μm)	Minimum mass% inert of total mass required for inerting
Methyl cellulose	70	$CaSO_4$	<15	70
Organic pigment	<10	$NH_4H_2PO_4$	29	65
Bituminous coal	20	$CaCO_3$	14	65
Bituminous coal	20	$NaHCO_3$	35	65
Sugar	30	$NaHCO_3$	35	50

Source: BIA (1987).

A.2.3
MINIMUM IGNITION TEMPERATURE OF THE DUST LAYER

The earlier USBM method differs significantly from the hot-plate method used to produce the data in Table A.1. The latter is illustrated in Figure 7.17 in Chapter 7. In the USBM method, 6 cm^3 of the dust was placed in a small stainless steel mesh basket kept suspended at the center of the Godbert-Greenwald furnace (see Figure 7.24 in Chapter 7), while a controlled, small flow of air was passed through the furnace. The temperature of the furnace was controlled and maintained at a predetermined value, and the temperature inside the dust sample was monitored by a thermocouple. Ignition was defined as a distinct increase in the dust temperature beyond that of the furnace within 5 minutes. The minimum ignition temperature was defined as the lowest furnace temperature at which ignition occurred.

As would be expected, the USBM layer ignition temperatures are generally significantly lower, by 100° or more, than the "glow temperatures" of Table A.1 for similar dusts.

A.2.4
MINIMUM IGNITION ENERGY OF THE DUST CLOUD (MIE)

Due to the design of the electric spark generator used earlier by the USBM, part of the stored capacitor energy $\frac{1}{2}CV^2$ was lost in a high-voltage transformer, and therefore the net spark energy was smaller than the nominal $\frac{1}{2}CV^2$ quoted as the spark energy. However, when comparing MIE data for similar dusts, determined by the earlier USBM method and the more recent methods described by Eckhoff (1975) and Berthold (1987), an approximate empirical correlation is indicated, as shown in Figure A.1 in Section A.1.2.7. Note that the correlation should not be extrapolated beyond the range of Figure A.1.

A.2.5
MINIMUM EXPLOSIBLE DUST CONCENTRATION

The earlier USBM method was based on the 1.2 liter open Hartmann tube, with its top opening covered by a paper diaphragm. A comparatively weak continuous induction spark source was used for ignition. The dust concentration was defined as the quantity of dust dispersed, divided by the 1.2 liter volume of the tube: In spite of several probable sources of error, this method often yielded reasonable values as compared with more recent methods such as Nordtest (1989). This is probably because the effect of some of the sources of error partly cancel each other. However, data from the early USBM method must be regarded as indicative only.

A.2.6
MAXIMUM EXPLOSION PRESSURE

The early USBM data were determined in the original version of the closed 1.2 liter Hartmann bomb. Due to incomplete combustion and cooling by the walls, the maximum explosion overpressures in the Hartmann bomb are generally considerably lower, by up to 50%, typically 25–30%, than those generated by the same dusts in larger vessels, such as the 1 m^3 standard ISO (1985) vessel and the 20 liter Siwek sphere. It does not seem advisable to indicate any general relationship between P_{max} from the early USBM tests and more recent data from larger vessels.

A.2.7
MAXIMUM RATE OF PRESSURE RISE

These data were determined in the same Hartmann bomb experiment as the maximum explosion pressures. However, there seems to be some justification for indicating the following tentative correlation between $(dP/dt)_{max}$ in the closed Hartmann bomb and the K_{St} from the 1 m^3 standard ISO (1985) method (see Table A.4).

Table A.4 Examples of correlation of rates of pressure rise

$(dP/dt)_{max,Hartm.}$ (bar/s)	K_{St} (bar·m/s)
100	35
200	70
400	140
800	280
1600	560
3200	1120

Note: For quite coarse powders (nonhomogeneous dust concentration distribution in Hartmann bomb) and for very fine, cohesive powders (poor dust dispersion in Hartmann bomb), this correlation can be substantially in error.

A.2.8
MAXIMUM PERMISSIBLE O_2 CONCENTRATION FOR INERTING

USBM used two methods, an open glass tube with electric spark ignition and the Godbert-Greenwald furnace at 850°C. As would be expected, the latter method gave considerably lower limiting O_2 concentrations for inerting than the former.

Generally, the values of Table A.2 fall somewhere between the two USBM values for similar dusts. The arithmetic mean of the two USBM values then might be compatible with the data in Table A.2.

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