Prevention and mitigation of dust explosions in the process industries: A survey of recent research and development

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The total amount of existing knowledge on industrial dust explosions, their origin, propagation, prevention and mitigation, is vast. And yet, further information is continually being generated through on-going research in a large number of countries. A few years ago, I had the opportunity to review some of the knowledge accumulated up to about 1990. About 900 references were covered, but they almost exclusively originate from English/American and German literature. There is little doubt that a lot more interesting and useful information can be retrieved by screening the large amount of research reported in languages other than English and German. Perhaps this could be accomplished by organizing a joint international translation/edition effort.

The present paper mainly summarizes works published from 1990 and onwards, and only more recent works than those quoted in the above mentioned textbook are cited explicitly. Earlier versions of the present survey were presented in Poland in April 1993 (and subsequently published) and in the People’s Republic of China.

There is a growing acceptance of the fact that adequate dust explosion prevention and mitigation in practice must be based on a proper understanding of the basic physical and chemical phenomena involved. Therefore, when reviewing existing knowledge on the prevention and mitigation of industrial dust explosions, it is appropriate to start by addressing the fundamental aspects. In the second part of the paper, knowledge and technology related to preventing and mitigating dust explosions in industrial practice will be addressed specifically. A separate third part is devoted to the important area of test methods for assessing the ignitability and explosibility of dusts. One main aim of the paper is to indicate areas where a more intimate integration of fundamental research and practical development in industry is timely.

Status and outstanding problems in fundamental research related to dust explosions

Dust cloud formation processes. What is ‘turbulence’ of a dust cloud?
This is an important and sometimes overlooked aspect of dust explosions. 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.

However, comparatively little fundamental quantitative knowledge exists about the processes by which dust clouds may be generated. Some work has been done on entrainment of dust particles by turbulent gas flows passing over dust layers and ridges in wind tunnels.
However, quantitative relationships between essential parameters of the dust cloud generation processes and the states of the resulting dust clouds are scarce, and more work is needed in this area. When designing experiments for fundamental studies, one should select configurations that can be related to industrial practice. Examples are bulk dust dropped into an air flow, and entrainment of dust layers by air flows in channels and galleries with and without flow-obstructing obstacles. 

Hauert et al.4 measured RMS turbulent velocities, global velocities and dust concentrations in experimental dust clouds in the standard 1 m³ ISO vessel, and in a 12 m³ 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, e.g. for testing (‘validating’) the performance of numerical codes for simulating dust cloud formation and development in real industrial situations. Such codes, in turn, will be an essential element in future comprehensive codes for simulating dust explosion propagation in industrial situations.

Hauert et al.4 applied laser Doppler anemometry 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? Could it be that the most important ‘turbulence’ mechanism is in some cases the movement of burning particles in relation to unburnt ones, rather than the movement of the gas phase? Could it be, therefore, that the movement of the particles is in fact in some cases a more appropriate measure of ‘turbulence’ than the movement of the gas phase? The answer depends on the nature of the particles. Very rapid devolatilization, with the combustion occurring mainly in the bulk of the gas phase, is an extreme case where the gas movement is indeed important. If, on the other hand, the combustion mainly occurs close to the particle surface, the particle movement is of primary importance.

The state of a dust cloud that influences the ignition sensitivity of the cloud will clearly be 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 state of the unburnt cloud ahead of the flame. Therefore, the initial state of the dust cloud at the moment of ignition may only be of secondary significance for the flame propagation once the explosion has developed beyond the initial stages.

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 from dust deposits and layers there. Lebecki et al.5 investigated such processes in a 100 m long gallery of cross-section 3 m². In order to establish an improved understanding of these processes, further experimental and theoretical studies of the influence of blast waves on dust clouds and dust layers/deposits need to be conducted. Work on this problem has also been performed by Ural7, Gelfand and Tsyganov7, and others. Gelfand and Tsyganov7 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. Kaufman et al.8 and Austin et al.9 have summarized their extensive research on entrainment of dust layers in long tubes by the blast wave heading a dust explosion propagating along the tube. Tamanini and Ural10 have summarized their work on characterizing the dispersibility of dust layers when exposed to air blasts.

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 (de-agglomeration), turbulence level and global velocities. For example, fundamental theoretical studies are being performed on the generation of dust clouds behind shock waves sweeping across a dust layer at 90° to the layer surface. Frolov et al.11 developed a mathematical diffusion model describing such a process. A similar model was developed by Lu et al.12. This kind of work is relevant in the context of propagation of secondary dust explosions. Nikolova13 developed a source code for numerical models for simulation of dust cloud flow. The code can be used for cold flows as well as flows with combustion. Medvedev et al.14 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.15 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.16 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. Geng et al.17 studied the influence of clouds of maize starch in oxygen on the peak pressures of incident shock waves of Mach numbers 5.4 and 6.0.

In order to guide fundamental research in this area in the direction of maximum practical relevance, information about dust cloud structures that are typical in industrial operation is required. This not only means the cloud structures in normal plant operation, but perhaps even more the structures existing during abnormal transient phases, including plant start-up and close-down, during which the occurrence of dust explostions may sometimes seem more likely than under normal steady-state conditions.

Dust layer and dust cloud ignition processes

Ignition is a broad field of research. The concept of thermal runaway is a common basis for understanding and describing ignition processes. Theories have been developed even for complex cases with reactant consumption during the process leading to ignition. However, it does not seem realistic for the time being to foresee the development of one single unified theory, usable
in practice, which covers all types of ignition sources. It is instead 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 pre-mixed 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. Many variables must be considered, which are partly related to the nature of the potential ignition source itself and partly to the combustible dust layer or cloud that is exposed to the source. Definition of good parameters and design of corresponding experimental test methods remain a central challenge.

Hensel and John\textsuperscript{18,19} provided further insight into the important relationship between the conditions required for initiating smouldering combustion of a dust layer on a hot plate, and the layer thickness. Hensel \textit{et al.}\textsuperscript{20} 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\textsuperscript{21}. It was pointed out that a critical heat flux relates more to real practice than a critical constant surface temperature.

Kaufman \textit{et al.}\textsuperscript{8} summarized their research on smouldering combustion of dust heaps and dust layers. Chernenko \textit{et al.}\textsuperscript{22} 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\textsuperscript{23} developed a mathematical model for self-heating in coal deposits, taking into account the effect of diffusion of air into the deposit. Sobolev\textsuperscript{24} developed a discrete, two-temperature mathematical model for heat conduction in a dust deposit. An informative overview of research on self-heating/self-ignition in dust deposits was given by Crowhurst\textsuperscript{25}. Zhang and Deng\textsuperscript{26} studied the combustion rate of coal dust layers on constant-temperature hot surfaces. Influences of hot surface temperature, oxygen content in the atmosphere and flow rate of air across the layer on the oxidation rate were investigated. Itagaki and Matsuda\textsuperscript{27} used both differential scanning calorimetry and accelerating rate calorimetry for measuring the exothermic reactivity of activated carbon dusts. Adsorbed nitrogen oxides or fluorine on the coal surface increased the exothermic reactivity markedly, with the onset temperature of exothermic reactions being as low as 30–40°C.

Glinka \textit{et al.}\textsuperscript{28} conducted an experimental and theoretical study of ignition of dust layers by thermal radiation. The ignition process was resolved in detail by means of high-speed Mach–Zehnder interferometry.

Van der Wel\textsuperscript{29} conducted a series of experiments in which laminar dust clouds were ignited by a short light pulse (100 µs or 10 ns) from an Nd:YAG laser (1064 nm wavelength). This kind of experiment can provide basic information about dust cloud ignition processes, and also about flame propagation processes in dust clouds. Van der Wel \textit{et al.}\textsuperscript{30} described how a simple, modified Semenov theory (no temperature gradients inside the heated volume) for auto-ignition was used for transforming the experimental laser-light-pulse ignition results to predicted minimum ignition temperatures and energies. The predicted values were in approximate agreement with measured minimum temperatures and energies for ignition. Gieras and Klemens\textsuperscript{31} studied the critical conditions for ignition of single coal particles in air, and in air containing methane. They also investigated the critical ignition conditions for clouds of coal dust in air and in 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 in industrial plant design. However, it has been known for some time that minimum ignition temperatures of dust clouds vary significantly with scale, and this has recently been confirmed by Wolanski\textsuperscript{32}. Further experimental and theoretical work is needed in this area.

\textbf{Ignition of dust clouds by small burning metal particles (impact sparks, metal sparks) generated by mechanical impact} is a very complex problem. A comprehensive, practically useful theory does not seem to be within sight. Such a theory must comprise several steps. The first is the generation and initial heating of the metal particle by the impact, which is in itself a very complex problem. 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.

In dust explosion statistics, the frequency data for occurrence of various categories of ignition sources are sometimes confusing, because the frequently used term 'friction sparks' is ambiguous. 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. Furthermore, one does not always distinguish between burning metal particles from one single accidental impact and from repeated impacts in rotary machinery such as grinding and cutting equipment. The categorization of ignition by burning metal particles from grinding and cutting operations is not always clear either. This is because ignition may have been caused by the hot surface being produced at the object being ground, rather than by the burning metal particles generated in the grinding process.

\textbf{Ignition of dust clouds by electric/electrostatic discharges} is another very complex topic. Theories have been developed for ignition of dust clouds by electric sparks between two metal electrodes, which is the simplest case, but even such theories are only rough approximations. The variables of the electric spark ignition problem include voltage and current characteristics across the spark gap, spark gap geometry and electrode material, and dust cloud variables such as particle material and particle size/shape distributions, dust moist-
Dahn et al.\textsuperscript{33} reviewed some published work on electric spark ignition of combustible dust clouds. Their own experiments with clouds of lycopodium confirmed the dramatic influence of the combination of capacitance and resistance of the experimental discharge circuit on the minimum capacitor energy for ignition.

Xu and Lin\textsuperscript{34} conducted a semi-quantitative 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 Reference 1).

With respect to the ever more complex one electrode discharge types (corona, brush, propagating brush etc.), valuable experimental insight has been gained during recent years, but so far no attempt at developing dust cloud ignition theories seems to have been made. Glor\textsuperscript{35} gave an informative overview of the present status on theory and experimentation. Some of this work, on possible incendiary discharges from powders poured into a heap, was presented by Glor and Maurer\textsuperscript{36}. The question of whether incendiary lightning type discharges can occur in dust clouds is still to be answered. Glor\textsuperscript{37} is also continuing his work on whether incendiary brush discharges can occur in dust clouds.

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 the case of dust clouds, this may not be as obvious a problem as for gases, but the concept of MESG does have some relevance in relation to explosion isolation (see section on 'Mitigating and controlling measures' below). Pioneering work has been performed in this area by Schuber (see Reference 1).

Initiation of dust explosions by shock waves has been studied by several workers, and valuable insight has been gained. The direct practical relevance of this knowledge is less obvious than for some other aspects of dust cloud ignition. One possibility is to make use of the induction time for shock wave ignition in a model of flame propagation in turbulent dust clouds (see next section). An informative analysis of shock wave ignition of dust clouds was given by Wolanski\textsuperscript{39} and research at University of Michigan, USA is reported by Kauffman et al.\textsuperscript{40}. Boiko and Papyrin\textsuperscript{41} studied dust dispersion behind a shock wave, using an advanced laser visualization method. Ignition delays of different dusts in incident and reflected shock waves were estimated. Geng et al.\textsuperscript{42} 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.\textsuperscript{43} used a vertical shock tube for measuring ignition delays of dust clouds behind an incident shock. Lu and Fan\textsuperscript{44} 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 et al.\textsuperscript{45} investigated the fast ignition and combustion of wheat flour behind a shock wave in a shock tube.

### Flame propagation processes in dust clouds

Some central topics are the same as for flame propagation in premixed gases, viz.:

- laminar flames
- flame acceleration mechanisms
- turbulent flames
- detonation

However, in the case of dust clouds

- ignition and combustion of single particles in a dust cloud

is an additional fundamental research topic.

An important difference between dust clouds and premixed gases is that inertial forces in dust clouds can produce fuel concentration gradients (displacement of particles in relation to the gas phase). Furthermore, thermal radiation may contribute significantly to the heat transfer from the flame to the unburnt cloud, depending on the type of particles (e.g. light metals).

Understanding laminar flame propagation processes in dust clouds may be the key to understanding how dust explosions develop in terms of pressure as a function of time. Mazurkiewicz and Jarosinski\textsuperscript{46} studied the gas composition just upstream of a stationary, stabilized maize starch/air flame front in a burner. It was found that CO, CO\textsubscript{2}, H\textsubscript{2} and CH\textsubscript{4} were the main components produced during the initial pyrolysis stage. The CO\textsubscript{2} content increased with decreasing temperature. In the gas phase oxidation reaction, burning of CO was most important. Mazurkiewicz and Jarosinski\textsuperscript{46} 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 unburnt dust cloud through the burner were in the range 0.61–0.65 m s\textsuperscript{-1}, 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\textsuperscript{-1}. Proust\textsuperscript{47} described independent experimental studies of laminar burning velocities and maximum flame temperatures in clouds of starch, lycopodium and sulfur in air, whereas Seshadri et al.\textsuperscript{48} studied the structure of laminar dust flames. Bradley et al.\textsuperscript{49} investigated the burning of clouds of fine graphite dust (4 \mu m) 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 suggests a basis for a mathematical model of the laminar combustion of clouds of ultrafine coal dust. Giers and Klemens\textsuperscript{50} compared flame propagation in clouds of coal dust in air and in methane/air, at normal and micro-gravity 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.

Van Wingerden\textsuperscript{51} performed basic work on laminar flame propagation in Norway, which has disclosed a need for reconsidering the phenomena involved in steady-state upwards laminar flame propagation in vertical ducts.
Krishenik and Shkadinskii\textsuperscript{50} developed a mathematical model for flame propagation in dust clouds of mixtures of two monosized particle fractions. Both conductive and radiative heat transfer were incorporated in the model. Deng \textit{et al.}\textsuperscript{51} 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.

Lee \textit{et al.}\textsuperscript{52} 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.

Wlodarczyk \textit{et al.}\textsuperscript{53} conducted experiments in a 5 litre spherical explosion bomb to determine the influence of the dust concentration in exploding aluminium/air clouds on the content of aluminium oxide in the reaction products. Fan \textit{et al.}\textsuperscript{54} 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.

Limiting cloud compositions for flame propagation is an important fundamental research topic for at least three different practical applications, viz. explosible/non-explosible assessment, assessment of minimum explosible dust concentration, and assessment of maximum permissible oxygen concentration for inerting. Mintz\textsuperscript{55} found evidence for the existence of a maximum explosible 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\textsuperscript{-3} was found. The results were interpreted in terms of a simple 'oxygen depletion' model. The influence of the particle size distribution on the minimum explosible dust concentration was investigated by Pole-taev and Korolchenko\textsuperscript{56}, using data from experiments with polysized polyethylene dusts. Promising agreement between theory and experiments was obtained.

Hertzberg \textit{et al.}\textsuperscript{57} measured minimum explosible 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 different metals. They found that for some metals flame propagation appears to occur in a mixture of metal vapour and air, similarly to the gas phase flame propagation mechanism in clouds of organic dusts.

Hertzberg \textit{et al.}\textsuperscript{58} determined the same parameters for nine different dusts of solid explosives when dispersed as clouds in air in a closed bomb. In the low-concentration range (∼400 g m\textsuperscript{-3}), the dusts behaved as dusts of normal carbonaceous and plastic materials. At higher concentrations, they became more hazardous.

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\textsuperscript{2} g\textsuperscript{-1} (N\textsubscript{2} adsorption). Wie- mann\textsuperscript{59} showed that dusts of such materials (active carbon/active coke) of considerably lower volatile content than 7–8% could give fully developed dust explosions in the 1 m\textsuperscript{3} ISO vessel.

Turbulent combustion in dust clouds has been studied experimentally and theoretically by several investigators. Eckhoff\textsuperscript{60} summarized some work on the influence of initial and explosion-induced turbulence on dust explosions in closed and vented vessels. Wei \textit{et al.}\textsuperscript{61,62} re-emphasized the important role played by turbulence in dust explosion propagation in closed vessels. Kauff- man \textit{et al.}\textsuperscript{61} and Austin \textit{et al.}\textsuperscript{62} summarized their research on turbulent combustion of premixed dust clouds, and Tamanini and Ural\textsuperscript{63} summarized their work on the effect of initial turbulence on flame propagation in dust clouds. Schueermann\textsuperscript{64} also investigated the influence of the initial dust cloud turbulence on the development of dust explosions in vented enclosures. Rzal-Rebière and Veyssièrè\textsuperscript{65} investigated the interaction of a laminar maize starch/air flame with an obstacle, viz. 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 towards improved understanding of the relationship between the dynamic state of a dust cloud and its combustion rate should be encouraged. Basic parameters need to be identified. Various strategies have been indicated. For example, an induction time for ignition may be taken as a global characteristic of the combustion chemistry (shock tube or stirred reactor). Geng \textit{et al.}\textsuperscript{66} measured the ignition delay behind an incident shock wave of Mach number 4–6 passing through a cloud of maize starch in oxygen. Ural\textsuperscript{67} emphasized the fact that different induction times are observed with incident and reflected shock waves, due to different ignition mechanisms. Boiko \textit{et al.}\textsuperscript{68} measured ignition delays for coal dust clouds exposed to reflected and incident shock waves.

An alternative approach is to consider the laminar burning velocity as the fundamental parameter, as suggested by Bradley \textit{et al.}\textsuperscript{69}. Empirical relationships between turbulent burning velocity and turbulence intensity are then established, using the laminar burning velocity as a normalizing parameter. As pointed out by van Wingerden\textsuperscript{69}, numerical 'flame libraries' can then be formulated and used for closing the positive-feedback loop combustion–expansion–flow–turbulence–combustion in numerical dust explosion simulation codes. The ongoing research and debate on numerical modelling of premixed gas combustion should be watched carefully to ensure that any elements that may contribute to solving the dust explosion modelling problem are explored.
Understanding flame acceleration, due to flame distortion and turbulence produced by the propagating explosion itself, is central for understanding both dust and gas explosions. Extensive experimental research programmes have been conducted to study these phenomena for gas explosions in obstructed geometries. If the experimental facilities used in these experiments are still available, it would seem relatively straightforward to repeat the experiments in the various vessels, using dust clouds instead of premixed gas. Systematic comparison of results with previous data from gas explosions would yield a valuable overview of similarities and discrepancies, which would help to focus basic research efforts on important areas where dust cloud combustion may differ significantly from combustion of premixed gases. Proust71 has given an informative review of the state-of-the-art on propagation of dust explosions in pipelines in relation to gas explosion propagation in pipelines. Pu et al.72 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⁻¹. Hu and Sun73 studied the mechanisms of fast combustion of Al powder suspended in atmospheres of different oxygen contents, using an explosion shock tube technique.

Much work has been, and is currently being done, on turbulent combustion of sprays and mists74, which is in part also relevant in the context of dust explosions. Huang et al.75 observed that burning clouds of aluminium dust in air are electrically conductive. They attributed this effect to generation of metal vapour by evaporation of the particles prior to combustion. Besides being of fundamental interest, the observed effect also has implications with respect to industrial safety.

The hope is that adequate mathematical codes for computer simulation of dust flame propagation processes will be available in a not too distant future. Kjellman76 has summarized his work on applying computational fluid dynamics to turbulent dust explosion propagation. Application of the numerical model to peat dust explosions in a closed 20 litre vessel showed promising agreement with experiments. Krause77 presented a comparatively simple two-dimensional model for numerical simulation of explosions in vented enclosures. The turbulence sub-model was empirical, and the explosible medium was regarded as a homogeneous, premixed gas. Comparison with more complex models gave reasonable agreement. Comparison with dust explosion experimental data was not reported. In a subsequent contribution, Krause78 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. He was able to predict the earlier experimental finding of Tamanini et al. (see Reference 1), that the maximum explosion pressure in the vented vessel increases with increasing initial turbulence intensity in the exploding cloud.

Finally, the singular phenomenon of dust cloud detonation should be mentioned. It is now generally accepted that this can occur, but further work is needed in order to establish an adequate understanding of the deflagration-to-detonation-transition process (DDT). An excellent review of the state-of-the-art and outstanding problems in dust cloud detonation research has been given by Kauffman et al.8. The current knowledge on dust cloud detonations was also summarized by Alexander et al.79. Kauffman et al.8 and Austin et al.9 summarized their extensive work on how detonations can develop from accelerating turbulent combustion of dust clouds in long tubes. Sichel and Kauffmann study the transition from deflagration to detonation 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 et al.80,81 determined experimentally the minimum critical tube diameter for detonation propagation in suspensions of a fine aluminium flake dust in air. The critical value found was in the range 0.040–0.055 m. Korobeinikov83 conducted a theoretical study of the propagation of detonation waves in dust clouds. The problem of establishing adequate scaling rules was given particular attention. Markov84 presented a new method for numerical simulation of non-steady detonations in dust clouds. Two-dimensional computations yield a multi-wave structure of the detonation process. Ding and Huang85 analysed the mathematical theory for the reaction zone in a detonation wave passing through a dust cloud, and proposed a new numerical criterion describing the Chapman–Jouguet condition. Tulis et al.86 conducted detailed experimental studies of the structure of detonation processes in clouds of aluminium in air. The influence of particle size and shape was studied, and various detonation wave structures were identified. Papinski and Wlodarczyk87 analysed the critical conditions for direct initiation of detonations in dust clouds of infinite size. Klemens et al.87 performed experiments in which detonation waves in hybrid mixtures of methane, air and oats dust were studied.

Blast waves generated by burning dust clouds
One case of practical interest is blast waves from explosions in partly confined geometries, e.g. deliberately vented, or bursting process equipment, and work rooms. The strength and shape of blast waves from dust explosions depend on the way in which the dust clouds burn. For example, Wirkner-Bott et al.88 conducted a fairly detailed study of the nature of the 'secondary explosion', i.e. the explosion of unburnt dust cloud outside the vent opening. This phenomenon was discussed further by Schumann and Wirkner-Bott89. Central variables influencing blast wave generation, in addition to type of dust cloud and geometry of system, include the dynamic state of the dust cloud at the moment of ignition, ignition point in relation to vent, the vent size, and the vent cover opening pressure. Van Wingerden90 gave 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.91.

Medvedev et al.92 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 author93 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 et al. presented a new mathematical model of shock wave propagation in dust clouds comprising poly-disperse systems, i.e. a range of different particle sizes within the same cloud. Inter-particle 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. Gelfand et al. investigated experimentally the attenuation of shock waves propagating through dust clouds in a 50 mm diameter shock tube. Reasonable agreement between experimental data and analytical and numerical predictions was found for incident shock waves of Mach number < 3.

A useful condensed introduction to the complex field of properties and effects of blast waves from explosions has been given by Harmanny. The effect of a given blast wave on humans, buildings and process equipment is an important area where more research is needed. Valuable reviews are given by Mercx and L'Abbe. Britan et al. 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. They also analysed the features of the transmitted shock wave and the waves reflected from the air/foam boundary and from the walls of the experimental channel.

**Status and outstanding problems in preventing and mitigating/controlling dust explosions in industrial practice**

**The role of fundamental knowledge in developing practical solutions**

The status on the fundamental side, outlined above, is necessarily also the status as regards the genuine understanding of the various corresponding phenomena in industrial practice, indicated in Table 1. As already emphasized, the strengthening of the links between fundamental research and industrial research and development should be encouraged. This will promote the use of available basic knowledge in the design of practical measures, as well as direct the basic research into areas useful for practice.

Deng and He pointed out the need to use thermodynamics, chemical reaction kinetics, and fluid dynamics for proper description of ignition and flame propagation phenomena in dust clouds and layers. These topics constitute central elements of classical chemical reaction engineering, and Deng and He proposed a corresponding concept 'Dust explosion reaction engineering' (DERE) for the dust explosion domain.

Siwek presented a concentrated overview of current methods for dust explosion prevention and mitigation in the process industries, based mainly on experimental research and development performed within the Swiss/German domain. Siwek's paper reflects the important fact that industry needs practicable solutions for today, and cannot wait for more ideal solutions that may become available in the future. However, industrial pragmatism must not, on the other hand, block the constant strive 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, industry and the researchers, is growing.

Eckhoff reviewed the state-of-the-art on preventing and mitigating dust explosions in the ferro-alloys industry. In general, both the electric spark ignition sensitivity and the explosion violence \( K_s \) of metal dusts increase with decreasing particle size, right down to the 1 \( \mu \)m region. In the past, this has not always been taken into account. Often particle size was merely specified in terms of 'less than 74 \( \mu \)m' or 'less than 63 \( \mu \)m', which is by no means satisfactory. More research is needed, in particular on alloys, where the most hazardous components may sometimes accumulate in the fine tail of the particle size distribution.

**Generation and states of industrial dust clouds**

Comparatively little quantitative knowledge of practical use has been generated. It is known, however, that the dynamic state of a dust cloud dramatically influences both its ignition sensitivity and its combustion rate. Therefore, it is clear that systematic quantitative assessment of this state is of great practical significance. Experimental investigation of typical processes of generation of dust clouds and the resulting states of the clouds, in various types of process equipment and modes of operation, should be encouraged. This is a typical area where close interaction of fundamental and applied research can be highly beneficial. The work of Hauert

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**Table 1.** Means for preventing and mitigating/controlling dust explosions in the process industries. Topics for applied research and development

<table>
<thead>
<tr>
<th>Prevention</th>
<th>Mitigation/Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prevention-pressure-resistant process equipment</td>
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<tr>
<td></td>
<td>Isolation</td>
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<td></td>
<td>Partial inerting by inert gas</td>
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<td></td>
<td>Explosion venting</td>
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<td></td>
<td>Explosion suppression</td>
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<tr>
<td></td>
<td>Preventing secondary explosions (good house-keeping for</td>
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<tr>
<td></td>
<td>preventing dust layer formation)</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Preventing ignition sources</th>
<th>Preventing explosible dust cloud</th>
</tr>
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<tbody>
<tr>
<td>Self-heating in dust deposits</td>
<td>Inverting by inert gas</td>
</tr>
<tr>
<td>Open flames</td>
<td>Inverting by inert dust</td>
</tr>
<tr>
<td>Hot surfaces</td>
<td>Keeping dust concentration outside explosive range</td>
</tr>
<tr>
<td>Burning metal particles</td>
<td></td>
</tr>
<tr>
<td>Electric sparks and arcs</td>
<td></td>
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<tr>
<td>Electrostatic discharges</td>
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et al., discussed above, constitutes an important step in the right direction.

**Preventing ignition sources**

A considerable amount of fundamental knowledge is available, and the time is ripe for accepting that the concept of ignition comprises a range of very complex processes. 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. Further development of correlations between results from standardized tests and actual critical ignition conditions in practice should be encouraged.

Gibson gave a valuable summary of methods for preventing ignition of powders and dusts in drying operations. Zockoll described a new system for early detection of self-heating/self-ignition in deposits of organic powders in spray dryers, based on detection of low concentrations of CO.

Xu et al. found that very weak electric spark discharges, in the range 0.1–1.0 mJ, are probably able to initiate smouldering combustion in linen flax. Electrostatic hazards in connection with industrial use of flexible big bags were discussed by Rogers and by Dahn et al. Pratt presented three case histories in which electrostatic spark discharges were generated during pneumatic transport of powders. Sun Keping charged powders being pneumatically conveyed in pipes. Kleinschmidt, who reported that the GreCon system discussed the electrostatic hazards in powder handling in connection with industrial use of flex-bags, constructed a new type of electric charge eliminator for charged powders being pneumatically conveyed in pipes. The method was tested out successfully in industrial practice during a period of one year. Wang and Lou 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 industrial hygiene aspects require careful consideration.

An example of commercially available equipment for preventing ignition in industrial plants was given by Kleinenschmidt, who reported that the GreCon system for detection and extinction of ‘sparks’ in terms of flying burning particles is being developed further with respect to optimizing system performance. The same applies to the Firefly system, which, according to Jansson, offers an adjustable lower particle temperature limit of detection, down to 150°C. A multi-zone 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, close-down of plant, or simply adjustment of plant running conditions to prevent further hot object generation. A similar ‘spark’ detection and extinguishing system has also been developed by T&B Electronic.

Lloyd and Laut presented the state-of-the-art on international standardization of classification of areas containing combustible dust, and guidelines for selection of electrical equipment for such areas. Central organizations involved in this work are the International Electrotechnical Commission (IEC), and CEN and CENELEC of the European Community.

Preventing exploisable dust clouds

Inerting of the dust cloud can be accomplished by adding gases such as nitrogen or carbon dioxide to lower the volume percentage of oxygen in the atmosphere to a level at which the dust cloud can no longer propagate a self-sustained flame. A fair amount of data exists for maximum permissible oxygen content in the atmosphere for inerting. However, there is room for improving the test methods by which such data are obtained. Furthermore, most 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. Giori determined maximum permissible O2 contents for inerting clouds of coal dusts at elevated temperatures and pressures. Wolinski and Hayashi determined standard explosibility parameters of dusts and various rare metal alloys in air containing halon 1301 and added nitrogen. Theories for flame propagation limits (see discussion above with reference to the third column of Table 1) would be useful even in this context, and their development should be encouraged. Krause et al. proposed a simplified, approximate method for first-order estimation of the minimum oxygen concentration for flame propagation in dust clouds. Maddison summarized some important aspects of inerting powder handling plants using nitrogen, carbon dioxide and other inert gases.

Gao et al. described a new system for injection of pulverized bituminous coal into a blast furnace for steel production, for which nitrogen inerting constitutes a central safety measure. Full or partial 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 Junyi et al. Whilst reducing the oxygen content in the atmosphere prevents dust explosions, it can introduce a suffocation hazard. However, it has been shown that adding a few vol% CO2 to the gas mixture considerably reduces the critical oxygen threshold for suffocation. An inert gas mixture (INERGEN) utilizing this effect is now being marketed by Dansk Fire Eater A/S. Further work to identify gas mixtures that keep the dust cloud inert without presenting a suffocation hazard should be welcomed.

**Inerting by adding non-combustible dust** is not generally applicable, because the inert dust will in most cases cause unacceptable contamination. However, there are cases where the dust/powder processed is already a mixture of combustible and non-combustible dusts, and where control of the composition ensures that dust clouds are non-flammable. It is then essential to avoid segregation of combustible and non-combustible components throughout the process. Zhang Zhancheng et al. 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 industrial hygiene aspects require careful consideration.

Keeping the dust concentration below the minimum exploisable concentration is a third means of maintaining dust clouds non-explosive. More work is needed to establish procedures for the determination of dust concentrations in industrial situations. Zockoll described
an apparatus, based on infra-red light attenuation, for determining the dust concentration of dust clouds generated in various situations in industry. Typical measurement results were reported, demonstrating the feasibility of the method. Xu Bowen et al.126 proposed a systematic method for estimating the dust explosion hazards in industrial plants. The method implies an empirical relationship between local dust concentration and the local rate of dust deposition from the cloud [mass (time area)]. Properties of the dust emission source must be known. Also, research is needed to establish the minimum mass of dust deposit per unit of surface area that is required for maintaining a self-sustained explosive combustion along the surface. The assumption that entrained dust will become distributed evenly throughout the available space may not 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. The conditions required for producing this kind of self-sustained shallow sweeping flames need to be investigated further in the context of the first column of Table 1.

Wolanski127 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 explosible 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.

Xu Bowen et al.128 found that the minimum explosible concentration 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. Mittal129 discussed various mathematical models for calculating minimum exploisible concentrations of dust clouds. Shao and Wang130 reviewed some non-intrusive methods for measuring the dust concentration in dust clouds, primarily in pipes and ducts.

Mitigating and controlling measures
The use of explosion-pressure-resistant process equipment for full explosion confinement is limited because of high equipment costs. Current experimental methods allow sufficiently accurate prediction of maximum explosion pressures in simple vessels with point source ignition. This also applies to explosions at elevated initial pressures. Torrent and Menéndez131 found that the proportionality between initial and final pressure found previously in small laboratory-scale vessels also holds in vessels of 1 m³ volume, up to 12 bar initial pressure. However, if complex dynamic pressure development, e.g. with pressure piling, is to be expected, closed-bomb test data are of limited value. There is also room for further improvement in the design of the process equipment itself, with respect to minimizing its heaviness. The German concept of pressure-shock-resistant design should be further developed. Crowhurst132 gave a useful overview of the state-of-the-art on design of equipment to withstand a given overpressure caused by a fully confined or vented explosion. Bartenev et al.133 developed a mathematical model for the failure of a process vessel subjected to an internal exothermic, comparatively slow process creating an overpressure, allowing the maximum initial velocities of fragments or vent covers to be estimated. Bartenev et al.134 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.

The objective of explosion isolation is to prevent dust explosions from spreading from the primary explosion location to other process units, workrooms, etc. Van Wingerden et al.135 reported on dust explosion experiments in integrated systems of various process equipment connected with ducts. Due to pressure piling, jet-initiated high initial turbulence and turbulent jet ignition, very high pressure peaks can be generated even in generously vented vessels. This investigation is a further demonstration of the need for effective means of explosion isolation in coupled systems. Various passive and active techniques for explosion isolation have been developed and are being used, but there is room for further improvement. If adequate performance can be achieved, passive techniques are clearly more attractive than active ones.

A basic understanding of flame propagation and pressure build-up in coupled geometries ('interconnected vessels') is important for the prediction of the performance of various active and passive isolation equipment. Valuable large-scale experimental work in this area was reported by Lunn136 and by van Wingerden and Alfert137. The understanding of flame propagation in long ducts and pipes is also very important. Vogl138 presented results from a comprehensive experimental investigation of the propagation of dust explosions in pipes for pneumatic powder transportation. 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. The parameters were: initial air velocity in the pipe, pipe diameter, location of the ignition source, dust concentration in the pipe, and the Ks value of the dust. Zellweger139 described further work to improve passive and active isolation valves of the VENTEX type. Closing times (from sensing of the explosion to valve 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 based on venting at a bend have been in use for some time. However, there is room for further exploration of the potential of this attractive, simple principle of explosion isolation. A new low-pressure-drop design was described by Alfert and Führe140 and by van Wingerden and Alfert137. Gloc17 reported work on the performance of explosion barriers in ducting connected to vessels with venting or automatic explosion suppression. Klincewicz and Kordylewski141 described a new, prom-
ising design of an explosion diverter for interrupting explosions in pipe lines. The new design avoids the pressure drop created in normal operation by passive diverters, but requires active triggering. Cybulski et al., addressing the problem of coal dust explosions in coal mines, used solar panels for automatic detection of the coal dust flame and simultaneous actuation of water barriers. The water was contained in plastic bags, which were opened by a detonating cord triggered by the flame-generated power from the solar panel.

Partial inerting by inert gas is a promising means for mitigating dust explosions, which deserves further attention. The idea is that as the oxygen content in the atmosphere is decreased, there is a gradual decrease of both ignition sensitivity and combustion rate of the dust cloud. In some cases, the explosion hazard may be reduced substantially by only a moderate reduction of the oxygen content in the gas. However, more research seems necessary in this area to establish a correlation between the oxygen content in the gas and various ignitability and explosibility parameters. Interesting new information is currently being produced in a joint European research programme (CREDIT), focusing on the influence of oxygen content of the atmosphere on the minimum energy and temperature for ignition of dust clouds.

Dust explosion venting remains a complex and controversial subject. Adequate understanding of flame propagation processes in dust clouds is essential for the design of optimal venting arrangements for industry. Useful reviews of various aspects of dust explosion venting in practice were given by Scholl and Lunn. 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 of given structures are generated, nor the way in which clouds of given initial structures burn, are well understood. Consequently, adequate venting theories do not exist, and one must rely on experiments. During the last few years, the need for differentiating vent area requirements in view of the different turbulence levels, degrees of dust dispersion and concentration distributions of dust clouds which occur in practice has become widely accepted. Eckhoff discussed this problem with particular reference to venting of large silo cells. Deng et al. conducted vented maize starch explosions in a 95 m³ vertical experimental silo of \( L/D = 3 \). The 3.4 m² vent was located in the silo roof. The maximum vented explosion pressures were comparatively low. Höchst et al. conducted systematic maize starch/air explosion experiments in a top-vented silo of volume 50 m³ and \( L/D = 4 \). Both dust concentration and initial turbulence (prior to ignition) were monitored. The dust injection process as well as the ignition point location were varied. Flame propagation and pressure build-up during the vented explosion were measured. Comparative experiments with methane/air in the silo were also performed.

Molkov et al. 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 et al. studied, theoretically as well as experimentally, the influences of details of the mounting flange arrangement on the static bursting pressure of bursting panels/membranes. They observed two distinctly different bursting patterns, viz. bursting of the membrane in its central region, and bursting along the edge.

The paper by Crowhurst on the design of enclosures to withstand a given maximum explosion pressure also applies to vented enclosures. Harmanny presented a new formula for predicting the duration of vented dust explosions in enclosures of volumes from 10 to 60 m³. 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.

A further dimension of complexity is added to the venting problem if the initial pressure (and/or temperature) deviates from atmospheric. Results from venting of dust explosions in air of elevated initial pressure were reported by Siwek. The effect of pressure piling and turbulent flame jet ignition on vent area requirements in systems of interconnected vessels were studied by Lunn.

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 et al. reported a series of large-scale venting experiments (40 m³ and 20 m³) where external blast waves and flame lengths were determined and compared with existing empirical correlations (see also the section above on 'Preventing exploisible dust clouds'). Peng et al. developed a 'labyrinth' type flame arrestor for mitigating flame and pressure effects from dust explosion venting. Experiments using a 2.7 m² enclosure and a 370 mm diameter vent opening suggested that this arrestor concept works satisfactorily for StI dusts. The maximum explosion pressures in the vented enclosure, with the arrestor mounted in the vent, were only a few per cent higher than the pressures without the arrestor, whereas both flame and pressure effects were substantially reduced. Li Gang et al. presented a new version of the quenching tube first developed in Norway (see Reference 1), in which the conventional bursting diaphragm had been replaced by a re-usable vent cover. This solution is of interest in situations where the expected frequency of explosions is comparatively high.

Venting of industrial buildings requires special considerations. A useful overview was given by Crowhurst.

The influence of vent ducts on the maximum explosion pressure in the vented vessel has been studied experimentally by several workers. Recently Ural presented a theoretical model for vented gas explosions by which he has been able to calculate pressure-versus-time characteristics in the vented vessel that agree well with corresponding experimental data. It remains to be investigated, however, whether this theory can reproduce existing experimental data.
Dust explosion venting remains an area in which considerably more work is required. The new German draft VDI-3673 venting guideline, issued in 1992, has met some objections in other countries. This in particular applies to the concept of 'heterogeneous' dust clouds. Nevertheless, computer-based 'software' for easier use of this draft guideline was presented by Alfert et al.158. Hattwig and Heinzel159 discussed deficiencies in the new VDI draft guideline on the basis of dust explosion experiments in 45 m³ (L/D = 2) and 85 m³ (L/D = 4) vented silos of square cross-sections.

Automatic explosion suppression is an active, comparatively sophisticated method of dust explosion mitigation/control, which is used when simpler and less expensive methods cannot be applied. Although this method has been in use for many years, there is still a need for research and development. Moore et al.160 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 by the VDI method used in previous experiments. Glor162 and Moore161 reported current work on the possibility of applying this method even in the case of highly explosive organic dusts of Kst > 300 bar m s⁻¹. In the case of aluminium powders, satisfactory suppression has not yet been achieved for powders of Kst > 200 bar m s⁻¹, which means that only dust explosions in clouds of relatively coarse aluminium powders can be suppressed. The influence of the dynamic state of the dust cloud at the moment of suppression injection, the influence of the suppressant injection on this state, and development of improved suppressants are some of the areas where further work would seem useful. Recent experiments have indicated that water can be an effective suppressant, if injected at a temperature >180°C. According to Tyldeley163, optimum suppression is found to require about 0.5 litres of water per m³ of vessel volume: 16–18% of the superheated water is flashed to steam, the remainder forms very small droplets. Reduced explosion pressures of 0.3–0.4 bar(g) were obtained in experiments in a 28 m³ experimental vessel, using a dust of Kst = 150 bar m s⁻¹. Gieras et al.164 conducted a series of experiments in order 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.

Siewe165 described experiments where a combination of explosion venting and automatic suppression was adopted for mitigating/controlling dust explosions in various enclosures. Śliz et al.166 investigated the performance of such a combined system for mitigating grain dust explosions in an 8 m³ experimental vessel. Different types of vent covers and suppressors were tested.

Prevention of secondary explosions outside process equipment remains an important issue. Proper housekeeping is an essential means of achieving this aim. However, further work is required for assessment of the maximum acceptable mass of deposited dust per unit area of surface for preventing secondary dust flame propagation under various conditions. Cybulski et al.167 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.168 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, e.g. in grain storage and handling plants.

Gieras et al.169 studied the development of combustible gases (H₂, CO and CH₄) 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.

Quantitative risk analysis (QRA) is receiving 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 a lack of relevant quantitative failure rate data. However, attempts are nevertheless being made to apply QRA to the dust explosion problem, as demonstrated by Wagner166. Mittal170 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. Li and Wang171 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 Frehill172 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.

Status and outstanding problems in testing of dust ignitability and explosibility

Historical background and standardization of methods
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/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 situation today is complex. It is realized that only a few of the dust parameters that are currently being used for characterizing ignition sensitivity and explosibility of dusts can be regarded even as approximate 'physical constants' for a given dust. In most cases, a
great number of variables are involved and a differentiated view is required. Typical examples are the minimum ignition energy and the explosion violence of dust clouds.

A number of standard test methods have been developed through the years, e.g. by IEC (International Electrotechnical Commission) and ISO (International Standardization Organization). In the USA, ASTM (American Society for Testing and Materials) has issued a number of standards in this area. Recently, the standardization organization of the European Union, CEN, has launched a multi-year programme to produce a series of standard methods for the testing of explosion propagation limits, ignition sensitivity and explosion violence of combustible dust clouds. Reference 1 gives a comprehensive presentation of the wide range of test methods in use in Europe and the USA.

Two alternative approaches for achieving differentiation
A first approach for handling this situation is to have several test methods for any given parameter, allowing 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 in fact been incorporated in the new IEC standard issued in 1994. Whereas an appreciable inductance is to be included in the capacitive discharge circuit in the case of standard testing, to obtain the most incendiary sparks, it is argued that this is not relevant if the test result is to be used for assessing the electrostatic spark discharge hazard.

A similar situation should arise when testing for explosion violence. It is now appreciated that the standard ISO $K_{IN}$ 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, for example, $K_{IN}$ values are still to be used for sizing of explosion vents, differentiation by varying the intensity of the dust cloud formation process used in the test to fit the practical situation of interest could be worthwhile considering. The work by Liu et al.\textsuperscript{17} is relevant in this context. They described introductory studies of the turbulence structure in experimental dust clouds in the 1.2 litre Hartmann bomb under various conditions of dust injection. This apparatus was traditionally used for characterizing the explosion violence to be expected from various dusts. Because of its small size, the Hartmann bomb has in recent years been replaced by larger test vessels.

However, there is a second, alternative approach for handling the need for differentiation. In this case, the measured dust ignitability or explosibility parameter should be of a more basic nature, and differentiation to meet various practical situations in industry should be via adequate theory, using the basic parameter as input. In the case of explosion violence assessment, the existing $K_{IN}$ concept may be replaced by the laminar burning velocity of the dust cloud, for example. It is clear, however, that theories for transforming such basic parameters to flame propagation rates in practice must involve complex fluid dynamic computer simulation codes.

In the case of minimum ignition energy, the transformation would imply that the basic test value be converted to minimum discharge energies for ignition of the same dust cloud by various kinds of discharges, such as direct electrostatic two-electrode sparks, break flashes (e.g. live wire rupture) and one-electrode discharges. However, theories are scarce and the time may not yet be ripe for this approach. Siwek and Ciesaula\textsuperscript{175} presented a new test apparatus for the determination of 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 Benmou et al.\textsuperscript{176} 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 $\mu$J were attainable, using a travelling-electrode system.

Limits of flame propagation – a special problem of scale
Determining limits of flame propagation constitutes an important test objective (explosible/non-explosible assessment, and assessment of minimum explosible dust concentration and maximum permissible oxygen concentration for inerting). However, special care must be exercised in designing flame-propagation-limit tests. One basic problem is that near the limits self-sustained flame propagation cannot be established unless a considerable amount of energy is supplied for initiating 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 recent results by Cashdollar et al.\textsuperscript{175} and Cashdollar and Chatrathi\textsuperscript{176} 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 being exposed to a 30 kJ chemical igniter. However, in a 20 litre chamber, fully developed explosions were generated even with a 5 kJ chemical igniter. The reason for this could be that in the small chamber, due to the initial combustion and expansion of the dust cloud directly affected by the ignition source, the pressure and temperature in the unburnt cloud ahead of the flame increase significantly before flame propagation no longer receives support from the ignition source. Consequently the self-sustained flame propagation, if any, occurs in an adiabatically pre-compressed 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 for any explosion limit determination.

Zhou Congzhang et al.\textsuperscript{177} proposed a new, interesting procedure for determining minimum explosible dust concentration values in closed-bomb explosion experiments. They presented experimental evidence indicating that at the minimum explosible concentration, the time interval from ignition to the pressure peak has its highest value. They proposed that this criterion be used instead of some arbitrary pressure rise criterion of explosion.
Matsuda and Itagaki\textsuperscript{178}, comparing dust explosions in a 30 litre explosion bomb, and in a 1 m\textsuperscript{3} vessel, found that the ranges of explosible concentrations in the 30 litre vessel were considerably wider than those in the 1 m\textsuperscript{3} vessel for the same dust. A marked increase of the explosible range was found in the 30 litre bomb when increasing the ignition energy from 1 to 10 kJ. This effect was practically absent in the 1 m\textsuperscript{3} vessel in the ignition energy range 4–20 kJ. Tian Renqu \textit{et al.}\textsuperscript{179}, using a 20 litre explosion bomb, found that the minimum explosible concentrations of coal dusts decreased by a factor of two or more when the ignition energy was increased from 2.5 to 10 kJ. When using a 2.5 kJ igniter, and adding 2 vol\% methane to the air, the minimum explosible dust concentration dropped by at least a factor of two, compared with the values for dust in air. This 'hybrid' effect has been studied previously by several other workers. Xu Tianrui \textit{et al.}\textsuperscript{180} also arrived at the conclusion that the apparent minimum explosible dust concentration determined in a 20 litre bomb depends markedly on the ignition energy. A value for ignition energy of 10 kJ was found to be too high to yield realistic results.

Pu \textit{et al.}\textsuperscript{181} concluded that the turbulence structure of experimental dust clouds in a standard 20 litre spherical dust explosion test bomb had little resemblance to turbulence structures in dust clouds in accidental dust explosions in industry.

Miscellaneous

Wang and Zhang\textsuperscript{182} determined the minimum ignition energy, the minimum explosible concentration, and the 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.

Expert systems – friends or enemies?

During recent years, there has been an increasing interest in developing sophisticated computer-based expert systems for evaluation of dust explosion hazards and assessment of optimal safety design features. Haefen and Schecker\textsuperscript{183} presented such a system for assessment of dust explosion hazards in industry and selection of appropriate means of prevention and mitigation, which is in all essentials based on the German protection philosophy. Wach\textsuperscript{184} presented another expert system designed for the same purpose, but the technical and philosophical basis was not explicitly stated. A comprehensive expert system developed in the UK was presented by Tyldesley\textsuperscript{185}, and the need for quality assurance of such systems was emphasized.

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 not only experts on computers, but also on the physics and chemistry of the phenomena treated, expert systems should indeed be welcomed. However, there may be a possibility of the future market place being offered software 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.

The time may very soon be ripe for making adequate quality assurance of this kind of system compulsory. A need may emerge for establishing some internationally recognized body of experts that can ensure that expert systems offered in the area of explosion prevention and mitigation are up to acceptable standards.

The human hazard factors

The present survey deals with the chemistry, physics and technology of dust explosion prevention and mitigation. However, a brief mention should also be made of the importance of the human factors in this effort. This aspect has been discussed by Fernando\textsuperscript{186}.

Joint research efforts in Europe, and research and development in the People’s Republic of China

Over recent years, a steadily growing potential for organizing joint European research efforts has emerged within the EU/EFTA/EUREKA system. This also applies to dust explosion research. The British Materials Handling Board (BMHB) in the UK has played a central role in this process\textsuperscript{187}. A number of parallel research programmes have been started within the European Union’s ‘Credit Project’. Gibson\textsuperscript{188} summarized the areas requiring further work under the headlines:

- combustion processes in dust clouds (experiments, theoretical models)
- identification and control of ignition sources
- design of methods to prevent/protect against dust explosions

These headlines in fact cover most of the research needs identified in the present review. In addition, mechanisms of generation of dust clouds, which are important because they set the stage for subsequent ignition and combustion, require further exploration.

Wang Dongyan\textsuperscript{189}, characterizing the People’s 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 coal industry, 17\% in the textile industry, 12\% in the metallurgical industry. With the rapid development of the chemical and metallurgical industries, the annual number of explosions may 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 6th International Colloquium on Dust Explosions in Shenyang, People’s Republic of China, in August/September 1994, demonstrated that research and development on dust explosion prevention and protection in this enormous country is growing at great pace.
Conclusion

Initiation and propagation of industrial dust explosions are, from a fundamental scientific point of view, extremely complex phenomena. Comprehensive mathematical theories for predicting ignition and combustion of dust clouds in industrial environments from fundamental physical and chemical principles are at present beyond reach.

It is not surprising, therefore, that existing knowledge of 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 emerge. Powerful computers are invaluable tools in this process. However, experiments will remain indispensable for 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, the more basic research and mathematical modelling should continue at full pace.

The current efforts to establish international cooperation in joint research programmes should be encouraged.

Acknowledgements

The author wishes to express his sincere gratitude to all those who kindly provided essential information without which this paper could not have been written. Sincere thanks are due also to Aaslaug Mikalsen for typing the manuscript.

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