RESOURCE ARTICLE

Dust explosion causation, prevention and mitigation: An overview

The current paper gives a general overview of factors that can cause a dust explosion and the means by which such an event can be prevented and mitigated. Important explosibility parameters (e.g., maximum explosion pressure and standardized maximum rate of pressure rise) are described in terms of their relation to explosion causation, prevention and mitigation. Causation is further explained by means of the fire triangle and the explosion pentagon, and standard risk reduction measures are placed in a hierarchical arrangement incorporating inherent safety, passive engineered safety, active engineered safety, and procedural safety. The importance of safety culture and a safety management system approach are emphasized by reference to an industrial case study.

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INTRODUCTION

A dust explosion can occur when particulate solid material is suspended in air and a sufficiently energetic ignition source is present. The consequences are often similar to those arising from a gas explosion in terms of impact on people, physical assets and business production. While most industrial practitioners are familiar with at least the basic concepts of gas explosions (e.g., the need for a fuel, oxidant and ignition source), the same cannot be said for dust explosions.

The primary distinguishing factor between dust and gas explosions is the phase of the fuel itself–solid versus gaseous. Particle size is therefore a dominant issue in efforts aimed at preventing dust explosions and mitigating their consequences. The National Fire Protection Association (NFPA) defines a dust as any finely divided solid, 420 μm or 0.017 in. or less in diameter (i.e., material capable of passing through a U.S. No. 40 Standard Sieve).[1] Since the range of explosible particle sizes for a given material can be quite large, this definition highlights the importance of considering the particle size distribution in addition to a mean or median particle diameter. Further, the shape for which a given material poses a dust explosion hazard may not be limited to spherical or near-spherical particles, but could include flakes, fibres and flocculent forms.

Dust Explosion Occurrence

One of the first recorded accounts of a dust explosion was written by Count Morozzo[2] in 1795, and gave a detailed account of an explosion in a flour warehouse in Turin, Italy (as described by Piccinini[3] and Eckhoff[4]). In 1845, Faraday and Lyell[5] elucidated the key role of coal dust in the devastating explosion in the Haswell (UK) coal mine the previous year.[6] Fast-forwarding to the 21st century, dust explosions remain a persistent and damaging industrial occurrence. The US Chemical Safety and Hazard Investigation Board (CSB) has recently completed a series of reports dealing with investigations into the causes of serious dust explosion incidents that occurred in the United States during 2003.[7–9] A fourth CSB report[10] gives the findings of a study of dust explosions in general industry which was initiated following the three catastrophic incidents in 2003. At the time of writing the current manuscript, the CSB is engaged in investigating the 2008 explosion and fire at the Imperial Sugar refinery near Savannah, GA.

Dust explosion incidents are not, however, restricted to coal mines and food-processing facilities; nor are they restricted to the scenario of an industrial disaster. Frank[11] gives incident data reported by the US CSB and FM Global, which illustrate that dust explosions have occurred, for example, in the following industries with the indicated typical commodities:

- Wood and paper products (dusts from sawing, cutting, grinding, etc.);
- Grain and foodstuffs (grain dust, flour);
- Metal and metal products (metal powders and dusts);
- Power generation (pulverized coal, peat and wood);
- Rubber;
- Chemical process industry (acetate flake, pharmaceuticals, dyes, pesticides);
- Plastic/polymer production and processing;
- Mining (coal, sulphide ores, sulphur); and

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1871-5532/$36.00
doi:10.1016/j.jchas.2009.05.002
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- Textile manufacturing (linen flax, cotton, wool).

Objectives of Paper

The primary objective of the current paper is to provide a general overview of the mechanisms by which dust explosions originate, and the methodologies by which they can be prevented and their consequences mitigated. The paper is intended for the generalist audience in industry. Other resources are available for specialists in industrial loss prevention and dust explosion research. For example, recent reviews cover in detail case histories, causes, consequences and control of dust explosions,[12] the role of powder science and technology in understanding dust explosion phenomena,[6] and the status of developments in basic knowledge and practical application with respect to dust explosion prevention and mitigation.[13]

An additional objective of the current paper is to link the fundamentals of dust explosion causation, prevention and mitigation with the concepts of safety culture, a safety management system, and inherent safety. Based on the experience of the authors, it is critically important to place technical knowledge in a context of demonstrable management commitment to dust explosion risk reduction.[4,14–16]

DUST EXPLOSION CAUSATION

As a first step to understanding dust explosion causation, it is important to distinguish between a dust explosion *hazard* and a dust explosion *risk*. While the terms *hazard* and *risk* are often used interchangeably, they represent very different concepts. Functional definitions of each term are given by Wilson and McCutcheon[17]:

Hazard: The potential of a machine, equipment, process, material or physical factor in the working environment to cause harm to people, environment, assets or production.

Risk: The possibility of injury, loss or environmental incident created by a hazard. The significance of risk is a function of the *probability* (or *likelihood*) of an unwanted incident and the *severity* of its consequences.

It is clear from the above definitions that risks are determined by assessment of the likely consequences of identified hazards. Thorough hazard identification is, therefore, key to the effective management of risk; one cannot manage the risk arising from a hazard that has not been identified. With respect to dust explosions, it is essential to determine whether a given material actually constitutes an explosion hazard, and if so–the degree of hazard as represented by various explosibility parameters. Only then can appropriate risk reduction measures aimed at prevention and mitigation be devised and implemented. Expressed from a practical, industrial perspective, hazard analysis identifies *what can go wrong*, whereas risk analysis assesses the *probable consequences* of these events in terms of probable loss of life, probable injuries, and probable loss of property, production capacity and market shares.

The above reasoning is illustrated in Figure 1. Here, the key step of hazard identification is shown as a precursor to various explosion prevention and mitigation measures, each of which has been linked to one or more specific explosibility parameters. These points are discussed in subsequent sections of the paper, as is the issue of management responsibility (as identified in the block at the bottom centre of Figure 1).

Explosibility Parameters

The purpose of this section is to provide a guide to some of the more important and commonly reported dust explosibility parameters. Parameter values for many materials can be found in the literature (e.g., NFPA 68[1] and Eckhoff[4]) or online databases (e.g., BGIA[18]). Such values should, however, only be used as indications, and not as the ultimate basis for design of actual safety measures in industry (which should be based on test data for the actual dust in question).[4]

When identifying dust explosion hazards, one is inevitably drawn to an examination of the material itself in an attempt to answer questions such as: (i) Can the dust yield dust explosions when dispersed as a cloud in air? (ii) How high is the resulting overpressure if the explosion occurs at constant volume? (iii) How quickly does the pressure rise if the explosion occurs at constant volume? (iv) What concentration of airborne dust is needed for an explosion? (v) How much energy, or how high a temperature, is needed for ignition? (vi) What minimum percentage of oxygen in the atmosphere is required to sustain flame propagation in the dust cloud?

These questions are addressed by determining the basic explosibility parameters of the dust in accordance with Figure 1 and as shown in Table 1. It is important to recognize that these parameters are not fundamental properties of a given material. They are strongly dependent on both material characteristics (e.g., moisture content and particle size, shape, and porosity) and experimental conditions (e.g., vessel volume, turbulence of the dust cloud, and applied ignition energy). The standard test methodologies (American Society for Testing and Materials) given as examples in Table 1 represent industry-consensus approaches to ensuring the measured parameters are applicable to the prevention and mitigation of industrial-scale dust explosions.

Most of the parameters listed in Table 1 are self-explanatory, with the exception of K_{St}, the volume-normalized maximum rate of pressure rise. The parameter $(dP/dt)_{max}$ is of course dependent on the volume of the explosion chamber, and is therefore of limited use on its own. For scaling to larger volumes, maximum rates of pressure rise are normalized by multiplying by the cube root of the explosion chamber volume, V:

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} \cdot V^{1/3} \qquad (1)$$

Eq. (1) is sometimes referred to as the cubic or cube root *law* and K_{St} as the *dust constant*. (The subscript 'St' derives from the German word for dust–*staub*.) It is preferable, however, to refer to Eq. (1) as the cubic *relationship* and K_{St} as the *volume-normalized (or standardized) maximum rate of pressure rise*, or simply as K_{St}. There

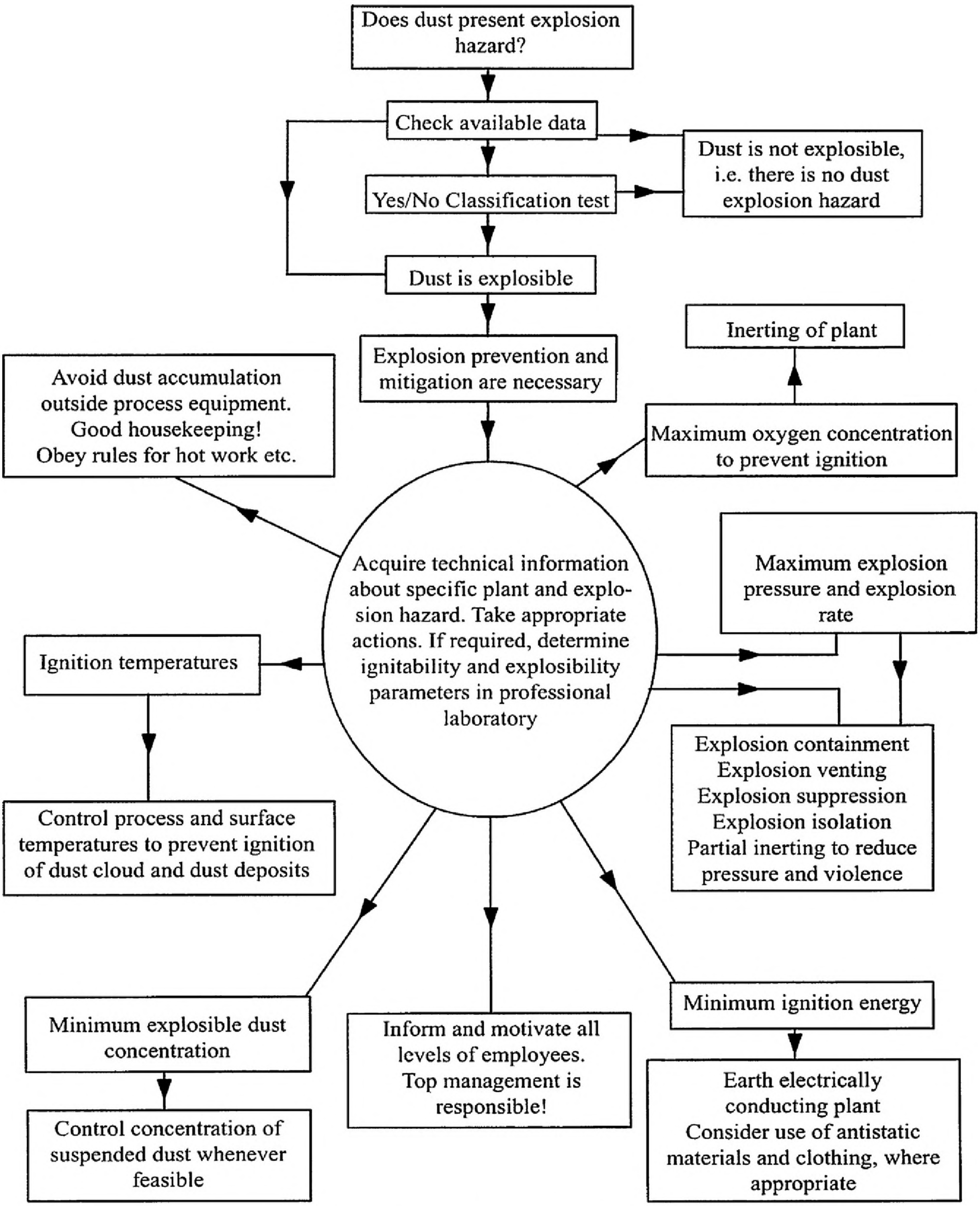

Figure 1. Logic diagram for dust explosion hazard identification and risk reduction.[4]

Table 1. Important dust explosibility parameters and their determination and application.

Parameter	Typical units	Description	Risk component addressed	Example test methodology	Example industrial applications (Figure 1)
P_{max}	bar(g)	Maximum explosion pressure in constant-volume explosion	Consequence severity	ASTM E1226-05	Containment, venting, suppression, isolation, partial inerting
$(dP/dt)_{max}$	bar/s	Maximum rate of pressure rise in constant-volume explosion	Consequence severity	ASTM E1226-05	As per P_{max}
K_{St}	bar m/s	Volume-normalized (or standardized) maximum rate of pressure rise in constant-volume explosion	Consequence severity	ASTM E1226-05	As per P_{max}
MEC	g/m^3	Minimum explosible (or explosive) dust concentration	Likelihood of occurrence	ASTM E1515-07	Control of dust concentrations
MIE	mJ	Minimum ignition energy of dust cloud (electric spark)	Likelihood of occurrence	ASTM E2019-03	Removal of ignition sources. Grounding and bonding
MIT	°C	Minimum ignition temperature of dust cloud	Likelihood of occurrence	ASTM E1491-06	Control of process and surface temperatures (dust clouds)
LIT	°C	Minimum ignition temperature of dust layer or dust deposit	Likelihood of occurrence	ASTM E2021-06	Control of process and surface temperatures (dust layers)
MOC (LOC)	volume%	Minimum (or limiting) oxygen concentration in the atmosphere for flame propagation in dust cloud	Likelihood of occurrence	ASTM WK1680	Inerting (with inert gas)

is nothing fundamental (in the sense of an inviolable law) or constant about either Eq. (1) or the K_{St} parameter. Again, K_{St} is not a fundamental property of a given material.

This observation is reinforced by the discussion in the text by Eckhoff,[4] in which the need for appropriate determination of K_{St} values is emphasized. An analysis of basic considerations reveals that the cubic relationship is valid only for geometrically similar vessels giving geometrically similar flame surfaces, and 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. In view of these issues, it is clear that K_{St} from a dust explosion in any arbitrary vessel is a correspondingly arbitrary measure of dust explosion violence, because both the turbulence and the vessel shape are arbitrary, and because the flame thickness is most probably considerable in relation to the vessel radius.

Table 2 shows a selection of K_{St} values for maize starch dust clouds in air, determined in various apparatus.[4] (Eckhoff[4] may be consulted for the listing of investigators and original references.) The values range from 3 to 6 bar m/s to over 200 bar m/s, corresponding to approximately an order of magnitude difference. Some of the discrepancies may arise from differences in moisture content and effective particle size of the starch, and to different data interpretation (peak or mean values). However, differences in turbulence of the dust clouds and significant flame thicknesses probably play the main roles.

Therefore, when using K_{St} values for sizing of areas of explosion vents and

Table 2. K_{St} values measured for clouds of maize starch dust in air in different closed vessels and arranged according to vessel volume.[4].

$(dP/dt)_{max}$ (bar/s)	Volume (V) of apparatus (m^3)	K_{St} (bar m/s)
680	0.0012	73
612	0.0012	66
220	0.0012	23
413	0.009	86
320	0.020	87
365	0.020	100
10–20	0.026	3–6
60–80	0.026	20–25
272	0.028	83
50	0.33	34
72	0.95	71
20	0.95	20
136	3.12	200
110	6.7	209
55	13.4	131

Table 3. Wood dust explosibility results.[19].

Dust	Particle size distribution	K_{St} (bar m/s)
Coarse	50 weight% <1 mm 0.3 weight% <75 μm	9
Fine	93 weight% <1 mm 35 weight% <125 μm 16 weight% <75 μm	130

for design of explosion isolation and explosion suppression systems according to current standards, it is absolutely essential to use data obtained from the authorized standard test methods for determining K_{St}. Applicable methods in this regard include those falling under the auspices of the American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO), and European Committee for Standardization (CEN).

Further guidance in the application of the K_{St} concept can be gained by examination of Table 3, which shows explosibility data for dust generated in a wood-processing facility[19] (with K_{St} determined in a 20-L spherical vessel according to ASTM E 1226-05). In the actual process, although the coarse dust was predominant, pockets of the fine dust were found in a dead-space in a process unit header. Recalling that K_{St} is used for sizing explosion relief vents (Table 1), it is clear that a vent design based on the K_{St} value of the coarse dust would be inadequate for protection from the effects of a dust explosion involving the fine wood dust.

The data in Table 3 also reinforce the need to distinguish between material *hazard* and process *risk* when dealing with dust explosion phenomena. As mentioned in the introduction, particle size distribution is one of the key properties of a dust that defines its material hazard. Knowledge of whether a particular size distribution is actually encountered in a given application is required to assess the process risk. This highlights the importance of gaining a thorough understanding of the dust handling process under consideration during both normal and upset conditions.

Although the preceding paragraph reinforces the difference between a dust explosion *hazard* and a dust explosion *risk*, it is equally important to recognize that the two – hazard and risk – are not independent of one another. This is evident from our previous comment that risk can only be assessed once hazards have been identified. There is thus an inevitable link between the two parameters. Selection of a dust sample for testing to see if the material represents an explosion hazard is often preceded by considerations related to process risk. For example, in plants with dust extraction systems, it is typical to select dust samples from filters. These samples will be finer than the main product and hence, will explode more violently and ignite more readily. Here, the reasoning behind the selection of the sample to be tested is directly or indirectly a part of the assessment of the process risk. This again is the point being made by the data in Table 3.

Fire Triangle

The most basic guide to understanding dust explosion causation is the familiar fire triangle (Figure 2). This simple concept indicates that three of the necessary conditions for a dust explosion are a fuel, an oxidant and an ignition source. As presented by the

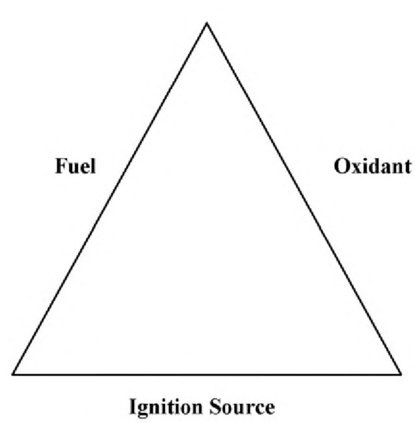

Figure 2. Fire triangle.

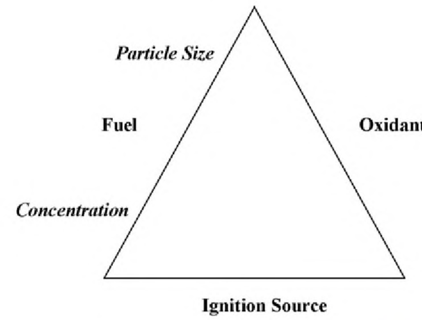

Figure 3. Fire triangle for dusts.[20]

IChemE[20] and illustrated in Figure 3, the unique fuel requirements for a dust can be expressed as follows: (i) the dust material must be combustible, (ii) the dust must be airborne, (iii) the dust must have a particle size distribution capable of propagating flame when dispersed as a cloud in air, and (iv) the dust concentrations must be within the explosible range.

Explosion Pentagon

The explosion pentagon, as described by Kauffman[21] and illustrated in Figure 4, expands the basic fire triangle to include mixing of the fuel and oxidant and confinement of the mixture. The first of these additional components illustrates the previously mentioned key difference between dust and gas explosions–a solid rather than a gaseous fuel. A gas explosion therefore involves a homogeneous system in which the smallest entities of fuel and air are separated only by molecular distances. Thorough mixing of fuel and oxidant is readily achieved and gravitational effects are negligible. However, in a dust/air mixture, the dust particles are strongly influenced by gravity; an essential prerequisite for a dust explosion is the formation of a dust/oxidant suspension.[22] Once combustion of the resultant mixture occurs, confinement (partial or complete) permits an overpressure to develop, thus enabling a fast-burning dust flame to transition to a dust explosion.

Primary Explosions

Dust explosions usually occur in industry inside process vessels and units such as mills, grinders, and dryers–i.e., inside equipment where the conditions of the explosion pentagon are satisfied. Such occurrences are

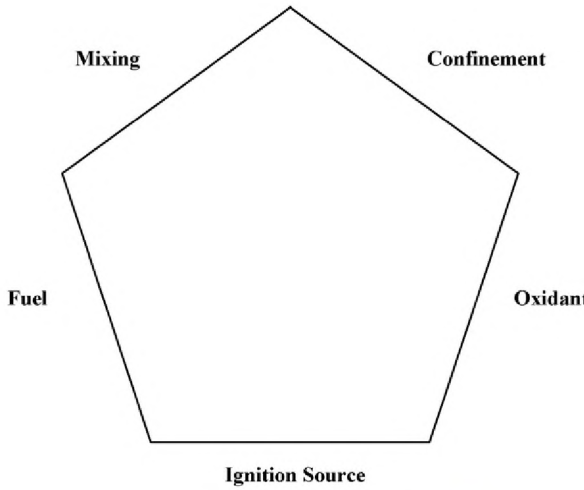

Figure 4. Explosion pentagon.[21]

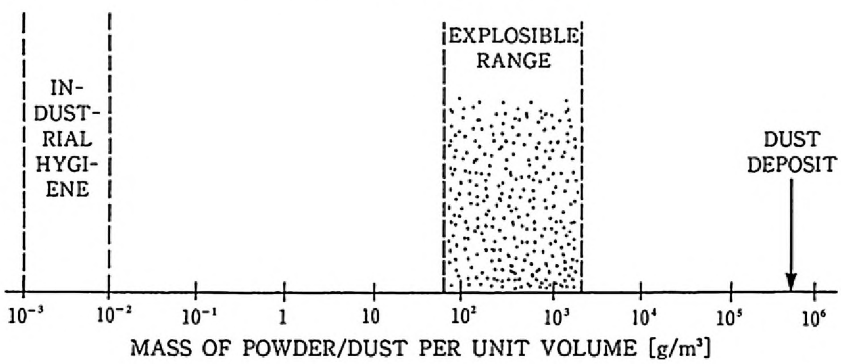

Figure 5. Typical ranges of dust concentrations in air at normal temperature and pressure for common natural organic dusts, for maximum permissible hygienic exposure, dust explosions, and dust deposit combustion (smoldering fires), respectively.[4]

often called *primary* explosions, especially if they result in *secondary* explosions external to the process unit (as described in the next section). The reason for the majority of dust explosions being initiated in this manner can be understood by examining Figure 5. Here, the range of explosible dust concentrations in air at normal temperature and pressure for a natural organic dust (e.g., cornstarch) is compared with the typical range of maximum permissible dust concentrations that are relevant in the context of industrial hygiene, and with a typical density of deposits or layers of natural organic dusts. Clearly, the range of explosible concentrations is orders of magnitude greater than the concentrations permitted in areas inhabited by workers.

Secondary Explosions

Notwithstanding the discussion in the previous section, dust explosions do occur in process areas, not just inside process units. A *secondary* explosion can be initiated due to entrainment of dust layers by the blast waves arising from a primary explosion. The primary event might be a dust explosion originating in a process unit, or could be any disturbance energetic enough to disperse explosible dust layered on the floor and various work surfaces. An example of such an energetic disturbance (other than a primary dust explosion) would be a gas explosion leading to a dust explosion. This is a well-documented phenomenon in the underground coal mining industry, where devastating effects can result from the overpressures and rates of pressure rise generated in a coal dust explosion that has been triggered by a methane explosion.

The required amount of layered dust which, once airborne, could sustain a secondary dust explosion is often grossly overestimated. For example, in the Westray mine explosion[23] described later in this paper, one of the contributing factors was the presence of coal dust layers several centimetres thick throughout the mine workings. In fact, the amount of coal dust that could be dispersed by an aerodynamic disturbance and then combusted with the available oxygen would have been significantly less than 'several centimetres'. This point is illustrated in a general manner by Figure 6, which shows the implications of the following expression:

$$C = (\rho_{\text{bulk}})\left(\frac{h}{H}\right) \quad (2)$$

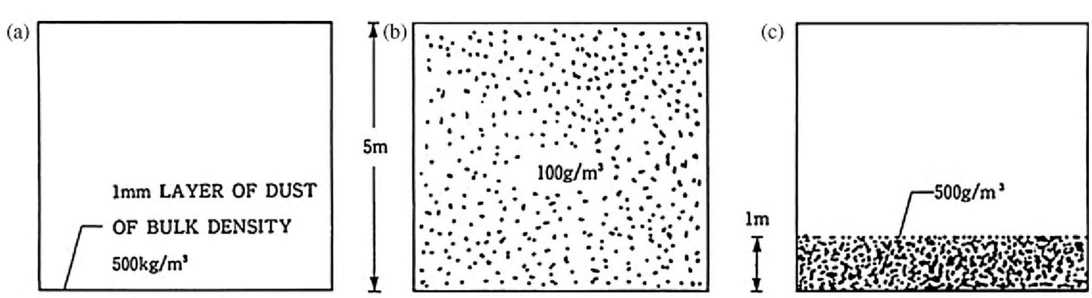

Figure 6. (a–c) Illustration of the potential for dust cloud generation from a dust layer.[4]

where ρ_{bulk} is the bulk density of a dust layer, h is the layer thickness, H is the height of the dust cloud produced from the layer, and C is the resulting dust concentration.

From Eq. (2) and as shown in Figure 6, a 1-mm thick layer of a dust of bulk density 500 kg/m^3 on the floor of a 5-m high room will generate a cloud of average concentration 100 g/m^3 if dispersed evenly all over the room.[6] Such a concentration is of the order of the minimum explosible concentration for many explosible dusts. Partial dispersion up to 1 m above the floor yields a dust concentration of 500 g/m^3; this is a concentration that is of the order of the optimum concentration (i.e., the concentration producing the most devastating overpressures and rates of pressure rise) for many explosible dusts.

Clearly, even seemingly harmless dust layers have the potential to rapidly escalate the risk of a dust explosion. This observation helps to explain the advice given by experienced industrial practitioners–such as: *there's too much layered dust if ... you can see your footprints in the dust ... you can write your initials in the dust.* These comments, although anecdotal, have a firm foundation in the chemistry and physics of dust explosions.

Hybrid Mixtures

Hybrid mixtures consist of a flammable gas and a combustible dust, each of which may be present in an amount less than its lower flammable limit (LFL)/minimum explosible concentration (MEC), and still give rise to an explosible mixture. The focus when discussing hybrid mixtures is, in fact, on admixture of a flammable gas in concentrations below the lower flammable limit of the gas itself. If the LFL for the gas is exceeded, one soon has a situation where the worst-case scenario for a primary explosion would be a pure gas explosion.

Perhaps the most well-known hybrid mixture is the methane/coal dust system often encountered in underground coal mining. There are also several examples of hybrid mixture formation in other industries, such as the natural gas/fly ash system in fossil-fuel burning power plants and various hydrocarbon/resin combinations occurring in the production of plastic powders.

The influence of the co-presence of a flammable gas on the explosibility parameters of a fuel dust alone is well established (e.g., Cashdollar[24]). These effects include higher values of maximum explosion pressure and maximum rate of pressure rise (and hence K_{St}), and lower values of minimum explosible concentration and minimum ignition energy. There is, of course, already a hazard that exists when an explosible dust is present in a quantity above its minimum explosible concentration. With flammable gas admixture, the scenario is now one of magnification of an already existing hazard, not the creation of a problem that did not already exist in some form already.

DUST EXPLOSION PREVENTION AND MITIGATION

When selecting dust explosion prevention and mitigation measures, it is helpful to employ a heuristic or framework for making appropriate choices.[25] The fire triangles shown in Figures 2 and 3, and the explosion pentagon shown in Figure 4, offer guidance in this area in addition to identifying dust explosion causation factors. For example, the triangle affords industrial practitioners several approaches to explosion prevention (e.g., removal of fuel by good housekeeping and removal of electrostatic ignition sources by grounding and bonding). The use of the pentagon to visualize explosion requirements leads to identification of measures for explosion mitigation such as venting (in relief of the confinement criterion).

What is missing in the above discussion, however, is guidance on which risk reduction techniques are most effective and in what order the various techniques should be considered. Prevention is obviously preferred to mitigation, but both are likely to be required in a given application. The question, then, is which of the various measures spanning out from the centre sphere in Figure 1 should receive priority? The following sections attempt to address this point by first considering a general loss prevention approach, and then tailoring that approach to prevention of loss from dust explosions.

Hierarchy of Controls

Industrial loss prevention is generally accomplished in three ways: (i) inherent safety, (ii) engineered safety (passive and active), and (iii) procedural safety.[14] Engineered, or add-on, safety involves the addition of safety devices at the end of the design. A general industrial example would be a machine guard; with respect to the subject of the current paper, an example of an engineered safety device is an automatic dust explosion suppression system. These safety devices do not perform any fundamental operation, but are designed to act when a process upset occurs. Procedural safety measures, or administrative controls, utilize safe work practices and procedures to reduce risk. Again, a general industrial example would be standard work practices for confined space entry; with respect to dust explosion prevention, hot-work permitting and procedures related to grounding and bonding are pertinent examples in this category.

On the other hand, inherent safety uses the properties of a material or process to eliminate or reduce the hazard. The fundamental difference between inherent safety and the other two categories is that inherent safety seeks to remove the hazard at the source as opposed to accepting the hazard and looking to prevent its occurrence or mitigate its effects.

Figure 7 illustrates a systematic approach to loss prevention that has found general acceptance in industry. With this approach, the preferred order of consideration for risk reduction measures (from most effective to least) is inherent, passive engineered, active engineered, and procedural safety. This is akin to the layer of protection analysis (LOPA) concept in which inherently safer process design sits at the central core of the layers. Hopkins[26] uses the phrase *hierarchy of controls* to describe essentially the same idea; i.e., that there is a hierarchical ordering of controls to deal with hazards, covering the spectrum from

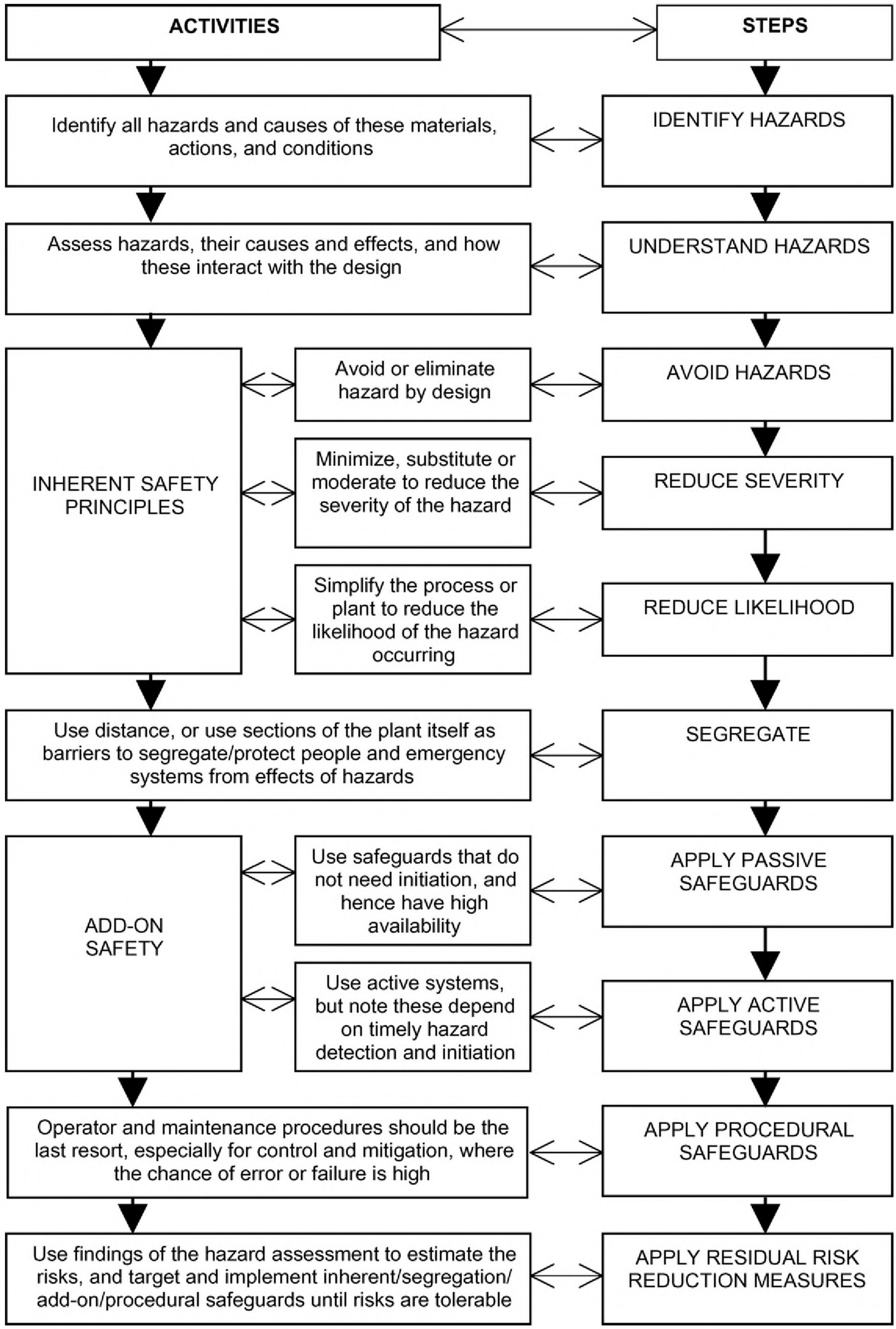

Figure 7. A systematic approach to loss prevention.[19]

elimination (at the top of the hierarchy) through engineering and administrative (procedural) controls, to PPE (personal protective equipment) at the bottom of the hierarchy.

Inherent safety

The formal concept of inherent safety in the process industries was first proposed by Trevor Kletz in the late 1970s in his Jubilee Lecture to the Society of Chemical Industry in Widnes, UK.[27] (The title of his paper, *what you don't have, can't leak*, provides an apt description of the main thrust of inherent safety.) Since that time, the concepts of inherent safety and inherently safer design have made several inroads into the process industries. Numerous research and review papers have been written, and a new text[28] represents the most recent major publication in the subject area. The four key principles of inherent safety are summarized in Table 4.

Various examples of the application of the principles in Table 4 to dust explosions have been given in a recent paper by Amyotte et al.[14] A brief recapitulation by inherent safety principle follows:

- Minimization
  - Avoidance of dust cloud formation (including operation below the minimum explosible concentration if possible).
  - Removal of dust deposits (avoidance of dust layers). The paper by Frank[11] is an excellent resource on the both the importance and the effectiveness of good housekeeping.
- Substitution
  - Substituting one work procedure for another (e.g., using an explosion-proof vacuum in place of sweeping with a broom to remove dust accumulations).
  - Replacement of bucket elevators and other mechanical conveying systems with dense-phase pneumatic transport (if feasible).
  - Substitution of process hardware with less hazardous materials of construction (e.g., avoiding unnecessary use of insulating materials).
  - Substitution of a process route that involves handling an explosible powder (e.g., earlier introduction of an inert powder that is a component of the final product).
  - Substitution of the hazardous material (i.e., explosible powder itself). This is often not feasible when the explosible powder is the desired product; one potential application is the replacement of pulverized coal with petroleum coke in a utility boiler.
- Moderation
  - Altering the composition of a dust by admixture of solid inertants.
  - Increasing the dust particle size so as to decrease its reactivity.
  - Avoiding the formation of hybrid mixtures of explosible dusts and flammable gases.
  - Limiting the effects of a process upset by using appropriate distances to separate process units.
- Simplification
  - Employing the concept of error tolerance by designing process equipment robust enough to withstand process upsets and other undesired events (e.g., shock- or pressure-resistant design).
  - Ensuring information on the hazardous properties of powders is clear and unambiguous (e.g., through effective use of Material Safety Data Sheets or MSDSs).

Passive engineered safety

Passive add-on devices, if adequately designed, manufactured and fitted for service, will perform their desired safety function simply by their presence. No actuation beyond the initiating event (e.g., dust explosion overpressure) is required for a passive device to fulfil its intended role. Explosion relief venting would fall in this category as would the use of physical barriers to isolate plant sections in an attempt to prevent domino or knock-on effects.

Active engineered safety

Active add-on devices require some degree of detection and activation to perform their desired safety function. In addition to adequate design and manufacturing, these devices require proper maintenance and testing to facilitate their reliable performance. Demand for active engineered measures is intentionally intermittent, and there is thus a strong need to limit the potential for failure when they are needed. Examples here would include automatic dust explosion suppression systems (as previously mentioned) and mechanical isolation valves, both of which employ detectors and actuators in addition to the actual safety device (suppressant-filled canister and metal plate, respectively).

Inerting is a dust explosion prevention/mitigation measure that could be classified as either inherent or active engineered safety depending on the method of application. As previously indicated, addition of an inert solid to an explosible dust so as to render the

Table 4. Inherent safety principles.[14].

Principle	Description
Minimization	Use smaller quantities of hazardous materials when the use of such materials cannot be avoided or eliminated. Perform a hazardous procedure as few times as possible when the procedure is unavoidable.
Substitution	Replace a substance with a less hazardous material or processing route with one that does not involve hazardous material. Replace a hazardous procedure with one that is less hazardous.
Moderation	Use hazardous materials in their least hazardous forms or identify processing options that involve less severe processing conditions.
Simplification	Design processes, processing equipment, and procedures to eliminate opportunities for errors by eliminating excessive use of add-on safety features and protective devices.

resulting mixture nonexplosible, is an example of the inherent safety principle of moderation–albeit through the procedural measure of adding the inert material. An example here is the admixture of inert limestone or dolomite to explosible coal dust as is practiced in underground coal mining. On the other hand, inerting or partial inerting by means of a nonreactive gas would likely be viewed as active engineered safety because of the need for physical devices for inert gas addition and monitoring.

Procedural safety

Although there is a strong human element to the previously described levels in the hierarchy of controls – after all, it is human beings who design, manufacture and install safety devices – the category of procedural safety is where the performance of plant personnel becomes critical to the success or failure of a given safe work practice or procedure. The potential for human error places procedural safety at the bottom of the hierarchy of controls; this fact must be recognized and managed by comprehensive consideration of the human factors involved in performing a safety-oriented task.

Procedural dust explosion risk reduction measures typically relate to attempts to remove ignition sources from the workplace. Examples include permit-to-work, and the previously mentioned hot-work permitting, and grounding and bonding. Although absolutely necessary as a line of defence against dust explosion occurrence and consequences, it is not advisable to rely solely on ignition source removal in this regard. Potential ignition sources abound in industry and sometimes arise as a result of a poorly designed or poorly followed procedure.

Summary of Prevention and Mitigation Measures

Eckhoff[6] has previously reported a tabular listing of the common means of preventing and mitigating dust explosions. With the analysis in the previous sections of the current paper, these means can now be categorized using the hierarchy of controls as shown in Table 5. There are several points to note in using Table 5 as a selection guide for dust explosion risk reduction measures:

- Inherent safety (inherently safer design) is the most effective way to deal with a dust explosion hazard. To paraphrase Kletz[27]: *what you don't have, can't explode.*
- Inherent safety achieves its greatest impact when considered early in the design life cycle. Once a process unit is built to withstand only moderate pressure excursions, it is likely too late to consider an explosion pressure-resistant design for that particular unit.
- Some inherent safety options may not be feasible in a given application. For example, a chemically inert dust cannot likely be substituted for an explosible dust if the latter is the actual desired product. But again, if the relevant inherent safety questions are not asked, then potential process or product alternatives cannot be explored.
- Inherent safety is not a stand-alone concept. It works through a hierarchical arrangement in concert with engineered (passive and active) and procedural safety to reduce risk.
- The hierarchy of controls does not invalidate the usefulness of engineered and procedural safety measures. Quite the opposite–the hierarchy of controls recognizes the importance of engineered and procedural safety by highlighting the need for careful examination of the reliability of both mechanical devices and human actions. These considerations must be incorporated into the dust explosion risk assessment process.

Role of Management

The discussion to this point has considered the technical knowledge needed to reduce the risk of a dust explosion: (i) thorough hazard identification in terms of causation factors and explosibility parameters, (ii) measures for preventing occurrence, and (iii) measures for mitigating the consequences. The following sections deal with the important matters of safety culture and safety management systems. In effect, these topics determine whether a company has the will to properly implement the above technical knowledge, and to do so in a systematic, organized manner. The final section gives a brief case study that illustrates what can happen when there is no apparent safety culture or safety management system.

Safety culture

The fundamental issue of whether a company (in particular, its senior managers) believes it is possible to achieve a higher standard of safety – in essence whether a company believes safety is 'the right thing to do' – has recently been addressed in the excellent book by Andrew Hopkins. Hopkins[26] describes three concepts that address a company's cultural approach to safety, and makes the argument that the three are essentially alternative ways of talking about the same phenomena: (i) safety culture, (ii) collective mindfulness, and (iii) risk-awareness. He further defines the concept of a safety culture as embodying the following subcultures: (i) a *reporting culture* in which people report errors, near-misses, and substandard conditions and practices, (ii) a *just culture* in which blame and punishment are reserved for behaviour involving defiance, recklessness or malice, such that incident reporting is not discouraged, (iii) a *learning culture* in which a company learns from its reported incidents, processes information in a conscientious manner, and makes changes accordingly, and (iv) a *flexible culture* in which decision-making processes are not so rigid that they cannot be varied according to the urgency of the decision and the expertise of the people involved.

Safety culture measurement requires the use of appropriate indicators. There has been much recent discussion in the literature on safety culture indicators (lagging and leading), and significant efforts aimed at developing suitable indicators have been undertaken by organizations such as the Health and Safety Executive in the UK and the Center for Chemical Process Safety of the American Institute of Chemical Engineers. An increasingly common thought promoted by Hopkins and others[15] is that safety culture

Table 5. A hierarchical view of various means of preventing and mitigating dust explosions.

Explosion prevention		
Preventing explosible dust clouds	Preventing ignition sources	Explosion mitigation
Process design to prevent undesired generation of dust clouds and particle size reduction and segregation *Inherent Safety–Minimization, Substitution, Moderation, Simplification*	Smouldering combustion in dust, dust fires *Procedural Safety–may also involve aspects of Inherent Safety or Engineered Safety*	Good housekeeping (dust removal/cleaning) Mitigation with respect to secondary dust explosions; prevention with respect to primary dust explosions *Inherent Safety–Minimization*
Keeping dust concentration outside explosible range *Inherent Safety–Minimization*	Other types of open flames (e.g., hot work) *Procedural Safety–may also involve aspects of Inherent Safety or Engineered Safety*	Explosion-pressure resistant construction *Inherent Safety–Simplification*
Inerting of dust cloud by adding inert dust *Inherent Safety–Moderation*	Hot surfaces (electrically or mechanically heated) *Procedural Safety–may also involve aspects of Inherent Safety or Engineered Safety*	Explosion isolation (sectioning) *Inherent Safety–Moderation (e.g., unit segregation, product choke, etc.) if not using mechanical devices. If mechanical devices are used to isolate plant sections, classification would be Engineered Safety–Passive in the case of physical barriers, or Engineered Safety–Active in the case of isolation valves.*
Intrinsic inerting of dust cloud by combustion gases *Engineered Safety–Active*	Heat from mechanical impact (metal sparks and hot-spots) *Procedural Safety–may also involve aspects of Inherent Safety or Engineered Safety*	Explosion venting *Engineered Safety–Passive*
Inerting of dust cloud by N_2, CO_2 and rare gases *Engineered Safety–Active*	Electric sparks and arcs and electrostatic discharges *Procedural Safety–may also involve aspects of Inherent Safety or Engineered Safety*	Automatic explosion suppression *Engineered Safety–Active* Partial inerting of dust cloud by inert gas *Engineered Safety–Active*

indicators must measure the effectiveness of the various measures comprising the risk control system. In other words, safety indicators must be related to the elements making up the safety management system.

Safety management systems

Safety management systems are recognized and accepted worldwide as best-practice methods for managing risk. They typically consist of 10–20 program elements that must be effectively carried out to manage the risks in an acceptable way. This need is based on the understanding that once a risk is accepted, it does not go away; it is there waiting for an opportunity to happen unless the management system is actively monitoring company operations for concerns and taking proactive actions to correct potential problems.

As a primary corporate objective, dust explosion prevention and mitigation would typically fall within the scope of a Process Safety Management system (i.e., a management system for process-related hazards such as fire, explosion, release of toxic materials, etc.) One such system widely used in industry is termed PSM, Process Safety Management–where PSM is defined as the application of management principles and systems to the identification, understanding and control of process hazards to prevent process-related injuries and accidents. The suite of PSM elements is shown in Table 6.

In light of the previous discussion on the hierarchy of controls, a strong case can be made for the need to demonstrate a commitment to the principles of inherent safety within each of the PSM elements listed in Table 6.[16] Thus, within element 6, process risk management, the hierarchical arrangement of dust explosion prevention and mitigation measures shown in Table 5 would find direct application. Additionally, within element 8, training and performance, a strong safety culture would necessitate the provision of workplace training in dust explosion hazards, and how these hazards can be alleviated by application of, for example, the inherent safety principle of minimization through effective housekeeping. As illustrated by the analysis that follows

Table 6. Elements of Process Safety Management, PSM.[16].

No.	Element
1	Accountability: objectives and goals
2	Process knowledge and documentation
3	Capital project review and design procedures
4	Process risk management
5	Management of change
6	Process and equipment integrity
7	Human factors
8	Training and performance
9	Incident investigation
10	Company standards, codes and regulations
11	Audits and corrective actions
12	Enhancement of process safety knowledge

for element 9, similar observations can be made for the other PSM elements in Table 6.

In a previous paper, Amyotte et al.[15] have demonstrated that three of Hopkins' four safety subcultures (*reporting*, *just* and *learning*) have an explicit link to the PSM element of incident investigation. With respect to the subject of the current paper, a company's commitment to just and reporting cultures will ultimately be expressed in the number of dust explosion incidents that are reported. In the spirit of a leading indicator, it would be important to also measure the number of near-miss and at-risk behaviour reports involving combustible powders. The outputs of reporting and investigating will manifest themselves as a measure of commitment to a learning culture; *lessons learned* is a key phrase in the industrial lexicon. The idea of learning from experience extends beyond the realm of incident investigation and into other safety management system elements (e.g., process risk management, management of change, and enhancement of process safety knowledge).

It may be tempting to dismiss talk of safety culture and safety management systems as being unimportant in relation to the chemistry, physics and engineering of dust explosions. Further, safety culture might be viewed by some as merely the current 'hot topic' in industrial safety–i.e., a relatively new concept that, given time, will be replaced by something else. On the first matter, the next section will hopefully dispel any notion that well-established technical knowledge, in the absence of a strong safety culture and management system, is sufficient to ensure an acceptably low dust explosion risk. On the second point, we offer the following quote from the last paragraph of Count Morozzo's report[2] describing the Turin flour warehouse explosion mentioned in the introduction:

> Ignorance of the fore-mentioned circumstances, and a culpable negligence of those precautions which ought to be taken, have often caused more misfortunes and loss than the most contriving malice. It is therefore of great importance that these facts should be universally known, that public utility may reap from them every possible advantage.

The above passage makes an eloquent case for the importance of a strong safety culture, incident investigation, and the sharing of lessons learned. It is instructive to also note that it was written over 200 years ago.

Case study—Westray coal mine explosion

The Westray coal mine explosion occurred in Plymouth, Nova Scotia, Canada, on May 9, 1992, killing 26 miners.[23] An indication of the destructive overpressures generated underground can be seen in Figure 8, which shows surface damage at the mine site. The methane levels in the mine were consistently higher than regulations, which was caused by inadequate ventilation in the mine. Dust accumulations also exceeded permissible levels due to inadequate cleanup of coal dust; additionally, there was no crew in charge of rock dusting (inerting the coal dust with limestone or dolomite). These and many other factors contributed to the poor work conditions that continually existed in the Westray mine and made it the site of an incident waiting to happen. All of these substandard conditions and practices could be attributed to the lack of concern that management had towards safety issues in the mine, which was one of the primary root causes of the problem at Westray.

The question may arise as to whether a coal dust explosion in an underground mine, which was initiated by a methane explosion, is a typical case in a dust explosion context. The choice of this particular case study is, however, regarded as fully justified given that it has been so well-documented[29] and thoroughly analysed.[23]

Lack of adequate loss prevention and management is generally due to deficiencies in one or more of three

Figure 8. Damage to portal at No. 1 main, Westray coal mine.[29]

Table 7. Hazard avoidance possibilities categorized by inherent safety principle.[15].

Principle	Recommendation to avoid hazard
Minimize	*Methane:* degasification (extraction of methane prior to mining) *Coal dust:* housekeeping program for continuous removal *Fuel storage:* elimination of underground storage *Ignition sources:* replacement of nonflameproof equipment (i.e., minimization of ignition sources by substitution of equipment) *Shift length:* reduction from 12 h
Substitute	*Auxiliary ventilation system*: forcing, rather than exhaust, system for adequate airflow to clear methane from the working face of the mine *Main ventilation fan*: alternate design and location so as not to pick up dust and other debris from the coal return conveyor belt.
Moderate	*Coal dust:* purchase and maintenance of an adequate inventory of rock dust; implementation of a program for rock dusting underground *Coal dust:* roadway consolidation (a process to control the formation and dispersal of dust on mine roadways by application of rock dust, moisture-absorbing material and a binding agent)
Simplify	*Methane:* installation of a reliable, robust mine air monitoring system

areas–the safety management system itself, the standards identified and set for the safety management system, and the degree of compliance with such standards.[15] A particular management system element may have missing components or may be entirely absent; alternatively the management system element may be present to some degree, but could have inappropriate standards–or perhaps standards for which there is little or no compliance.

Management system elements (reference Table 6) that contributed to the Westray explosion include inadequate:

- Management commitment and accountability to safety matters (which is a key element in establishing an effective company safety culture).
- Management of change procedures.
- Incident investigation (including near-miss reporting and investigation).
- Training (orientation, safety, task-related, etc.).
- Task definition and safe work practices and procedures.
- Workplace inspections and more proactive hazard identification methodologies.
- Program evaluation and audits.

System standards that contributed to the Westray explosion include standards (i.e., levels of performance) relating to virtually all the system elements listed above, including inadequate:

- Concern expressed by management toward safety matters (in terms of the standard of care one would reasonably expect and which, from a legal perspective, should be considered mandatory).
- Follow-through on inspections for substandard practices and conditions.
- Action on hazard reports submitted by employees.
- Job instructions for employees.
- Equipment maintenance.
- Scheduling of management/employee meetings to discuss safety concerns.

Compliance factors that contributed to the Westray explosion include:

- Poor correlation between management actions and official company policy concerning the relationship between safety and production (as evidenced by the same management personnel holding responsibility for both production and underground safety).
- Inadequate compliance to industry practice and legislated standards concerning numerous aspects of coal mining: methane concentrations, rock dusting, control of ignition sources underground, etc.

With reference to dust explosion causation, prevention and mitigation, the hierarchy of controls (in particular the inherent safety control level) was essentially ignored at the Westray site. Had there been a commitment to the principles of inherent safety, some of the hazard avoidance recommendations given in Table 7 would have been implemented. It is particularly poignant to note that all of the measures listed in Table 7 are well known and are commonly practiced in the underground coal mining industry.

CONCLUSION

Dust explosions occur in a variety of industries and have a recorded history stretching back over 200 years. In North America, a series of high-profile dust explosions investigated by the US CSB have renewed efforts to understand their causation, prevention and mitigation. While the dust explosion hazard may exist for many powders handled in industry, the risk of an explosion is a function of likelihood and consequence severity considerations reflected in a number of important explosibility and ignitability parameters of dust clouds. These include the (i) maximum explosion pressure and maximum rate of rise of the explosion pressure in standardized closed-vessel tests (yielding also the volume-normalized maximum rate of pressure rise), (ii) minimum explosible dust concentration, (iii) minimum (limiting) oxygen concentration of the atmosphere for flame propagation, (iv) minimum spark ignition energy, and (v) minimum dust cloud ignition temperature. In addition, knowing the minimum ignition temperatures of dust layers and dust deposits for various layer thicknesses and deposit volumes is important to prevent open and smoldering dust fires.

A dust explosion occurs when an explosible dust cloud (consisting of an adequately mixed fuel and oxidant) is formed and ignited by a sufficiently energetic ignition source in a confined or partially confined environment. Such explosions originate as either primary or secondary events, and may also involve the co-presence of a flammable gas (leading to the creation of a hybrid mixture).

Dust explosion prevention and mitigation measures can be hierarchically organized from most to least effective in terms of measures related to: inherent safety (minimization, substitution, moderation and simplification), passive engineered safety, active engineered safety, and procedural safety. Consideration of all levels in this hierarchy of controls is required for effective dust explosion risk reduction.

Equally, if not more important to dust explosion control, is the key role played by senior management in ensuring a strong safety culture and an effective safety management system. Technical knowledge without the commensurate management commitment and program to ensure implementation of such knowledge is doomed to failure, as evidenced by the 1992 Westray mine explosion.

ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the funding agencies and industrial companies that have supported their research efforts over the years.

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