

Fighting dust explosion hazards in the process industries

by

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1. How my own research on industrial dust explosion issues started

After graduation in chemical engineering and completion of my compulsory military service I joined Chr. Michelsen Institute in Bergen, Norway at the end of 1963. My first task there was to measure particle size distributions of emulsion PVC-particles by Coulter counter and transmission electron microscopy. About two years later it was brought to my attention that professor H.E. Rose at King's College, London, was offering training courses and research programs in the broader field of powder technology. He agreed that I could come and do some research with him within the area of particle size measurement of very small particles. However, not long before leaving Norway for England with my family I got a letter from professor Rose saying that he had changed his mind: My research should not be on particle size measurement but on dust explosions. When I got this letter I did not even know that the phenomenon of dust explosions existed. So, without any background knowledge whatsoever I embarked on my postgraduate studies on ignition of dust clouds by electric sparks. After arrival in London, my first urgent task naturally was to collect and read relevant information. To give me an effective start, professor Rose advised me to pay a visit to Fire Research Station (FRS), at Borehamwood, just north of central London. There Ken Palmer, later director of FRS, and author of the pioneering book "Dust explosions and Fires" (1973), gave me a copy of an excellent literature review by Brown and James (1962). Then, by frequently visiting the Patent Office Library in Chancery Lane in The City of London I could obtain copies of the important papers and reports that I needed for my studies and research.

2. "Organizations have no memory"

Sometimes general managements of companies producing and/or handling materials that can give accidental dust explosions do not realize that focus on explosion prevention and mitigation in their company must be a continued, dedicated effort. They do not appreciate the obvious fact that ultimate success of continuous dedicated work to prevent dust explosions from happening is that they just do not happen. Sometimes this result of hard persistent work is misinterpreted by general company managements. They may think that because they have not experienced any dust explosions in their companies, they just cannot happen there.

In my files I keep a precious one-page manuscript of "A sketch for chemical engineers". The sketch title is "*It must never happen again*", the author is K. Asher and the time of printing August/September 1983, possibly in the journal "Loss Prevention".

The sketch consists of two short acts describing two important meetings of the board of a company. The second board meeting takes place ten years after the first one. In the first meeting the highly urgent issue is a report on a recent explosion in a crap grinder in the company's plant. The board agrees that this very untimely and serious event requires their utmost attention.

Consequently, a working group, headed by one of the company's key technical people, Dr Nitpicker, was set up, presumably for working out plans for the measures to be taken to prevent such explosions in the future.

In the second board meeting (second act), ten years after the first one, the issue is rather different. A presumably new company director announces that one of the company's employees, a lone ranger, Dr Nitpicker, has agreed to accept early retirement. Apparently none of the board members knows precisely what this person has been occupied with over the last years.

The second act ends as follows: *Chairman: "Right. Early retirement of this Dr Nitpicker is agreed. Let's move on to the next item."*

*Then a **loud explosion** is heard off-stage, followed by a loud voice, also off stage: "**The crap grinder's exploded!**"*

3. Topics calling for continued research and development on accidental dust explosions

A list of some global headlines may look as follows:

- Dust cloud formation processes
- Dust cloud ignition processes
- Flame propagation processes in dust clouds
- Dust explosion prevention methods
- Dust explosion mitigation methods
- National and international standards

Each of these topic areas embraces a wide range of specific sub problem areas asking for further research and development.

This for example applies to *flame propagation processes*. Here continued work on *numerical modelling of dust flame propagation* in process environments should be encouraged. Skjold (2018) reviewed some of the advancements made over the last years, mainly based on the computational-fluid-dynamics concept (CFD) that has been used successfully for modelling flame propagation processes in accidental gas explosions. However, because of the two-phase nature of dust clouds, dust explosions are much more complex to model than explosions in premixed gases. Sub models of the influence of the combustion of individual dust particles on the global flame propagation are required. Eckhoff (2003) reviewed some earlier work ignition and combustion of single particles of various materials. However, much more work is needed in this area. One example of recent research is that of Sundaram *et al.* (2016). They developed a theory of ignition and combustion of both nm and μm particles of aluminium. Another very recent example is Serrano *et al.* (2020). They carried out both experiments and a computational CFD-DEM analyses of dispersion and combustion of clouds in air of wheat starch and carbon black powders, in a closed 20-l vessel.

Another wide topic requiring continuous professional attention is *national and international standards* for preventing and mitigating industrial dust explosions, and for testing of ignitability and explosibility of dusts. Central standardization organizations include CEN (European Union), IEC (international), and NFPA and ASTM (USA). New standards are being developed and old ones updated continuously by all these organizations. However, continued research must be an integer part of this important continued work.

4 More detailed reviews of two challenging issues

4.1 Inherently safer process design

Outline of basic concept

Amyotte (2013) has given the following definition of this rather new concept: *Inherently safer process design is a proactive approach in which hazards are eliminated or lessened so as to reduce risks with decreased reliance on “add-on” devices and “add on” procedural measures.* This concept has been developed over the past 40 years or so, beginning with the pioneering work of the late Professor Trevor Kletz. His initial work was largely a response to the catastrophic cyclohexane explosion (vapour and mist) at Flixborough, UK, in 1974. As pointed out by Amyotte (2013), over the years four basic principles to facilitate inherent safety implementation in industry have been developed and gained widespread acceptance. Amyotte *et al.* (2010) and Chapter 13 in Kletz and Amyotte (2010) give numerous examples of application of the four basic principles for reducing dust explosion risks in the process industries. Amyotte and Eckhoff (2010) specifically discussed specific technical measures that may be taken when applying the four basic principles to dust explosion risks in the process industries. The four basic principles, as defined by Amyotte (2013) are:

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.

Replacement: Replace a hazardous substance with a less hazardous material, or replace a 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 introduce processing options that involve less severe processing conditions.

Simplification: Design processes, processing equipment, and procedures to eliminate possible errors associated with excessive use of add-on safety features and protective devices.

3.2 An example of inherently safer process design in a dust explosion context: Design of inherently safer silos

In the process industries silos of various sizes for storage of combustible powders/dusts are often of the “funnel flow” type, as illustrated in Figs. 1a and 1b. A characteristic feature of this type of silo is that the flow out of it takes place in a limited core zone round the silo axis. The flow is often unreliable, and gravity flow alone may not empty the silo completely, leaving behind “dead” zones in which self-heating and self-ignition can develop, as illustrated in Fig. 1a. This, in turn, can lead to serious silo fires and explosions, in spite of all efforts to even out temperature gradients in the material in the silo by re-cycling procedures.

Fig. 1b illustrates another hazard associated with funnel flow silos. Sometimes the flow of material out of the silo gets fluidized (“flooding”) on its way downwards through the central core of the silo. As soon as the fluidized material exits the silo, explosible dust clouds may be generated outside the process equipment. Also, dust layers may accumulate in the area outside the silo, which when dispersed can give rise serious secondary dust explosions.

Fig. 2 illustrates an inherently much safer solution. Here the principle of *substitution* is adopted, i.e. “*use of a process, which is less likely to give rise to hazardous situations*”. The silo

in Fig. 2 has been specifically designed to give “mass” flow instead of “funnel” flow during discharge of the stored material in the silo. This eliminates the risks illustrated in Figs. 1a and 1b. Another advantage is this: Sometimes material stored in a silo has become horizontally segregated during silo filling from the top. If the silo is of the mass flow type, horizontally segregated material will to some extent become re-mixed horizontally as the material leaves the silo and gets loaded onto a conveyor belt, as illustrated in Fig 2.

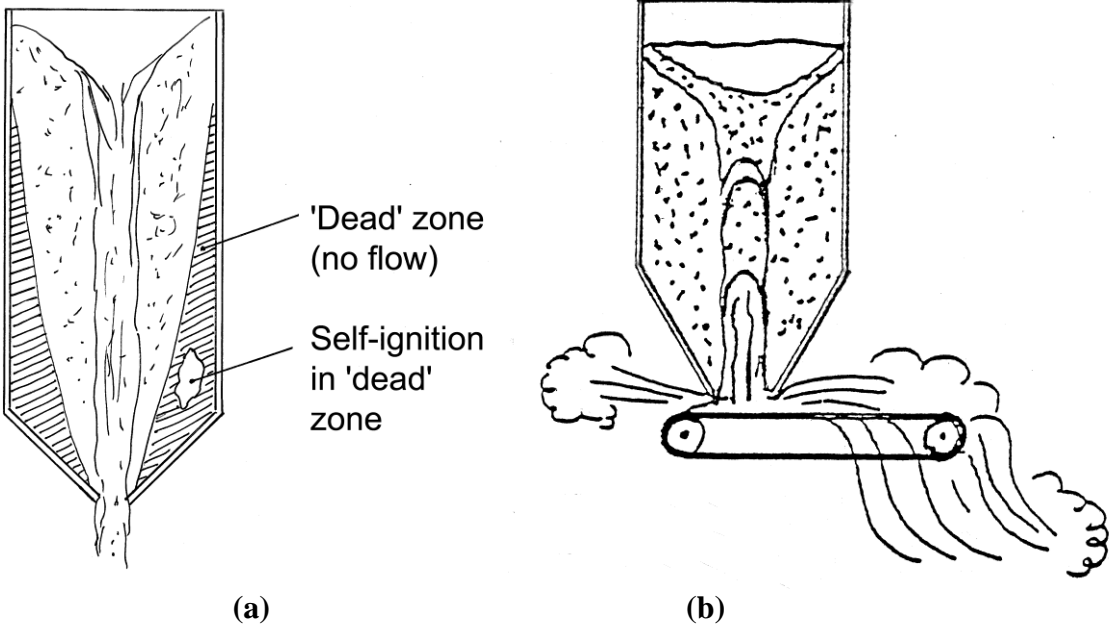


Fig. 1. Illustration of a funnel flow silo with (a) “dead” zones in which self-ignition can develop in spite of recycling of the rest of the material in the silo, and (b) with uncontrolled “flooding” of the material, which can cause spillage of combustible dust into the work rooms, both as clouds and layers. From Eckhoff (2016)

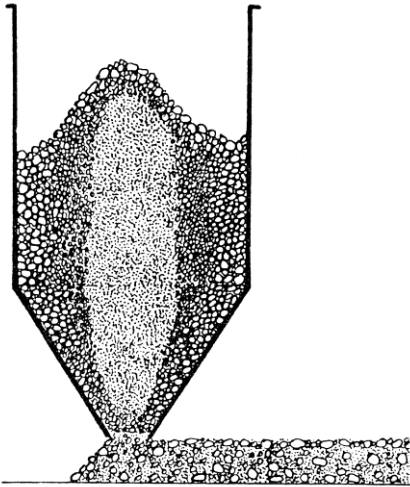


Fig. 2. A mass flow silo in which the entire horizontal cross section of material flows simultaneously downwards during the discharge process. Besides preventing “dead” zones and “flooding” mass flow promotes re-mixing of horizontally segregated material in the silo as the powder exits the silo. From Eckhoff (2016)

4 Generation, ignition and explosion of nm-particle dust clouds

4.1 Dust cloud formation by air dispersion of deposits of nm-powder deposits

The basic problem

In some special situations such as in air jet mills, explosive dust clouds may be generated *in situ*, i.e. the dust particles become suspended in the air as they are produced. However, very often in industry explosive dust clouds are generated by re-entrainment and re-dispersion of powders and dusts that have been produced at an earlier stage and allowed to accumulate as deposits or layers. In the case of very small particles, re-dispersion of such layers/deposits may not create dust clouds of individual primary particles. Instead, considerably larger particle agglomerates are often produced. This means that the effective particle size in the dust cloud will be considerably larger than the size of the individual primary particles. This is particularly so if the primary particles are of nm size.

Dust dispersibility and inter-particle attraction forces

More than 140 years ago Weber (1878), a pioneer in dust explosion research in Germany, pointed at the close relationship between dust *cohesion* and dust *dispersibility*. A given mass of powder, at equilibrium with the ambient atmosphere, contains a finite number of inter-particle bonds, each of which requires a specific amount of work to be broken. In principle the total minimum work needed to break all these bonds in a given mass of powder can be calculated by integrating the work required for breaking all the individual inter-particle bonds in that mass. In Eckhoff (2003), chapter 3, a highly generalized theoretical upper limit of dust/powder *dispersibility* was defined. The attraction forces between particles in a powder deposit clearly play a decisive role in determining the extent to which a given dust dispersion process is capable of dispersion the powder into a cloud of individual primary particles. The most important types of particle-to-particle attraction forces include *van der Waals' forces*, *electrostatic forces*, and *forces due to liquid bridges*.

Role of coagulation (re-agglomeration) of particles in a dispersed dust cloud

Experience has shown that MIEs of most combustible μm powders/dusts drop steadily and K_{St} values increase steadily with decreasing particle size down to sizes in the range 1-10 μm . However, according to Green and Lane (1964) there are two basic physical reasons why this trend may not continue right down to the range of nm particles. Firstly, complete *dispersion* of bulk powders consisting of nm primary particles into dust clouds consisting primarily of such minute individual particles is extremely difficult to accomplish. The reason is the comparatively very strong inter-particle cohesion forces in the powder. Furthermore, should perfect dispersion nevertheless be achieved, extremely fast particle *coagulation* in clouds of explosive mass concentrations would transform the primary nm-particles into much larger agglomerates within fractions of a second.

In dust clouds in air of organic powders/dusts and coals of particle sizes $<$ a few μm , the rate controlling step in flame propagation is the combustion of the mixture of air and the pyrolysis gases released by the particles. Based on this argument alone the dust clouds consisting of nm primary particles of organic materials and coal would probably not exhibit more severe MIEs and K_{St} -values than clouds of μm primary particles. However, with metal powders/dusts, this argument may not apply. Very fast *coagulation* of nm particles is then the likely main reason for the low K_{St} -values.

In this context the investigation by Ali and Asif (2012) on stabilizing the degree of dust dispersion and homogeneity of a fluidized bed of solid particles by pulsation of the air feed to the bed, may be relevant. Striking an optimal balance between dispersion and coagulation on a continuous basis may have been a main aim of their investigation.

However, experiments have shown that MIEs of clouds in air of some metal powders can be significantly lower for nm particles than for μm particles. Eckhoff (2012) indicated a possible reason for this: The temperatures of electric spark plasmas are very high, of the order of at least 10,000 K, which is substantially higher than typical dust flame temperatures. Therefore, due to extreme thermally induced stresses, particle agglomerates that would retain their integrity in flame propagation processes, may disintegrate into primary nm-particles if located very close to the spark plasma channel. This could produce a tiny zone of well-dispersed nm particles just adjacent to the spark plasma channel, which could then be ignited by even very low spark energies. The resulting initial small dust flame kernel would then ignite the main bulk of the dust cloud.

4. 2 Ignition and explosion of dust clouds of nm-powders

Background

Bouillard *et al.* (2009) were probably amongst the first researchers to ask if dust clouds of nm-particles (smaller than 100 nm) of a combustible material present an enhanced dust explosion hazard compared with dust clouds in air of the same materials of μm size particles. Bouillard *et al.* (2009) had a good reason for asking this question. An increasing range of new nm-particle types are currently produced for use in various consumer products ranging from cosmetics, sunscreens, toothpastes, pharmaceuticals and clothing, to electronics, plastics and tires. Over the last decades this development has escalated.

Up to quite recently most publications on production of combustible nm-particles such as those of carbon and various metals, referred to production methods and facilities of laboratory or small pilot scales. Some years before the paper of Bouillard *et al.* (2009), Kónya *et al.* (2002) discussed a method for what they named ‘large scale’ production of carbon nano-tubes. However, their ‘large scale’ only implied rather small batch charges of up to 100 g. In the context of industrial dust explosions such small quantities of powder would be regarded as close to negligible.

However, some years later Wei *et al.* (2008) constructed a pilot plant capable of producing high-purity multi-walled carbon nano-tubes (MWCNT) at a yield of some kg/hour, which would perhaps mean 10 – 20 tons per year on a continuous-production basis. With such quantities the dust explosion hazard would become a concern. It may well be that since the paper by Wei *et al.* (2008) genuine large-scale plants for production of various types of such particles have become a reality.

Recent developments on ignitability and explosibility of nm-particle dust clouds in air

The experiments by Wu *et al.* (2009) showed that minimum electric spark ignition energies (MIEs) of dust clouds in air nm-powders of both titanium and iron were considerably lower than MIEs of μm -powders of the same materials. Clouds in air of nm-particles of both titanium and iron ignited readily in the standard “Mike3” test apparatus with the lowest spark energy that this apparatus can produce, i.e. about 1 mJ. Holbrow *et al.* (2010) also found very low MIEs (< 1 mJ) for clouds in air of some nm metal powders. Because all existing standard methods for MIE determination of dust clouds have a lower spark energy limit of about 1 mJ, Wu *et al.* (2009) called for a new

generator capable of generating synchronized electric sparks of energies < 1 mJ. Work in this direction was reported by Randeberg and Eckhoff (2007). However, as discussed by Eckhoff and Olsen (2010) the Randeberg and Eckhoff (2007) spark generator would need to be developed further to become suitable for the intended purpose. An electronic solution to the problem was described by Olsen *et al.* (2015).

Vignes *et al.* (2009) determined maximum explosion pressures (P_{\max}) and maximum rates of rise of the explosion pressure $(dP/dt)_{\max}$ of three kinds of nm-particle powders, in the standard 20-litre explosion bomb. For aluminium it was found that down to particle sizes of the order of $1 \mu\text{m}$ both P_{\max} and $(dP/dt)_{\max}$ increased systematically with decreasing particle size. However, when the particle size was decreased further down to the genuine nm-particle region (particles smaller than 100 nm), both P_{\max} and $(dP/dt)_{\max}$ decreased. Vignes *et al.* indicated two possible reasons for this. The first was uncontrolled pre-ignition of the dust cloud by friction/impact during injection/dispersion of the powder into the explosion test vessel. The second reason was increased content of alumina in the aluminium with decreasing particle size due to oxidation of the particle surface. Eckhoff (2012) suggested that a third possible reason could be enhanced agglomeration and very rapid coagulation of the tiny primary nm particles.

Holbrow *et al.* (2010) reported on similar results from experiments in their specially constructed 2-litre closed explosion bomb. They concluded that both P_{\max} and $(dP/dt)_{\max}$ of clouds in air of nm powders were very similar to the values found for μm -particle powders of the same materials. However, the average particle sizes of the two aluminium powders tested were 0.1 and $0.2 \mu\text{m}$ respectively, i.e. in the upper range of particle sizes qualifying for being classified as genuine nm particle powders.

Wu *et al.* (2010) investigated the ignition sensitivity to *friction and impact* of some nm particle metal powders during conveyance from the pre-compressed dust dispersion reservoir of a standard 20-l Siwek/Kühner-type explosion bomb into the bomb itself. They found that nm titanium powder ignited in this way at all the air flow velocities tested. An iron nm powder ignited at all velocities but the lowest (3.5 m/s). An aluminum nm powder did not ignite even at the highest air velocity investigated.

Sundaram *et al.* (2016) developed a general theory for ignition and combustion of both nm and μm sized aluminium particles.

Bouillard *et al.* (2010) arrived at the same conclusion as Wu *et al.* (2009) as regards MIEs of nm powders. They also found that MITs (minimum ignition temperatures) were somewhat lower for clouds in air of nm powders than for clouds of μm powders of the same materials, whereas the MECs (minimum explosible dusts concentrations) were not significantly reduced when moving from μm particles to nm particles,

Boillard *et al.* (2013) compared the explosion violence of μm and nm titanium powders using standard test equipment (Siwek 20-l explosion chamber, MIKE 3 apparatus, and BAM oven).

Wu *et al.* (2014) studied whether ignition would take place during production of nm powders in air jet mills. They worked with a pilot size air-jet mill for production of nm powders of titanium and iron. The mass of material in the mill was 20 kg . The powder in the mill ignited about 5 min . after the initiation of a 23.5 m/s airflow speed in the mill. Another observation was that the inflammation occurred when the electrostatic voltage on a plastic hose of the grinder reached about 2 kV . The paper does not suggest whether the inflammation was caused by friction or electrostatics.

Turkevich *et al.* (2015) investigated the ignition and explosion properties of clouds in air of a range of carbonaceous nm powders including carbon black, graphene, and graphite. The minimum explosible dust concentrations (MECs) were in the range 100 g/m^3 , which is comparable to MECs of μm coal dust, fine-particle carbon blacks and graphites. All the nm carbon dusts had K_{St} values below 200 bar-m/s, which is comparable to the values for μm dusts of the same materials. The MIEs were comparatively high, about 100 J, i.e. at least an order of magnitude higher than typical MIEs of μm coal dusts. The main conclusion of Turkevich *et al.* is that the explosion severities (K_{St}) of the nm carbon dusts tested are comparable those of μm coal dusts, whereas their MIEs are significantly higher than those of the μm coal dusts. Perhaps agglomeration/coagulation is a main reason for this.

Krietsch *et al.* (2015) presented results from experiments with several un-oxidized metallic nm powders of aluminium, iron, zinc, titanium and copper in a modified 20-l Siwek bomb. In some cases they allowed the particles to become pre-oxidized in air for several minutes before the explosion experiments. They found that this comparatively long-lasting pre-oxidation did not significantly reduce the ignition sensitivity nor the explosion violence compared with the performance of clouds in air of particles that had only been exposed to air for a very short time before getting ignited.

It has been known for a long time that experimentally determined minimum electric spark ignition energies (MIEs) of clouds in air of various μm powders/dusts decrease systematically with decreasing particle size down to mean particle sizes in the range 1-10 μm . Experimental data illustrating this were discussed by Eckhoff (2003, 2016).

Similarly, the rate of pressure rise of dust explosions with μm powders/dusts in closed explosion bombs, increase systematically with decreasing particle size of the powder/dust down to about the same range of particle sizes.

The question is then if these trends continue right down into the nm particle size range. Two important physical processes tend to limit the extent to which this happens. The first is the limited *dispersibility* of nm-particle powders. The second is the exceptionally high *coagulation* rates of fully dispersed nano-size particles clouds of flammable/explosive mass concentrations.

5 Conclusion

From my personal point of view the objective of this paper will be fulfilled if it encourages just a single young, curious person to “get cracking” on one of the many challenging aspects of dust explosion prevention and mitigation that still require dedicated research and development.

Acknowledement

As a professor emeritus at the Department of physics and technology at the University of Bergen, Norway, I wish to express my indebtedness to the same Department for so generously allowing me to keep an office there and for providing me with the infrastructure that makes it possible for me to carry on with my writing.

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