Are enhanced dust explosion hazards to be foreseen in production, processing and handling of powders consisting of nano-size particles?

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Abstract. Based on experience with powders having particle sizes down to the range 1 – 0.1 µm one might expect that dust clouds from combustible nm-particle powders would exhibit extreme ignition sensitivities (very low MIEs) and extreme explosion rates (very high K_{Sr}-values). However, there are two basic physical reasons why this may not necessarily be the case. Firstly, the formation of clouds of well-dispersed primary particles from bulk powders consisting of nm-particles is extremely difficult to achieve, due to the comparatively very strong inter-particle cohesion forces. Secondly, should such a dispersion process nevertheless be fully successful, extremely fast coagulation processes in clouds within the explosive mass concentration range, would transform the primary nm-particles into much larger agglomerates within fractions of a second. Furthermore, for organic dusts and coal, the basic mechanism of flame propagation in the dust cloud is a further reason for not expecting extreme ignition sensitivities and explosion rates dust clouds from nm-particles. The overall conclusion is that dust clouds consisting of nm primary particles would not necessarily be expected to exhibit more severe MIE and K_{Sr}-values than those of dust clouds of µm primary particles. Recent experimental evidence confirms that this is in fact the case for K_{Sr}, whereas for MIE the values for some metals are significantly lower for nm primary particles than for µm ones.

1. Introduction

1.1. Nm-particles in a dust explosion context

As pointed out by Bouillard et al. [1] a range of new types of nm-particles are currently being produced and used in a number of consumer products ranging from cosmetics, sunscreens, toothpastes, pharmaceuticals and clothing, to electronics, plastics and tires. As a consequence, “nano-safety” has emerged as a new field requiring concern.

This paper addresses the question of whether production, handling and use of powders/dusts consisting of nm-particles can present an enhanced dust explosion risk compared to the risk presented by powders/dusts of larger particles. This limits the group of particle materials of concern to combustible ones only, which with few exception means

- Natural organic materials (grain, linen, sugar etc.)
- Synthetic organic materials (plastics, pigments, pesticides etc.)
- Carbon, coal and peat
- Metals (aluminium, magnesium, silicon, zinc, iron, titanium etc.)

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So far most publications on production of nm-particles of combustible materials such as carbon and various metals, refer to production methods and facilities of laboratory- or fairly small pilot-scale. Kónya et al. [2] discussed a method for 'large scale' production of carbon nano-tubes, but their 'large scale' only implied batch charges of up to 100 g. In the common context of industrial dust explosions such small quantities of powder would be regarded as negligible. However, Wei et al. [3] 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 seem that the issue of a possible enhanced dust explosion risk during production and handling of nm-particle powders may sometimes be irrelevant simply because of the small scales of production and handling. On the other hand it may well be that genuine large-scale plants for production of various types of such particles may become a reality in a not too distant future.

1.2. Influence of particle size and dust concentration on ignitability and explosibility of dust clouds with primary particle sizes down to 1 µm

It has been shown experimentally decades ago that flammable dust clouds of most solid combustible materials will become more sensitive to electric spark ignition and burn with increasing violence as the size of the primary particles in the cloud decreases down to the order of 1-10 µm. Figure 1 shows how experimentally determined minimum electric spark ignition energies (MIE) of clouds in air of three different dusts decreases systematically with particle size.

![Figure 1. Minimum electric spark ignition energy of clouds in air, of 3 different types of dust, as a function of the median particle size of the dust. Experimental data from Bartknecht and theoretical line from Kalkert and Schecker. Figure 1.30 in [4]](image)

The vertical scale in the figure is by orders of magnitude, and hence the influence of particle size on MIE is substantial. Theoretical considerations indicate that MIE for some particle materials is proportional to the cube of the particle diameter, as indicated in figure 1 by the predicted relationship for polyethylene particles.

The experimental data in figure 2 show how the combustion rate of clouds of aluminium dust in air increases systematically with the specific surface area of the dust (area of particle surface per unit mass), i.e. with decreasing particle size. A specific surface area of 6.5 m²/g corresponds to mono-sized aluminium spheres of diameter 0.34 µm, or flakes of thickness 0.11 µm, which is in the far upper range of what would be considered as genuine nm particles. The question is then whether this trend continues into the range of genuine nm particles.
Figure 3 gives some further data for the maximum rate of pressure rise for various dusts as functions of particle size. The data for organic powders cover only the particle size range down to about 15 \( \mu \text{m} \). With particles of organic materials smaller than about 10 \( \mu \text{m} \) the pyrolysis stage and subsequent mixing of pyrolysis gases and air, are so rapid that they will no longer be the rate controlling stages in the combustion process. Instead the controlling stage will be the homogeneous combustion of the pyrolysis gas/air mixture.

![Figure 2](image1.png)

**Figure 2.** Influence of specific surface area of aluminium dust on maximum rate of pressure rise in dust explosions in a standard closed 1 m\(^3\) ISO vessel. (Figure 1.23 in [4])

![Figure 3](image2.png)

**Figure 3.** Influence of median/average particle size of various dusts on the maximum rate of pressure rise generated by dust explosions in a standard closed 1 litre Hartmann bomb. (Figure 1.28 in [4])

If the trends indicated in figures 1-3 for metal powders were just to be extrapolated into the nm-particle range, extreme ignition sensitivities and explosion rates would be predicted. However, two important physical processes will tend to limit the dust explosion hazard in the case of nm particles. The first is the limited dispersibility of nm-particle powders. The second is the very high coagulation rates of nano-size particles in clouds of flammable/explosive mass concentrations. In the following these two aspects will be discussed in more detail.

2. **Formation of dust clouds by dispersion of powder deposits consisting of nm primary particles**

2.1. **Background**

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, in most cases 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.

There is a ratio of about 100 between the bulk density of a given powder when appearing as a deposit or a layer, and the maximum explosive concentration of a cloud of that powder in air.
Therefore, in order to obtain an explosive dust cloud from a deposit or layer, some process of re-entrainment and re-dispersion is required. Generation of powder/dust deposits may either be intentional (e.g. collection of powders and dusts in silos, hoppers and bag filters), or unintentional (e.g. deposition of dust on beams, external surfaces of process equipment or walls and floors of work and storage rooms). Also the re-entrainment and re-dispersion of such dust deposits may be either intentional (handling/transport in mixers, bucket elevators, pneumatic transport lines etc.), or unintentional (bursting of sacks and bags containing powder, leaks of powder/dust from pressurized process equipment, and dispersion by blasts of air generated by an explosion that has started elsewhere in the plant). In dust explosion hazard assessment the important role played by dispersion processes has often been overlooked. It has not always been realized that fine, cohesive powders cannot be dispersed in a gas to form a cloud of individual primary particles unless particle agglomerates are exposed to very high shear or tensile stresses. This means that the effective particle size in dust clouds in practice may be much larger than the size of the primary particles.

Professor Weber (quoted in chapter 3 in [4]), one of the pioneers of dust explosion research in Germany about 130 years ago, stressed the close relationship between dust cohesion and dust dispersibility, or dustability. In a paper on the ignitibility and explosibility of wheat flour he emphasized that cohesion of the flour, caused by inter-particle adhesion, plays an important role with respect to the ability of the flour to disperse into explosive dust clouds. Using simple but convincing laboratory experiments he demonstrated that the dispersibility of one specific flour increased systematically with decreasing moisture content in the flour. Weber suggested that two large dust explosion disasters, one in Stettin (Szczecin) and one in München, were mainly due to the low moisture content and hence the high dispersibility of the flours involved.

2.2. An overall structure of the dust dispersibility problem
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. The total minimum work $W_{\text{min}}$ needed to break all these bonds in one unit mass of powder could in principle be calculated by integrating the work required for breaking all the individual inter-particle bonds. In accordance with [4], chapter 3, one could then define a theoretical upper limit value of the ‘dispersibility’ $D_{\max}$ for that specific powder deposit by:

$$D_{\max} = 1/W_{\text{min}}$$  \hspace{1cm} (1)

When defined in this way, the dispersibility has the dimension mass per unit of energy or work, and is thus a measure of the quantity of powder that can be completely dispersed by spending one unit of energy from external sources in the process. However, no realistic dispersion process is one-hundred per cent efficient. This can be accounted for by incorporating an efficiency factor, $k$:

$$D_{\text{real}} = k/W_{\text{min}}, \ 0 < k < 1$$  \hspace{1cm} (2)

Clearly, the particle size distribution has a great influence on $W_{\text{min}}$ at a given powder bulk density. Furthermore, the bulk density of a given cohesive bulk powder will vary with the degree of compaction. This means that the number of inter-particle bonds per unit mass of cohesive powder will increase with increasing compaction of the powder. Therefore $W_{\text{min}}$ also increases with increasing compaction. Moisture increases $W_{\text{min}}$ by increasing the strength of certain types of inter-particle bonds.

The close link between $W_{\text{min}}$ and the nature and number density of the inter-particle bonds in a powder has given rise to detailed studies of various types of such bonds. Attempts have also been made at predicting aggregated powder-mechanical strength properties of powder deposits from microscopic inter-particle structure and forces.

However, the efficiency factor $0 < k < 1$ in Equation (2) allows $D_{\text{real}}$ to have any value between zero and $D_{\max}$, depending on the way in which the work $W_{\text{min}}$ is applied to the powder to be dispersed. This in turn depends on the geometrical arrangement of the powder and the form of the energy available for the dispersion process. In the case of cohesive powders composed of very small particles,
inter-particle forces play a major role and inter-particle bonds may not be broken unless the particle agglomerates are exposed to high velocity flow fields, or high-velocity impacts.

2.3. Attraction forces between particles in powder deposits

2.3.1. Van der Waals’ forces

As discussed in [4], chapter 3, the theoretical van der Waals’ force $F_W$ between two spherical particles is:

$$F_W = A/a^2 \cdot (x_1 x_2)/(x_1 + x_2)$$  (3)

Here $A$ is a constant, $a$ the smallest distance between the sphere surfaces, and $x_1$ and $x_2$ the diameters of the two spheres. Van der Waals’ forces between particles are of significance as long as $x < 100$ nm. If $x_1 \gg x_2$, the force is only determined by the size of the smallest particle, and equation (3) reduces to

$$F_W = A/a^2 \cdot x_2$$  (4)

Because $F_W$ is proportional to the diameter of the smallest particle, it will play the dominating role in systems of very small particles, compared to forces due to gravity and viscous drag.

Most particles in real life are not smooth spheres, but of irregular shape and surface topography. Schubert [5] showed that $F_w$ between a plane surface and a point on an irregular particle of diameter $x$, having a small elevation of radius $r$ that touches the plane surface, is:

$$F_W = A \cdot (x/(r + a_o)^2 + 2r/ a_o^2)$$  (5)

The distance, $a_o$, is the smallest distance that can exist between two solid bodies in touch, and it is estimated at 0.4 nm.

2.3.2. Electrostatic forces

In the case of electrically conducting particles, electrostatic inter-particulate attraction between touching particles may occur even if the particles do not initially carry any net excess charge, provided their electron work functions are different. Electrons will then be transferred from one particle to the other. Different electron work functions can occur in particle systems of apparently identical materials, due to differences in impurities, oxide layers etc. Provided the smallest distance $a$ between the two surfaces is shorter than 100 nm, i.e. the particles are in electrical contact, the electrostatic contact attraction force $F_E$ between the two conducting particles is ([4], chapter 3):

$$F_E = \pi \varepsilon \varepsilon_0 \cdot U^2/\alpha \cdot (x_1 x_2)/(x_1 + x_2)$$  (6)

Here $\varepsilon_o$ is the permittivity of vacuum and $\varepsilon_1$ the dielectric constant of the gas surrounding the particles. $U$ is the contact potential between the two particle surfaces.

For electrically non-conducting particles, such as plastics, the electrostatic contact force is negligible. In this case, electrostatic attraction between particles is caused by excess charges on the particle surfaces, acquired tribo-electrically during preceding production and handling. The attraction force between two non-conducting particles having total excess opposite charges on the surfaces of $q_1$ and $q_2$, equals:

$$F_E = (q_1 q_2/4\pi \varepsilon \varepsilon_0) \cdot ((x_1 + x_2)/2 + a)^2$$  (7)

For $a >> (x_1 + x_2)$, equation (7) reduces to Coulomb’s equation for attraction between two opposite point charges. If $a$ is much smaller than the diameter of the largest particle, $F_E$ will essentially be independent of $a$.

Equations (3)–(7) are all concerned with the attraction between two single particles under idealized conditions. Therefore, these equations are of limited value for predicting inter-particle attraction forces in real powders and dusts where many particles are interacting and particle shape and surface properties may be complex. In the case of electrostatic forces, realistic assessment of the particle charges $q_1$ and $q_2$ is also difficult, even for idealized particle geometries.
2.3.3. Inter-particle forces due to liquids
In agreement with the findings of professor Weber discussed above, it is common experience from practice in industry that dry dusts are usually easier to disperse than moist dusts (one exception can be heavily electrostatically charged dry plastic powders). Even small quantities of adsorbed moisture can in some cases increase the attraction forces between particles considerably. Adsorbed layers of up to 3 nm thickness can adhere firmly to the particle surface and make it smoother. This can reduce the effective distance between two touching particles appreciably. For a spherical particle of 1 μm diameter the volume of a 3 nm layer of liquid water constitutes only 2% of the particle volume. For smaller particles the percentage will increase. Adding small amounts of liquids to dusts is sometimes used intentionally in industry for reducing dust dispersibility. One application of this method is addition of soya bean oil to grain for preventing generation of grain dust clouds in grain storage plants.

At higher powder moisture contents excess water starts to form liquid bridges between particles. With further increase of the moisture content, a transition range is reached, at which the space between the particles becomes completely filled with water. Within this capillary range the capillary under pressure is the main source of the cohesion. If the water content is increased beyond this point, the system transforms from a cohesive powder to a suspension of particles in a liquid.

2.4. Dispersion of agglomerates suspended in gas, by forced flow through a nozzle
Depending on the actual dispersion process, or de-agglomeration process, the effective particle size distribution in dust clouds from a given cohesive powder can differ considerably. Because agglomerates in a dust cloud may behave as single particles of the agglomerate size when they burn, both ignition sensitivity and explosibility of such clouds will vary correspondingly.

In view of this the investigation by Yamamoto and Suganuma ([4], chapter 3) is of considerable interest. They studied the break-up of particle agglomerates in an air flow when the flow was passed through a nozzle at various velocities. A sample of the resulting dispersed dust cloud downstream of the nozzle was fed through a cascade impactor to determine the effective, aerodynamic in situ size distribution in the secondary dust cloud. Figure 4 gives a typical set of results.

Figure 4. Effective particle size distributions of an airborne talc dust after dispersal by different orifices and air velocities. R_w is the percentage by weight of the effective ‘particles’ that are larger than the size x (Investigation by Yamamoto and Suganuma in 1984 quoted by [4])
The distribution of effective particle sizes is shifted systematically towards smaller particles as the dispersion process in the nozzle gets more effective, i.e. as the average air velocity through the nozzle increases.

The effect is quite dramatic. For an air velocity in the nozzle of 10.5 m/s, the median effective particle size is somewhat larger than 10 μm, whereas for velocities in the range 100–150 m/s it is only 1 μm. For the primary dust cloud, which was generated in a way that would be typical in industry, the median particle size would probably be considerably larger than 10 μm. It can be observed from figure 4 that at the highest air velocities in the nozzle, the distribution of the sizes of ‘effective’ particles in the secondary dust cloud approached the size distribution found by means of a sedimentation balance, after having dispersed the powder in a liquid in a way that would be expected to produce close to perfect dispersion.

2.5. Concluding remark
The understanding of how explosive dust clouds can be generated by dispersion of powder layers/deposits requires knowledge both of the nature of the powder (\(W_{\text{min}}\)) and of the actual dispersion process (value of efficiency factor \(k\)). The latter depends very much on the actual industrial situation, which is different in bucket elevators, pneumatic transport systems, fluidized beds, various kinds of mills, driers, mixers, cyclones, filters and silos. Therefore, intimate knowledge of the nature of the industrial environment in which the dust is dispersed is required to enable any reasonable estimate of \(k\).

3. Coagulation of particles in nm-particle dust clouds in air

3.1. Introduction
The following discussion is based on the chapter on particle coagulation in the classical text by Green and Lane [6]. The point is that the presence of agglomerates in dust clouds of very small particles is not only due to incomplete particle dispersion. In addition new agglomerates are formed continually by inter-particle collision. Green and Lane named this process coagulation and pointed out that continuous and spontaneous coagulation is one of the most striking characteristics of dust clouds. The particles in the cloud, of whatever substance they are composed, will coalesce or stick together if they make contact. The process goes on continuously so that the effective particle size increases and the particles finally settle out of suspension. Because the mean inter-particle distance for a given dust mass concentration decreases proportionally with the mean particle size, the initial coagulation rate for a given mass concentration also increases with decreasing initial particle size.

According to [6] the first clear evidence of coagulation in clouds of very small particles was obtained by Tolman and his collaborators in 1919, who measured the variation with time of the intensity of a Tyndall beam in clouds of various dusts. They were able to correlate the Tyndall beam readings with both the mass concentration of dust particles in their experimental clouds, and with the average particle size. It then became clear that the observed marked decrease of the Tyndall beam intensity could only be explained by coagulation.

3.2. The coagulation constant
The nature of the coagulation process in dust clouds was, according to Green and Lane, first resolved experimentally in the pioneering research by Whytlaw-Gray and co-workers in 1932. They were able to count the particles per unit volume of dust cloud, and hence to determine the variation with time of this number. They found that coagulation of many types of small particles suspended in air followed a single simple law. When the average volume of cloud occupied by a single dust particle was plotted against the elapsed time, a straight line was obtained for a wide range of dust particles, as shown in Figure 5 for dilute smoke particles in air. If \(n\) is the number of particles per cm³ of cloud at any time \(t\), and \(n_0\) is the number present at the moment when the dust cloud is first formed, and before onset of coagulation, then:
\[ \frac{1}{n} - \frac{1}{n_0} = K t \] (8)

The constant \( K \) is named the “coagulation constant”. The unit on the vertical axis is \( 10^6 \) times the average volume of dust cloud occupied by one particle, the volume unit being cm\(^3\). When converted to m\(^3\), the number 8 on the vertical axis in figure 5 means that the average volume occupied by one particle is \( 8 \times 10^{-12} \text{ m}^3 \), or the number of particles per m\(^3\) equals \( 1/8 \times 10^{12} \). This may seem a high number, but for small particles the mass concentration will be low.

![Figure 5](image)

**Figure 5.** Average volumes of dust cloud occupied by one particle for various dust types, as functions of elapsed time: (a) stearic acid, (b) ammonium chloride, (c) cadmium oxide, (d) benzene-azo-b-naphthol. Figure 5.1 in [6].

Hence, for an organic material of density \( 1 \text{ g/cm}^3 \) and particle size 1 µm, the mass concentration will only be about 0.1 g/m\(^3\), which is orders of magnitude below typical minimum explosive concentrations for powder dusts. It is clear, therefore, that figure 5 is only relevant to explosive dust clouds of nm particles if the straight lines hold also for much smaller \( 10^6/n \) values than those resolvable on the vertical axis in figure 5. This assumption is the basis of the discussion in the following.

The coagulation constants for the various materials investigated by Whytlaw-Gray and co-workers are equal to the slopes \( K \) of the straight lines in figure 5. Table 1 gives experimentally determined \( K \) values for a selection of particle types, ranging from metallic oxides, via various solid organic compounds to liquid droplets of organic substances.

**Table 1.** Coagulation constants \( K \) for some particle materials. Table 5.1 in [6].

| Substance             | \( K \) \((10^{-9} \text{ cm}^3/\text{s})\) |
|-----------------------|--------------------------------------------|
| Ammonium chloride     | 0.60                                       |
| Ferric oxide          | 0.66                                       |
| Magnesium oxide       | 0.83                                       |
| Cadmium oxide         | 0.80                                       |
| Stearic acid          | 0.51                                       |
| Oleic acid            | 0.51                                       |
| Resin                 | 0.49                                       |
| Paraffin oil          | 0.50                                       |
| p-xylene-azo-β-naphthol | 0.63                                    |

In spite of the substantially different nature of the particles, the \( K \)-values in Table 1 are very similar, the ratio between the largest and the smallest value being only 1.7. Therefore Green and Lane concluded that in air at normal temperature and pressure the coagulation process does not depend significantly on the dust type.

Green and Lane [6] also pointed out that equation (8) is of the same form as that established by Rutherford for the rate of combination of small ions. The equation also applies to large atmospheric ions, and to the disappearance of nuclei. Naturally, because of the lower mobilities, \( K \) is smaller for dust particles than for ions. By differentiation of equation (8) it follows that the rate at which the
particles disappear by coagulation at any instant depends on the square of the number present at that instant and the constant $K$:

$$- \frac{dn}{dt} = Kn^2$$

Coagulation is very rapid in the early stages when the number of particles $n$ per unit volume of dust cloud is high. Using equation (8) the time interval $\Delta t$ required for halving $n$ can be assessed. Hence, for $K = 0.5 \times 10^9$ cm$^3$/s and $n = 10^{11}$ particles/cm$^3$, $\Delta t$ equals 0.02 s, whereas for $n = 10^6$ particles/cm$^3$ $\Delta t$ equals 33 min, and for $10^5$ particles/cm$^3$ $\Delta t$ equals 5.5 hours. The time taken to generate an aerosol containing $2.5 \times 10^6$ particles per cm$^3$ by coagulation is nearly the same whether the initial number is $5 \times 10^{12}$ per cm$^3$ or $5 \times 10^8$ per cm$^3$. As pointed out by Green and Lane this explains why, when dust clouds are formed from different quantities of material, the particle number may be the same by the time the cloud is ready to be examined experimentally, whereas the average effective particle size can vary appreciably.

3.3. Effect of poly-dispersity (particle size distribution)

No coagulating dust cloud can be truly mono-disperse, although it may be nearly so at the onset of coagulation in certain cases. Most often the cloud consists of particles of a wide range of sizes, depending on its past history. According to Green and Lane [6] experiments have confirmed that the more the dust particles in a dust cloud deviate from mono-dispersity, the faster the cloud coagulates. However, considerable difficulties arise when attempts are made to calculate precisely the effect of poly-dispersity. According to theory the probability of collision between particles of unequal sizes is greater than that of collision between mono-sized particles. But because most collisions occur between particles of equal size or nearly so, the effect due to poly-dispersity is counterbalanced by the comparative rarity of collisions between particles of large size differences.

In a poly-disperse dust cloud exposed to gravitational or centrifugal forces, the larger particles will move faster than the smaller ones. The probability that large particles will collide with smaller ones is thereby increased. This type of coagulation, due to different settling rates, is negligible in clouds of primary particles of nm-size but will become more significant as the particle size increase.

3.4. Effect of particle shape

As mentioned in [6], the original coagulation equations were based on the assumption that the particles were spherical. However, in practice most particles will have irregular shapes. Slight irregularities in shape make only little difference to the mobility of a particle in a gas, and therefore the effect on the coagulation rate should be only minor. The exception is chain-like structures, for which a considerable variation in the mobility, and consequently in the coagulation rate, might be expected.

Experimental evidence confirms that the rate of coagulation of particles in dust clouds is not greatly influenced by the particle shape. The values of $K$ for clouds of particles of stearic and oleic acids agree closely with theory, whereas that for ferric oxide of the same weight concentration is only 30 per cent greater. When these particle systems were allowed to coagulate until the particle agglomerates had grown to the order of 1 µm, the stearic acid agglomerates were of a compact, equi-dimensional form, whereas those of ferric oxide were loosely built chain-like structures. If the nm-particles possessed the same form as those of the order of 1 µm, the coagulation constants $K$ of stearic acid and ferric oxide would have differed greatly. On the other hand electron microscopic examination showed that the chain-like ferric oxide aggregates did not appear until the particle size approached the 1 µm range.

3.5. Effect of temperature, pressure and viscosity of the air

As also pointed out by Green and Lane [6] the coagulation rate of mono-disperse particles also depends on the temperature, pressure and viscosity of the air in which the particles are suspended. Because the viscosity of air also increases with temperature, the increase of the coagulation constant $K$ will not be proportional to the absolute temperature, but will nevertheless increase with temperature.
The sole effect of reduction of the gas pressure upon $K$ is to increase the mean free path of the gas. This is because, except at very low pressures, the gas viscosity is practically independent of pressure. According to [6], experiments on ferric oxide dust clouds at various pressures showed that the coagulation rate increased markedly as the gas pressure was reduced.

3.6. Effect of foreign vapours mixed with the air

The experimental values for the coagulation constant for various dust clouds reported by Green and Lane [6] were in reasonable agreement with the value calculated from theory on the assumption that all collisions between the particles are irreversible, i.e. the particle were sticking together permanently after having collided. It had been suggested by some investigators that a thin layer of adsorbed foreign vapour or liquid on the particles might alter the particle surface in such a way that, on collision, the particles would not readily stick together. Systematic experiments were carried out with a number of different dust particle types in air to which vapours of phenol, oleic acid, glycerine and water had been added. In every case the measured rate of coagulation was found to be the same, within the experimental error, as the rate of coagulation in pure air, determined in control experiments.

3.7. Effect of dust cloud turbulence

One way of increasing the coagulation rate of a particulate cloud is to make it turbulent by stirring it with a fan. Eddies and swirls are then formed and the velocities of the particles relative to each other increase. Therefore the chance of collision of particles with one another must also increase, which in turn means an increased coagulation rate. As discussed in [6], this problem was investigated systematically by Langstroth and Gillespie in a study of the coagulation and surface deposition of ammonium chloride particle suspended in quiescent and turbulent air. They used a chamber of approximately 1 m$^3$ capacity as illustrated in figure 6. In the case of the experiments with turbulent air, a large motor-driven paddle, pierced with numerous holes, was oscillated at the desired frequency through an angle of 180° from the vertical, throughout the experiment. The readings of a small non-directional thermocouple anemometer, averaged over various positions in the dust cloud chamber, were taken as measures of the average air velocities. A set of results are reproduced in Figure 7. As can be seen, there is a systematic increase of the average volume of dust cloud occupied by one particle at any instant, with the average air velocity (turbulence).

Förster [7] suggested that accidental generation of large, explosive clouds of sprays/mists of organic liquids of high boiling points is not very likely. The reason is that the mean droplet-droplet distance in the explosive range is of the order of only 10 droplet diameters, which in a turbulent cloud makes fast coalescence of the small droplets to larger ones highly effective. The larger droplets will then “rain out” and the fuel concentration in the cloud will very soon fall below the explosive range. Förster confirmed experimentally that with a high-boiling-point liquid (octanol) it was very difficult indeed to generate an explosive spray in a 1 m$^3$ explosion chamber, unless a highly sophisticated spray nozzle system was adopted.

Figure 6. The 1 m$^3$ dust cloud chamber with oscillating paddle used by Langstroth and Gillespie. Figure 5.7 in [6].
It should be pointed out that, when a dust cloud is stirred in a closed chamber, reduction of the number of particles in the cloud will not only be due to coagulation. Irreversible deposition of particles on the chamber wall will also contribute. Some of the increased volume of dust cloud per particle (reduction of the number of particles per unit volume of dust cloud) in Figure 7 is probably due to enhanced deposition of particles on the internal chamber surfaces. However, the relative importance of wall deposition decreases with increasing number of particles in the dust cloud. Therefore this affect probably plays a minor role in the case of the very high particle concentrations of interest in the context of dust explosions with nm-particles. For a more extensive discussion of the significance of the wall deposition problem reference is made to Green and Lane [6].

3.8. Coagulation of electrically charged particles
As also discussed in [6], the presence of electric charges on the particles in a dust cloud aerosol may alter the rate of coagulation appreciably. It is possible to calculate the coagulation constant $K$ from knowledge of the amount of electric charge and the size distribution of the particles. For a dust cloud with a symmetrical electric charge distribution the influence of electric charge on the coagulation rate depends upon the fraction of negatively charged particles, the fraction of positively charged particles, the average charge of each sign and the average particle diameter. However, any change in the electric charge distribution brought about by coagulation may greatly alter the coagulation rate.

3.9. Coagulation in an acoustic field
Particles suspended in a gas coagulate readily when exposed to powerful sound waves, in particular standing waves in resonant enclosures. According to [6], various investigators have shown that coagulation occurs both at sonic and ultrasonic frequencies. Direct evidence of this effect was obtained from comparing photomicrographs of particles settled out of dust clouds which had been subjected to intense sound waves, and particles settled out of clouds that had not been exposed to such waves.
4. Expected ignition sensitivities and explosibilities of clouds of nm particles in air based on indirect evidence

4.1. Mechanism of flame propagation in clouds in air of organic and coal nm-particles

According to Hertzberg et al. [8-10] and Ballal [11] the following three consecutive processes take place in the propagation of a flame through a cloud of organic dust or coal dust in air:

1. Heating and pyrolysis/devolatilization of dust particles
2. Mixing of the pyrolysis gases/volatiles with air
3. Gas phase combustion of the premixed gas phase

In a subsequent stage 4. carbon residue particles burn as individual entities behind the gas flame front. The characteristic time constants for the three consecutive processes 1.--3. may be denoted \( \tau_d \), \( \tau_m \), and \( \tau_c \). According to [8], mixing of pyrolysis gases/volatiles with air is a very rapid process and \( \tau_m \) will be shorter than \( \tau_c \). Furthermore, for small particles \( \tau_d \ll \tau_m \), and the flame propagation process will essentially be controlled by the premixed gas combustion (time constant \( \tau_c \)). For smaller particles than the order of 10 \( \mu \)m, \( \tau_d \) and \( \tau_m \) are negligible compared to \( \tau_c \) and particle size has no longer any influence on the burning rate, which is essentially limited by the rate of gas phase combustion.

With organic and coal powders/dusts the ultimate limits of ignition sensitivity and explosibility would probably be the values of the premixed pyrolysis/devolatilization gases/vapours only. The actual values of MIE and \( K_{St} \) would then be expected to vary with the composition of the gases/vapours. With a large fraction of the gas/vapour molecules being unsaturated compounds, quite low MIEs and high \( K_{St} \)-values would be expected, in agreement with typical values for gas groups IIB and IIC.

4.2. Mechanism of flame propagation in clouds in air of carbon and metal nano-size particles

In the case of pure carbon and various metals including aluminium and magnesium, the combustion process mainly occurs at or near the particle surface. In most cases a homogeneous combustible gas phase throughout the flame front in the cloud will not be formed in the same way with organic materials. At outset, therefore, both the ignition sensitivity and the explosibility of dust clouds of most metals and carbon would be expected to increase systematically with decreasing primary-particle size right down to the nm-range. On the other hand reduced dispersibility and fast coagulation of the very small particles would probably limit the effect of the reduced primary-particle size, as will be discussed below.

4.3. Degree of dust dispersion and particle coagulation

The minimum explosive dust concentration (MEC) for organic materials is of the order of 100 g/m\(^3\), irrespective of particle size. For metals it is generally higher and roughly proportional with the particle density. It is then of interest to consider the number of mono-sized particles \( n_o \) that would be contained in one cm\(^3\) of a perfectly dispersed dust cloud at MEC before any coagulation has started. For cubical particles, taking the particle edge as the particle ‘size’, and with a particle density of 1 g/cm\(^3\) (organic materials), one cm\(^3\) of dust cloud will contain \( 10^{13} \) particles of particle size 1 nm, \( 10^{14} \) particles of size 10 nm, and \( 10^{11} \) particles of size 100 nm. This means that with a coagulation constant \( K \) equal to \( 0.5 \cdot 10^9 \) cm\(^3\)//s agglomeration would have reduced the number of particles per cm\(^3\) of dust cloud to about \( 10^9 \) per cm\(^3\) within only 1 s irrespective of the initial particle size before onset of coagulation. The average effective particle size would then have increased to > 100 nm.

The question is then whether an ignition delay of 1 s is long or short compared with the delays between dust cloud generation and ignition in situations relevant to the practice. Two different contexts are of interest. The first is industrial scale dust clouds in process equipment, for which ignition delays of the order of 1 s would appear relatively short. In such cases coagulation will, by the time of ignition, have increased the effective particle size to the order of 0.1 – 1 \( \mu \)m.
However, in dust clouds in small scale laboratory test apparatuses for assessment of dust cloud ignitability and explosibility the situation will be different. In the tests for minimum ignition energy (MIE) and explosion violence (K_{St}), the experimental dust clouds are normally created by quite violent dispersion processes to ensure that even quite small particles are dispersed into individual entities in the gas. Triggering of the ignition source follows within 20 – 60 ms after onset of the dispersion process, which means that ignition occurs while the coagulation of the particles in the cloud may only be in its initial phase. On the other hand, dispersing samples of nm-particle powder into clouds in air consisting of independent primary nm-particles only would be virtually impossible by means of the dust dispersion method used in these test methods.

5. Explosibility and ignition sensitivity of nm-particle clouds in air. Experimental evidence

5.1. Explosibility

45 years ago Helwig [12], using a 43 litre closed bomb for his experiments, found that the rate of combustion, i.e. (dp/dt)_{max} of clouds in air of coal dust containing 10–50% volatiles, did not increase monotonically with decreasing particle size. Instead the explosion rate for the finest fraction, of particle size 0–10 μm, was in fact lower than for the most explosive size range 20–30 μm, probably because of incomplete dispersion and/or rapid coagulation of the finest particle fraction.

More recently Vignes at al. [13] examined the explosibility of three kinds of nm-particle powders by means of the standard 20-litre explosion bomb. The data obtained were compared with those of μm-particle powders of similar materials. For aluminium it was found that down to particle sizes corresponding to a specific surface area of a few m^2/g both P_{max} and (dp/dt)_{max} increased systematically with decreasing particle size. This is in agreement with the data in figure 2. However, Vignes at al. [13] also found that both P_{max} and (dp/dt)_{max} in fact decreased systematically when the specific surface area was increased further into the genuine nm-particle region. Three reasons for this were indicated. The first was uncontrolled pre-ignition of the dust cloud by friction/impact during injection/dispersion of the powder tested. The second possible reason was increased content of alumina in the aluminium with increasing specific surface area of the particles (oxidation of the particle surface). As a third possible reason was enhanced agglomeration/coagulation of the primary particles as they got very small.

Very recently Holbrow et al. [14] reported on similar experiments in a specially constructed 2-litre closed explosion bomb. The results are summarized in table 2.

Table 2. Maximum explosion pressures and maximum rates of pressure rise of clouds of nano-particle powders in air in a 2-litre explosion chamber. Table 9 in [14].

| Sample number | Material                      | P_{max} (bar g) | dP/dt (bar/s) | Equivalent K_{St} (bar m/s) |
|---------------|--------------------------------|-----------------|--------------|----------------------------|
| EC/011/09     | Aluminium nanopowder (210 nm)  | 12.5            | 1677         | 449                        |
| EC/104/07     | Aluminium nanopowder (100 nm)  | 11.2            | 2000         | 536                        |
| EC/147/07     | Iron nanopowder                | 2.9             | 68           | 18                         |
| EC/152/07     | Zinc nanopowder                | 5.6             | 377          | 101                        |
| EC/148/07     | Copper nanopowder              | 1.2             | 10           | 3                          |
| EC/042/08     | Carbon nanofibre               | 5.2             | 62.5         | 17                         |
| EC/158/07     | Carbon nanofibre               | 6.0             | 112          | 30                         |
| EC/116/08     | Carbon nanofibre               | 6.9             | 591          | 158                        |
| EC/117/08     | Carbon nanofibre               | 5.6             | 137          | 37                         |
| EC/153/07     | Carbon nanofibre               | 6.4             | 339          | 91                         |
The overall conclusion to be drawn from Table 2 is that the maximum explosion pressure and the maximum rate of pressure rise \( (K_{st}) \) of clouds in air of powders consisting of nm primary particles were very similar to the values of conventional \( \mu \)m-particle powders. However, the particle sizes of the two aluminium powders of 0.21 and 0.1 \( \mu \)m respectively are in the upper range of what would perhaps qualify for classification as genuine nm particle powders.

### 5.2. Ignition sensitivity

#### 5.2.1. Electric/electrostatic sparks

The situation seems to somewhat different with the ignition sensitivity of the dust clouds. As illustrated by table 3 and figures 8 and 9, Wu et al. [15] demonstrated that experimental MIE values for nm-powders of both titanium and iron were in fact considerably lower than those of a \( \mu \)m-powder of the same materials. Clouds in air of nm-powders of both materials ignited readily in the Mike3 test apparatus with the lowest spark energy that this apparatus can produce, i.e. about 1 mJ. This means that dust clouds in air of some nm-powders may be more easily ignited by electric/electrostatic sparks than clouds of \( \mu \)m-powders of the same materials. Table 3 summarizes the results by Wu et al. [15].

**Table 3.** From [15]

| Nanoscale               | Micrometer scale |
|-------------------------|------------------|
| **Diameter** | **Minimum ignition energy** | **Diameter** | **Minimum ignition energy** |
| Ti powder               |                  | 3 \( \mu \)m | <1 mJ  |
| 35 nm                   | <1 mJ            | 8 \( \mu \)m | 21.91 mJ |
| 75 nm                   | <1 mJ            | 20 \( \mu \)m| 18.73 mJ |
| 100 nm                  | <1 mJ            | 45 \( \mu \)m| 21.91 mJ |
| Fe powder               |                  | 150 \( \mu \)m| -----  |
| 15 nm                   | <1 mJ            | 35 \( \mu \)m| -----  |
| 65 nm                   | <1 mJ            | 65 \( \mu \)m| -----  |

(The long table continues...)

| Nanoscale               | Micrometer scale |
|-------------------------|------------------|
| **Diameter** | **Minimum ignition energy** | **Diameter** | **Minimum ignition energy** |
| Ti powder               |                  | 3 \( \mu \)m | <1 mJ  |
| 35 nm                   | <1 mJ            | 8 \( \mu \)m | 21.91 mJ |
| 75 nm                   | <1 mJ            | 20 \( \mu \)m| 18.73 mJ |
| 100 nm                  | <1 mJ            | 45 \( \mu \)m| 21.91 mJ |
| Fe powder               |                  | 150 \( \mu \)m| -----  |
| 15 nm                   | <1 mJ            | 35 \( \mu \)m| -----  |
| 65 nm                   | <1 mJ            | 65 \( \mu \)m| -----  |

The question is then why the ignition sensitivity increase (MIEs decrease) when moving from \( \mu \)m-particle dust clouds to nm-particle clouds, whereas the explosion violence \( (K_{st}) \) does not increase? The extremely high temperatures of electric sparks compared to the temperature of the dust cloud flame could be a possible reason. Particle agglomerates than may remain agglomerates in flame propagation may disintegrate into primary nm-particles when they approach the extremely hot spark channel, and a small zone of genuine nm-particles may be generated in the vicinity of the spark and facilitate ignition of the dust cloud.

Table 4 shows that Holbrow et al. [14] obtained similar results for metals, whereas for the carbon nano-tubes the MIEs were quite high. As pointed out by Wu et al. [15] an alternative MIE apparatus capable of producing synchronized electric sparks of energies below 1 mJ is required to allow determination of the actual MIEs of very ignition-sensitive powders of MIEs < 1 mJ. Work in this direction was reported by Randeberg et al. [16], but as discussed by Eckhoff and Olsen [17], the spark generator used by Randeberg et al. needs to developed further to become suitable for the intended purpose.

It must be pointed out that very low MIEs have not only been measured for clouds in air of metal dusts. According to the data published by BIA [18] a number of synthetic organic substances, and sulphur, have MIEs < 1 mJ. It is not clear, however, whether the sizes of the particles in the powders tested were in the nm or in the \( \mu \)m range.
5.2.2. Heat from friction/impact

Further evidence of the extreme ignition sensitivity exhibited by some nano-particle metal powders was presented by Wu et al. [19]. They performed a detailed study of the conveyance of various types of such powders from the pre-compressed dust dispersion reservoir of a 20 litre Siwek/Kühner-type explosion bomb into the bomb itself. The powder then had to pass through the narrow tube with a bend connecting the powder reservoir to the main explosion volume of the bomb via a valve. The purpose of the experiments was to determine the maximum air velocity in the tube at which the powders could be conveyed through the tube without the dust cloud entering the bomb being spontaneously ignited by the conveyance process itself.

Wu et al. [19] assumed that ignition was due to the impact of the dust particles on the tube wall when passing through the bend. Four different air velocities were used, viz. 13, 8.5, 6.5, and 3.5 m/s. The powders tested were 30-nm titanium, 35-nm iron and 35-nm aluminum. The minimum ignition energy (MIE) of clouds in air of the three powders, as determined by the standard Kühner MIKE3 apparatus, which has a lower spark energy limit of 1 mJ, were all below this limit. Wu et al. found that the titanium powder ignited spontaneously at all the air flow velocities used. The iron powder ignited at all velocities but the lowest (3.5 m/s), whereas the aluminum powder did not ignite even at the highest velocity.

6. Consequences for the practice

6.1. Dust explosion violence

As discussed above, theoretical considerations as well as experimental evidence from laboratory-scale experiments suggest that $K_{S3}$ of powders consisting of nm primary particles will not be any higher than for powders consisting of primary particles of µm size. This means that dust explosion venting, suppression and isolation should be just as feasible with nm primary particles as with primary particles of µm size.
6.2. Dust cloud ignition sensitivity

Experimental evidence suggests that dust clouds in air of powders consisting of nm primary particles do in fact ignite more easily than µm-particle clouds of the same materials. The question is then whether this makes any difference with regard to the precautions required to prevent dust cloud ignition in industrial plants. Two different categories of ignition sources must be considered, viz. electrical/electrostatic sparks and mechanical friction/impact.

Table 4. Minimum ignition energies of clouds of nano-particle powders in air in a modified MIKE3 test apparatus. Table 10 in [14].

| Sample number | Material          | Minimum Ignition Energy (mJ) |
|---------------|-------------------|------------------------------|
| EC/104/08     | Aluminium nanopowder | < 1 mJ                       |
| EC/011/09     | Aluminium nanopowder | < 1 mJ                       |
| EC/153/07     | Carbon nanotubes   | > 1000 mJ                    |
| EC/116/08     | Carbon nanotubes   | > 1000 mJ                    |
| EC/147/07     | Iron nanopowder    | < 1 mJ                       |
| EC/152/07     | Zinc nanopowder    | 3 – 10 mJ                    |
| EC/148/07     | Copper nanopowder  | > 1000 mJ                    |

As regards electrostatic sparks, Glor [20] suggested that the occurrence of accidental electrostatic sparks of energies << 1 mJ may not be very likely. He pointed out that small objects of capacitances of the order of 1 pF encountered in industry normally have some sharp edges or corners, which give rise to charge drain by corona discharge as soon as the voltage of the object reaches the order of 7-10 kV. Furthermore, the time constant RC for the draining of any charge on such small capacitances to earth will be very short, of the order of 1 s or less even when the resistance to earth is of the order of 10^{12} Ω (tera ohms). Hence, such small objects cannot be charged to any high voltages unless the charging times are significantly shorter than the short time constants for charge drainage to earth.

If this were to be all that could be said, the conclusion would be that accidental electrostatic spark discharges of energies below the order of 1 mJ would in fact be unlikely in the process industries. Hence, the same safety procedures could be applied to any plant producing/ handling powders/dusts of MIE < 3 mJ, irrespective of the actual MIE of the powder. However, based on the description of the phenomenon of ‘electrostatic induction’ discussed by Lüttgens and Wilson [21] it is possible to envisage at least one situation where the charging of small objects would fast enough to generate very high voltages. Consider a small metal object (tramp metal) that enters an earthed metal silo together with the powder being fed into the silo. If the powder has acquired a significant charge, the settled powder in the silo may give rise to a strong electric field. When the small falling metal object enters this field the electrons inside it may become displaced by influence/induction. If one end of the metal object approaches the earthed silo wall whilst this electron displacement exists, a spark discharge may take place. The situation is illustrated in Figure 10. Because of the very short discharge times to be expected (< 10 μs), the spark gap length will stay approximately constant during such a spark discharge. For example, an object approaching an earthed wall at 20 m/s will move only 0.2 mm during 10 μs.
Figure 10. Illustration of how a spark discharge may be generated from an electrically neutral tramp metal piece falling into a silo, because of charge displacement in the metal piece when it enters the electric field in the silo generated by electrostatically charged powder there.

Lüttgens et al. [22] presented a brief report on a dust explosion in a silo, which was assumed to be initiated by a similar type of spark discharge. The silo was part of an assembly of a number of silos, made of aluminium, and used for intermediate storage of a plastic dust. Following several years of production without any accidents, a dust explosion unexpectedly occurred during discharge of one of the silos. At the moment of the explosion only about 20% of the silo volume was filled with powder. After careful investigation, all ignition sources but an electrostatic spark discharge had been ruled out. However, a likely mechanism of generation of the electrostatic spark was not disclosed until part of the shaft of an aluminium spade was found close to the silo wall, just below the powder surface. It was concluded that excess charge accumulated on this object due to influence, was discharged as a spark when the object approached the silo wall.

So far indications of MIEs $< 1 \text{ mJ}$ of nm-particle dust clouds in air only exist for metals. Then the question arises whether bulk resistivities of heaps of such particles are sufficiently high to render spark discharge processes as illustrated in figure 10 possible. Two factors may be considered. Firstly, it would be expected that oxide layers on metal nm-particles, e.g. aluminium, will be comparatively thick in relation to the particle diameters. Secondly, poured bulk densities of bulk powders of nm-particles would be expected to be very low. The combined effect of these two factors might result in high bulk resistivities even for metal powders.

It should also be pointed out that MIEs of $< 1 \text{ mJ}$ have also, according to BIA [18], been found for a number of synthetic organic substances and sulphur. It is not clear, however, whether this is mainly due very small sizes of the primary particles, or to extreme reactivity of the particle substances.

At high voltages sparks of very low energies may not only be generated by very small charged capacitances. However, low-energy sparks may also result from discharge of larger capacitances that have been charged to only moderate voltages, say of the order of a one kV or even less. This would clearly also present an increased ignition risk with dusts of exceptionally low MIEs. With $C = 20 \text{ pF}$, and $U = 1 \text{ kV}$, the stored energy $\frac{1}{2}CU^2 = 0.01 \text{ mJ}$, which might be of the order of the MIEs of some very spark-ignition sensitive dust. Clearly, with only 1 kV across the spark gap, the gap length has to be quite short, but with dusts of MIE $< 1 \text{ mJ}$, the quenching distances are also likely to be very small.

With regard to ignition by mechanical friction/impact the findings by Wu et al. [19] indicate that careful precautions have to be taken to prevent ignition of clouds in air of some nm-particle metal powders by heat from mechanical impact of friction. However, further research to obtain more specific knowledge in this area is required and should be encouraged.
7. Conclusions

1. By extrapolating the trends exhibited by dust clouds having primary particles of sizes down to the order of 1 µm, dust clouds from combustible nm-particle powders would be expected to exhibit extreme ignition sensitivities (very low MIEs) and extreme explosion rates (very high $K_{St}$-values). However, this may not necessarily be the case for the following reasons:
   a) Formation of clouds of well-dispersed primary particles from bulk powders consisting of nm-particles is extremely difficult to achieve by dust dispersion processes normally operating in the process industries, due to the strong inter-particle cohesion forces.
   b) Should perfect dispersion nevertheless become a reality, extremely fast coagulation will transform the primary particles into much larger agglomerates within fractions of a second.
   c) For particles smaller than the order of 10 µm particle size will for most organic materials and coals particle size no longer influence the explosion violence/rate, because combustion of pyrolysis gases/volatiles becomes the rate controlling process in the flame propagation.

2. The delay between the moment of formation of a well-dispersed nm-particle dust cloud and the moment of ignition of the cloud is decisive for the extent of coagulation. In laboratory scale experiments to determine MIE and $K_{St}$, typical delays between dust cloud generation and ignition are of the order of 20-60 ms, and coagulation may still be only in its initial phase. Therefore, results from laboratory tests may overestimate the ignition sensitivity and explosion severity of real industrial clouds, if expected ignition delays in accidental explosion scenarios are significantly longer than in the laboratory test.

3. Dust cloud turbulence is an important parameter. Coagulation rates generally increase with increasing turbulence. This will enhance the increase of MIE with increasing turbulence. However, for the dust cloud combustion rate the net influence of turbulence is less clear. In the absence of coagulation, turbulence will increase the combustion rate. But with coagulation, the effective particle size in the cloud will increase, which will decrease combustion rate.

4. Laboratory-scale experiments have shown that nm-particle dust clouds of given materials do not have any larger $K_{St}$-values than clouds of dust clouds of µm-particle powders.

5. However, the MIE values of some metals are lower for dust clouds of nm primary particles than for clouds of µm primary particles. MIEs < 1 mJ have also been reported for some synthetic organic powders and sulphur, but it is not clear whether this is due to very small primary-particles sizes, or to highly reactive chemical compositions.

6. A new MIE test apparatus capable of producing synchronized electrical sparks of energies below 1 mJ is required for further clarification of this issue.

7. More research is needed before ignition sensitivities and combustion rates of all kinds of combustible nm-particle dust clouds in practical industrial accidental explosion scenarios can be reliably predicted.

8. Because $K_{St}$ of powders consisting of nm primary particles do not appear to be any higher than of powders consisting of µm of primary particles, dust explosion venting, suppression and isolation should be just as feasible with nm primary particles as with primary particles of µm size.

9. Because of the very low MIEs (< 1 mJ) of clouds of some nm-particle dust clouds in air, the possibility of ignition by subtle electrostatic spark discharges of very low energies have to be considered.

10. In addition, careful precautions have to be taken to prevent ignition of clouds of nm-particle metal powders by heat from mechanical impact and friction.

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