

Focus Article

Ashes to Ashes, Dust to Dust... and Dust to Ashes

The impact of variables on dust explosion properties



One challenging and poorly understood question is “**what should we test**”?

Combustible dust explosions continue to be the source of fatal accidents around the world. In North America, OSHA's National Emphasis Program on Combustible Dusts followed by NFPA 652 (Standard on the Fundamentals of Combustible Dust) seeks to raise awareness and seed good practices just as the ATEX Directives in Europe with the same intention but using a regulatory instrument to enforce compliance. Despite these initiatives incidents continue to occur.

The cornerstone of ensuring that a robust “safe system of work” or “basis of safety” exists for dust explosion risks is having sufficient knowledge of the characteristics of the dust on which sound procedural and engineering control / safety measures can be based. How can an explosion be avoided reliably if the ignition sensitivity of the dust is unknown?

When assessing dust explosion risks in industrial environments, one challenging and poorly understood question is “what should we test”? For liquids and gases, flammability data (at least under atmospheric pressure and normal temperature conditions) are well understood and available in the open literature for most common liquids and gases. Such data for dusts is more limited because of the major impact of particle size, moisture content and even particle morphology. The complexity is compounded often as many products are made up of a number of components, so that there is a virtually unlimited number of “materials” in existence with properties different from the individual components. Even worse is the situation that those secondary components are not always obvious in the name. For example, icing sugar may contain starch to improve the flow properties, which is not at all obvious from the name which is still “sugar”. In addition to these variables, ambient temperature and atmospheric relative humidity can also markedly alter material characteristics. In the case of dusts, the hydrophobic / hydrophilic nature of the material will dictate the effect of atmospheric humidity – and in most cases, this will dominate compared to the effect of atmospheric humidity on dust cloud explosion behaviour. This paper examines the impact of this range of material variables on the dust explosion behaviour of powders and seeks to guide those involved in dust explosion prevention and protection to ensure that they test the right materials, in the right tests, under the right conditions – and then, critically, apply the data in the right way.





Critical Parameters for Dust Explosion Characterisation

The main hazard characteristics of powders associated with dust explosion can be categorised as ignition sensitivity, explosion severity, flammable limits and electrostatic properties. Table 1 below summarises the key data within each group. Note: Not all of these data have to be collected for all products. What is critical is that the data required for the specified basis of safety is available – and obtained on the right material using the right test method.

Category	Test	Data generated/comments
Ignition sensitivity	Minimum Ignition Energy (MIE)	Minimum spark energy capable of igniting a combustible dust cloud. Two methods exist to account for the differences between electrostatic sparks and mechanical sparks.
	Minimum (Cloud) Ignition Temperature (MIT)	Minimum surface temperature capable of igniting a combustible dust cloud.
	(5 mm) Layer Ignition Temperature (LIT)	Minimum surface temperature capable of igniting a dust layer.
Explosion severity	Explosion severity analysis using 20 L or 1 m ³ sphere	The test generates data for maximum dust explosion pressure (P _{max}), dust explosion constant (K _{st}) and class (St).
Flammable limits	Limiting oxygen for combustion (LOC)	Lowest atmospheric oxygen concentration in air capable of supporting combustion of the combustible dust cloud.
	Minimum explosive concentration (MEC)	Minimum concentration of explosible dust in air capable of propagating a dust explosion. Broadly equivalent to the lower explosive limit (LEL) of a gas or vapour. Note: The maximum explosive dust concentration (upper limit of dust flammability) is not relevant nor does a method exist for its determination.
Electrostatic properties	Powder volume resistivity	Resistivity (inverse of conductivity) of the dust – related to the ability of the powder to dissipate any accumulated electrostatic charge.
	Powder charge relaxation time	Direct measurement of the rate at which any electrostatic charge is dissipated. Typically reported as the time taken for charge to decay to 1/e (37%) of an initial value.
	Powder chargeability	The propensity of the powder to accumulate electrostatic charge (measured under pneumatic transfer conditions) in air.
Thermal stability properties	Various exist, specific to the processing environment	Onset temperature of decomposition / self-reaction is an important parameter. Even if such events do not represent a hazard in themselves, they can present ignition sources for cloud ignition.

NOTE: This table presents data relevant to combustible dust explosion hazards only. A range of other safety characteristics are also highly relevant and should be assessed (such as condensed phase explosive properties, etc).

What is critical is that the **data required** for the specified basis of safety is **available**



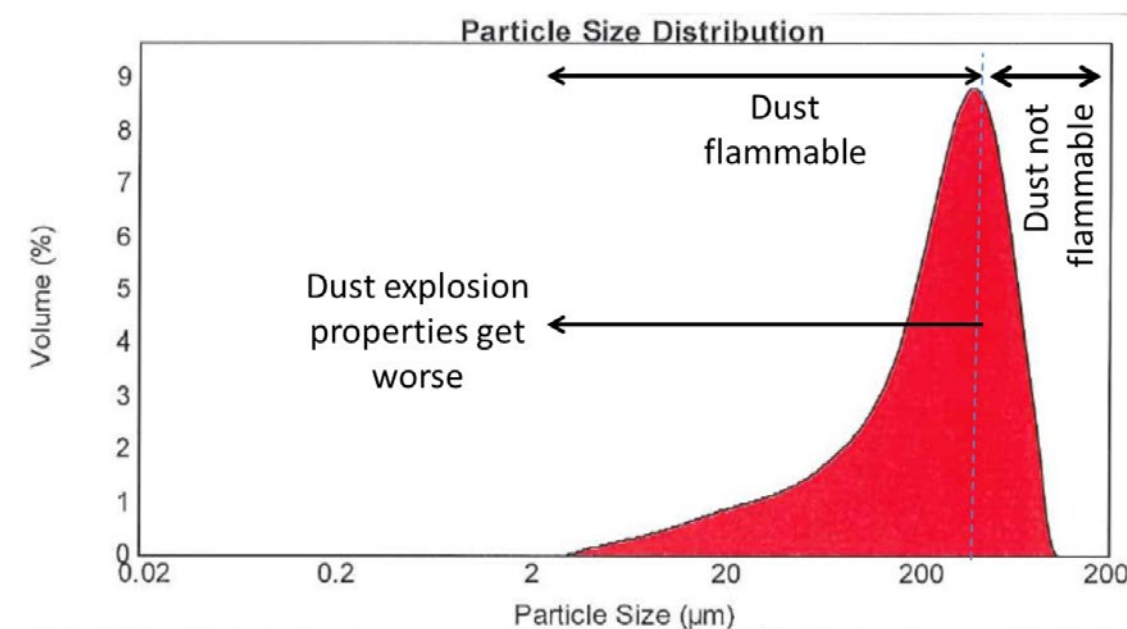
When a dust is dispersed in air, it is also inevitable that larger particles will fall by gravity faster

When experimentally determining these properties, the impact of variables can be very substantial. These variables are explored below with real data exemplifying the effect.

1. Effect of Particle Size

The particle size distribution of a powder is a critical influence on dust explosion characteristics. Although it varies for different substances, a rule of thumb (based on our experience) is that dust explosion propagation occurs with dusts below 500 micron particle size – but all powders should be screened for explosibility. As the median particle diameter reduces below this threshold, the dust explosion properties of the powder get progressively worse. Testing standards are often not highly prescriptive on the particle size to test – albeit, the IEC/EN standards often refer to < 63 micron, ASTM standards suggest 95% less than 75 micron and < 350 micron for Layer Ignition Temperature determination. However, the standards do allow latitude for recording results for larger fractions but all tend towards “finest and driest”. For any given dust handled in a plant, the particle size will normally be a distribution – there will be a finer portion and a coarser portion. Figure 1 below provides a typical particle size distribution of a sample of chocolate powder measured using a Malvern Mastersizer 2000 Laser Diffraction Particle Size Analyser.

In this case, the material has 10% of the powder < 44 micron, 50% < 290 micron and 90% < 690 micron. The median diameter of 290 micron is in the range where dust explosion properties are likely to be considerably less severe than finer fractions.



If this material were tested in the “as received” condition with this wide range of particle sizes, the coarser particles will dilute the measured properties to some extent - but is it appropriate to conduct the measurement on the “as received” powder? The answer to this question should be addressed directly with reference to the large scale environment in which the material will be processed – and where we will be applying the data.

When a dust is dispersed in air, it is also inevitable that larger particles will fall by gravity faster, often leaving a “fines-rich” cloud. So testing a representative “as received” distribution may yield non-conservative data.

The advent of nano-powder technology extends the severity range potential of powders – further increasing the surface area for propagation of the combustion process and causing further acceleration (making properties significantly worse). A common exception to this general rule is for metal powders. Specifically, for those that are prone to the formation of oxide films which are seen to significantly dampen explosion properties. Aluminium is a good example, where at submicron and nano-particle sizes, the dust explosion properties start to get less severe (after adequate exposure to oxygen). Agglomeration of very fine particles can also cause an apparent exception to the “finer is worse” rule.

Generally speaking, therefore, more severe explosion properties arise with finer particles and testing the fine fraction is not only conservative, but also realistic. Determining worst case parameters has a substantial advantage. If a plant is designed to cope with the fine fraction properties, it will cope with the “as received” properties – the reverse is most definitely not true.



The **first decision** to be made is “is there a benefit in testing “**as received**”?”

1.1 Is it ever acceptable to use data from “tested as received” materials?

For existing plant, data for the fine fraction can show that:

- existing explosion vents or other protection systems are not adequate, or
- people require earthing when this is difficult to implement in practice (although people earthing solutions can normally be found in most situations), or
- all plastics must be static dissipative, or
- inerting should be used when the site has no experience of inert gas handling or when the equipment is not suitable for maintaining inert conditions.

Upgrading explosion protection systems on existing plant can be very expensive and difficult to achieve. In these cases, an analysis of the “as received” material would be justified. It is unusual for analysis of the “as received” material to benefit electrical equipment selection e.g. T ratings based on MIT / LIT. In our experience, it is unlikely that a change in particle size will significantly alter the LIT / MIT so much that it takes the T rating above a critical threshold. Most equipment is available as standard with T ratings (120°C or less – ie. IEC T5) which cover most powders.

The first decision to be made is “is there a benefit in testing “as received”?”. If the powder is very fine to start with, then it is unlikely to make much difference. But if the powder is quite coarse e.g. granulated sugar and requires significant preparation (e.g. grinding) to get it below 63 microns, then clearly it is likely that “as received” data will be less pessimistic.

Now comes the hard part – deciding under what circumstances ‘as received’ data can be justified. The decision usually revolves around how the powder is handled and the type of equipment, and hence the likelihood of fine fractions separating from the material and remaining suspended with a sufficient concentration.

There are many variables affecting this including:-

- The actual fines content of the “as received” material.
If it is inherently low in fines, then there is less chance that suspended fines will have sufficient concentration alone
- How friable the material is.
Sugar, for example, is quite friable so even if it is low in fines at the manufacturers end, by the time it has been mechanically handled, it is likely to increase in fines content. Contrarily, plastic pellets are usually non-friable.
- The process itself.
For example, how much energy is applied and hence how likely is it that fines will be created or separated.
- How cohesive the material is.
This may make it difficult for the primary particle size to ever be ‘exposed’. However, cohesive powders are usually very fine powders anyway.
- Equipment volumes / diameters.
Large volumes such as silos provide a large diameter and hence are most likely to permit entrainment and slow settling of fines (and hence separation)
- Consistency and quality control of the supplier.
How consistent is the particle size distribution? This is a tough one as it is usually out of the processors’ control unless they sample each batch and check the distribution.
- The consistency of their process conditions, operator skills, training etc.



It is advised to **start** with **testing the fine** **fraction**

There are equipment types where “as received” data would rarely be accepted:

- A dust extraction system is the most obvious.
The standard processed powder is likely to have a substantially larger median particle diameter than the fines conveyed in to and collected in the bag / filter
- Pneumatic conveying or gravity free fall into a silo or bin is another obvious situation where fines may separate.
The larger the diameter of the silo, the more likely fines will remain airborne for longer.
- Milling and other high energy size reduction processes
- Bucket elevators and other vertical type conveyors where fines often spill over and free fall
- Fluid beds e.g. fluid bed dryers
- Spray dryers – unless there was evidence of consistent particle size control to achieve the ‘as received’ particle size and a good history of monitoring this.
- Large scale tipping such as truck tipping of powder / granules (for example this is often done in grain handling).

The types of equipment / operations where testing “as received” may be considered include:

- Batch mixing processes, particularly in small mixers and particularly where the speed is not too high. High speed = higher chance of fines entrainment, especially if there is a large ullage volume.
- Sack tipping stations – especially where fall height is low (say 1-2 m max)
- Scooping and other small scale powder transfer / dispensing operations
- Screw conveying (and other types of ‘plug flow’ type conveyors e.g. drag link, chain and disc conveyors)
- Conveying into small hoppers e.g. PTS systems, small bins – pneumatic or gravity free fall. The delineation should be more dependent on the nature of the material and shape of the bin rather than a defined critical volume.

As previously noted, it is advised to start with testing the fine fraction. Any deviation from this would / should always come with a caveat. But where the benefits outweigh the risk, then there is sometimes a case to test material of a larger particle size or “as received” provided it reflects the likely reality of the worst case plant situation. National regulatory bodies would typically always expect the finest fraction to be tested and deviation would require strong justification.



The key issue is the **size of the bin** which means if the granular material **has enough fines**, then it is possible for **separation to occur**

1.2 A "Real-life" Example

A major pharmaceutical company conveys a granular material pneumatically into a bin. The bin is Pressure Shock Resistant (PSR) to just over 8 barg but historical data on the material from the supplier indicates a maximum explosion pressure (P_{max}) of 9 barg. This is not based on test of the actual material (as received or fine fraction). Replacing the bin with a higher pressure shock resistant one, due to its size, location and downtime issues is a major undertaking and would be very expensive. After a lot of thought and considering the 7 factors above, it was agreed to test "as received" to see if there was a justification for retaining the 8 barg PSR bin (in parallel with testing the fine fraction as the legacy data was old, not wholly representative and hence even the fines of this material might have a P_{max} lower than 9 barg). Analysis of the particle size 'as received' is also being made to assess the fines quantity. If the P_{max} of the fines is > 8 barg and 'as received' < 8 barg, it would be necessary to conduct a risk / benefit type analysis. The key issue is the size of the bin which means if the granular material has enough fines, then it is possible for separation to occur. However, if the P_{max} of the fine fraction is only marginally above 8 barg, it would likely be suggested that the client retains the 8 barg vessel as the likelihood of getting that 'perfect' dispersion of just fines in the headspace, to an optimum concentration, is not impossible but almost inconceivable.





For **electrostatic properties**, the impact of residual water is **substantial** – water being generally **highly conductive**

2. Effect of Moisture Content

2.1 Solvent Damp Powders

Where powders are damp with flammable solvent the flammability properties of the solvent vapour should be used (specifically ignition sensitivity data – MIE, AIT). Explosion severity properties should be tested for the solvent damp material as the data obtained for such a hybrid mixture may be worse than for the separate solvent* or dust (typically, the worst case property should be used irrespective of whether it relates to powder, solvent or hybrid). With higher levels of moisture – and for certain types of powders – agglomeration becomes dominant (i.e. the powder particles coalesce and stick together such that the material no longer behaves as a fine powder). In such cases, there is no risk of dust cloud formation and the solvent vapour risk is the sole flammability issue. However, special care is required in adopting this approach as there may be areas of plant where material dries out and returns to its fine particle state.

2.2 Water Damp Powders

Water is an extremely effective inerting agent – so elevated moisture content will suppress dust explosion properties. There are few rules of thumb in this area – but the biggest impact of water is to inhibit formation of clouds by causing particle agglomeration (as described above). The testing standards generally propose <10% moisture content for testing. One critical aspect to consider for testing approach is “is moisture content uniform in your powder?”. Are there areas of plant with lower moisture content – do fugitive dust emissions dry out? For electrostatic properties, the impact of residual water is substantial – water being generally highly conductive. This extreme sensitivity to moisture content extends to the impact of environmental atmospheric moisture content (relative humidity). Some (hygroscopic) powders absorb atmospheric moisture which lessens the severity of electrostatic properties. Sugar is an example of such a material. Electrostatic properties can change by orders of magnitude with changing relative humidity conditions (especially if the powder has a hygroscopic nature) and there are numerous examples of explosions at low relative humidity where identical processing at higher humidity yields no such history.

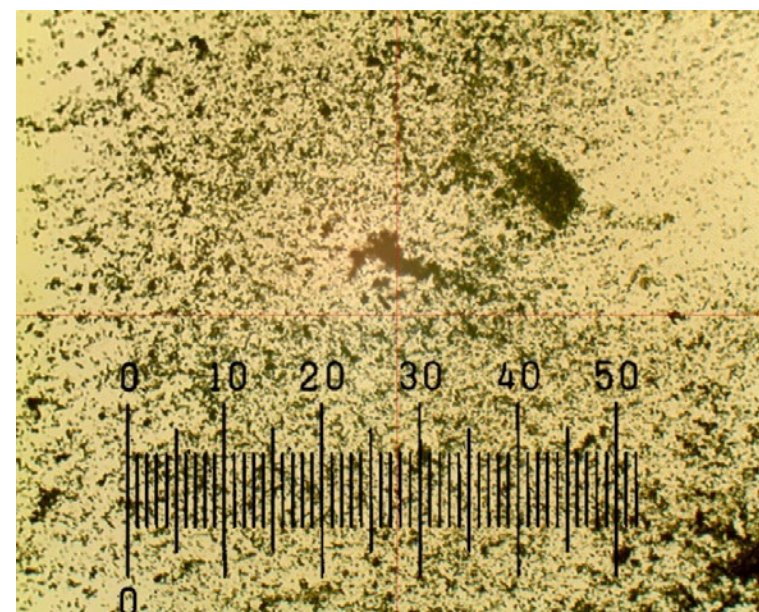
* Literature data for explosion properties of gases and vapours are typically collected under quiescent conditions. Properties can be more severe with increased turbulence.



In some cases, testing **under the specific conditions** are required to generate **reliable data** as mathematical correlations do not exist.

3. Particle shape / morphology

Even particle morphology can make a substantial difference to explosion properties. Whilst the impact is generally small for some parameters (eg. explosion severity) it can be significant on others (e.g. minimum ignition energy). A project conducted for a global pharmaceutical company perfectly illustrates this point. A process was conducted in two locations yielding a chemically-identical dust. The only difference in processing method was the crystallisation step. This led to two different particle morphology profiles - a needle particle shape and the other yielding an amorphous shape. Even though the particle size distributions were similar, the test results were startlingly different.



Particles produced in Location A



Particles produced in Location B

Variable	Location A Material	Location B Material
Particle Size (d50; μm)	32.1	19.1
Moisture content (% w/w)	1.5	1.5
MIE (mJ)	40-50	3-4

Material from plant location B required much more stringent electrostatic precautions than the relative insensitive material produced in location A – even though the materials were chemically identical and exhibited the same (residual) moisture content and broadly similar particle size distributions.

4. Environmental Variables and their Impact

Environmental temperature also alters data – more so for some properties than others. For MIE, for example, increasing temperature causes a substantial increase in sensitivity (lower MIE) and increasing initial pressure proportionally increases severity. When applying data obtained at ambient temperature, mathematical correction of data to account for environmental temperature and initial pressure changes should always be performed – if possible. In some cases, testing under the specific conditions are required to generate reliable data as mathematical correlations do not exist.



Summary

5. Summary of the Impact of Material and Environmental Variables

A summary of the impact of variables is summarised concisely in the table below:

Variable	MIE	Pmax	Kst	MEC	LOC	Powder Volume Resistivity
Decreasing Particle Size	↓	↑	↑	↓	↓	↕ (note 3)
Decreasing Moisture Content	↓	↑	↑	↓	↓	↑
Decreasing atmospheric relative humidity	↔	↔	↔	↔	↔	↑ (note 1)
Increasing temperature	↓↓ (note 2)	↓	↕	↓	↓	↕ (note 4)
Increasing pressure	↓	↑	↑	↓	↓	

Key: ↑ = increases; ↓ = decreases; ↕ = varies; ↔ = little change

Note 1: Atmospheric relative humidity has a very limited effect on most flammability parameters, but can have an indirect effect. Hygroscopic materials will tend to absorb moisture in a higher relative humidity environment and this will suppress flammability parameters. However, when processed in dry / arid environments, moisture may be desorbed hence making parameters worse.

Note 2: Temperature effect on the MIE is particularly strong, identified in the table with a double arrow.

Note 3: Particle size can affect bulk density/powder compaction which could in turn influence volume resistivity and other electrostatic parameters.

Note 4: An increase in temperature could made insulating materials more conductive and conductive materials more insulating.



What does this mean for **dust producers and handlers**?

What does this mean for dust producers and handlers?

- Always test your own powders – literature data, where it exists, will rarely replicate the particle size, moisture content and particle morphology of your powder.
- Always test the finest fraction of your dust – this will be what persists in the atmosphere following a release / transfer operation and will create the worst case dust explosion risk. Justifying exceptions are possible, but fraught with dangers.
- Always test the driest fraction of your dust – this will allow for variances and drying out of powder in areas of your facility.
- Always test different particle shapes – and recheck your data following any change in chemical, crystallisation or size reduction process.
- Under elevated temperature and pressure conditions, correct data for key parameters.

In following these steps, you are guaranteed to know the worst case characteristics of your dusts and be able to take protective / preventative measures accordingly and with confidence.

At DEKRA, we specialise in the collection of data and – at least as importantly – its appropriate application and use. Please consult our specialists to focus your efforts in dust explosion management to rationalise testing but maximise effectiveness.



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Stephen Rowe manages the activities of the UK headquarters of DEKRA Process Safety (Chilworth Technology Ltd). He has a career background in the assessment of chemical reaction hazards and the laboratory assessment of a full range of process safety hazards including dust, gas and vapour flammability and explosives characterisation. He is an experienced trainer and regular contributor to national and international process safety conferences and symposia. As a manager, Stephen Rowe focuses on building successful teams and growing the organisation in a customer-centric manner. He oversees and is actively engaged in the company's quality and safety management systems (ISO9001 and OHSAS18001).

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