GESTIS-DUST-EX

Database

Combustion and explosion characteristics of dusts

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Hauptverband der
gewerblichen
Berufsgenossenschaften

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Authors:
H. Beck, N. Glienke, C. Möhlmann
Berufsgenossenschaftliches Institut für Arbeitssicherheit - BIA (Institute for Occupational Safety of the German Federation of Institutions for Statutory Accident Insurance and Prevention)

Publisher:
Hauptverband der gewerblichen Berufsgenossenschaften — HVBG
Alte Heerstraße 111, 53757 Sankt Augustin, Germany
Tel.: + 49 - 2241 / 231 - 01
Fax: + 49 - 2241 / 231 - 1333
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Contents

1 Introduction

A prerequisite for the safe handling of solid materials with a fine particle size (e.g. powder, flour, dust) is that the properties which affect safety are known. In addition to health aspects, these include flammability and explosibility. The more comprehensive our knowledge of the combustion and explosion behaviour, the more effectively the necessary preventive and protective measures can be taken.

In collaboration with the Bergbau Versuchsstrecke – BVS (Mining Test Facility) and with the financial support of the *Hauptverband des gewerblichen Berufsgenossenschaften* (German Federation of Institutions for Statutory Accident Insurance and Prevention), a research project to determine the combustion and explosion characteristics of representative dusts was designed and carried out at the end of the 70s. The results were published in 1980 in a research report entitled "Dust explosions, combustion and explosion characteristics of dusts" [1].

Combustion and explosion characteristics were determined for over 800 dusts and dust-type products. Although not all the safety characteristics of a substance were recorded, the data in the tables constituted a useful basis for practical work safety, and was welcomed especially by safety experts and supervisory authorities.

The loose-leaf compilation of the BIA Manual took into account the frequently expressed desire for the publication of further characteristics. Apart from data from the Mining Test Facility – BVS and the *Berufsgenossenschaftliches Institut für Arbeitssicherheit* – BIA (BG Institute for Occupational Safety), data from the Berufsgenossenschaft Nahrungsmittel und Gaststätten (Institution for Statutory Accident Insurance and Prevention in the Foodstuff Industry and Catering Trade) – BGN -was also included so that the second edition of the tables contained explosion characteristics of almost 1900 dusts. Two additional tables containing data on minimum ignition energies and limiting oxygen concentrations were new [2].

Within the framework of a project sponsored by the Commission of the European Community, further data records with characteristics determined by various testing stations were included on a large scale in the table. The table now contains data records from approximately 4300 dust samples and is now available in a database format also.

The testing stations involved in the EU project with data records are:

- Berufsgenossenschaftliches Institut für Arbeitssicherheit – BIA (BG Institute for Occupational Safety), Sankt Augustin, Germany

- Berufsgenossenschaft Nahrungsmittel und Gaststätten – BGN (Institution for Statutory Accident Insurance and Prevention in the Foodstuff Industry and Catering Trade)/Forschungsgesellschaft für angewandte Systemsicherheit und Arbeitsmedizin e.V. – FSA (Research Association for Applied System Safety and Occupational Medicine) Mannheim, Germany

- CHEMSAFE – Database for assessed characteristics in safety technology, German Society for Chemical Apparatus, Chemical Engineering and Biotechnology e.V. – DECHEMA, Frankfurt/Main, Germany; Federal Institute for Materials Research and Testing – BAM, Berlin, Germany/Federal Institute of Physics and Metrology – PTB, Brunswick, Germany

- DMT-Gesellschaft für Forschung und Prüfung mbH (association for research and testing), expert body for surface fire and explosion protection - mining test facility, Dortmund, Germany

- Henkel KGaA, TTA-Safety Technology, Düsseldorf, Germany

The test methods upon which the characteristics listed in the tables are based are described in various national and international standards [3 to 6]. The most important basis for this table is the VDI 2263-1 [3]. As far as possible, the terms correspond to the definitions of the EN 1127-1 [7].

2 Definitions/characteristics

Cubic law

Volume-dependence of the maximum rate of explosion pressure rise

$(dp/dt)_{max.} \cdot V^{1/3} = \text{const} = K_{St}$.

Dust

Finely divided solid substance of any shape, structure and density below a particle size of about 500 µm.

Dust/air mixture

Dust whirled up in air (dust cloud). The dust concentration is the characteristic quantity.

Dust explosion classes

Categories, into which dusts are classified on the basis of their K_{St} values.

Dust explosion class	K_{St} in bar · m · s^{-1}
St 1	>0 to 200
St 2	>200 to 300
St 3	>300

Explosion

Abrupt oxidation reaction producing an increase in temperature, pressure, or in both simultaneously.

K_{St} value

Parameter specific to dust and test method, which is calculated according to the cubic law. It is numerically equal to the value for the maximum rate of explosion pressure rise in the 1 m^3 vessel under the test conditions specified in VDI Guidelines 3673, Part 1 and 2263, Part 1 as well ISO 6184/1.

Limiting oxygen concentration *LOC*

The maximum oxygen concentration in a dust/air/inert gas mixture, at which an explosion does not occur, under specified test conditions.

Lower explosion limit *LEL*

Lower limit of the range of the concentration of dust in air, at which the dust/air mixture can be caused to explode.

Maximum explosion (over)pressure p_{max}

The maximum pressure value occurring during the explosion of a dust/air mixture of optimum concentration in a closed vessel under specified test conditions.

Maximum rate of explosion pressure rise $(dp/dt)_{max}$

Maximum value of the pressure rise per unit time in a closed vessel occurring during the explosion of a dust/air mixture of optimum concentration under specified test conditions (see also "Cubic law").

Median value *MV*

Value for the mean particle size (50 % in weight of the dust is coarser and 50 % in weight is finer than the median value).

Minimum ignition energy *MIE or* E_{min}

Lowest electrical energy stored in a capacitor, which upon discharge is sufficient to ignite the most ignitable mixture of dust and air, under specified test conditions.

Minimum ignition temperature of a dust cloud (ignition temperature) *IT*

Lowest temperature of a hot surface at which the most flammable mixture of dust and air ignites under specified test conditions.

Minimum ignition temperature of a dust layer of 5 mm thickness (glowing temperature) *GT*

Lowest temperature of a hot surface on which ignition occurs in a 5 mm thick layer of dust under specified test conditions.

3 Preventive and protective measures and characteristics to be noted

According to the explosion prevention and protection guidelines (EX-RL), VDI 2263 [8,3] and the new European regulations [7, 9, 10] a distinction is made between two types of measures:

- preventive explosion measures (avoidance of explosions)
- protective explosion measures (avoidance of the dangerous impact of explosions by constructional protective measures).

The aim of the preventive explosion protection measures is to prevent the occurrence of explosions by eliminating or avoiding the conditions for explosions. If this aim cannot be fulfilled or can only be fulfilled with considerable effort, comparable safety can be achieved by limiting the effects of an unavoidable explosion to an acceptable extent.

Knowledge of the combustion and explosion characteristics of the dusts to be handled is required for appropriate selection and dimensioning of preventive and protective measures (see Table 1).

Preventive / Protective measure	**Pertinent characteristics**
Prevention of combustible dusts	Combustibility, explosibility
Limiting concentration	Explosion limits
Inerting	Limiting oxygen concentration
Prevention of ignition sources	Minimum ignition energy, ignition temperature, glowing temperature, auto-ignition behaviour, exothermic decomposition, electrostatic behaviour, impact sensitivity, smouldering point
Explosion-resistant design	Maximum explosion overpressure
Explosion relief	K_{St}-value, maximum explosion overpressure
Explosion suppression	K_{St}-value, maximum explosion overpressure

Table 1: Correlation of preventive/protective measures with safety characteristics

Advice on the implementation of preventive and protective measures is included in the guidelines and publications listed in the references. Of particular interest here are VDI 2263 [3] and EN 1127-1 [7].

4 Test framework

A comprehensive knowledge of the combustion and explosion behaviour of the substances concerned is necessary to be able to evaluate the safety of plants and processes. Firstly, the chemical composition of the substances must be known. If oxidisability of a substance can be precluded, tests can be dispensed with. It can then be designated non-flammable and non-explosive.

If oxidisability is likely or cannot be precluded, the characteristics must be determined by means of experiments. It is not yet possible to calculate these characteristics from basic data, on combustion heat, for example. Fig. 1 shows a tried and tested framework for testing combustion and explosion behaviour [3, 7, 8, 11, 12, 14, 18, 24].

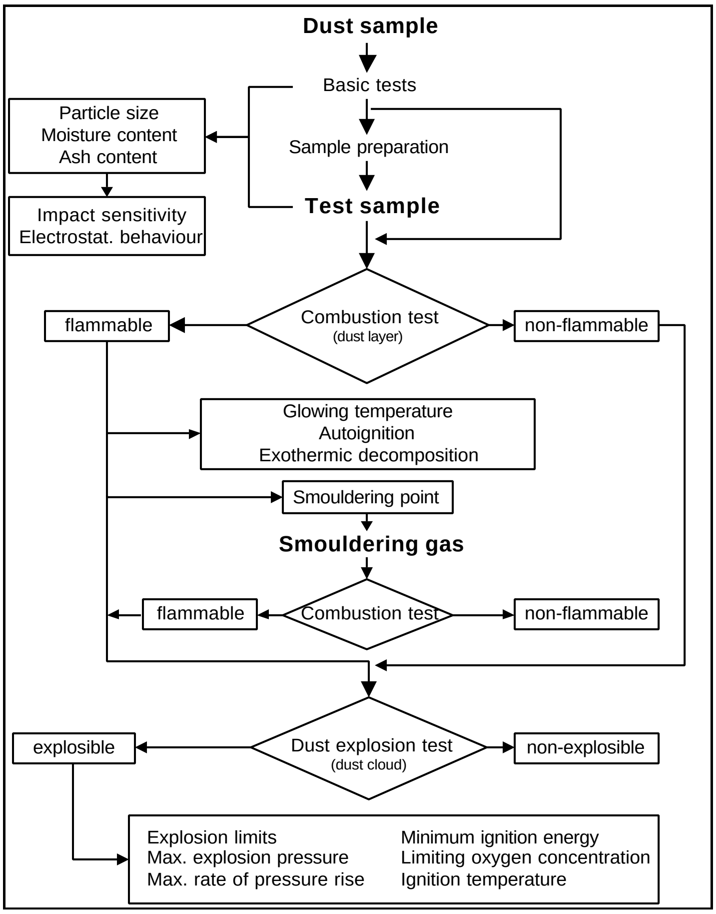

Fig. 1: Flow diagram for investigation of the combustion and explosion behaviour of dusts

The characteristics should initially be determined for fine dusts to find out the most critical conditions to be expected in practice. This is especially important if the degree of fineness changes or the number of fine particles increases during a process (e.g. by grinding, abrasion, exhaustion or sedimentation). The tests on deposited dust are generally conducted with the fraction < 250 µm and those on whirled-up dust with the fraction < 63 µm. It might be necessary to prepare the test sample by suitable treatment.

To solve certain problems, however, it might also be useful to test the dust without special treatment, in other words in its "operational condition".

5 Test methods

The characteristics listed in the tables have been determined according to the methods briefly described below.

Particle size distribution, median value

The particle size distribution of a dust is always determined by a screen analysis. To this effect, the dust to be tested is sieved onto standard test screens and the screen residue is weighed. If the residue in weight per cent is plotted over the particle diameter in the RRSB grid, a distribution curve occurs, indicating the median value of the tested dust. The median value can be used to roughly characterise the fineness of the dust sample. If a screen analysis cannot be carried out, wet or sifting methods are used to determine particle size distribution.

Moisture content

The moisture content of the substance to be tested is measured as the difference between the weight of wet dust and the weight of dried dust. This is determined by carefully drying the dust until a constant weight is achieved.

Lower explosion limit

The lower explosion limit is determined by the explosion tests described below to determine p_{max} and K_{St}. It can also be estimated approximately on the basis of the tests in the modified Hartmann tube.

Maximum explosion pressure, maximum rate of explosion pressure rise, K_{St} value

Reliable values for these explosion characteristics of dusts are obtained if a sphere-shaped vessel with a volume ≥ 20 l is used. The values in the tables are based on tests in the 1 m^3 vessel and/or 20 l sphere.

In the **1 m^3 vessel** (Fig. 2), the dust to be tested is poured into a 5 l dust container located outside the explosion vessel. The dust is usually blown into the explosion vessel via a semicircular perforated 3/4" pipe running along the inside wall of the vessel. The diameter of the 20 or 13 holes in the pipe wall is 5 mm or 6 mm respectively. Compressed air under an overpressure of 20 bar in the dust container ensures sufficiently quick discharge of the dust and a right turbulence inside the explosion vessel after a blasting cap or electro-pneumatically activated valve is opened, so that an adequately homogeneous dust/air mixture with a defined concentration is present in the explosion vessel at the ignition time. The ignition delay time, i.e. the time between the start of dust injection and triggering of the ignition source, is an arbitrary quantity for the degree of turbulence at the moment of ignition.

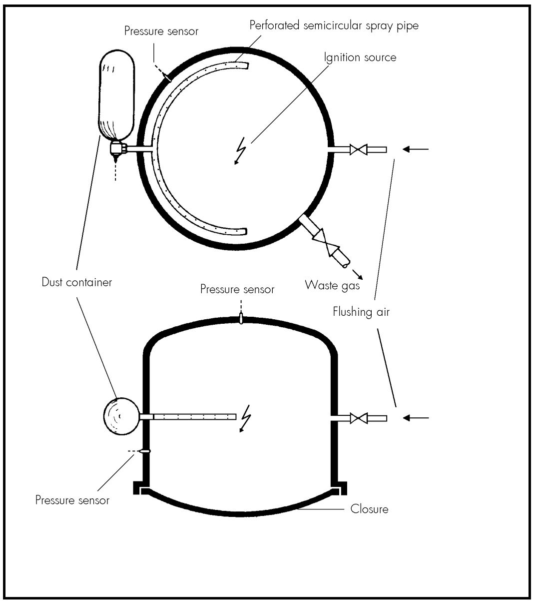

Fig. 2: Test apparatus for the determination of the explosion behaviour of dusts ($1 m^3$ vessel, schematic)

Turbulence is necessary, on the one hand, to keep the dust in suspension, on the other, it affects the course of the explosion. With diminishing ignition delay time the turbulence increases and the values for the maximum rate of explosion pressure rise and the maximum explosion pressure increase. The latter approaches a maximum value, which is achieved when the dust to be tested has just been fully discharged from the dust container. The associated ignition delay time is 0.6 s (Fig. 3). Shortening of the ignition delay time to values below 0.6 s results in an increase in the rate of explosion pressure rise. All tests are based on an ignition delay time of 0.6 s.

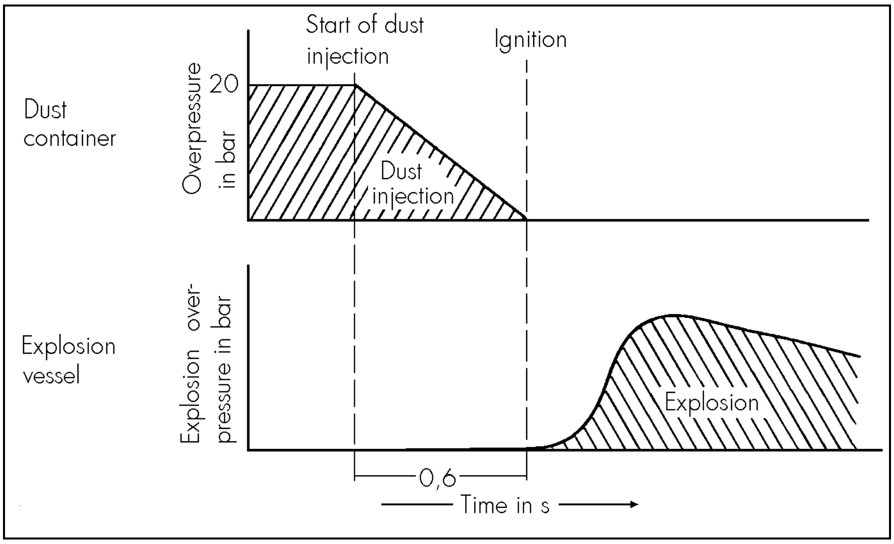

Fig. 3: Course of the explosion at the tests of dusts in the $1 m^3$ vessel (schematic)

The dust/air mixture is ignited in the centre of the explosion vessel. Two chemical igniters with a total energy of 10 000 J are always used as ignition source. The course of the explosion is recorded time resolved via pressure sensors inserted in the vessel wall. In the course of a series of tests, the dust concentrations are varied, and the explosion pressure and the rate of explosion pressure rise of the reaction is determined. Starting with a dust concentration of 500 g m^{-3} in each case, the concentration is increased gradually by 250 g m^{-3} and, if necessary, reduced by halving the concentration until the maximum values for the pressure and the rate of pressure rise are clearly ascertained.

The concentration, at which ignition of the dust/air mixture no longer occurs is determined by further reduction of the dust concentration according to the same method.

By reducing the dust concentration stepwise in the same way, the concentration is determined at which no ignition of the dust/air mixture occurs at least three times. If this result is the same when using an ignition delay time of 0.3 s this dust concentration will be called the lower explosion limit of the tested dust.

In the case of the **20 l sphere**, the test method and the construction of the equipment are basically the same as for the 1 m^3 vessel. They are specified in such a way that values comparable to those in the 1 m^3 vessel are obtained within the measuring accuracy limits.

Apart from vessel size, the most important differences are that partial evacuation must be undertaken before the actual test (to achieve atmospheric pressure in the explosion vessel after the dust is blown in), and that the ignition delay time is only 0.06 s. A further difference is that the investigations over the wide concentration range are conducted in three series and the maximum explosion pressure and maximum rate of explosion pressure rise are calculated by forming the mean value of the maximum values of each series.

With the aid of the "cubic law"

$$(\mathrm{d}p/\mathrm{d}t)_{max.} \cdot V^{1/3} = \mathrm{const} = K_{St}$$

the maximum rate of explosion pressure rise is converted to the K_{St} value which is independent of the volume. As it is the case in the 1 m^3 vessel, two chemical igniters with a total energy of 10 000 J are used as ignition source [3, 4, 5, 16].

Dust explosibility/dust explosion class

Dust explosibility exists if a flame spreads after ignition in a dust/air mixture, causing a pressure increase in a closed vessel. Explosibility is preferably determined in closed apparatuses according to the described methods. While the same ignition source is used in the 1 m^3 vessel as in the test to determine the characteristics p_{max} and K_{St} (E = 10 kJ), the ignition energy to determine dust explosibility in the 20 l sphere is only 1 kJ to 2 kJ [3].

If the described method produces no pressure build-up ($\Delta p < 0.5$ bar above the initial process-related pressure), the dust in the tested form (composition, particle size, moisture content) is regarded as **non-dust explosible**. If a pressure value of ≥ 0.5 bar above the initial process-related pressure occurs, the dust is regarded as in mixture with air explosible (**dust explosible**).

The **modified Hartmann tube** can also indicate to a certain extent explosibility and dust explosion class. The modified Hartmann tube (Fig. 4) consists of a vertically arranged glass tube with a volume of about 1.2 l, which is closed at the top by a hinged lid. The dust to be tested is placed on the bottom of the apparatus and distributed by a defined air blast guided via a mushroom-shaped atomiser from a preceding compressed-air reservoir (V = 50 ml, p = 8 bar).

The dust quantity introduced is varied over a wide range in each of three test series. A continuous spark gap serves as ignition source. In the event of non-ignition, the test is repeated with a stronger ignition source in the form of a glowing coil [17].

Depending on the reaction of the dust/air mixture, the lid is opened to a varying extent and the opening angle displayed digitally in three stages via inductive transmitters. The maximum reactions are evaluated according to the following method:

- Indication "0" (without visually perceptible independent flame propagation) merely means that no ignition occurs under these test conditions. However, classification of the dust particle as non-dust explosible is not justified. More extensive tests in closed vessels are necessary.

- "1" indicates that the dust in the mixture with air is explosible and should be classified in the **dust explosion class St 1**. Visually perceptible independent flame propagation, even without deflection of the hinged lid, is equal to "1".

- "2" also indicates that dust explosibility is present, but does not permit classification in a dust explosion class. More extensive tests in closed equipment are required.

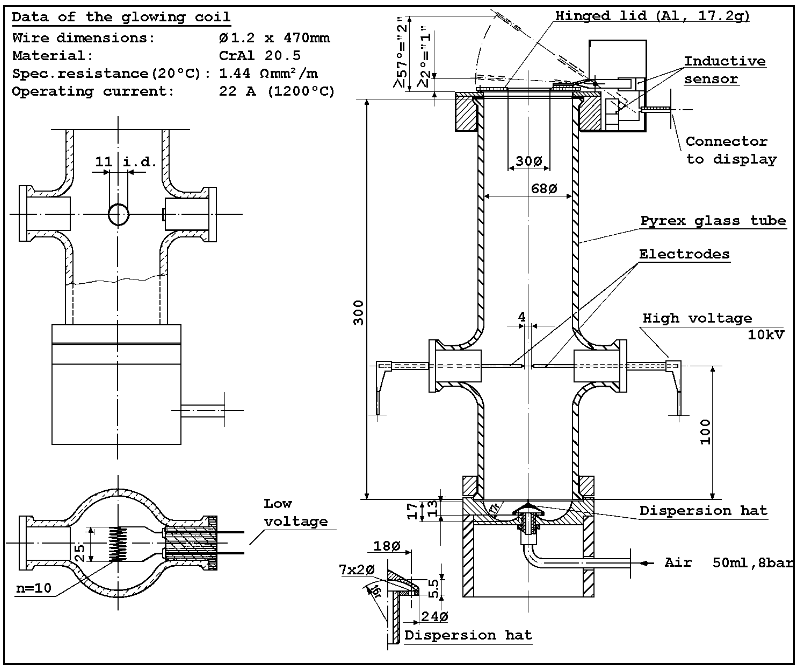

Fig. 4: Modified Hartmann tube (schematic; left: application with glowing coil, right: application with induction spark)

Limiting oxygen concentration

For the determination of the limiting oxygen concentration the same apparatus and procedures are used as for the dust explosibility. Starting with the optimum dust concentration in air the oxygen concentration will be reduced by steps of 1 % V/V admixing inert gas until the mixture can not be ignited. The decrease of the optimum dust concentration when decreasing the oxygen concentration has to be taken into account. The quoted values of the limiting oxygen concentration are based on nitrogen as inert gas. Generally, the values will be higher for other inert gases [3].

Minimum ignition energy

The lowest value of capacitively stored electric energy, which is just adequate to ignite the most flammable mixture of dust and air at atmospheric pressure and room temperature during the discharge prolonged by an inductance in the discharge circuit via a spark gap, is referred to as the minimum ignition energy of a combustible dust in mixture with air.

The minimum ignition energy can be determined as well in the modified Hartmann tube as in the 20 l sphere or in the 1 m^3 vessel with use of a suitable capacitor discharge device [15,19].

The results are usually indicated as a pair of varieties in the logarithmic graduation. The lower value refers to the energy which caused no reaction according to the specified process. The higher value refers to the lowest used energy which led to ignition.

Minimum ignition temperature of a dust-cloud (ignition temperature)

To determine the ignition temperature according to **Godbert-Greenwald** [Fig. 5] a small quantity of dust (0.1 g to 3.5 g) is blown down into an electrically heated, vertically arranged tube 36 mm in diameter and 400 mm long by means of a variable air blast ($V = 50\ \text{cm}^3$ to $300\ \text{cm}^3$, $p = 1.1$ bar to 1.6 bar).

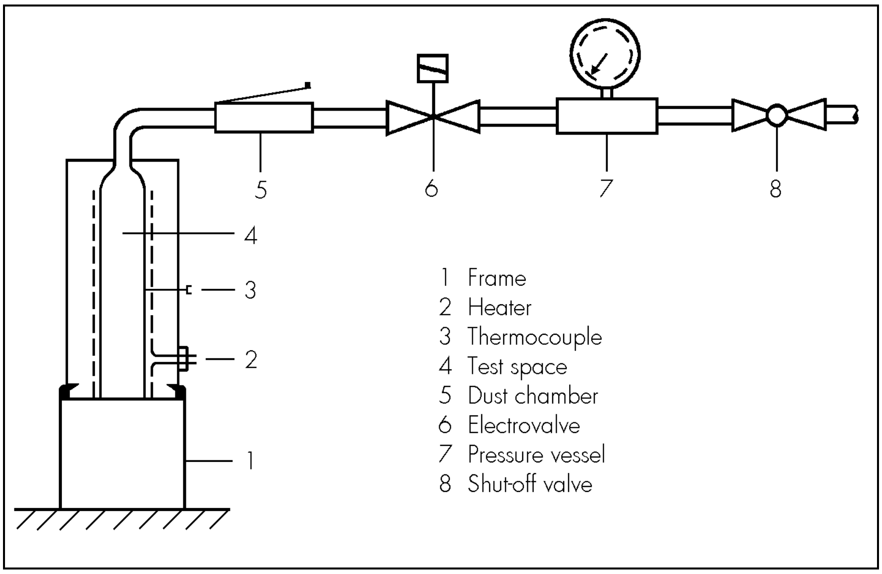

Fig. 5: Godbert-Greenwald equipment (schematic)

In the so-called **BAM-oven**, the dust to be tested is blown against a vertical impact surface, the hottest point inside the horizontal oven. The concentration of the dust/air mixture is varied within certain limits through the input of different quantities of dust and the lowest temperature, at which ignition occurs, is determined.
The aim of these tests is therefore to determine the ignition behaviour of a dust cloud in transient contact with a hot surface in a closed temperature field. The lowest temperature at which the dust/air mixture tested in the described equipment burns with a closed flame, is referred to as the ignition temperature.

In the case of sedimentation of the dust caused by the horizontal arrangement of the BAM-oven, smouldering gases may arise, so that the values determined in this equipment may be lower than those determined with the Godbert-Greenwald equipment [3, 13, 18, 20].

Minimum ignition temperature of a dust layer of 5 mm thickness (glowing temperature)

The glowing temperature is determined on an electrically heated plate 185 mm in diameter, the temperature of which is controlled with an accuracy of ± 2 °C by thermostats. The sample is spread in a circular shape (100 mm diameter) in a 5 mm thick layer in the centre of the preheated plate and the reaction behaviour observed - sometimes with the aid of a sensitive thermocouple. Signs of glowing phenomena are made clearer, if necessary, by careful fanning. The lowest plate temperature, at which parts of the sample glow within two hours after application, is referred to as glowing temperature [3, 6, 13, 18].

Combustion test

These test checks whether and to what extent a fire started by external ignition can spread in deposited dust. An attempt is made to ignite the dust sample heaped to form a strip of product about 2 cm wide and 4 cm long at one end with a glowing platinum wire with a temperature of about 1000 °C. The wire is immersed only briefly in the dust sample, so that the latter is not heated. A 5 mm to 20 mm thick ceramic plate is used as a base. In the case of melting substances, a modified combustion test is also carried out on a sample to which 20 % in weight kieselgur has been added. The result frequently indicates obvious combustion behaviour. The flammability is evaluated by the class numbers BZ 1 to BZ 6 according to the following classification:

Does not catch fire	BZ 1
Catches fire briefly and extinguishes rapidly	BZ 2
Local burning or glowing without spread	BZ 3
Spread of a glowing fire	BZ 4
Spread of an open fire	BZ 5
Very rapid combustion	BZ 6

6 Effect of different parameters on the explosion behaviour

As already mentioned, various parameters may affect the explosion behaviour of dusts. These include, in particular, the fineness and water content of the solid material, the presence of solvent vapours, combustible or smouldering gases and the oxygen content in the mixture.

Fineness

The explosion behaviour of dusts depends to a large extent on the particle size distribution. Hence, the latter must be specified at the same time as values for the explosion characteristics. Often only the median value is mentioned as a guide. The dependence of the maximum explosion overpressure and maximum rate of explosion pressure rise on the median values is plotted for different dusts in Fig. 6.

It is evident that with diminishing particle size the tendency of the dusts to explode increases. Finer dusts ignite more easily and react more violently than coarser ones. The increase in the proportion of coarse particles in the dust sample, e.g. by admixing granulate not explosible by itself to explosible fine dust, leads only to a dampening of the explosion and thus to reduced values of the characteristics p_{max} and K_{St} or to higher values, for example, for the minimum ignition energy or the limiting oxygen concentration. As long as the fine dust proportion in the mixture with air is above the lower explosion limit, in general a dust explosion is possible. In this connection it should be noted that abrasion of coarse dust, caused by a variety of reasons in practice, may produce fine dust.

Water content

Basically, the values for the explosion characteristics diminish as water content increases. This effect plays hardly any role up to a water content of about 10 % in weight. Only the raisability of the materials can be reduced. Clear reduction of the explosion characteristics p_{max} and K_{st} occurs only above 20 % in weight to 30 % in weight water content (Fig. 7).

Combustible gases and vapours

The explosion behaviour of dusts may be affected and increased by the addition of combustible gases, smouldering gases or solvent vapours. Such combinations of combustibles are referred to as **hybrid mixtures**. In the case of hybrid mixtures, the maximum rate of explosion pressure rise in particular becomes higher (Fig. 8) and the minimum ignition energy lower than in pure dust/air mixtures. Hybrid mixtures may even be explosible if the concentrations of the gases, vapours or dusts are individually below their lower explosion limit.

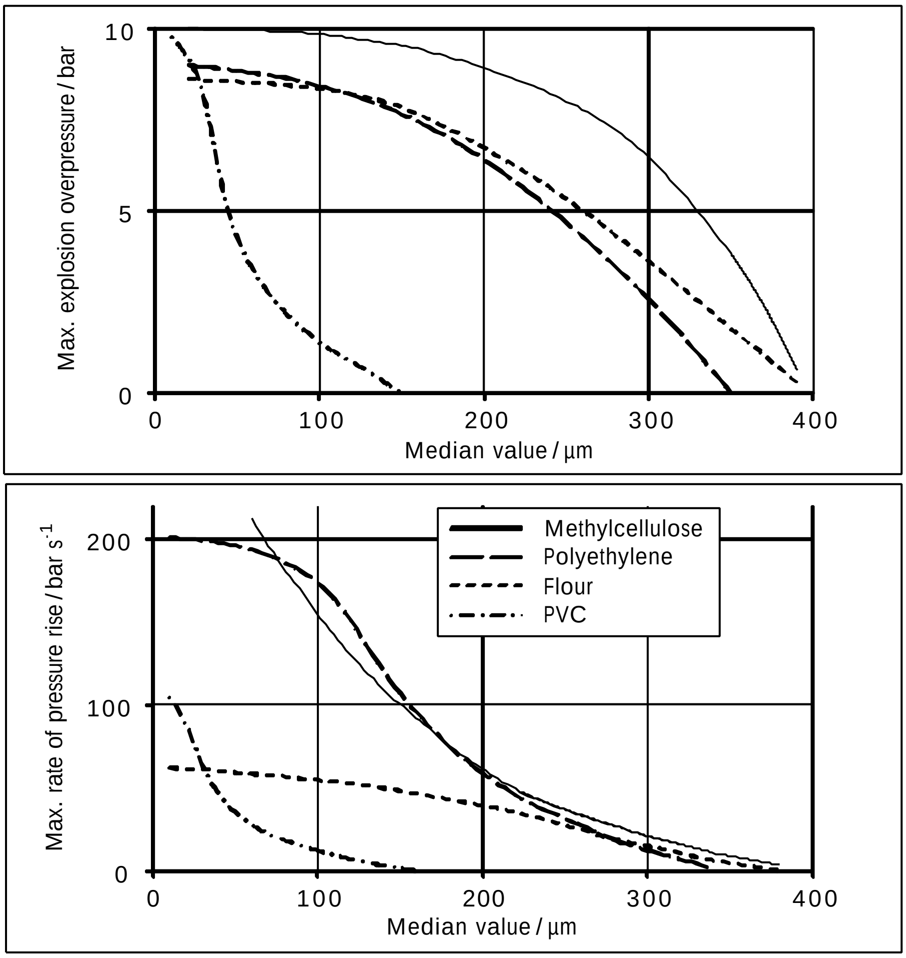

Fig. 6: Effect of the median value on the explosion behaviour (*V* = 1m³, *E* = 10 000 J)

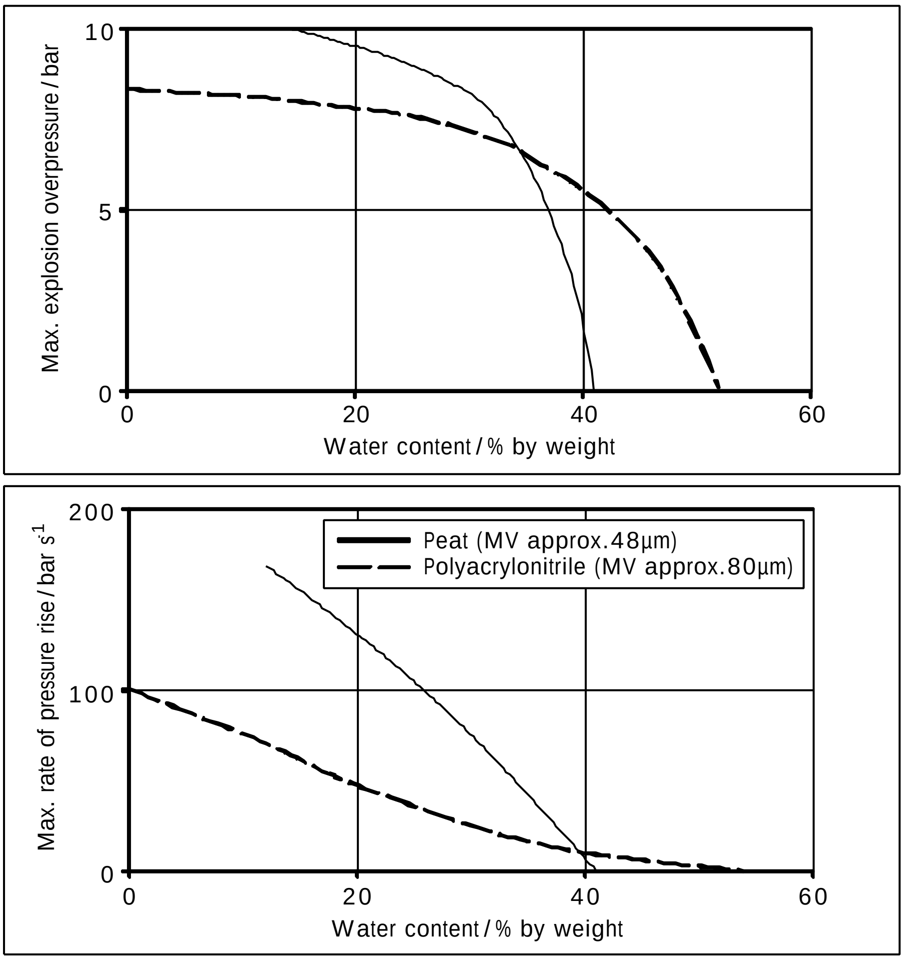

Fig. 7: Effect of the water content on the explosion behaviour ($V = 1 m^3$, $E = 10\ 000$ J)

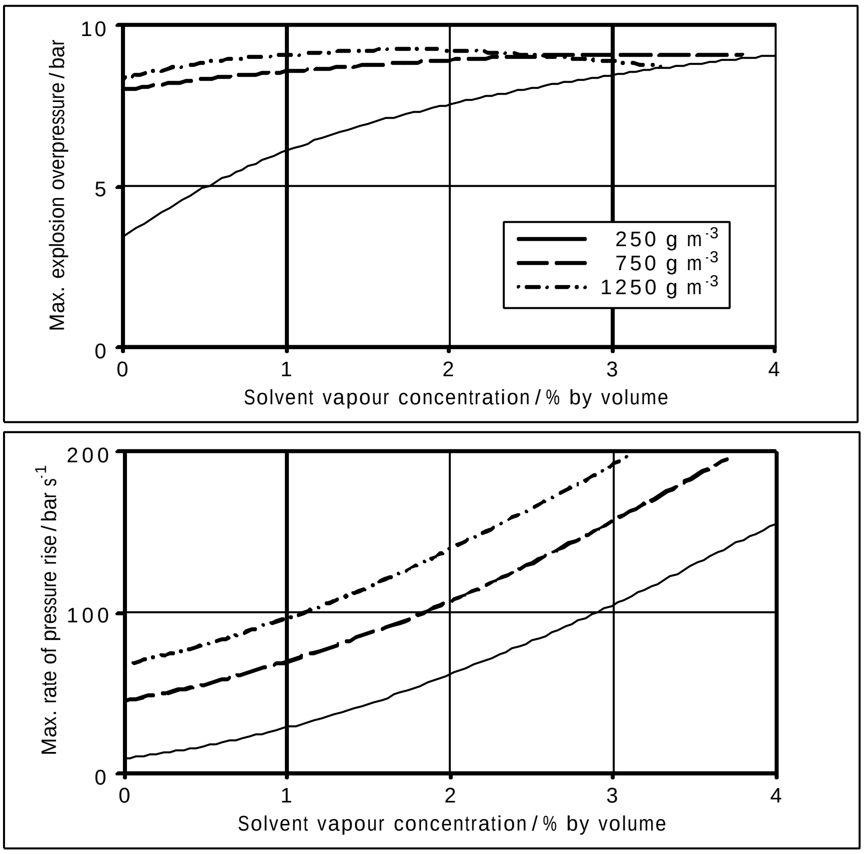

Fig. 8: Effect of the solvent vapour concentration on the explosion behaviour of a pharmaceutical substance with different concentrations ($V = 1 m^3$, $E = 10\ 000$ J)

Oxygen concentration

Reduction of the oxygen content of a combustion atmosphere, e.g. through the addition of inert gas, reduces the force of an explosion. If the limiting oxygen concentration is not achieved, it is no longer possible to initiate an explosion [21 to 25].

Content of non-combustible solids

The admixing of non-combustible (inert) solids to a dust/air mixture reduces the explosion severity and is a type of inerting. The proportions of inert substances in the entire mixture of fuel and inert substance, in which it is no longer possible to initiate ignition by customary test methods, are specified in Table 2 on the basis of some examples.

Fuel	Median value	Inert solid material	Median value	Proportion in the total weight
	µm		µm	% by weight
Methyl cellulose	70	Calcium sulphate ($CaSO_4$)	< 15	70
Organic pigment	< 10	Ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	29	65
Bituminous coal	20	Calcium carbonate ($CaCO_3$)	14	65
Bituminous coal	20	Sodium hydrogen carbonate ($NaHCO_3$)	35	65
sugar	30	Sodium hydrogen carbonate ($NaHCO_3$)	35	50

Table 2: Inerting of combustible dusts by admixing inert solid materials ($V = 1 m^3$, $E = 10\ 000$ J)

7 Limits of applicability

There are **limits of applicability** of the combustion and explosion characteristics specified in these tables. They are based on the wide variation possibilities in the nature of the dusts (e.g. composition, particle size distribution, surface structure, moisture content), on the one hand, and on the dependence of the numerical value of the characteristics on the test methods, on the other. Hence, the user must always be aware that the tabulated values can only serve as a guideline for the design of preventive and protective measures.

Above all, the tables should indicate which substances have already been tested, whether the substances are dust-explosible and on what scale the most important data can be expected. They frequently illustrate the problem involved with combustible dusts, i.e. that very different values can occur for what appear to be the same dusts. This highlights the need to test the dust to be handled whenever it is unclear if certain important influencing factors, such as composition, fineness and moisture content, coincide completely with the existing conditions in the case to be assessed.

This applies also concerning the fact that despite careful compilation mistakes can not be excluded at this large extent of data.

In some cases where numerous data are available, however, it might be legitimate to "play safe" in that the assessment is based on the most critical values.

The characteristics listed in the tables are comparable both with each other and also with other characteristics determined by the same methods. They are not comparable, however, with values determined by other methods.

It should be noted that higher values for the maximum explosion pressure and the maximum rate of explosion pressure rise or the K_{St} value as well as lower values for the lower explosion limit, for the ignition temperature and for the minimum ignition energy may occur with diminishing particle size and moisture; hence the numerical values of the explosion characteristics vary towards the "more hazardous" side (cf. Section 6, Effect of different parameters on explosion behaviour).

The characteristics in the tables apply to the following conditions in the operating plants:

Pressure	from 0.9 bar to 1.1 bar
Oxygen	approx. 21 % V/V
Temperature	from 0 °C to 30 °C

If conditions other than these so-called "atmospheric conditions" exist in practice, special considerations should be made and, if necessary, the characteristics determined under the boundary conditions existing in the factory. Increased pressure, oxygen content and temperature also point to a more critical combustion and explosion behaviour.

The tabulated values do not apply if the simultaneous presence of combustible dust and gases, vapours or mists (hybrid mixtures) can be anticipated (cf. Section 6, combustible gases and vapours).

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