



Determination of parameters used to prevent ignition of stored materials and to protect against explosions in food industries

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ABSTRACT

There are always risks associated with silos when the stored material has been characterized as prone to self-ignition or explosion. Further research focused on the characterization of agricultural materials stored in silos is needed due to the lack of data found in the literature. The aim of this study was to determine the ignitability and explosive parameters of several agricultural products commonly stored in silos in order to assess the risk of ignition and dust explosion. Minimum Ignition Temperature, with dust forming a cloud and deposited in a layer, Lower Explosive Limit, Minimum Ignition Energy, Maximum Explosion Pressure and Maximum Explosion Pressure Rise were determined for seven agricultural materials: icing sugar, maize, wheat and barley grain dust, alfalfa, bread-making wheat and soybean dust. Following characterization, these were found to be prone to producing self-ignition when stored in silos under certain conditions.

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1. Introduction

It is well-known that preservation problems frequently arise during storage and handling of agricultural products, which usually present variations in temperature, moisture content, etc. However, of even greater concern is the fact that inappropriate storage and handling of the stored material may result in fires and explosions, possibly causing injuries to employees, sometimes loss of lives and also considerable economic loss together with environmental damage.

Agricultural products are combustible and thus any source of ignition (sparks, flames or warm materials) is enough to trigger a fire. Sometimes, biological attacks are responsible for the fires; insect attacks, fungi [1] or bacteria [2] can contribute to self-ignition of the agricultural material or spontaneous combustion [3].

There are always fine dust particles attached to agricultural products. Some industrial processes contribute to detaching these fine particles and, as a result, dangerous clouds of dust are produced, varying environmental conditions [4]. It is at this point that hyperbaric processes can develop, increasing the risk of explosion [5].

Although the danger of fires and explosions arising from combustible materials would seem to be less obvious than the danger presented by liquids and flammable gases, the potential risks are well-known. Proof of this is the fact that fires and explosions still occur, [6] and that research into prevention and protection has been on-going since the 18th Century [7–9].

Determining properties such as those related to the ease with which stored materials ignite, or to explosion consequences, is the key to avoiding many accidents. The acquisition of knowledge about the direct or indirect causes influencing these processes is essential nowadays for the processing industries.

Characterization of the materials handled by the industry is of crucial importance because the results obtained by other researchers in other research centres are not physical constants [10].

1.1. Data from previous research

The parameters shown in Table 1 were determined using the results obtained in previous research carried out in Lérida [11], which focused on the characterization of products stored by the food industries.

1.2. Need for data on ignition and explosive parameters of stored materials

Risk assessment in food industries can be carried out by determining the flammability and explosibility parameters of materials

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Table 1
Ignitability and explosibility parameters for some agricultural products.

Material	MIT-I (°C)	MIT-c (°C)	LEL (g/m ³)	MIE (mJ)	P _{max} (bar)	K _{max} (bar m/s)
Sunflower flour	–	480	125	–	660	24
Maize gluten	340	470	100	6300	670	28
Soy grass	–	510	–	–	520	8
Colza	–	460	150	2000	670	39
Dressing of wheat	290	440	30	1000	720	71
Mix of flour and bran	–	420	100	1800	680	40
Mix accumulated in silos	290	490	90	450	710	61
Mix accumulated in reception	290	440	25	120	780	102
Poultry feed	–	420	215	–	580	16

(temperature, concentration and Minimum Ignition Energy (MIE); Maximum Explosion Pressure and Maximum Explosion Pressure Rise).

Some researchers have been working in this field for many years [12,13]. It is therefore possible nowadays to locate some data in the literature regarding different types of dust.

However, these data should not be considered applicable in all cases, and more data is still required. There are several reasons for this:

- The specific characteristics of laboratory tested stored materials, such as moisture content, purity or particle size distribution may be different from those of the stored materials processed by the food industries. These parameters, especially particle size distribution, have a significant influence on the explosibility and ignitability properties of the material [14–16]. Even when the same material is considered, large differences may be found. Therefore, where possible, tests should be carried out using samples of materials actually processed by the industry in order to realistically assess the risk of explosion and ignition.
- Usually, these tables do not specify the variety of the agricultural material tested or the chemical composition. Climate, soil composition, the seeds and type of fertilizer used may differ from one country to another, and may also differ within the same country over the years. Therefore, the crops cultivated in one place or in a specific year may be different even when dealing with the same type of material.
- Nowadays, some of the apparatuses and test methods used in the past have become obsolete [17,18]. For example, it has been shown that the electrical circuit used to determine ignition energies involved high energy losses. This implied an overestimation of the energy of the electrical discharges that causes the dust ignition. Sparks with an energy value of below 1 mJ are not available in current standard tests; however a number of dusts were found to have minimum ignition energies much lower than this limit [19]. Another example would be tables showing Maximum Explosion Pressure and Maximum Explosion Pressure Rise values which have been determined using the Hartmann bomb [12], the geometry and test conditions of which have proved to be inadequate, providing very low explosive values.
- The dust found in diverse parts of the installations, such as the elevators, is frequently a mixture of several different dusts that had been stored previously. Therefore, the composition, cohesion, moisture content, particle size distribution and ignition

Table 2
Maximum Explosion Pressure and Maximum Explosion Pressure Rise for maize.

Parameter	P. Field	M. Jacobson
Maximum Explosion Pressure (bar)	5.7	7.7
Maximum Explosion Pressure Rise (bar/s)	24	408

energy of this mixed dust depend on the different quantities of each individual type of dust present in these mixes [4].

- In each type of food industry, market demand (buying and selling price, stocks, etc.) implies the continual use of different raw materials. In addition, more and more new materials are being used which have not been used before and, therefore, their explosibility properties have not yet been studied [11].

As an example, Table 2 shows results for maize grain dust that differ considerably between samples [20,21].

The aim of the present research was to determine the ignitability and explosive parameters of agricultural products commonly stored in silos. Quantitative data will be provided in order to contribute towards the design of prevention and protection systems combating fires and dust explosions in food industries.

2. Methodology

Seven agricultural materials commonly stored in silos were studied. Different process industries were visited in order to select sites for dust collection. The main criterion used for selection of dust collection sites was whether the location in question was considered to present the risk of explosion or fire (silo interiors, pneumatic conveyors, etc.) or not. However, when access to these sites was not possible, or the amount of material was insufficient, other locations were considered, such as bulk bag fillers. Samples were taken by selecting the finest and driest available fraction, taking into account that they had to be representative of the existing product undergoing processing. The majority of the tests were carried out following European Standards, as described below. Table 3 shows the description, collection site and moisture content of the materials tested.

The following properties were determined for the materials tested.

2.1. Physical properties

The materials were tested as received. Moisture content was measured by using a halogenous analyzer and particle characterization was carried out by a dry laser-diffraction technique using a Malvern Mastersizer 2000 instrument.

Table 3
Tested materials.

Identification	Material	Description	Place of collection
UNI-1	Icing sugar	Powder	Storage
UNI-7	Maize	Grain dust	Silo walls
UNI-8	Wheat	Grain dust	Pneumatic conveyor line
UNI-9	Barley	Grain dust	Silo walls
UNI-10	Alfalfa	Dust	Bulk bag filler
UNI-13	Bread-making wheat	Powder	Pneumatic conveyor line
UNI-14	Soybean	Dust	Silo walls

2.2. Ignition sensitivity

2.2.1. Minimum Ignition Temperature (MIT)

The lowest temperature at which the dust ignition process starts. The corresponding tests were carried out either with the dust forming a cloud (MIT-c) or deposited in a layer (MIT-l), following procedures set out in the standard EN 50281-2-1 (2000) [22]. The test device used for MIT-c consisted of a vertical cylinder. The interior was electrically heated to a fixed temperature (usually 500 °C to start tests). The appearance of flames made ignition evident at the fixed temperature. The test apparatus used for MIT-l was a metallic plate with adjustable temperature, onto which the dust was deposited in a 5 mm thick layer. If the temperature within the layer exceeded the plate temperature, it was understood that ignition had been produced, even if no flame was seen. The uncertainty of the results obtained is ±5 K. Alternative methods are being proposed [23].

2.2.2. Lower Explosive Limit (LEL)

The highest concentration of a combustible dust mixed with air at which no ignition was recorded. It represents the limit from where the dust-air mixture becomes potentially explosive. The LEL was determined in this research by using a classical method based on the Hartmann Tube [24], comprising a dispersion plate where the previously weighed dust sample was deposited, and a vertical tube where dust dispersion was produced, passing through an ignition source. When an open flame was observed, ignition was assumed to have occurred for the concentration obtained in the known tube volume. Another method could have been the above test procedure based on the dispersion of decreasing quantities of dust samples in the spherical 20-l apparatus, producing ignition by means of chemical igniters (2000 J), until no explosion is recorded [25].

Ignition of the dust (dust explosion) was considered to have taken place when the measured overpressure, p_{ex} , (including influence of the chemical igniters) relative to the initial pressure, p_i , was ≥ 0.5 bar [$p_{ex} \geq (p_i + 0.5 \text{ bar})$]. The uncertainty of the results obtained is 1 g/m³.

2.2.3. Minimum Ignition Energy

The lowest energy value of a high-voltage capacitor discharge required to ignite the most suitable dust/air mixture, obtained by varying the concentration of dust in the air. The apparatus used was the MIKE 3 [26], based on a Hartmann Tube [27]. The energy (E) (J) was calculated from Eq. (1):

$$E = \frac{1}{2} CU^2 \quad (1)$$

where C was the total capacity of the discharge circuit (Farads) and U was the applied voltage (V). An inductance of 1 mH was included in the triggering circuit. The MIE lay between the lowest energy value (E_2) at which ignition occurred and the energy (E_1) at which in at least 10 successive experiments no ignition was observed. It was possible to calculate a unique statistic value, E_s , by estimating the probability of ignition.

Optimum dust concentration and lowest turbulence level cannot be obtained in one step. An iterative procedure is therefore required, and thus, in accordance with the test method in the standard EN 13821 (2002) [26], a minimum of 5 evenly distributed dust concentrations were tested to determine the ignition/no ignition behaviour of the sample. Once the tests had been carried out, it was possible to estimate the position of MIE in the range (E_1, E_2) by dividing the number of dust concentrations with ignition by the total number of dust concentrations tested (2):

$$E_s = 10^{\log E_2 - \frac{I[E_2] \cdot (\log E_2 - \log E_1)}{(NI + I)[E_2] + 1}} \quad (2)$$

Table 4
Explosion class from K_{max} values.

Explosion class	K_{max} (m bar/s)
St0	0
St1	1–200
St2	201–300
St3	>300

where $I[E_2]$ = number of tests with ignition at energy E_2 .
($NI + I$)[E_2] = total number of tests at energy E_2 .

The uncertainty of the results obtained for this parameter is 1 mJ.

2.3. Explosion severity

Maximum Explosion Pressure (P_{max}). The difference between pressure at time of ignition (normal pressure) and pressure at the highest point in the pressure-time record. The test device used was a Kühner 20-l sphere [28]. Three series of tests were carried out, and those results showing a deviation of less than 10% from the average were considered acceptable. The **Maximum Explosion Pressure Rise** (dP/dt)_{max} is defined as the maximum slope of the tangent to the pressure vs. time curve at each nominal fuel concentration. The **characteristic constant** (K_{max}) is obtained from the product (dP/dt)_{max} multiplied by the cubic root of the explosion enclosure volume. The explosion class is defined as a function of the K_{max} values, as indicated in Table 4.

P_{max} and K_{max} values were obtained for every nominal dust concentration in the test device, using tested material concentrations of between 125 and 1500 g/m³. The explosion chamber used for this study was a hollow, stainless steel sphere. A water jacket served to dissipate the heat of explosions or to maintain thermostatically controlled test temperatures. During tests, the dust was dispersed into the sphere from a pressurised storage chamber via the outlet valve and a nozzle (known as the rebound nozzle). The outlet valve was opened and closed pneumatically by means of an auxiliary piston. The compressed air valves were electrically activated. A control unit provided all the timing and control signals to carry out the tests. Compressed air was used to power the outlet valve and was also connected to the storage chamber inlet valve. Pressure in the storage chamber directly corresponded to that of the external compressed air system (20 bar g).

Prior to dust dispersion, the sphere was evacuated to the point where the remaining pressure, together with the air contained in the storage chamber, registered at the desired starting pressure for the explosion test (normally 1 bar abs). After product dispersion, the ignition source, consisting of two pyrotechnical igniters with a total energy of 10,000 J, was activated in the geometrical centre of the sphere. The dispersion device ensured even distribution of the dust inside the vessel. The delay between dispersion and activation of ignition source was 60 ms, producing uniform and reproducible turbulent conditions. Two piezoelectric pressure sensors were used to enable later checking and therefore avoid measuring errors. The signal was recorded and processed on a control computer.

Parameters, tests devices and standards applied are shown in Table 5, together with the uncertainty of the results obtained with the procedures applied.

3. Results and discussion

As stated in the standard EN 1127-1 (2007) [29] on methodology for explosion prevention and protection in explosive atmospheres, it should be borne in mind that safety data are not physical constants but depend, for instance, on the techniques used for their measurement. In addition, tabulated safety data for dusts are for

Table 5
Standards, test devices and uncertainty of the test for the different parameters studied.

Parameter	Initials	Standards	Test device	Uncertainty
Minimum Ignition Temperature of dust layer	MIT-I	EN 50281-2-1:2000	Flat oven (plate)	5 K
Minimum Ignition Temperature of dust cloud	MIT-c	EN 50281-2-1:2000	Vertical oven	5 K
Minimum Explosive Concentration	MEC	UNE 22335:1992	Hartmann Tube	0.6 g/m ³
Minimum Ignition Energy	MIE	EN 13821:2002	MIKE 3	1 mJ
Maximum Explosion Pressure (overpressure)	P_{\max}	EN 26184-1:1991	20-l sphere	1 mJ
Characteristic Constant of Product	K_{\max}	EN 26184-1:1991	20-l sphere	5 bar m/s

guidance only, as the values depend on particle size and shape, moisture content and the presence of additives even in trace concentrations. For a specific application, samples of the dust to be stored in the equipment should be tested and the data obtained used for hazard identification.

Thus, some well-known explosion data sources, such as BIA-report 13/97 [30], provide a large quantity of data showing wide variation of values for the different explosion parameters. For example, the K_{\max} value for maize ranges from 7 to 75 bar m/s, P_{\max} from 4.0 to 9.4 and LEL from 60 to 500 g/m³; for icing sugar only the classification as St2 product is stated, but no value for K_{\max} is given, and there are no data at all for alfalfa. Other sources, such as the US Bureau of Mines Report of Investigation 5753, should be considered with caution, due to the use of obsolete test devices for obtaining some parameter values [21].

Since real explosion data were required for explosion risk assessment at various agro-industrial processes and installations, it was decided to carry out the appropriate characterization tests.

The median value obtained from particle size distribution is shown in Table 6, as well as moisture content, in order to characterize the materials tested.

The values obtained for the different materials tested depend on the nature, composition and texture of the product. The most important factors that influence the behaviour of the materials tested are particle size and moisture content, so that both factors are always measured and stated together with the results. There are other factors that play an important role such as the density or the particle shape depending on the type of material tested. Heterogeneous materials with low density such as fibres present a higher dispersion than homogeneous materials. The scattering of results is higher so that the number of tests will usually be higher for this type of materials.

3.1. Ignition sensibility

Table 7 gives the results of the parameters obtained to determine tested material flammability: Minimum Ignition Temperature with dust forming a cloud (MIT-c) or in a layer (MIT-I), LEL, and MIE. In practice, these parameters are primarily used to design and implement explosion prevention measurements.

The lower the temperatures, concentrations or energies needed to ignite a dust material, the more sensitive the product to ignition [31] and the more rigorous prevention measures need to be. Process equipment surface temperatures must be controlled, dust layers eliminated by cleaning and maintenance, potential sparks

Table 6
Median particle size values and moisture contents.

Material	Moisture content (%)	Median particle size d50 (µm)
Icing sugar	0.2	17.9
Maize grain dust	13.5	215.1
Wheat grain dust	7.7	36.4
Barley grain dust	7.7	33.9
Alfalfa	5.6	39.0
Bread-making wheat	13.4	55.6
Soybean dust	10.5	51.7

or electrostatics avoided through earthing and the use of antistatic materials, etc.

Minimum Temperatures of Ignition obtained for the materials tested were quite similar except for icing sugar, which melted at 170 °C, and bread-making wheat, which carbonised at 360 °C. Values obtained for the other materials were about 300 °C. It should be noted that the latter comprise grain dusts whilst the former are fine powders. Identical values were found in the literature for wheat and barley grain dusts [4,30]. Values of Minimum Temperatures of Ignition with dust forming a cloud are slightly lower than those obtained for the material deposited in a layer. These values correspond to two different practical situations. Dust deposited in a layer implies the risk of fire: it usually needs more time to ignite than when it is forming a cloud, but reaches ignition at lower temperatures (the lower the temperature, the thicker the layer of settled dust [32]). The explosion is produced when the dust is dispersed, forming a cloud. Therefore, settled dust is equivalent to a latent risk, whilst a cloud of dust represents a potential explosive atmosphere.

Among the tested materials, the detached dust from soybean dust seems to be the least prone to flammability near warm surfaces. The temperature reached with soybean dust was 560 °C whilst the material most prone to the development of this phenomenon, icing sugar, obtained a value of 400 °C. A lack of data was found in the literature concerning soybean dust material. Data on the explosive parameters of this material were found in the standard NFPA-61 (2008) [33]. However, the same standard did not give Minimum Ignition Temperature values. Similar values for this parameter were found in the literature for icing sugar [4,30]. However, moisture content and median particle size distribution values of the materials compared did not match.

Following standardized procedures, a comparison of the different results obtained in laboratories at different research centres can be made. However, care should be taken when interpreting the results, as there is no direct relation between laboratory tests and reality. Some factors may have an influence, such as the use of a specific ignition source prescribed by a standard to determine the MIE or LEL when it has been observed that the nature of this source when produced in an industrial context may be different. Ignition sources present before a fire or explosion are due to electrical wiring faults, sparks produced due to crown effects, etc. The data obtained for wheat is especially remarkable, where concentrations higher than 30 g/m³ are capable of producing an explosion.

Data on the LEL of wheat flour were found in the literature [4]. These data were comparable with the results obtained from tests carried out on bread-making wheat, they presented a similar

Table 7
Ignitability parameters.

Material	MIT-c (°C)	MIT-I (°C)	LEL (g/m ³)	MIE (mJ)
Icing sugar	Melt at 170	400	210	15
Maize grain dust	300	420	150	>1000
Wheat grain dust	290	510	30	130
Barley grain dust	290	480	180	>1000
Alfalfa	300	460	150	>1000
Bread-making wheat	Carbonize at 360	440	60	380
Soybean dust	300	560	NI	>1000

Table 8
Explosibility parameters.

Material	P_{\max} (bar)	$(dP/dt)_{\max}$ (bar/s)	K_{\max} (bar m/s)
Icing sugar	7.5	249	68
Maize grain dust	7.5	298	81
Wheat grain dust	8.1	544	148
Barley grain dust	7.1	185	50
Alfalfa	7.0	186	50
Bread-making wheat	8.1	530	144
Soybean dust	7.0	270	73

median particle size values. An identical LEL value was observed (60 g/m^3) for different samples of this material.

3.2. Explosion severity

The explosive parameters shown in Table 8 and the test methods used and described above are usually the ones employed to characterize dusts or fibre materials. The aim of such characterization is to develop explosion risk prevention and protection measures; prevention aimed at avoiding triggering the explosion, and protection aimed at controlling the explosion, such as the installation of suppression and decompression systems.

Generally, the more flammable concentrations do not usually coincide with the concentrations providing maximum values of pressure or maximum values of pressure rise. Therefore, this must be determined in order to evaluate the effects produced by the explosion. In this case, the values for wheat grain dust and bread-making wheat were higher than the values for the other materials.

When a flammable process occurs in an unconfined space, the effects of the explosion are dispersed by the air. Consequently, in order to measure and register the mechanical effects produced under controlled conditions, the flammable process must take place in an enclosed space to ensure that material ignition leads to an explosion.

The large number of materials handled in the food industries led to the classification of the different types of dusts based on the value of the parameter K_{\max} , as seen in Table 4 [34].

This classification ranks the effect of the expected explosion for different materials. St3 class includes metallic materials such as aluminium or magnesium. These materials display quasi-detonation characteristics and present unique technical difficulties in the implementation of protection systems due to the speed with which the explosion develops. St2 class corresponds to materials presenting high explosion severity that usually require special protection systems. Finally, St1 class, the classification of materials tested in this research work, comprises the majority of flammable solid products. It was observed in the literature that wheat grain dust and icing sugar were located in St1 and St2 classes [30]. Among the data found in the literature for icing sugar, similar moisture content and median particle size values were found and classification compared. However, this was not the case for wheat grain dust, which was classified within St2 class. However, the moisture content and median particle size values did not match with those of the tested samples in this research.

It is important, when using this classification, that the K_{\max} is determined according to a strict test method. Certain operative conditions should be established using a specific criterion because if not, the values obtained for maximum pressure rise will vary considerably, and therefore the K_{\max} will not be constant. Wheat grain dust and bread-making wheat were the materials with the highest K_{\max} and P_{\max} values, whilst lowest values were recorded for alfalfa and soybean dust. In the case of alfalfa, P_{\max} values were similar to those provided by the NFPA-61 (2008) [32] but, K_{\max} values and moisture content were different. More detailed information about the samples is required in order to obtain conclusions.

Table 9
Factors that influence in the velocity of reaction.

Factor	The maximum value of dP/dt corresponds with
Particle size	The finest
Dust concentrations	Much higher than LEL
Energy of the ignition source	Strong sources
Location of the ignition source	Centred positions
Initial temperature	High
Initial pressure	High
Turbulence	High
Presence of gases	Flammable gases

Given that the maximum pressure rise depends on the speed of particle combustion, it is possible to observe the random character of K_{\max} in industrial contexts (particle size distributions, geometry and characteristics of the specific process units and the industry, location where the ignition source may appear, etc.). It is known that the nature of the explosion phenomenon is probabilistic. Systematic studies have been proposed in food industries to design venting panels [35,36].

In order to discover the real conditions and the real K_{\max} value of the material handled in the industry, it would be useful to review the relation with maximum pressure rise. Table 9 presents some factors affecting the development and severity of dust explosions.

All factors mentioned in Table 9 can be measured or controlled when a material is tested, independently of the type and volume of the explosion vessel. The test methods are well-known in test stations, and there are standard procedures used throughout the world; in Europe, EN standards are followed and a significant and continuous effort is made by the standardization committees to keep standard procedures updated such as the CEN/TC 305. European Committee for Standardization. Potentially Explosive Atmospheres—Explosion prevention and protection. The aim is, where possible, to reproduce and repeat the tests obtaining similar data under laboratory conditions, and to reproduce the conditions necessary for obtaining highest reaction speed and highest K_{\max} value by means of suitable variations of these experimental factors.

Some of these factors will produce relatively small changes in the chemical reaction; others will lead to important increments in combustion speed as well as in maximum pressure rise.

The maximum rate of pressure rise is dependent on the explosion volume. Therefore, it will be influenced by a scale factor when dealing with real vessels in the industry. The K_{\max} value, independent of volume, is used in these tests instead the maximum rate of pressure rise.

The parameters of this research work have been determined following standardized procedures that aim to reproduce real industrial conditions. These procedures have been developed considering variables that are difficult to predict or to reproduce such as the type of ignition source before an explosion in a food industry or initial conditions [37] respectively.

4. Conclusions

Seven materials usually stored in process industries have been characterized and the parameters defining their ignition sensitivity or explosion severity have been determined.

Of the seven materials tested in this study, icing sugar was the most sensitive material, scoring highest for ignition, whilst soybean dust was the least prone to flammability near warm surfaces. Minimum Temperatures of Ignition obtained were quite similar for all the materials except for icing sugar and bread-making wheat, both fine powders.

In relation to the effects produced by explosions, wheat grain dust and bread-making wheat were found to produce the most severe effects, whilst barley grain dust and alfalfa caused the least

severe effects. A reproducible methodology was followed by using several standards in this research. Thus, the same procedures can be followed by other research centres and results compared.

The literature reviewed for this research lacked data on these parameters for these materials, especially for alfalfa. More tests are necessary for these types of materials and others in order to enable the elaboration of prevention and safety measures for the process industries. A comparison of the obtained parameters with those found in the literature showed the influence of sample moisture content and particle size distribution on the results, which are also related to the location of the collection site. Therefore, the results obtained should be considered as a guideline and, when possible, it is recommended that tests using samples of the materials presented in the industry are carried out in order to assess the risk of explosion.

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