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Dust sample collection and analysis method for assessing the risks of explosions of dust in suspension in grain receiving and storing units

Método de coleta e análise de amostras de poeira para avaliação de riscos de explosões de pós em suspensão em unidades de recebimento e armazenagem de grãos

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Abstract: Fires and explosions resulting from organic dust in suspension represent potentially fatal risks in all operations where the formation of powdery materials in certain stages of the production process is a secondary result. This article presents a dust sample collection and analysis method to assess the risks of explosions of dust in suspension. The research method was tested in a grain (soybean) receiving, cleaning, drying, storing and shipping unit. It consisted in evaluating the total dust concentration in sectors considered at higher risk for dust explosions, which in this case study included the hopper with manual discharge, the hopper with bascule lift discharge, the dryer, the underground tunnel, the redler conveyor, the elevator, and the cleaning machine. The total concentrations in the sectors under study after 8 hours of use exceeded the recommended levels in four of the seven sampled locations. An increase in concentration was observed according to the time of operation of the unit, emphasizing that, based on the analysis of the values found, one portion of the powder settles quickly, whereas the portion with smaller particle size remains suspended in the air for a long time, representing a very high risk factor. Finally, preventive measures to avoid explosions in locations where concentrations within the detonation range can be found are described.

Keywords: Risk management; Workplace safety; Accident prevention; Dust explosions; Receiving and storing of grains.

Resumo: *O fogo e a explosão devido à poeira orgânica em suspensão são riscos potencialmente mortais em toda a operação que tem como resultado secundário a formação de materiais pulverulentos em algumas etapas de seu processo produtivo. Este artigo apresenta um método de coleta e análise de amostras de poeira para avaliação de riscos de explosões de pós em suspensão, e foi testado em uma unidade de recebimento, limpeza, secagem, armazenagem e expedição de grãos (soja). O método de pesquisa consiste na avaliação da concentração de poeira total nos setores considerados de maior risco quanto à explosão de pó, sendo, neste estudo de caso, a moega com descarga manual, a moega com descarga através de tombador, o secador, o túnel subterrâneo, o redler, o elevador e a máquina de limpeza. Dentre os resultados destaca-se que as concentrações totais nos setores pesquisados após 8 horas de utilização ultrapassaram o recomendado em quatro locais dos sete amostrados. Observou-se o crescimento da concentração conforme o tempo de operação da unidade, ressaltando que, a partir da análise dos valores encontrados, uma parcela do pó decanta rapidamente e outra, com granulometria menor, permanece suspensa no ar por um longo tempo, o que consiste em um fator de risco altíssimo. Por fim, descreveram-se as medidas preventivas para evitar explosões em locais onde podem ser encontradas concentrações dentro da faixa de explosividade.*

Palavras-chave: *Gerenciamento de riscos; Segurança do trabalho; Prevenção de acidentes; Explosões de pós; Recebimento e armazenagem de grãos.*

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1 Introduction

Any industrial activity can generate solid, liquid or gaseous waste during its transformation process due to losses and inefficiencies in the process. The characteristics of this waste vary and may be flammable and explosive, affecting the works and physical parts of the industry, in addition to neighboring communities and the environment, through emissions to the outside or movements within the internal environment of the industry.

Processing industries that produce dust at any stage represent facilities with a potential risk for fires and explosions. These industries include the storage, drying and processing facilities of agricultural products, balanced feed manufacturers, food industries, metallurgical industries, pharmaceuticals, plastic manufacturers, coal and wood processing facilities. Before being deployed, such facilities must perform an accurate analysis of their risks and take the necessary precautions to mitigate the inherent risks (Sá, 1997).

The industrial activities described above involve risks to workers, including physical, chemical, biological and ergonomic risks. Among the main risks observed in such installations, however, accidents caused by fires and explosions by dust in suspension are the most damaging for the property, often resulting in irreparable losses (including to human life), countless days of downtime, loss of markets and competitiveness, and requiring significant investments to put the complex in operation again, in addition to the psychological consequences that this represents in the future, because there will always be someone who was involved or witnessed the disasters who will have difficulties in living with it again.

Explosions of dust in suspension are low frequency phenomena, but when they happen, their consequences are disastrous. As such, this phenomenon makes the search for prevention methods even more urgent. The objective of this article is therefore to propose a method to evaluate the risks of suspended dust explosions, which was tested in various sectors of an agricultural product (soy beans, to be more precise) receiving, drying, cleaning, storage and shipping unit.

2 Explosions in grain storage units

2.1 Brief history of dust explosions

Several studies have reported accidents with dust explosions, such as Abbasi & Abbasi (2007), who presented a detailed history of accidents from 1911 until 2004. Vijayaraghavan (2004), on the other hand, described 36 dust explosions with injury and 123 explosions without injury from 1979 to 1988 based on information from the Health & Safety Executive. As can be seen in Figure 1, the main equipment items involved in the accidents were plants, mills and filters, with the events that occurred in ducts being classified in the category "others".

In Brazil, the explosion of cell C-2 of the vertical silo of the Port of Paranaguá, Curitiba (PR), stands out, which caused the death of two workers in addition to injuring five. The likely cause pointed to the explosion of the dust from the barley that was stored on the site during a cleaning operation that was happening on the tenth floor of the silo, which had 13 floors and was 55 meters tall (Rangel, 2007).

In 2008, a huge explosion occurred at the Imperial sugar refinery in Savannah, USA, killing 14 and injuring 38 people. Although the exact cause of ignition is unknown, the explosion began on a sugar carrier in the silos of the company. The primary explosion raised the sugar dust that had accumulated on the floors and elevated horizontal surfaces, spreading more dust and explosions through the buildings.

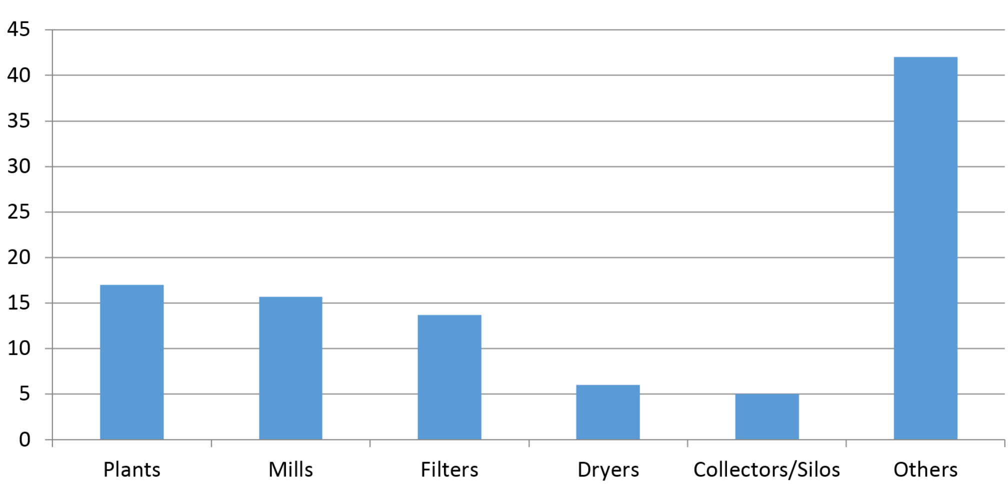

Figure 1. Equipment involved in dust explosion accidents. Source: adapted from Vijayaraghavan (2004).

The secondary dust explosions occurred throughout the packaging, refinery and sugar loading buildings. The pressure waves of the explosions detached concrete floors and collapsed brick walls, blocking the stairs and other emergency exit routes, increasing the tragedy (DEI, 2012).

With respect to the statistics on dust explosion accidents in Brazil and abroad, one could highlight that the frequency is low, but that the severity is very high; which justifies this study.

2.2 Brazilian and foreign standards

In Brazil there are no standards dealing specifically with the dust explosion phenomenon. Abroad, there have been more in-depth studies. The United States has the NFPA 68 standard from the agency bearing the same name, which regulates the procedures to fight fires and explosions (NFPA, 2007). The NFPA works in conjunction with OSHA. To avoid explosion hazards, protection rules in the form of laws, specifications and standards have been developed in many countries in order to ensure that a high level of safety is observed. The conditions for the complete harmonization were created in the European Union by Directive EC 9194. Directive 94/9/EC was released in 1994 to standardize the protection against explosions (EC, 1994).

The ABNT collaborates with the north-american agencies NFPA, NEMA, NEC and IEC, as well as the European Standards EN and DIN, among others at the global level. In Brazil, the NRs define safety standards for environments that are considered hazardous to human work. The risk products are classified by NBR 5418 into 4 groups: I, IIA, IIB, IIC, which is based on the European IEC Instruction 79/14 1984 (ABNT, 1995).

The international regulations use IEC 79-10, which distinguishes the following categories of hazardous areas: zone 0, zone 1 and zone 2. These zones are geographical, but it's not easy to define the limits between each precisely. One zone can move for various reasons: heating of the products, ventilation failure on the site, climatic variations, handling errors. In zone 0, the explosive atmosphere is always present, in zone 1, the explosive atmosphere is frequently present, in zone 2, the explosive atmosphere may accidentally be present. The ABNT adopts the classification by zones. The NFPA and NEC, on the other hand, adopt the same classification, calling them divisions (ABNT, 1995).

The operation of electrical equipment in potentially explosive atmospheres, by its very nature, is a source of ignition and should comply with the requirements laid down in the international standards. Grain and bran dust are classified as class II, group G. These standards present the criteria to define the classified area according to the potential risk of flammable substances (NFPA, 2011).

For electrical equipment there is also the classification according to Explosion Groups, where electrical appliances for all other remaining potentially explosive environments are classified as group II. As such, electrical appliances in grain and bran storage facilities fall into this group. The identification label of electrical equipment must show for which Explosion Group it is designated (Schaltgerate & Fordertechnik, 1999).

Regulatory Standard NR-31 is the legal directive that defines the minimum worker safety requirements in the agricultural segment and it outlines guidelines for the running of safe silo facilities (Brasil, 2011).

2.3 Dust explosions

Industries that process products which at some state are presented in dust form have a high risk potential for fires and explosions. Prior to their deployment, an accurate risk analysis should be performed and precautions should be taken, since solutions are more simple and effective if implemented in the design phase. Already deployed industries, however, can also solve these problems well with the aid of a competent professional, thus mitigating the inherent risks. Among the industrial activities that are known to be hazardous regarding the risk of fires and explosions, the following should be highlighted: processing industries of agricultural products, animal feed industries, food industries, metallurgical industries, pharmaceutical industries, plastic industries, wood processing industries and coal industries (Eckhoff, 2005).

For Eckhoff (2009), one should not fail to highlight the great risk of explosions, which often occur on the referred processing units, where the dust has combustible properties. First, however, it is necessary that this dust is dispersed in the air at the right concentrations. This occurs in points of the facilities where there are milling, discharge, handling and transport operations, among others, provided there is no exhaust control and that the triggering factors are present, of course.

When the dust suspended in the air ignites, this can generate large explosions. In general, therefore, these finely pulverized combustible mixtures are very dangerous, being caused by deposits of combustible dust on beams and on the machines of the site.

> After the detonation in a given point is processed, the dissipated calorific energy will be used in the detonation of another point. This will result in a series of detonations as long as there are favorable conditions that are established by the existence of oxidizing agents and fuel and the occurrence of ignition point temperatures. As such, the detonation process is quick, but not instantaneous, with the

> series of detonations attaining propagation speeds of up to 7000 m/s, exerting pressures of up to 550 KPa and generating shock waves with speeds of 300 m/s. (Silva, 1999, p. 1).

According to Abbasi & Abbasi (2007), while fire is caused by three factors (fuel, oxidant and ignition), the so-called "the fire triangle"; a dust explosion requires two more factors: a mixture of dust and air, in addition to confinement (of the dust cloud). The "dust explosion pentagon" is therefore formed when these five factors occur together:

1. Presence of combustible dust in a finely divided form;
2. Availability of an oxidizing agent;
3. Presence of an ignition source;
4. Some degree of containment;
5. State of mixed reagents.

The danger of a certain class of dust is related to the ease of their ignition and with the severity of the resulting explosion. To this end, in the United States an experimental piece of equipment to test explosive dust was created with various sensors to enable the characteristics of dust atmospheres to be known. The ignition sensitivity is a function of the ignition temperature and energy required, whereas the severity of the explosion is determined by the maximum explosion pressure and the maximum rate of growth of the pressure. To make the comparisons of the explosion data derived from the mentioned tests easier, all results were related to a coal dust known as "Pittsburgh", taking a concentration of 0.5 kg/m^3 for the sample, i.e. kg of powder of coal per m^3 of air, except for metal powders. The smaller the particle size of the dust, the easier it is for the cloud to ignite, since a greater surface area is exposed per unit of weight of the matter (specific surface area). The particle size also influences the pressure growth rate: for a given concentration of dust in weight, the dust formed by coarse particulates has a lower pressure increase velocity than the same fine dust concentration. The minimum concentration required for there to be an explosion, the ignition temperature, and the energy needed for the ignition are reduced as the dust particles get smaller. Various studies have pointed to this effect in a great variety of dusts. The particle size also increases the electric capacity of dust clouds, i.e. the size of the electrical charge that can accumulate in the particles of the cloud (Sá, 1998).

According to the same author, the most violent explosions are observed when produced by a slightly greater concentration than required so that a reaction occurs with all the oxygen available in the atmosphere. With lower concentrations, less heat and a lower head pressure is generated. With higher concentrations than those that cause violent explosions, the absorption of heat by the unburnt dust may be the reason why smaller explosion pressures are generated.

For Sá (1998), inert gas is effective in the prevention of dust explosions, since it dilutes the O_2 to very low concentrations. When selecting the most appropriate inert gas, one should take care to ensure that it doesn't react with the dust. Certain metal dusts, for example, will react with CO_2 or with the N_2, and in this case helium or argon should be used.

The high concentration of dust generated by the handling of grains is the main fuel for the occurrence of explosions. In the states of Goiás, Mato Grosso, Minas Gerais and Bahia, where there also is intense grain handling activity, the risks are even greater because of the low relative humidity of the air, transforming the grain storage units in veritable gunpowder barrels. The concentration of the incidence of fire and explosions in Brazilian silos is still an unknown fact for experts.

The probability of a dust cloud explosion is conditioned by the size of its particles, its concentration, the impurities, the oxygen concentration and the power of the ignition source. Dust explosions are often produced in series. Many times the initial blast is very small, but of sufficient intensity to place the dust in suspension or break parts of machines or installations within the building, such as dust collectors. This creates a larger cloud through which secondary explosions can propagate, even from one building to another (Eckhoff, 2003).

With respect to the concentration, according to studies by Couto (2007), the most dangerous range to generate an explosion varies between 20 g/m^3 and 4,000 g/m^3, which was adopted in this paper. The effects of an explosion are generally grandiose and are continuously propagated as long as favorable conditions are present. Abbasi & Abbasi (2007), however, reported that the dust concentrations that pose a risk of explosion vary between 50-100 g/m^3 and 2000-3000 g/m^3.

2.4 Preventive measures that can avoid explosions

According to Eckhoff (2009), the main preventive measures to avoid explosions can be classified into three classes:

- Prevention of the explosion of the dust cloud;
- Prevention of ignition sources;
- Mitigation of explosions.

Some of the measures to prevent dust explosions include: careful control of the relative air humidity, with values below 50% being characterized as a critical risk range; Regular cleaning of the dust collection systems, exchanging the filters in the periods defined by manufacturers; Performing the daily cleaning of the residual dust deposited on the machinery, equipment and installations; Training of operators and other employees about the potential explosive risks; Performing periodic maintenance of electromechanical equipment; Checking the status of electrical cables on a regular basis; Taking the necessary care when using welding apparatus in maintenance services; Preventing people from smoking inside or in the vicinity of silos; Conservation and maintenance of buildings (São Paulo, 2010).

According to Schoeff (2004), a dust explosion cannot occur without the presence of the dust itself. The best prevention method, therefore, is a good cleaning service, because the dust accumulates visually but not immediately. That is why the cleaning service is so important, if not the most important aspect, and it's the responsibility of all employees. Managers have to understand that they have to take care of the dust to keep these locations safe, and thus the focus should be on controlling the dust, keeping it out of suspension or controlling the concentration.

For the prevention of ignition sources, on the other hand, the control of the dust concentration in the environment, warnings about the smoking ban, the maintenance of electrical networks, the use of lamp protectors and the employment of shielded engines, stand out as basic and fundamental measures. Other preventive measures provide for explosion proof electrical installations in the silos, such as encapsulated bulbs and sockets, the control of the relative air humidity (below 50% is characterized as the critical risk range), control of static electricity through grounding systems of the silos, control of open flames when using welding apparatus, matches and during metal grinding operations, in addition to the installation of lightning protection systems.

Among the best practices to mitigate the effects of explosions, Taveau (2012) highlights two main methods:

- Ventilation techniques to release the excess pressure in the environment, in addition to resistant extinguishing systems or equipment to limit the consequences of a primary explosion;
- Systems to insulate the facility from explosions, including valves, locks and flame arresters to prevent the spread of the primary explosion.

2.4.1 Possible ignition sources

The possible sources of ignition for an explosion arise from: the accumulation of electrostatic charges; short circuits; atmospheric discharges; friction of metal components; inattention during the use of welding apparatus.

According to statistics (Betenheuser et al., 2005), the main ignition sources causing accidents with dust explosions are: mechanical sparks (50%); static electricity, cutting and welding, electric arcs (35%) and overheating (15%).

The main equipment and/or critical locations for these accidents are: mills and grinders (40%); elevators (35%); carriers (35%); dust collectors and silos (15%) and dryers (10%) (Betenheuser et al., 2005).

According to the DEI (2012) statistics, a dust explosion will only occur if a powder is dispersed in air or oxygen within the explosive range, and if, at the same time, an appropriate source of ignition is present, which may be an open flame or hot surface, spontaneous heating, friction sparks, an electrical plant and static electricity, among others.

3 Methodological procedures

3.1 Dust sample collection and analysis method for assessing the risks of explosions of dust in suspension

3.1.1 Identification of the dust generating locations

In order to initially analyze the main dust generating locations, one should interview the employees working in the unit to identify these locations. Among these locations, the following can be cited as the main dust recipients: the grain receiving hopper with manual and bascule lift discharge, the dryer, the underground tunnel, the redler for horizontal transport, the cleaning machines, the underground gallery and the elevator for vertical transport.

These locations should be analyzed because most stages of the grain storage process generate explosion threats in silos that do not have the appropriate safety measures in place. From the hopper (place where the grained is received), the conveyor belts located in tunnels, cleaning and drying machines to the storage silos.

3.1.2 Collection of dust samples

Collection procedures are performed in the places with the greatest incidence of dust. In this study, the main dust generating locations in a grain industry are described, with samples being recommended for the hopper, the underground gallery, the cleaning machine, the transport redler, the transport elevator and the dryer. The samples are taken through three measurements, all in the same place and on different days, with one collection being carried out at the beginning of the operation, another after 4 hours and the latest after 8 hours of the unit's operation. The objective of these measurements is to check the facility at the beginning of the operation, when no dust should yet be present or only the dust remaining from the previous day's process; at the end of the operation when the concentration should be at its maximum; and the concentration at the half-way point of the process (4 hours).

3.1.2.1 Collection of samples with the use of filters

The membrane filters to be used in the collection of the samples are carefully removed from the original packaging with the aid of tweezers and deposited on the lower part of the filter-holders. At this moment, any possible defect of the filters is checked (discarding defective filters). Next, two filters from the same packaging that was used for the preparation of the collection filters are chosen to be mounted as described in the item above. Then a code is chosen for each original packaging of 100 to 50 filters and the filter-holders are identified with this code: Packaging A (filters A-01 to A-100).

Subsequently, the filter-holders containing the already manually weighed filters with the aid of a wooden board are closed and then the fittings of the filter-holders are sealed with 03 layers of teflon tape.

The filters should be used one day after their weighing so no modifications occur in the scales or the stabilization conditions of the lab between the weighings before and after the collection, affecting the analytical results. As can be seen on the validity on the frame of the filter door, generally, the limit is one week after the weighing. One of the frequent sources of error in the collection by filtration is the seal of the filter door. To ensure that all of the collected material passes through the filter, the seals of the filter-holders are tested, in addition to the possibility of the filter itself being ruptured, through the measurement of loss of load.

The method used to collect dust in the work environment should follow the standard NBR 12085: Chemical Agents in the Air - Collection of Airborne Agents through Filtration (ABNT, 1991). According to the method of gravimetric analysis of airborne agents from solids collected on membrane filters, the weighing of the membrane filter should be done before and after collection of the dust suspended in the air to determine the mass of the sample through the difference, considering the variations between these two weighings.

3.1.2.2 Collection of samples with the use of volumetric flow pumps

The sample pumps have a system of constant volumetric flow control, which consists of a pressure variation sensor installed on the air outlet and a revolutions per minute sensor on the pump. The data collected by these two sensors are constantly compared with the internal parameters of the pump, enabling the continuous monitoring of the flow. A monitoring software instantly adjusts the pump flow to keep it within the flow range chosen by the user, which in this case was 1.7 l/min, even varying the altitude.

The dust samples are obtained with an appropriate collection device, through which a certain volume of air is passed through a polyvinyl chloride (PVC) membrane filter of 37 millimeters (mm) in diameter and with pores of 5 micrometer (um). This is coupled directly with a hose to the sampling pump. A stopwatch is used to accurately measure the collection time of the samples of each explosive risk activity considered.

3.1.3 Laboratory procedures carried out after data collection in the field

In the analysis of dust samples by gravimetry, an analytical scale is used with a sensitivity of 0.01 mg, previously calibrated with traceable standards in the range of analytic interest. The pump calibration, on the other hand, should be performed using a flow calibrator, according to standard NBR105-62: Flow calibration through the soap bubble method of low flow pumps used in the evaluation of chemical agents in the air (ABNT, 1988).

The installation location of the analytical scale should be in a room equipped with an air-conditioning system with moisture control. The scale is installed on a table that serves to protect from potential vibrations. The location intended for the weighings is reserved and independent from other activities that may interfere in its proper progress. It should be a site without incidence of solar light and with little movement of people.

The temperature of the weighing room in this study varied from 20 to 25 °C, considering the region of Chapecó, equipped with an air-conditioning system. The moisture range must be established considering the characteristics of the region found during a year, however, controlling it within a range of 10% between minimum and maximum.

After the data collection in the field, the following laboratory procedures were adopted: weighing of the filters after collection, cleaning of materials and the scale, expression of the results, procedure notes, sample analysis and determination of the dust concentrations.

To express the results, the mass of the samples collected on the filter is established by calculating the difference between the mass of the loaded filter and the mass of the unused filter (Equation 1).

$$SAMPLE\ MASS = (mass\ of\ loaded\ filter) - (mass\ of\ unused\ filter) \quad (1)$$

Next, the correction factor of the weighings is established in the following form (Equation 2):

$$F = ((c-a) + (d-b)) / 2 \quad (2)$$

Where: F = correction factor

a = initial mass of sample filter T_1

b = initial mass of sample filter T_2

c = final mass of sample filter T_1

d = final mass of sample filter T_2

The samples that exhibit detached material on the filter are considered invalid, but they can be weighed just for an estimate of the sampled mass. The results of the gravimetric analysis of these samples should not be considered for the purpose of concentration calculations, and must always be accompanied by observations about the condition of the sample at the time of weighing.

The analysis of the samples is carried out in a laboratory by the gravimetry method, which enables the determination of the total dust mass collected on the membrane of the previously weighed filters and provided by the laboratory.

The dust concentrations are determined as concentrations of total dust. In order to calculate this in different work environments, only the dust samples that fall within the quality criteria established by Fundacentro are considered. The analytical technique to be used in the analysis of the dust is a gravimetric analysis of airborne agents from solids collected on membrane filters (FUNDACENTRO, 2001).

3.2 Definition of the case study

The choice of the grain receiving and storing unit was made because it was located in the city of Chapecó, because all activities of the process were performed in the same unit, from receiving, transporting, drying, cleaning, storing and shipping the grain, which included corn, soybeans and wheat. Another important point for the choice was the great product storage and handling capacity, with a storage capacity of 75,000 tons of product and a handling capacity of 180,000 tons per year, since it's a centralized unit that supplies a vegetable oil industry and a wheat flour industry located in the same city.

The case study validated the proposed method for the collection and analysis of the dust samples generated in the unit. The selected methods were defined in order to identify the mass concentration of suspended dust in the air in all work environments considered prone to explosion, such as: the *hopper* (location for receiving grain with manual and bascule lift discharge), *underground gallery* (confined space responsible for transporting the product through conveyor belts), *cleaning machines* (where the product is cleaned, removing impurities), *redlers* (equipment that carries the product horizontally), *elevators* (responsible for the vertical transport through buckets leading it from the underground gallery to the upper walkway) and the *dryer* (where the product is dried, allowing storage in ideal conditions and inert to deterioration).

These points mentioned above are displayed in Figure 2, where they serve for the collection of samples for the case study in order to verify the total concentration.

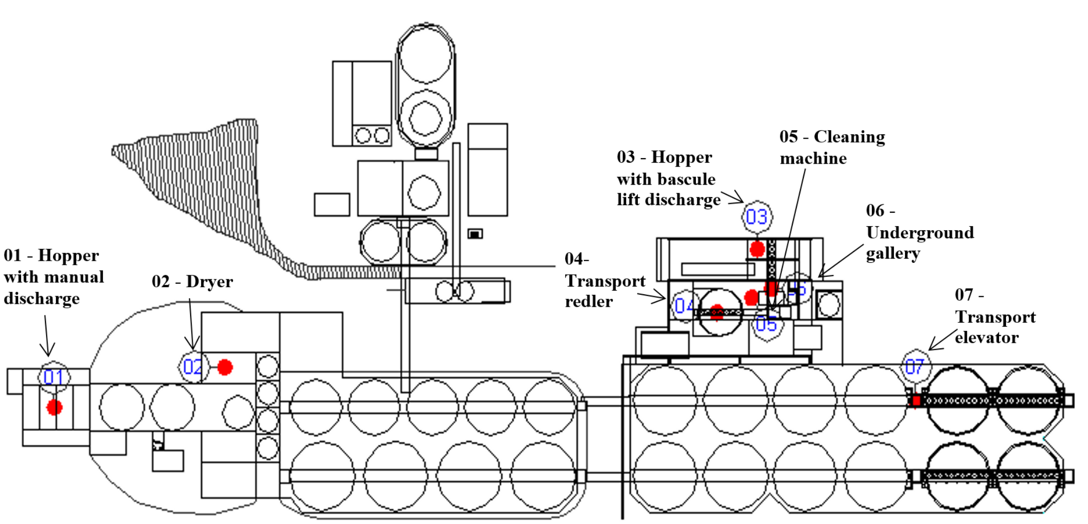

Figure 2. Identification of the dust generating and sample collections points. Source: Developed by the authors.

3.3 Test in an experimental model

This test, which is not mandatory, was performed with the aid of an experimental scale model used for the training of workers exposed to the explosive risks of the grain. To this end, the soy dust is gathered in the locations where the measurements were carried out and, in proportion to the volume of air of the scale model, the quantity of dust is weighed (Figure 3), verifying the occurrence or not of the explosion with the concentrations found. By checking the weight of the collected dust, the bulk density of the soy powder in the study was confirmed to be 284 kg/m3.

All concentrations found were tested for explosion by introducing the oxygen and electrical spark required to cause an explosion with the dust. Figure 4 shows a picture of the scale models that were used in the explosion tests of this study.

Figure 3. Weighing of the dust of the measuring locations for the simulation in the scale model. Source: Developed by the authors.

Figure 4. Experimental scale model used for the simulation of explosions. Source: Developed by the authors.

3.4 Qualitative assessment of risks

Another way to corroborate the results, in addition to the proposed method and the experimental scale model, is by using a risk assessment technique. The qualitative risk assessment technique (Cardella, 1999) was performed at the company through a seminar with the participation of the authors of the article, the work safety engineer and two safety technicians of the unit under study. The evaluation consisted in assessing the probability and severity of dust explosions in the elevator and redler after 8 hours of operation. The probability was evaluated by assessing the frequency and severity of the accident through the analysis of the consequences of the explosion.

4 Results and sample analysis

4.1 Dust concentration in the unit and possibility of explosion

The results of the dust evaluations are presented as the concentration of total dust, in grams per cubic meter (g/m^3). The sectors or steps in the grain receiving, storing and shipping process were grouped, contemplating the hopper with manual and bascule lift discharge, the underground tunnel, cleaning machines, the transport elevator, the dryer and redlers. The concentrations are related to the samples collected at the beginning, after 4 hours and after 8 hours of the unit's operation.

The three stages were measured in the same location in order to obtain a better analysis of the concentrations and information about the settling and the variation in the total dust concentration as a function of the unit's operating time. Table 1 presents the final results of this study for the concentrations found in the three measurements performed.

The results of the total concentrations found in the ***hopper with manual discharge*** revealed to be of little concern, since the three measurements taken in this site were below the explosive range, between 20 g/m^3 and 4,000 g/m^3. When analyzing the result of the concentrations in this location, these values were attributed because the hopper is an environment that is considered to be large and open to two sides, allowing a large portion of the dust generated at this site to spread over the environment or even to be carried by the wind to outside the hopper, being dissipated in the external environment. Taking the low concentrations into account, the training of operators and other employees is still advisable as the potential risks of explosions are closely related to the cleanliness of the premises, which should avoid the accumulation of dust, thus maintaining the place clean and avoiding any type of situation that may generate a spark.

Table 1. Result of the total concentrations found in the collection sites.

LOCATION	TOTAL DUST CONCENTRATION Beginning of the operation (g/m^3)	4 h after the beginning of the operation (g/m^3)	8 h after the beginning of the operation (g/m^3)
Hopper - Manual discharge	***0.33***	***2.62***	***4.45***
Hopper - Bascule lift discharge	***0.80***	***16.17***	***31.18***
Dryer	***0.84***	***10.87***	***17.31***
Underground tunnel	***0.94***	***21.43***	***41.25***
Cleaning machine	***0.04***	***0.23***	***0.43***
Transport elevator	***7.99***	***99.65***	***122.65***
Transport redler	***7.62***	***98.76***	***113.39***

Source: Developed by the authors.

With regard to the results of the total concentrations found in the ***hopper with bascule lift discharge***, a concern emerged regarding dust explosions after 8 hours of the unit's operation, with a total concentration of 31.18 g/m^3, which falls within the detonation range. A specific safety measure for this site would be to install dust collection systems for hoppers, which should decrease the concentration of dust in suspension and avoid sparks in this location.

When analyzing the total concentrations found in the ***grain dryer*** in the three performed measurements, one can see that the results stayed below the explosive range. After 8 hours of operation, a concentration of 17.31 g/m^3 was found, very near the lower explosive limit. It is concluded that it's a location conducive to the existence of sparks, which could cause ignition and thus an explosion. As safety measures, operators and other employees should be trained regarding the potential risk of explosions, a periodic cleaning of the site should occur and the flame cutting duct between the furnace and the dryer should be carefully checked so that it doesn't allow a spark to reach the grain mass.

In addition to being considered a confined space, the ***underground tunnels*** showed results within the explosive range in two of the three measurements, 21.43 g/m^3 and 41.25 g/m^3 after 4 and 8 hours of the unit's operation, respectively. Analyzing the measurements reveals that with every hour of operation of the conveyor belt, the dust concentration tends to increase because it is a confined space where the dust has no place to go. As safety measures, one should highlight a focus on the daily cleaning of the site, keeping the drive belts taut, avoiding friction between it and the motor pulley and, as the main measure, installing dust collection systems in these tunnels in order to decrease the concentration of dust in suspension.

A very low dust concentration was found in the ***cleaning machines,*** with all three measurements revealing values well below the lower explosive limit. Even so, the training of operators and employees on the potential risks of explosions and on the daily cleaning of the site was highlighted.

The results for the total concentrations in the ***transport elevator*** reveal that there should be great concern regarding the risk of detonation in this location. Two of the three measurements taken fell within the explosive concentration range, namely after 4 hours of operation, with 99.65 g/m^3, and after 8 hours of operation, with 122.65 g/m^3. The two concentrations are significantly above the lower explosive limit and one can see that the dust concentration increases the longer the equipment is in operation. The safety measures that can be adopted for this site include the installation of openings at the top of the elevator and to cover it only with a Chinese-hat-type cone, thus avoiding the rupture of other parts; the installation of explosion suppression systems to avoid the spread of the flame to the outside in case of an explosion; the installation of explosion windows to blow off pressure when they occur; the installation of explosion proof motors; greater care in the use of welding apparatus; the installation of plastic buckets; and the performance of preventive maintenance, among others.

The concentrations found in the ***transport redler*** reveal a significant risk of detonation in this location. Two of the three measurements revealed concentrations within the explosive range, one with 98.76 g/m^3 and another with 113.39 g/m^3 after 4 and 8 hours of operation, respectively. In its interior, sparks can occur through the contact between the metallic parts and it is a location where welding maintenance takes place. Just as in the elevators, the dust concentrations can be seen to increase with each hour of the redler's operation. The recommended safety measures include the installation of explosion windows to relieve the pressure in the event of an explosion, the installation of explosion proof redler motors, being careful during the use of welding apparatus, the installation of plastic buckets and the performance of preventative maintenance.

Figure 5 shows the locations and the moments in which the samples indicate ideal concentrations

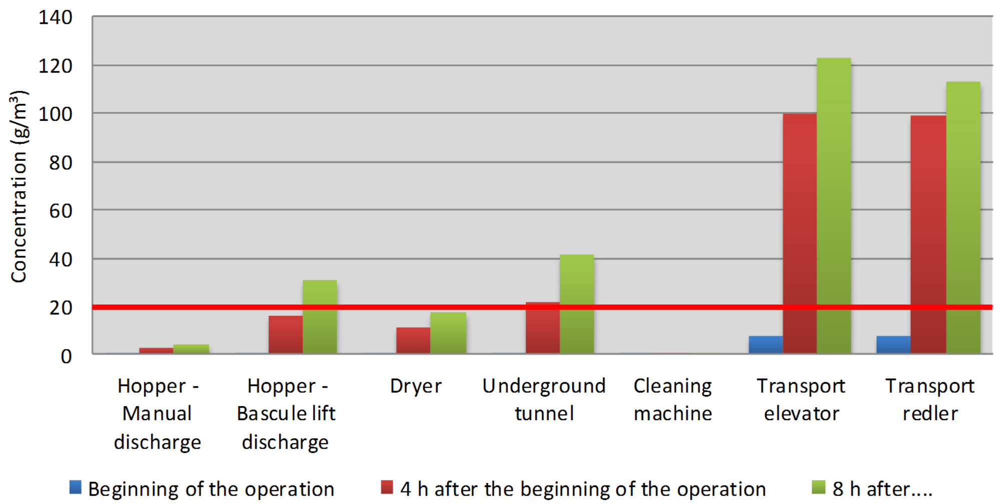

Figure 5. Total dust concentration exceeding the lower explosive limit of 20 g/m³. Source: Developed by the authors.

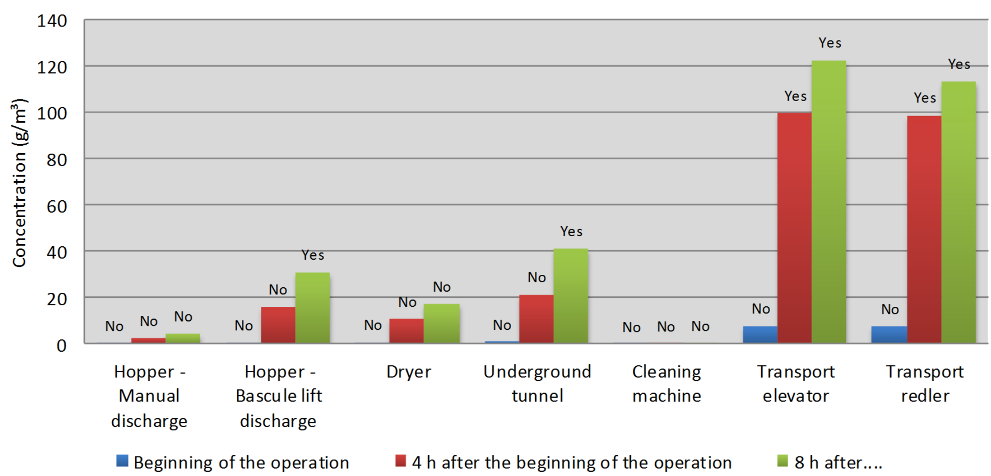

Figure 6. Result of the tests performed with the concentrations found in order to check the occurrence or not of explosions. Source: Developed by the authors.

for the occurrence of explosions. One can see that there are concentrations that are likely to cause explosions in the hopper with bascule lift discharge, the underground tunnel, the elevator and the redler.

4.2 Tests in an experimental model

The results of the tests performed on the experimental scale model in order to corroborate the dust explosion potential are shown in figure 6.

Figure 6 reveals the great risk and likelihood of an explosion occurring in the elevator, redler, tunnel and hopper with bascule lift discharge, since according to studies that have already been performed and corroborated by the tests, these structures have concentrations within the explosive limit.

4.3 Qualitative assessment of risks

The results of the qualitative risk assessment didn't seek to perform ad hoc evaluations, such as was the case of the results of the data collection. To assess the risks, it was established that those locations would be evaluated that presented greater danger of explosion after 8 hours of operation in the hazard identification procedure conducted by the company for the drafting of the Environmental Risks Prevention Program (PPRA): the elevator and the redler.

The outcome of the risk assessment is shown in Figure 7, which resulted in a frequency category of 2, which corresponds to an event that is expected to occur rarely in the exercise of the activity or during the life cycle of the installation, and a consequence category of 8, which means that in case of an explosion, some

Frequency categories	Consequence categories									
	0	1	2	3	4	5	6	7	8	9
	Risk categories									
0	0	0	0	0	0	1	1	1	1	1
1	0	0	1	1	2	2	2	3	3	3
2	2	2	2	3	3	4	4	5	5	5
3	2	3	4	5	5	5	6	7	8	8
4	3	4	4	5	6	6	7	8	9	9

Figure 7. Result of the qualitative risk assessment in the elevator and redler after 8 hours of operation. Source: Developed by the authors.

deaths may be expected to occur. This results in a risk category of 5, which is the alert representing an intolerable medium risk, which requires a specific risk control program. This control was deployed so that the elevators and supply systems of the silos should be designed and operated in such a way as to avoid the accumulation of dust, in particular at those points where the generation of sparks by static electricity is possible.

5 Concluding remarks

The performed study evaluated the total dust concentrations in sectors considered of higher risk for dust explosions. It showed the reader how to perform these tests in other industries in the sector, and considered the hopper with manual discharge, the hopper with bascule lift discharge, the dryer, the underground tunnel, the redler, the elevator and the cleaning machine as being of higher risk. The results were corroborated by a test on a scale model and by a qualitative risk assessment.

The results of the three measurement stages of total dust concentrations (start, 4 hours, and 8 hours of the unit's normal operation) revealed a great variation of values, in which it was possible to see exactly which sites were of greater concern regarding the risk of detonation, enabling preventive measures to be taken in the establihed critical points.

The total concentrations found in this study in several process steps of the unit's operation revealed that the concentration increases the longer the unit operates, and it is concluded that a portion of the dust settles quickly, while another, with smaller particle size, remains suspended in air for a long time.

It is therefore necessary to develop studies about the effects of static electricity formed by the friction between dust particles in suspension and the surfaces of equipment and buildings. With this, new systems and equipment should arise to neutralize the formation of factors and situations that influence and/or minimize the damage in the occurrence of dust explosions.

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