MARY KAY O'CONNOR
PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

21st Annual International Symposium
October 23-25, 2018 | College Station, Texas

A Risk-based Dust Hazard Analysis (DHA)

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Keywords: combustible dust, dust hazard, risk-based, dust hazard analysis (DHA)

Abstract

Combustible dusts are finely divided particles that present an explosion hazard when suspended in air. Dust explosion may become more severe in a confined space, especially due to the occurrence of second dust explosion. Combustible dust explosions have caused numerous fatalities and catastrophic property damages in industries. They are now a recognized hazard that plant owners, managers, and workers cannot ignore. Many industry-specific NFPA dust standards (e.g., NFPA 61, 484, 655, 664) on combustible dust contain provisions for conducting DHAs. NFPA 654 applies to general combustible dusts for preventing combustible dust flash fires and explosion, which requires designing the fire and explosion safety provisions based on the dust PHA. The newest standard of NFPA 652 (Standard on the Fundamentals of Combustible Dust) became effective on September 7, 2015. It requires that dust hazards analysis (DHA) be completed on existing facilities and significant modifications before September 7, 2018. Assessment of what can go wrong, however, may not be an easy task for dust-handling plants. NFPA performance-based dust hazard assessment and OSHA regulatory compliance requirements lack detailed guidance on how to conduct DHA. Meanwhile, standard or code-based prescriptive DHA may create redundantly unnecessary overprotection for hazard-involved dust processes and equipment. In this research, a risk-based approach is developed by incorporating both likelihood analysis and consequence analysis to define safeguard requirements for any of potential process deviations, operating upsets, human errors, and equipment failures. By comparing safeguard requirements with the credit provided through safeguard availability analysis, a risk-based DHA will provide a sufficient understanding of dust hazards, as well as the safeguard level of demand for dust process safety work activity.

1. Background

A great many finely divided solid matters represent a serious industrial problem. A dust hazard, especially a dust explosion, is a great threat to industries handling combustible dusts. The U.S. Chemical Safety Board reported 281 major dust explosion incidents, which killed 119 workers and injured 718 more, from 1989 to 2005 [1]. Primarily the dust explosions are common in coal mining, flour milling, and grain storage [2]. Frank gives incident data reported by US CSB and FM Global, which illustrate that dust explosions have mainly occurred in the following industries [3]:

- Wood and paper products (e.g., dust from sawing, cutting, and grinding, etc.);
- Grain and foodstuffs (e.g., grain dust, flour);
- Metal and metal products (e.g., metal powders and dusts);
- Power generation (e.g., pulverized coal, peat and wood);
- Chemical process industry (e.g., acetate flake, pharmaceuticals, dyes, pesticides);
- Plastic/polymer production and processing;
- Mining (e.g., coal, sulfide ores, sulfur); and
- Textile manufacturing (e.g., linen flax, cotton, wool).

2. Dust Hazards

Any oxidizable material with sufficiently small particle sizes, under the right circumstances, is potentially capable of combustion. Combustible dust presents three types of combustible hazards: dust explosion, flash fire, and smoldering fires. A dust explosion is the most severe of these hazards.

A dust explosion requires five necessary conditions: fuel, oxidizer, suspension, ignition source, and containment, which is normally symbolized as a dust explosion pentagon. When dust disperses in air within a non-congested area or an open space, a rapidly burning flash fire can result at a certain range of dust concentration. Dust flash fires can cause fatal injuries. Dusts that settle on a hot surface (e.g., motors or steam piping) may develop smoldering and potentially auto-ignite due to exothermic oxidation. Dust smoldering fires can also occur in bulk solids in the absence of hot surfaces. If a dust layer is thick enough to prevent heat from escaping, the heat from oxidation can cause smoldering to continue. Smoldering fires themselves may not be immediately hazardous to people, but they can act as ignition sources for flash fires and explosions, as well as a source of toxic gases (e.g., CO) emission.

A Dust explosion domino can occur due to the secondary or tertiary dust explosions triggered by the initial one. That is usually the main contributor to the severe losses in the solid-processing industries. When the overpressure produced from the initial explosion reaches a dust layer, a potentially large amount of dust could be dispersed and ignited by the initial dust flames, resulting in far more destructive overpressure. Moreover, secondary or tertiary dust explosions are often observed far from the location where the primary one occurs, which induces difficulties in safety measure application.

Dust explosion DDT (deflagration-to-detonation) is a particularly hazardous event. It may cause an overpressure that is much greater than the strength of most industrial buildings. In a dust explosion accident, a detonation is unlikely to occur spontaneously. It usually requires a DDT event. A DDT develops typically due to a dust flame propagation into a confined space combining with secondary/tertiary dust explosions.

3. Regulations and Standards for Dust Hazards Controlling

As a primary regulatory organization in charge of process safety, U.S. Occupational Safety and Health Administration (OSHA) began its combustible dust National Emphasis Program (NEP) in October 2007 to help lower the risk of workers being exposed to explosive dust hazards. In March 2008, OSHA issued the OSHA Fact Sheet of "Hazard Alert: Combustible Dust Explosions" to address the importance of dust hazard awareness. "In many combustible dust incidents, employers and employees were unaware that a hazard even existed. It is important to determine if a company has this hazard and, if it does, an action must be taken now to prevent tragic consequences [4]". From this Fact Sheet, OSHA also requires a thorough dust hazard analysis for all dust handled, all operations conducted (including by-products), all spaces (including hidden ones), and all potential ignition sources. In 2009, OSHA published Hazard Communication Guidance for Combustible Dust (OSHA 3371-08). This guidance is not a regulation, but an advisory document to help manufacturers and importers of chemicals recognize the potential for dust explosion and to identify appropriate protective measures as part of their hazard determination under the Hazard Communication Standard (HCS). As mandatory requirements, the following Federal OSHA standards address certain aspect of combustible dust hazards [5]:

- 29 CFR 1910.22 Housekeeping
- OSH Act: Section 5(a)(1) General Duty Clause
- 29 CFR 1910.94 Ventilation
- 29 CFR 1910.272 Grain Handling Facilities
- 29 CFR 1910.176 Housekeeping in Storage Areas
- 29 CFR 1910.269 Housekeeping at Coal-handling Operations
- 29 CFR 1910.1200 Hazard Communications
- 29 CFR 1910.178 Powered Industrial Trucks
- 29 CFR 1910.307 Hazardous (Classified) Locations
- 29 CFR 1910.132 Personal Protective Equipment (PPE)
- 29 CFR 1910.119 Process Safety Management
- 29 CFR 1910.252 Welding, Cutting, and Brazing Operations

In addition to OSHA standards, there are several industry consensus standards that address combustible dust issues. The primary National Fire Protection Association (NFPA) consensus standards and documents related to dust hazards include:

- NFPA 61, Standard for the Prevention of Fire and Dust Explosions in Agricultural and Food Processing Facility.
- NFPA 484, Standard for Combustible Metals.
- NFPA 655, Standard for the Prevention of Sulfur Fires and Explosions.
- NFPA 664, Standard for the Prevention of Fires and Explosions in Wood Processing and Wood-working Facility.
- NFPA 68, Standard on Explosion Prevention by Deflagration Venting.
- NFPA 69, Standard on Explosion Prevention Systems.

- NFPA 499, Recommended Practice for the Classification of Combustible Dusts and Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas.
- NFPA 77, Recommended Practice on Static Electricity.
- NFPA 654, Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids.
- NFPA 652, Standard on the Fundamentals of Combustible Dust.
- NFPA Fire Protection Handbook.

NFPA 652 was released in September 2015. It requires a dust hazard analysis (DHA) for those facilities and operations that manufacture, process, blend, convey, repackage, generate, or handle combustible dusts or particulate solids. A DHA for the existing facilities can be retroactive. The time limit to finish the DHA is three years from the date the standard became effective.

In addition to NFPA standards, OSHA has also referenced FM7-76, Prevention and Mitigation of Combustible Dust Explosions and Fires for dust hazard controlling. Some state and local fire codes may apply. There are two predominant model fire codes (International Code Council's International Fire Code, and NFPA's Uniform Fire Code) adopted by many jurisdictions.

4. A Risk-Based DHA

Based on CCPS's definition, a risk is a measure of human injuries, environmental damages, or economic losses in term of both the incident likelihood and the magnitude of the loss or injury. A risk-based DHA is a risk-analyzed approach for dust hazards identification and evaluation, which inherently includes the consequence prediction from a dust fire/explosion/toxic hazard and its likelihood estimation. A risk-based DHA can provide organizations with a method to implement risk tolerance criteria. It also provides a logical method of demonstrating that a performance-based protection option meets the intent of a regulatory or standards-based option. A risk-based approach may also be useful if standards don't have a prescriptive requirement for a particular piece of equipment [6].

In this paper, a systematic procedure is developed for a risk-based DHA study, which is illustrated in Figure 1 and discussed below in details.

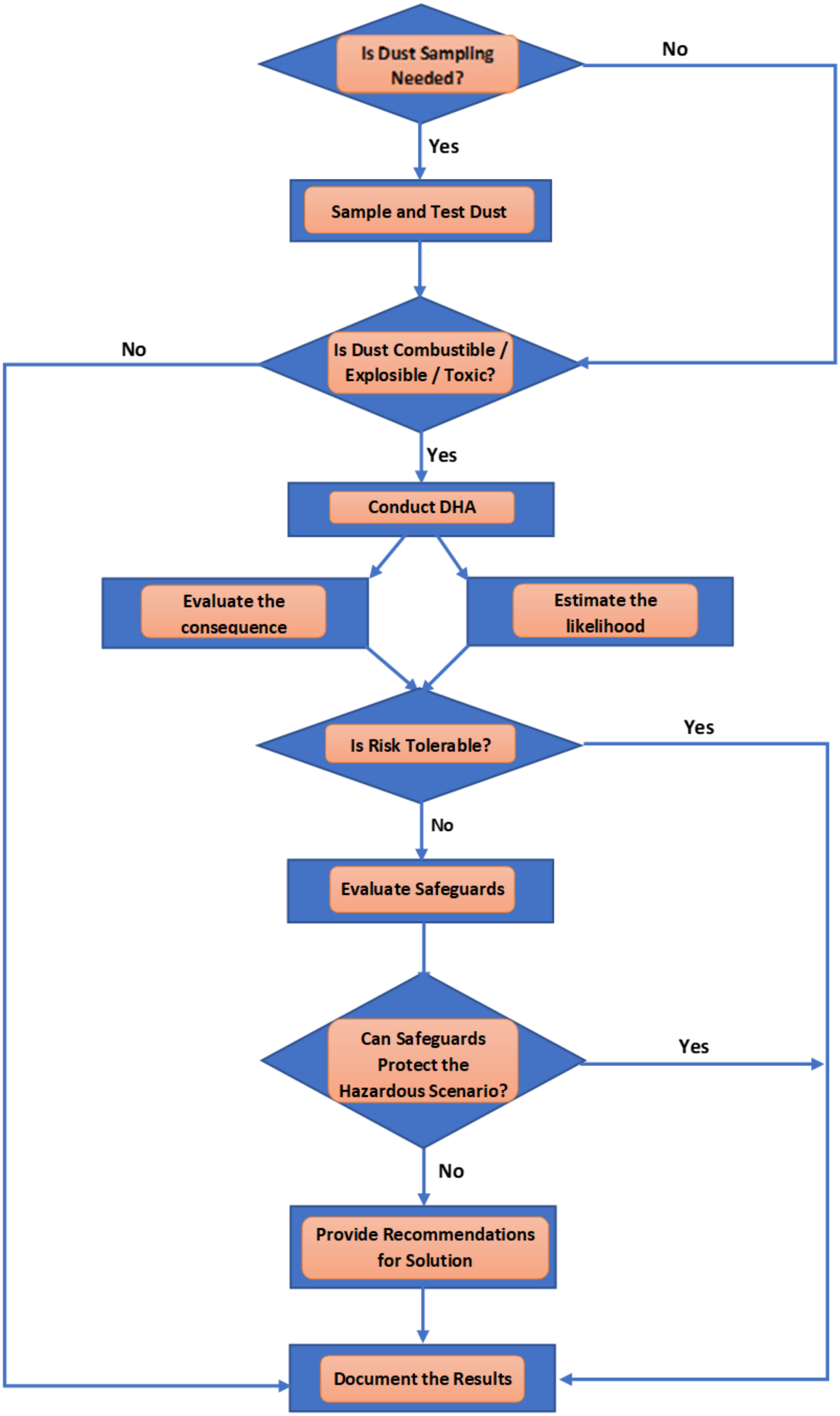

Figure 1 Flowchart for a Risk-based DHA

4.1 Dust Sampling

To identify dust hazards, a dust sampling plan should be developed and documented to provide data as needed to comply with the requirements from NFPA 652. Dust sampling may be optional under certain conditions, e.g., (1) Existing dust sampling/testing data are good representatives of the materials in dust process equipment or collected on surfaces at their near locations; or (2) Dust sampling/testing data are available from facility historical records or literature resources, which can be verified to be good representations of currently processing materials and operating conditions; or (3) Processing dust material is unlikely to be combustible or explosible. Material Safety Data Sheets (MSDS) are not reliable sources for a dust hazard identification. The U.S. Chemical Safety Board (CSB) reviewed the MSDS of 140 known substances that produce combustible dusts and found that 41% of the MSDS did not warn users about potential explosion hazards [1].

A successful dust sampling plan should include the following [7]:

- Identification of all the locations where dusts are present
- Identification and collection of representative samples
- Preservation of dust sample integrity
- Communication with the test laboratory regarding dust handling
- Documentation of samples taken

4.2 Dust Sample Testing

A number of dust physical properties (e.g., dust particulate size, moisture content, volume electrical resistance, etc.) and explosion parameters (e.g., K_{st}, P_{max}, MEC, MIE, MAIT, LOC, etc.) are commonly needed for a dust hazard analysis, particularly for a dust ignition probability analysis and a fire/explosion consequence prediction.

In general, dust sample testing shall be run on the materials as sampled. Many test procedures call for the sample to be dried to less than 5% moisture and screened, and the test run on material less than 200 mesh (75 microns) in size. This is done to represent a worst case for determining a material combustibility or explosivity property, but sometimes can be overly conservative.

To determine whether a dust has an explosion hazard or not, a "Go/No-Go" explosibility screening test is normally used by following ASTM E1226 standard. The pressure rise in the testing chamber is measured. If the ratio of the final pressure from the deflagration to the initial pressure is higher than 2, the dust is considered to be explosible. When the dispersed dust concentration in air falls within its flammability range, dust ignitibility is mainly dependent on the minimum ignition energy (MIE) if an ignition source exists, or the minimum autoignition temperature (MAIT) when no credible ignition sources are available. Dust MIE data can be collected by following the ASTM E2019 standard. ASTM E1491 provides the detailed guidance on MAIT testing. For dust layer fire due to a hot surface, a standard test by following ASTM E2021 can be applied. The parameters of dust minimum explosible concentration (MEC) and limiting oxygen concentration (LOC) are mostly referred for dust cloud inerting or dust flash fire/explosion prevention. The related standards ASTM E1515 and ASTM E2931 are designated for dust MEC and LOC testing, respectively.

4.3 Conduct a Risk-based DHA

Whenever a facility is determined to have combustible or explosible dust materials, the facility owner/employer shall be responsible to ensure a DHA is completed in accordance with the requirements of NFPA 652, as well as to comply with other applicable regulations and standards.

A DHA is designed to identify and evaluate dust-involved hazards to personnel, property, or the environment. Dust hazards may include flash fire, layer fire, explosion, or toxicity. A risk-based DHA analyzes a dust hazard's consequence, and the corresponding likelihood. A risk value will be assigned to each of the specific hazardous events, and then compared with organization's risk criteria to recommend prevention or mitigation measures if necessary. Similar to a typical HAZOP process hazard analysis, a risk-based DHA is a qualitative approach, which includes a systematic logic flow as follows:

4.3.1 Identify Initial Events

To be consistent with the requirements from NFPA 652, a dust hazard analysis should consider the combustible hazardous dusts present within the equipment, or dust accumulation on surfaces within buildings or building compartments. Dusts outside of buildings are not within the DHA scope unless frequent personnel exposures happen. If a large amount of toxic dusts or their by-products release to atmosphere, both onsite and off-site safety and/or environmental concerns are included in the risk-based DHA.

Based on insurance organization's data, FM-Global provides a list of common process equipment involved in dust fires and explosions [8]: air-material separators (e.g., cyclones, baghouse filters, cartridge filters); solid size reduction equipment (e.g., grinders, mills); dryers (e.g., spray dryers, flash dryers, fluid bed dryers, agitation dryers); dust storage vessels (e.g., silos, hoppers); conveyors (e.g., screw conveyers, belt conveyers, bucket conveyers, pneumatic conveyers); portable containers (e.g., RIBCs, FIBCs, fiber drums); blenders/mixers; and others. Dusts in equipment can always be treated as in a confined space. For most of dust-involved processes, air is present in the equipment therefore, dust explosion contingencies are primarily based on the potential ignition source's identification.

In the absence of good housekeeping practices, the accumulation of dust on different surfaces can occur slowly through nearly invisible fugitive dust leaks. In addition to floors under and around processing equipment, dust accumulation can occur on any horizontal or slightly inclined surface, including beams and supports, ledges, conduit and pipe racks, cable trays, ducts, above suspended ceilings, etc. Such surfaces can easily have enough dust to create a dust fire, or a worse dust explosion hazard, especially the secondary or tertiary dust explosions in congested areas. A risk-based DHA is required for a building with poor dust housekeeping. Same to the dust hazard contingencies analysis within equipment, potential ignition sources introduction or generation within the buildings will be analyzed systematically.

Process deviations within a pre-noded operation are the basis for dust hazards initial events identification. Compared with a typical HAZOP study, some generally applied parameters, e.g., temperature, pressure, flow, and level, may work but could not well represent an abnormal operation. For example, a high or low temperature is not normally a credible scenario as most dust processes are at ambient conditions; a high or low dust flowrate is not the dependence for dust explosion severity but a potential for the secondary or tertiary explosion. In a risk-based

DHA, any potential ignition sources introduction or generation is applied as a process deviation to identify a dust hazard initial event. Potential ignition sources may be an open flame, a hot surface, a mechanic/electrical spark, overheating from mechanical friction or abnormal heat input, an electrostatic discharge, or others. Here are some typical examples for a dust-involved process deviation:

- Overheating from mechanical friction, e.g., lubrication loss to a bearing, conveyer belt mis-alignment
- Overheating from an abnormal heat input, e.g., a control valve leading to more hot air inflow into a dryer
- Smoldering from a dust layer decomposition or reaction
- Loss of cooling
- Hot surfaces, e.g., furnaces, electrical motor, or exchangers
- Open flames
- Hot work, e.g., cutting, welding, and grinding
- Mechanic spark from, e.g., tramp metal, loss of hammer, or friction
- Ignition sources from an upstream feed
- Electrical spark/arc generated from electrical equipment
- Electrostatic discharge
- External events, e.g., Incident fires
- Industrial truck
- Others

4.3.2 Predict Dust Hazard Severity

An uncontrolled initial event may propagate into any of the ultimate consequences, e.g., onsite or off-site injuries or fatalities, property losses, and/or environment damages. As an example, Table 1 describes the dust hazard consequence categories.

Table 1 Risk-based DHA Consequence Categories

Category	**Description**	**Onsite/Off-site People**	**Business/Asset**	**Environment**
A	Catastrophic	Public: Serious injury or fatality Onsite: Several fatalities (≥ 2)	> 10 M dollars of loss	Large uncontained toxic release off-site
B	Very Serious	Public: Medical treatment Onsite: 1 fatality, or permanent disabilities	1 M – 10 M dollars of loss	Moderate toxic release off-site
C	Serious	Public: No impact Onsite: no fatality, irreversible disabilities	100 K – 1 M dollars of loss	Minor reportable toxic release off-site
D	Minor	Public: No impact Onsite: Minor reversible injuries	10 K – 100 K dollars of loss	On-site clean-up

In this risk-based DHA, prediction of dust hazard severity is a qualitative estimation in term of the combination effect from different factors, for example, dust combustibility or explosibility (e.g., K_{st}, P_{max}, $(dP/dt)_{max}$), dust toxicity (e.g., exposure limits on 8-hours TWA), dust physical properties (e.g., particulate size and moisture content), occupancy nearby, dust dispersion space and confinement, hybrid mixture, secondary dust explosion tendency, and so on. For a dust explosion, its severity will become worse if the dusts are:

- More finely divided
- Higher K_{st}, or more reactive
- More irregularly shaped
- With less moisture content, or drier
- Less agglomerated
- Slightly higher than the stoichiometric concentrations
- Larger amount of dust dispersion
- More turbulent conditions
- With a more confined degree
- Combustible gas/vapor contained (a hybrid system)

4.3.3 Estimate likelihood

Normally, the likelihood of a dust-involved failure scenario could not simply be taken as the frequency of initiating event. The probability of the series of other unplanned events needs to occur to lead to an undesirable consequence. For example, the presence of credible ignition sources, or the presence of suspended dust within the explosible range. The probability of occupancy is commonly used as a frequency modifier based on the data of time-at-risk. Eq. (1) below gives the formula to calculate the overall likelihood of a dust explosion failure scenario before safeguards are applied.

$$P_t = P_e \times P_i \times P_s \times P_r \qquad \text{Eq. (1)}$$

Where,

P_t is the overall likelihood of a dust-involved failure scenario before safeguards are applied in the unit of times per one year.

P_e is the frequency of an initial event in the unit of times per one year. A reliable data source should be sought after from the facility historical incidents or near-miss data records, or other facilities with the similar process operations. Industrial generic databases, e.g., CCPS books, UK HSE, or US OGP can be referred for an initial event frequency estimation if the facility's specific failure data is not available. Table 2 lists some generic initial events failure frequency data based on a CCPS book [9].

P_i is the probability of a dust ignition, which is dependent on the presence of credible ignition sources. It is unitless. The value of probability is between 0 and 1, where 0 means very unlikely, and 1 is very likely. Probability of a dust ignition is closely related to dust material characteristics (e.g., MIE, MAIT, particle size, moisture content, etc.) when combustible dusts suspend in air within flammability limit range. Dahn, Reyes, and Kusmierz gave some ignition ease criteria for dust fire and explosion engineering hazards analysis (in Table 3 below) based on different stimuli and the levels of stimuli [10]. Some common ignition sources and ignition probabilities are discussed below:

- Open flames: The probability of a dust ignition can be 1 since an open flame is generally capable of igniting any combustible dust.
- Overheating from mechanic friction: Friction from hot bearings or jammed belts represents a very high portion of ignition sources [8]. A very high temperature may generate from mechanic friction due to a loss of lubrication or misalignment. The probability of dust ignition can be conservatively taken to be 1 for a bearing friction [11].
- Hot work (e.g., cutting, grinding, welding): Hot work can release very high energy intensity heat or spark, which may have 100% of potential chance to ignite combustible dusts [11].
- Overheating from abnormal heat input or loss of cooling: Combustible dust MAIT is a main factor to be referred to for this type of ignition probability estimation. Attention should be paid to dust moisture loss during the abnormal heat input or loss of cooling phase, since a drier dust may have a much lower MAIT than the sampled one, and the ignition probability can increase dramatically.
- Mechanical impact/friction sparks: Combustible dust ignition probability from mechanical sparks depends on both its MIE and MAIT. The International Social Security Agency (ISSA) provides some guidance on dust cloud ignitability prediction using spark equivalent electrical energy and ignition temperature. Figure 2 gives an example based on steel grinding spark and steel friction spark [12], where the intersection of the MIE and MAIT can be located to identify whether dust is ignitable from a mechanical grinding/friction spark.
- Electrical Sparks or arcs: Electrical equipment can produce sparks or arcs that may ignite a dust cloud. Combustible dusts ignition by electrical arcs has very high probability (can be 1 for a conservative purpose). Electrical sparks to ignite a dust cloud can be similar to mechanical sparks depending on dust MIE and MAIT.
- Electrostatic discharges: Static electricity is often generated by the flow of solids during handling, transfer and processing. The susceptibility of combustible dust to ignition by electrostatic discharge is a function of the MIE of the dust. Table 4 includes the data of ignition probability based on MIE range for a dust ignitability analysis [11].
- Smoldering: Smoldering is a flameless combustion. If a smoldering dust pile is disturbed, it can lead to a dust deflagration in the form of flash fire or explosion. The likelihood of ignition for smoldering nests depends on the material being handled. An organization needs to determine this from historical information or appropriate testing.

P_S is the probability of the presence of a suspended dust within the explosible range. It is unitless. Most explosible dusts have the explosible range of 50-100 g/m^3 on the lean side, and 2-3 kg/m^3 on the rich one [13]. Per NFPA 654, a dust layer larger than 1/32 inch accumulated on surface areas of at least 5% of a room's floor or above ceiling presents a significant explosion hazard [14]. The probability of dust suspension in air to form a combustible dust-air mixture is highly dependent on the total dust amount, air stability, and dust movement conditions. For conservative purpose, this probability is normally taken to be 1 unless there is a firm basis for other values.

P_O is the probability of time at risk, which can be determined based on the fraction of time the "at-risk" condition exists. In general, it can be calculated using equation as Eq. (2).

$$P_r = {}^{Hours\ at\ risk}\!/_{Total\ hours\ (1\ year)} \qquad \text{Eq. (2)}$$

By combining the initial event frequency with all other applicable probabilities from frequency modifiers and/or other unplanned events, the likelihood of a dust-involved failure scenario can be estimated and categorized as described in Table 5. Note that the estimated likelihood is before safeguards applied.

Table 2 Initial Event Frequencies

Item	**Description**	**Frequency**
BPCS Control Loop	The process parameter controlled by the BPCS control loop deviates without the ability to recover on its own, resulting in a consequence of concern.	0.1/yr
Safety Controls, Alarms, and Interlocks (SCAI)	The spurious operation of SCAI may lead to an upset or other consequence of concern.	0.1 - 1/yr
Human Error (Routine task performed >= 1/week)	A human error occurs on a task that is performed at a frequency of once per week or more often. The consequences are dependent on the task being performed by the person.	1/yr
Human Error (Routine task performed 1/week to 1/month)	A human error occurs on a task that is performed at a frequency between once per week to once per month. The consequences are dependent on the task being performed by the person.	0.1/yr
Human Error (Routine task performed < 1/month)	A human error occurs on a task that is performed at a frequency of less than once per month. The consequences are dependent on the task being performed by the person.	0.01/yr
Pressure Regulator Failure	This scenario covers a self-contained pressure regulator in pressure reducing or backpressure service, operating in continuous control mode, which fails to operate as designed (opened or closed)	0.1/yr
Screw Conveyor Failure	The failure of the screw conveyor stops the process flow, resulting in an upstream and/or downstream upset or other consequence of concern.	1 to 10/yr
Screw Conveyor Overheating of Materials	Overheating of the conveyed material, potentially resulting in ignition or decomposition of material within the conveyor.	0.1/yr
Fan or blower failure	This loss of operation could result in process upset, with a number of possible consequences as a result of process deviation.	0.1/yr
Single Circuit Loss of Power	Complete or partial loss of local power due to a component failure in single circuit. Does not include frequency of site-wide power loss.	0.1/yr

Hose failure, leak and rupture	Applies to leaks or complete failure due to age, external damage, wear, etc.	0.1/yr (leak) 0.01/yr (rupture)

Table 3 Ignition ease criteria for dust fire and explosion hazard analysis

Stimuli	Ease of Ignition	Levels of Stimuli
Thermal (Heat)	Low Temperature	$< 100\ ^{O}C$
	Medium Temperature	$100\ ^{O}C$-$300\ ^{O}C$
	High Temperature	$> 100\ ^{O}C$
Electrostatic Discharge	Easy	< 5 mJ
	Moderate	5-30 mJ
	Difficult	30-200 mJ
	Hard to Ignite	> 200 mJ
Impact	Low Energy	0.5 kg-m
	Moderate Energy	0.5-5 kg-m
	High Energy	> 5kg-m
Friction	Easy	100-2000 psi@7fps
	Moderate	2000-15000 psi@7fps
	Hard to Ignite	> 15000 psi@7fps
Chemical Decomposition	Low	< 100 cal/gm
	Moderate	100-500 cal/gm
	Higher	500-1500 cal/gm
	Highest	> 1500 cal/gm

Table 4 MIE *vs.* dust ignition probability

MIE	Ignition Probability
0 – 10 mJ	1
10 – 100 mJ	0.1
>100 mJ	0.01

Table 5 Likelihood and Frequency code for a Risk-Based DHA

Likelihood P_t (times/yr)	Unmitigated Event Frequency Code	Description
≥ 1	1	Very frequent: occurs at least once per year

0.1 - 1	2	Frequent: likely occurs at least once in 10 years
0.01 – 0.1	3	Infrequent: likely occurs at least once in 100 years
≤ 0.01	4	Improbable: likely occurs less than once in 100 years

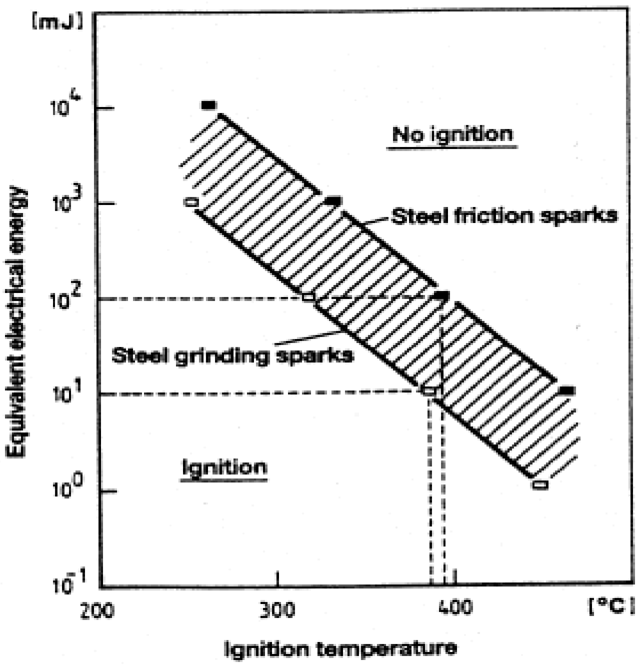

Figure 2 Conditions for ignition of dust by mechanical grinding and friction sparks.

4.3.4 Conduct Risk Ranking

By applying the organization approved risk matrix, each cause-consequence combination which constitutes a hazard scenario can be risk-ranked. As an example, Figure 2 shows the number of credible safeguards or independent protection layers (IPLs) required based on the initial event consequence and likelihood before safeguards applied, where risks are tolerable for failure scenarios of Severity “D”/Likelihood “3” and “4”, as well as Severity “C”/Likelihood “4”.

Likelihood

Consequence

	1	**2**	**3**	**4**
A	4	4	3	2
B	4	3	2	1

C	3	2	1	NR
D	2	1	NR	NR

Figure 2 Risk Matrix for a Risk-based DHA

4.3.5 Determine Safeguard Credits

This step is designed to review and document credible safeguards or IPLs for prevention and/or mitigation of the consequences. Safeguards are engineered system(s) as defined in the P&IDs and other engineering information, and the administrative controls, such as operator response to alarms, that can prevent or mitigate the hazard including, but not necessarily limited to, such items as:

- Prevention safeguards
    - Prevent dust presence (e.g., no dust leakage)
    - Prevent dust dispersion (e.g., wet conditions, large particle size)
    - Control dust concentration outside of flammability range (e.g., inerting)
    - Remove ignition sources (e.g., no hot surface/flame, grounding and bonding, electrical area classification, control of hot work, lubrication, vibration/temperature monitoring)
- Mitigation safeguards
    - Explosion containment (e.g., vessel designed to contain explosion, install an explosion cover/shield)
    - Explosion suppression (e.g., inject explosion suppressants)
    - Explosion isolation (e.g., shut-off valve, rotary valve, physical barriers)
    - Explosion venting (e.g., overpressure venting and relief systems)
    - Fire and toxic response system (e.g., sprinklers, toxic powder/gas detectors)
- Administrative Safeguards
    - Housekeeping programs
    - Emergency response/PPE
    - Training programs

Each safeguard or IPL will be assigned a credit value. These values are obtained by referring to various databases and guidance books, such as CCPS and an example is shown in Table 6 [6, 15]. The assignment of the credit values should be verified with facility process engineers, operators and instrument professionals if extra information is needed.

4.3.6 Provide Recommendations

Based on the IPLs required and IPLs available, the gap will be calculated and the recommendations will be made if the IPLs required are less than credible safeguards or IPL credits. Additional IPLs recommended to be added should reduce the risk by: (1) preventing the consequences altogether via design alternatives; (2) lowering the likelihood of the failure scenarios; (3) and/or mitigating the consequences.

The risk-based DHA team should review the engineering design solutions or administrative controls to ensure that the proposed recommendations would sufficiently reduce the risk and not introduce new hazards or risks. After applying the recommended solutions, a revalidation of the failure scenarios should be conducted promptly to determine if the recommended solutions reduce the risk to an acceptable level.

During a risk-based DHA study, the DHA team may recommend some more detailed analysis, e.g., semi-quantitative LOPA, or quantitative QRA, for those failure scenarios with high severity or/and risk.

Table 6 Common Safeguards and Assigned Credits

Item	**Description**	**credit**
Safety Interlock	Safety interlocks prevent progression of a scenario to the consequence of concern following an initiating event.	1
SIS Loop	A SIS loop presents progression of a scenario following an initiating event.	SIL-1: 1 SIL-2: 2 SIL-3: 3
Explosion isolation valve	The explosion isolation valve protects against the propagation of flame between interconnected equipment.	1
Explosion panels on process equipment	Proper operation of explosion panels during an internal dust explosion can protect a vessel or duct from excessive overpressure.	2
Vent panels or enclosures	Vent panels prevent damage to an enclosure or room. However, activation of the panel does result in a pressure wave and loss of containment of dust. If the vent panel relieves into an occupied area, a vent panel may not be an effective IPL against impact to nearby workers.	2
Automatic fire suppression system	Within process equipment: the automated fire suppression system prevents propagation of a fire outside of process equipment.	1
Automatic fire suppression system	For local application: fire suppression systems for local application mitigate fires in small areas.	1
Automatic fire suppression system	For a Room: fire suppression systems mitigate fire in a room or small enclosure.	1
Human response to an abnormal condition	Human response to an abnormal condition can prevent a variety of possible consequences of concern.	1
Automatic explosion suppression system	The explosion suppression system protects against explosions that could cause equipment damage, including rupture. More quantitative analysis may support a lower PFD value for a specific system than the generic PFD provided.	1
Personal Protective Equipment (PPE)	PPE prevents consequences associated with exposure of people within the area of potential impact to a hazard of concern.	1
Dike	Will reduce the frequency of large consequences (widespread spill) of a tank overfill/rupture/spill etc.	2
Open Vent (no	Will prevent overpressure.	2

valve)		
Fireproofing	Will reduce rate of heat input and provide additional time for depressurizing/firefighting/etc.	2
Blast-wall/bunker	Will reduce the frequency of large consequences of and explosion by confining blast and protecting equipment/buildings/etc.	3
"Inherently Safe" Design	If properly implemented can significantly reduce the frequency of consequences associated with a scenario. Note: the LOPA rules for some companies allow inherently safe design features to eliminate certain scenarios (e.g., vessel design pressure exceeds all possible high-pressure challenges).	2
Flame/Detonation Arrestors	If properly designed, installed and maintained these should eliminate the potential for flashback through a piping system or into a vessel or tank.	2
Relief Valve	Prevents system exceeding specified overpressure. Effectiveness of this device is sensitive to service and experience.	2
Rupture Disk	Prevents system exceeding specified overpressure. Effectiveness can be very sensitive to service and experience.	2
Basic Process Control System	Can be credited as an IPL if not associated with the initiating event being considered.	1

4 Conclusion

For any facility with hazardous dusts that present an explosion, flash fire, layer fire, or toxic hazard, a dust hazard analysis is mandatorily required per NFPA 652. However, NFPA 652 lacks the detailed guidance on dust hazard assessment. Other industry-specified NFPA standards are mostly about the prescriptive DHA, which may not have a prescriptive requirement for a particular piece of equipment or may create unnecessary overprotection for some hazard-involved dust processes and equipment.

In this paper, a risk-based approach is developed by incorporating both likelihood and consequence to estimate the risk for any failure scenario. By applying the organization’s risk tolerance criteria, a ranked risk value will be given to the analyzed scenario as the safeguard or IPL requirements. For any unacceptable consequence, safeguard availability review and IPL credit evaluation will be conducted. The gap between the IPL requirements and safeguard IPL credits will warn the risk-based DHA study team to provide risk-reduction recommendations. Compared to a prescriptive DHA, a risk-based DHA provides a sufficient understanding of dust hazards, as well as the appropriate safeguard level of demand for dust process safety work activity.

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