Application of a short cut risk analysis methodology for analyzing dust explosion hazards

Kees van Wingerden
GexCon AS
Fantoftvegen 38, Bergen, Norway
kees@gexcon.com

Geir Pedersen
GexCon AS
Fantoftvegen 38, Bergen, Norway
geir@gexcon.com

Scott Davis
GexCon US Inc
7735 Old Georgetown Road, Suite 1010, Bethesda, MD 20814
sgdavis@gexcon.com

Prepared for Presentation at
American Institute of Chemical Engineers
2010 Spring Meeting
6th Global Congress on Process Safety
San Antonio, Texas
March 22-24, 2010

UNPUBLISHED

Application of a short cut risk analysis methodology for analyzing dust explosion hazards

Kees van Wingerden
GexCon AS
Fantoftvegen 38, Bergen, Norway
kees@gexcon.com

Geir Pedersen
GexCon AS

Scott Davis
GexCon US Inc

Keywords: Risk analysis, dust explosion, preventive measures, protective measures

Abstract

In this paper a semi-quantitative short-cut risk analysis method (SCRAM) is presented, allowing for the assessment of dust explosion hazards. The method is first described and two application examples are presented.

SCRAM is based on semi-quantitative descriptions of both the likelihood of dust explosions occurring and the consequences of such explosions. The likelihood of dust explosions occurring is based on the ignition probability and the probability of flammable dust clouds arising. While all possible ignition sources are reviewed, the most important ones include open flames, mechanical sparks, hot surfaces, electric equipment, smoldering combustion (self-ignition) and electrostatic sparks and discharges. Apart from the machinery, the ignitibility and explosibility of the dust will also play an important role.

The consequences of dust explosions are described as consequences for personnel and consequences for equipment. The method reviews the consequences of both primary and secondary events. Factors determining the consequences of dust explosions include the how frequently personnel are present, the equipment strength, housekeeping and implemented consequence-reducing measures. Both the likelihood of dust explosions and consequences are described by classes ranging from low probabilities and limited local damage, to high probability of occurrence and catastrophic damage. Acceptance criteria are based on the likelihood and consequence of the events.

The method allows for optimal choice of adequate preventive and protective measures.

To demonstrate the method an application of the method is presented: a milk powder production facility.

Note: Do not add page numbers. Do not refer to page numbers when referencing different portions of the paper

1. Introduction

Dust explosions are a continuous threat in companies producing flammable powders and dust as final and intermediate products. Sad recent examples include the serious accidents in Kinston, North Carolina in 2003 (killing 6), Savannah, Georgia in 2008 (killing 14), and one year later the explosion in a coal silo injuring 7 in Oak Creek, Wisconsin (2009). These serious accidents are accompanied by many smaller dust explosion accidents in industry causing limited damage and minor or no injuries. Some of them could however have led to more serious consequences.

Dust explosion risks prevailing in industrial facilities are dependent on a large variety of factors that include process parameters, such as pressure and temperature, as well as equipment properties, such as the presence of moving elements, the mechanical strength of such dust handling equipment, dust explosion characteristics, and mitigating measures taken including housekeeping and protective measures such as explosion venting.

In this document a semi-quantitative short-cut risk analysis method (SCRAM) is presented, allowing for the assessment of dust explosion risks and choosing adequate preventive and protective measures. The performance of an analysis as described here would make industry aware of the most hazardous areas in their facilities and associated consequences in case of an explosion.

The method is described and an application example presented. The example demonstrates the strength of the method and the support it offers to industry for choosing appropriate risk mitigating measures.

2. Description of the short-cut risk analysis method

This chapter describes the methodology used to determine the risk for dust explosions in industrial facilities. The risk for a dust explosion is the product of the probability of a dust explosion occurring and the consequences of the dust explosion. The consequences can be divided in primary consequences such as failure of the piece of equipment in which the dust explosion occurs and secondary consequences such as a an ensuing fire and secondary explosions in connected equipment or in the working area due to whirling up and subsequent ignition of dust layers there.

2.1 Estimating the probability of an explosion occurring

For a dust explosion to occur a flammable atmosphere must be present and simultaneously a sufficiently strong ignition source. The dust concentration in this atmosphere must exceed a certain limits, typically 30 g/m^3, and the particle size distribution must be sufficiently small. Dust with particle size distribution from 10 to 40 micron and dust concentration range from 250 to 1500 g/m^3 have shown to ignite easiest and produce the most severe explosions. Finer dust might produce more severe explosions if the dispersion process has enough force to break up the agglomerates and produce a dust cloud consisting of primary particles.

To be able to quantify the probability for the occurrence of an explosive atmosphere, properties of the combustible material should be considered, together with how likely it is that the combustible material will be mixed with air.
The probability of a specific ignition source being able to ignite the explosive atmosphere is considered based on different criteria, such as the energy released by the ignition source, the period in which this energy is supplied, the surface temperature of the ignition source and its size. For mechanically generated sparks, collision speed, friction, contact time and physical properties of the colliding materials are included.

Whether an ignition source is capable of igniting an explosive atmosphere depends on several properties of the atmosphere, for instance the fuel concentration and the turbulence level and the ignition properties of the explosive atmosphere (normally described by the minimum ignition energy and minimum ignition temperature).

The factors mentioned above are considered individually and form the basis for estimating how often an explosion can occur. It is not possible to give the exact frequencies for an explosion. In a risk analysis the probability for an explosive atmosphere and the probability for an ignition source are ranged from "*I*" to "*V*", where "*I*" has the lowest probability and "*V*" has the highest probability. Each "range" (I, II, III, IV and V) describes a range in "probability" or "frequency".

The probability of an explosion occurring depends on the probability of the presence of an effective ignition source and the probability of having an explosive atmosphere. The probability of an explosion will be the product of these two probabilities (as long as the two are generated independent from each other). Definitions and explanations of the values used are described below.

The probability for a secondary event depends on the probability for the primary event and is normally lower than that of the primary event.

2.2 Estimating the consequences of an explosion

The consequence for personnel (D_p) and equipment (D_e) is estimated based on the expected effect of the explosion. This is estimated based on expected damage caused by the heat, pressure or loose items after the definitions given below. The consequence for personnel and equipment from an explosion depends on the explosion pressure and the heat intensity from the explosion. Pressure build-up in enclosed units might cause the units to rupture resulting in heat radiation from flames, dispersion of pressure waves and flying objects.
The strength of an explosion depends on several factors, for example the initial conditions of the dust cloud, including the fuel concentration, initial turbulence and the position of the ignition source. The properties of the combustible material are also important, including chemical composition. The properties of the explosive atmosphere will change over time hence, the time of the explosion is important for the explosion propagation.
Flames propagating out from a ruptured vessel release heat that might injure personnel or cause damage to equipment. The convective heat transfer during an explosion causes the most severe burns. Burns/damage might be the result if personnel or equipment are in direct contact with the explosion flame.

2.3 Definitions

The probability or the frequency of an explosion occurring and the potential consequences is estimated from I to V, as described previously. The definition and description of the different values are given below.

Table 1 Definition of the probability and consequence for explosions under normal operation

Probability of the formation of an explosive atmosphere	
Range, D_a	**Description**
I	Very unlikely
II	Unlikely
III	Somewhat likely
IV	Likely
V	Very likely

Probability of the formation of an effective ignition source	
Range D_i	**Description**
I	Very unlikely
II	Unlikely
III	Somewhat likely
IV	Likely
V	Very likely

Probability for an explosion to occur		
Range D_e	***Description***	***Definition***
I	Very unlikely	< 1/ 10000 per year
II	Unlikely	> 1/10000 per year < 1/100 year
III	Somewhat likely	> 1/100 < 1/10 per year
IV	Likely	> 1/10 year < 1 per year
V	Very likely	> 1 per year

Consequence for personnel and equipment		
Range D_p D_e	**Description**	**Definition**
I	Personnel	No injury.
	Equipment	Marginal damage to process units. Process shut down.
II	Personnel	Limited injury.
	Equipment	Damage to process unit (<$ 20, 000).
III	Personnel	Personnel injury.
	Equipment	Process unit collapse and possible damage to corresponding units (> $ 20, 000; < $ 200, 000).
IV	Personnel	Serious personnel injury, possible loss of life.
	Equipment	Significant damage to several process units (> $200, 000; < $2, 000 000).
V	Personnel	Loss of one or several lives.
	Equipment	Plant fully damaged (> $2, 000 000).

2.4 Estimating the explosion risk

The explosion risk is the product of the probability of an explosion occurring and its consequences. In the present risk analysis a qualitative risk evaluation is completed for each process unit. The risk level for explosions can be estimated from the matrix given in Figure 1 below, based on the probability and consequence, as described in the above section, and after the definitions in Table 1 also above. The risk level increases from E to A.

Consequence	**V**	C	B	A	A	A
	IV	D	C	B	A	A
	III	E	D	C	B	A
	II	E	E	D	C	B
	I	E	E	E	D	C
		I	**II**	**III**	**IV**	**V**
	Probability					

Figure 1 Risk matrix

2.5 Acceptance criteria

The risk level and the "recommended acceptance criteria" are selected and based on the probability for human and economical loss according to Table 1 above. The selected criteria are given in Table 2 below. It should be emphasized that these acceptance criteria are a proposal only and may be chosen differently.

Table 2 Risk level – definitions and recommended acceptance criteria

	Risk level	Acceptance criteria	Recommended action
A	Very high	Unacceptable	Risk reducing measures must be implemented
B	High	Unacceptable	Risk reducing measures must be implemented
C	Medium	Medium	Risk reducing measures should be implemented
D	Low	Acceptable	Risk reducing measures can be implemented
E	Very low	Acceptable	Risk reducing measures are not required

In the application example given in this document, the estimations of probabilities and consequences are summarized in tables. These tables also include estimations of ignition source probability and an estimate of the risk of secondary incidents/events.
Below, explanations to the different parts of the tables are given.

Table 3 Example of table summarizing the assessment of probability and consequences of a dust explosion in a process unit.

Process unit	**Probability of flammable atmosphere**	**Probability of ignition**					**Probability of explosion**
Example		*Equipment (electric and mechanical)*	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flames and smoldering combustion*	
	IV	II	I	I	I	I	II

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	II	III	III	E	D
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	I	V	V	C	C
Comments: ***EXAMPLE***					

Process unit: The process unit the analysis applies to.

Probability: The estimated explosion probability. The probability of an explosion is the product of the probability for "an explosive atmosphere" and "effective ignition source".

Consequence: The consequences for an event considering both personal injuries and damage to equipment. Both primary and secondary consequences are given. Definitions for explosion related probability, (and consequences) are given in the above section.

Risk: The product of *probability* and *consequence*. Both the risk of primary and secondary events is estimated. See Table 2 for acceptance criteria.

Ignition source: Probability for occurrence of the five most common ignition sources are given.

3. Application example: a spray dryer installation for milk powder

To demonstrate the method an analysis performed for a spray dryer installation used for drying milk powder (see Figure 2) is presented. The total height of the spray dryer is 15 m, the height of the cylindrical part is 6.3 m supported by a conical part (angle 60º). To move dried powder out of the conical part a pneumatic hammer has been provide. The temperature of the hot air to dry the milk slurry is 200 º C. The temperature of the air leaving the dryer is 90 ºC. Based on air and product throughput the average dust concentration in the dryer would be 30 g/m^3. The dried powder collected in the cone of the spray dryer is transferred into a fluidized bed for further drying or cooling. The powder taken along with the air flow out of the dryer is removed from the air by cyclones and a bag filter. Also the air from the fluidized bed is cleaned in cyclones and the bag filter. The dust collected in the cyclones is returned to the fluidized bed by pneumatic transport.

The described spray dryer installation has not been provided/equipped with any special preventive or protective measures. The installation is located inside a building. Personnel is around the installation only occasionally for inspection reasons.

3.1 Analysis

The analysis has been performed for the dryer only.

To perform the risk analysis the explosion properties of milk powder need to be known. Although it is strongly preferred to have these properties determined for the milk powder in question the present study was performed using literature data. This may lead to overconservative preventive and protective measures resulting from the analysis since one would normally base oneself on the most conservative values of published data. On the other hand an underestimate of the hazards may also be possible, especially for dusts where only a limited set of explosion properties is available. For milk powder the use of literature data is acceptable since there is a rather big number of well-described data available which are not varying much. The data found for milk powder are presented in Table 4 (from Beck et al, 1997).

Table 4 Explosion properties of milk powder (Beck et al., 1997)

Explosion property	Value
Maximum explosion pressure P_{max} (bar)	6-7
Dust explosion constant K_{St} (bar.m/s)	80-130
Minimum ignition energy (MIE) (mJ)	> 50
Minimum ignition temperature (MIT) (ºC)	450-600
Lower explosion limit (LEL) (g/m^3)	60-150

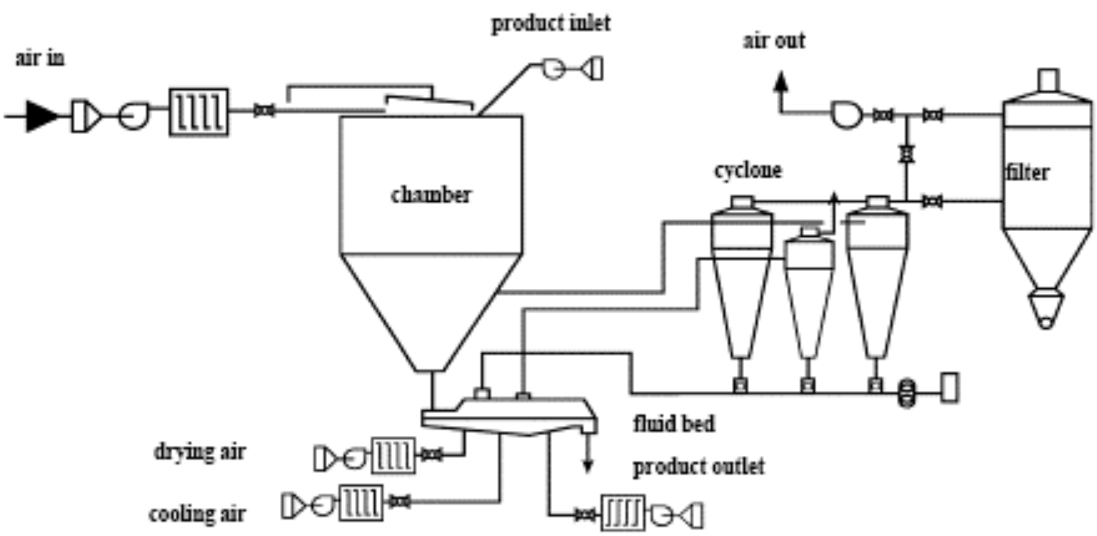

Figure 2 Analyzed milk powder spray dryer installation

In addition to the properties presented in Table 4 it is known that milk powder stored in bulk might self-ignite when exposed to a higher temperature over a longer period. Tests show that storage at a temperature of 80-90 ºC during a period exceeding 20 hours results in self-ignition (Le Maillard reaction).

Hazards identification

Under normal operating conditions the average dust concentration in the dryer is below the lower explosion concentration. Locally in the cone however one can expect that flammable concentrations can be reached though being it intermittently. An initial local explosion could however whirl up dust present on the cone walls causing a stronger secondary explosion (Siwek et al., 2004). Potential ignition sources include mechanical sparks due to the rotating spraying wheel in the top of the dryer coming loose and hitting the wall of the dryer (In the light of the minimum ignition temperature and minimum ignition energy of milk powder this ignition source is most likely not able to cause ignition) and self-heating of layers of milk powder. The latter would especially be possible if the rotating spraying wheel, in case of an anomaly, is distributing the milk slurry against the walls of the cylindrical part of the dryer. The hot drying air could cause the resulting milk powder cake to self-ignite. The smoldering material could come loose and fall into the cone of the dryer, causing either ignition of a flammable dust cloud there or whirl up dust and causing this to ignite.

The probability of the latter is relatively high and based on historical evidence an explosion should be expected with a frequency of between 10^{-1} and 10^{-2} per year (probability class III). Here it is assumed that the ignition source also causes the dust cloud (a smoldering cake of milk powder falling into the cone of the dryer).

A final ignition source could be an explosion occurring in other parts of the drying installation running back into the dryer. This ignition source, although very realistic, is not considered here since in a full risk analysis of the spray dryer installation it has to be considered in the analysis of the other pieces of equipment of the installation. In this document it is assumed that sufficient preventive and protective measures are taken to prevent this from happening, i.e. the likelihood of this ignition source occurring is assumed to be sufficiently low.

The consequence of the explosion is most likely the failure of the dryer (explosion tests reported by Siwek et al. (2004) show that pressure up to 1 bar are possible; it should be mentioned however that these tests were performed under conservative conditions) potentially injuring personnel or even causing fatalities if in the vicinity of the dryer at that very moment (consequence classes III and IV respectively). Moreover there is a possibility that the explosion propagates into the fluid bed or the cyclones and into the bag filter (secondary incident). This probability is however lower than the probability of an explosion (probability class II). The consequences are however more severe: loss of the plant (consequence class IV) and most likely loss of one or several lives (consequence class V).

The analysis is summarized in Table 5. The table also determines the risk based on the various probabilities and associated consequences.

Risk evaluation

The results of the analysis of the spray dryer as summarized in Table 5. The Table shows that the risks are either medium (implying that risk reducing measures should be implemented) or high (implying risk reducing measures must be implemented). Hence two alternatives are investigated: one where a single preventive measure is introduced reducing the probability of explosions and a second one where this preventive measure is combined with protective measures.

3.2 New analysis investigating the introduction of preventive measures

To reduce the probability of explosions from occurring it is proposed to introduce a carbon monoxide-detection system. Smoldering results in the generation of carbon monoxide (CO) due to incomplete combustion. A CO-detection system could warn the operator on ongoing smoldering before a hazardous situation arises (Steenbergen et al, 2007). Including this preventive measure a new analysis has been performed of the explosion risks of the spray dryer.

Table 5 Summarizing the probabilities and consequences of primary and secondary events in the spray dryer and the associated risks for personnel and equipment.

Process unit	Probability of flammable atmosphere	Probability of ignition					Probability of explosion
		Equipment (electric and mechanical)	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flame and smoldering combustion*	
Spray dryer	V	I	I	I	I	III	III

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	III	IV	III	C	C
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	II	V	IV	B	C
Comments:					

<u>Hazard identification</u>

The introduction of a CO-detection system will reduce the probability of an explosion. An early detection of smoldering combustion is assumed to reduce the probability of explosions by at least a factor of 10 implying a probability of explosions of class II. The probability of equipment be damaged and personnel being affected will be reduced accordingly both for primary and secondary incidents. The consequences are however still similar. This results in risks as summarized in Table 6.

<u>Risk evaluation</u>

Table 6 shows that risks have been reduced by introducing a CO-detection system compared to Table 5 presenting the original risks without any preventive or protective measure. The

Table 6 Summarizing the probabilities and consequences of primary and secondary events in the spray dryer and the associated risks for personnel and equipment after implementation of a CO-detection system.

Process unit	Probability of flammable atmosphere	Probability of ignition					Probability of explosion
Spray dryer		*Equipment (electric and mechanical)*	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flame and smoldering combustion*	
	V	I	I	I	I	II	II

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	II	IV	III	C	D
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	I	V	IV	C	D
Comments: A CO-detection system has been included.					

remaining risks for personnel which are described as medium according to the acceptance criteria proposed in Table 2 should be addressed by introducing further risk reducing measures. A described in section 3.1 an additional analysis is presented where the preventive measure of CO-detection is combined with protective measures. A combination of explosion venting and explosion isolation by extinguishing barriers between the dryer and fluidized bed and the dryer and the cyclones is investigated.

3.3 New analysis investigating the introduction of preventive measures in combination with protective measures

Reducing the probability of an explosion by introducing CO-detection still leaves personnel exposed to a medium risk. Hence additional protective measures are proposed. The effects of introducing a combination of explosion venting and explosion isolation (extinguishing barriers) have been investigated.

Hazard identification

The probability of explosions assuming an early detection of smoldering combustion is still as described in section 3.2 equivalent to a probability class II. The consequences of possible explosions are however reduced considerably. Assuming use of appropriate venting devices, sufficient venting surface and taking into account the effect of vent ducts (which are necessary since the spray dryer is installed inside a building) and adequate installation distances for the extinguishing barriers (containing sufficient extinguishing powder to extinguish flames) the risk of explosion in the spray dryer can be reduced considerably. The consequences of an explosion are now reduced to limited or no damage both for the primary and secondary events (consequence class I).

Risk evaluation

Introducing explosion protective measures as described reduces the risks both for the equipment and personnel to acceptable levels. The reduction of consequences to consequence class I (replacement of vent panels and refilling of extinguishing barriers (neglecting the costs of loss of some produced milk powder)) results in risk levels E implying that no further measures would be necessary. Results of the analysis have been presented in Table 7.

4. Conclusions

A semi-quantitative short-cut risk analysis method (SCRAM) has been presented, allowing for the assessment of dust explosion risks and choosing adequate preventive and protective measures. The performance of such an analysis makes industry aware of the most hazardous areas in their facilities and associated consequences in case of an explosion.

The application example demonstrates the strength of the method and the support it offers to industry for choosing appropriate risk mitigating measures.

Table 7 Summarizing the probabilities and consequences of primary and secondary events in the spray dryer and the associated risks for personnel and equipment after implementation of a CO-detection system in combination with explosion venting and explosion isolation towards fluidized bed and cyclones.

Process unit	**Probability of flammable atmosphere**	**Probability of ignition**					**Probability of explosion**
		Equipment (electric and mechanical)	*Hot surfaces*	*Electric and electrostatic sparks and discharges*	*Mechanical sparks*	*Flame and smoldering combustion*	
Spray dryer	V	I	I	I	I	II	II

EXPOSURE TO EXPLOSION					
PRIMARY EXPLOSION					
Probability (injury/damage)		Consequence		Risk	
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
II	II	I	I	E	E
SECONDARY INCIDENTS (inclusive explosions)					
Personnel	Equipment	Personnel	Equipment	Personnel	Equipment
I	I	I	I	E	E
Comments: A CO-detection system has been included combined with explosion venting and isolation.					

5. References

Beck H., Glinke N.and Mohlman C., BIA-Report: Combustion and explosion characteristics of dust, HVBG, Berufsgenossenschaftliches Institut für Arbeitssicherheit BIA 13/97, 1997.

Siwek, R., van Wingerden, K., Hansen, O.R., Sutter, G., Schwartzbach, Chr., Ginger, G., & Meili, R., Dust explosion venting and suppression of conventional spray driers. *Eleventh International Symposium on Loss Prevention*, Prague, May 31 – June 3, 2004.

Steenbergen, A.E., Van Houwelingen, G. and Straatsma, J., System for early detection of fire in a spray drier, *International Journal of Dairy Technology,* **44**, no. 3, pp. 76-79, 2007.