# State of the art: Promotion of early inherently safer design against dust explosions


Olivier DUFAUD, Laurent PERRIN and André LAURENT
Laboratoire des Sciences du Génie Chimique, Nancy-Université, CNRS, INPL, ENSIC
1 Rue Grandville, BP 20451, F-54001 NANCY Cedex.



Inherent safety is an alternative way to eliminate or reduce the dust explosion hazard. Inherent safety aims at removing the hazard at the first instance in contrast to hazard acceptation, prevention and mitigation. The key principles to attain an inherently safer design are respectively minimization, substitution, moderation and simplification. These inherent safety principles are reviewed from the dust explosion risk point of view. Some examples are given to illustrate the potential impact of the inherent safer design when applied at the source step of the processes containing combustible dusts or hybrid gas-solid mixtures.


## 1. Introduction

In the industry, there is a great concern over the loss prevention and mitigation of risk to the process, equipment and labour. Explosions arising from the combustion of powders and dusts are a major source of loss in this sector. However, dust explosions are one of the least understood hazards facing the process industries today. Dust explosion hazards can be and should be identified for each process step and each piece of equipment. A summary of explosion consequence, frequency and potential ignition sources for various processes and equipments including dust production, treatment, transfer, transport and storage was proposed by Dastidar et al. (2005). Most commonly the dust explosion hazard is fought by adding preventive, protective and mitigation measures to an existing process. On the contrary, inherent safety is a preliminary alternative approach to remove the hazard early at the source.

## 2. Principles of inherent safety

The concept of inherent safety was first proposed by Kletz (1998). The used terminology of inherent safety varies somewhat throughout the process safety community. According to the approach of Bollinger et al. (1996) the four key principles to attain an inherently safer design are respectively minimization, substitution, moderation and simplification:

*Minimization* (intensification) uses smaller quantities of hazardous materials when the use of such materials cannot be avoided.

*Substitution* replaces a hazardous substance by a less hazardous material or a hazardous process route by one that does not involve hazardous substances.

*Moderation* (attenuation, limitation of effects, avoiding knock-on effects) uses hazardous materials in their least hazardous forms or identity options that involve less severe/safer operating conditions.

*Simplification* (error tolerance, preventing an incorrect assembly) designs processes and equipments to eliminate opportunities for errors by identifying ways to eliminate the excessive use of add-on safety features and protective devices.

## 3. Application of the inherent safety principles to dust explosion risk reduction

Amyotte et al. (2009) described in great detail how the inherent safety principles can be implemented in practice to prevent and mitigate accidental dust explosions in process plants. Here are some instances of applications from the literature and our own works.

### 31 - Minimization

*311 - Minimize the volume of the process equipment*

A general rule is that the volume of process equipment should not be larger than the volume required by the process. Nevertheless, one sometimes finds industrial plants with for example silos that are considerably larger than required by the process. This can be either due to inadequate design in the first place or due to the plant being used for another purpose than originally designed (Eckhoff, 2005). This overestimation could lead to dust explosions, which are more severe than for smaller processes.

*312 - Minimize the volume of dust clouds generated at transfer points*

Undesired dust clouds are practically always generated when powder, dust, pellet material is falling freely under gravity or is subjected to strong mechanical agitation or to vibrations; when transferred by belt conveyors for instance. Efforts should be made to design transfer points in such a way that the material is flowing smoothly in bulk rather than being dispersed in a cloud. For example by having an inclined chute at transfer points between chain or belt conveyors, dusting can be reduced considerably. Another example is the very smooth discharge of material from a silo onto a chain or belt conveyor, which can be obtained if the silo hopper is designed to produce mass flow rather than funnel flow (Eckhoff, 2003).

*313 - Minimize the formation of dust layers*

A primary dust explosion can generate secondary dust explosion by entraining dust deposits and layers. For example, a 1 mm layer of wood dust, of bulk density of 500 $kg.m^{-3}$ on the floor, in a 5 m high room will generate a cloud of average concentration of 100 $g.m^{-3}$ if well evenly dispersed over the room (Eckhoff, 2009). The hazardous material minimization can be applied by removal of dust deposits from the workplace in a manner to limit the formation of a new dust suspension and to avoid dust layers ignition on hot surfaces. Frank (2004) notably underlined the importance of housekeeping in preventing dust explosions.

### 32 - Substitution

*321 - Substitute the combustible dust*

Substitution of the explosive dust itself will be difficult to realize in most cases given that the dust is the actual desired product or a valorising component of the process. Nevertheless, Amyotte et al. (2003a) demonstrated this feasibility in their investigation of petroleum coke as a partial replacement for pulverized coal in the feed to utility boilers. Petroleum coke was found to be an inherently safer fuel than coal from the point of view of explosion pressure and rate of pressure rise. The use of silica beads as fluidizing agent in icing sugar instead of starch beads, which are combustible, could also be an example.

*322 - Substitute a hazardous material of construction*

The materials for constructing plant items and equipments must not induce fire and explosions hazards. Kong (2006) analysed a dust explosion initiated by a propagating brush discharge when feeding a combustible powder with a charging hopper into a reactor from a FIBC. He explains that the unnecessary use of insulating materials, such as the glass and PTFE linings for the feeding pipe section should have been avoided.

*323 – Substitute a hazardous process route*

It has been a common practice to add small amounts of metallic powders (Si-Al-Mg or Al-Mg alloy) to the refractory bricks (MgO) to slow their deterioration via oxidation on the carbon bonding present in the brick. The production of the fine metallic powders is primarily done via atomization or grinding. The both processes are prone to explosions and fires. On the contrary, the grinding of inert refractory materials is accomplished by milling/crushing operation without risk. Mintz et al. (1996) described a safer process route to prepare powdered metals for refractory use. By introducing the inert dust at an early stage of the process, i.e. by using a co-milling operation with the appropriate mixtures of metals and fireproof materials, it is possible to greatly increase the safety with respect to the explosions during manufacture, transportation and use of the final powder. Note that this example combines the principle of moderation (with the inert material) and substitution.

It may be also possible to eliminate solids handling by processing in a solution, in a wet paste or slurry. For example, using wet benzoyl peroxides instead of dry ones reduces the hazards of these extremely reactive materials (CCPS, 2005).

*324 - Substitute a work procedure*

This way proposes simply to substitute one work procedure for another. For example, Frank (2004) described the overarching importance of housekeeping in facilities handling combustible particulate solids and listed the means of adequate housekeeping. He recommended the use of an explosion-proof vacuum cleaner instead of vigorous sweeping with a broom or blowing with steam or compressed air.

Another example previously mentioned is the use of mass flow silo and hopper instead of the frequently use funnel flow types (Eckhoff, 2009).

In the same way, whenever feasible, consideration should be given to use continuous equipment rather batch type equipment for handling and processing particulate solids as continuous type equipment is often inherently safer. In fact, continuous equipment contains smaller quantities of hazardous particulate solids. Moreover, batch equipment would normally have more frequent start-ups and shutdowns, more product changeovers, more frequent cleaning requirements and thus more opening and closing of the system (CCPS, 2005).

Amyotte et al. (2003b) analyzed the explosion in a dust filter in an acrylonitrile butadiene styrene (ABS) polymer production process. Although the plant was constructed to minimize dust explosion hazards and consequences, the authors demonstrated that an inherently safer approach of the process would be to transport the ABS polymer with recycle $N_2$ by complete substitution of the transport air medium.

**33 - Moderation**

*331 - Control the specific surface area*

Vignes (2008) investigated the particle size influence of Al dust clouds on Minimum Explosible Concentration (MEC), Minimum Ignition Energy (MIE) and Minimum Ignition Temperature (MIT) and explosion severity ($P_{max}$ and $K_{st}$). Results shown on table 1 demonstrate that, on a micrometric range, the reactivity of the dust drops significantly when the particle size distribution increases, i.e. when the specific surface area decreases. Similar results have been found by Nifuku et al. (2007) on Al and Mg dust clouds generated during shredding processes involved in industrial recycling. The authors concluded that the recycle process could be inherently safer by avoiding the production of fine dusts. Thus, the risk of dust explosion can be reduced or eliminated by processing the material in pellets or in slurry form. Amyotte et al. (2009) caught on a point of caution with respect to particle size effects. Even in the presence of coarse powders it is always possible for finer particles to accumulate inside the equipments.

However, the previous trend should not be considered as a general one as it is not always valid for particles on the nanometre range: aggregation and agglomeration leading to lower explosion characteristics and for some, to lower ignition characteristics (for carbon nanotubes and carbon blacks, for instance) (Vignes, 2008).

Moreover, attention should also be paid to the influence of the particle shape for particles having the same particle size distribution; thus Jacobson et al. (1965) noted that both pressure and rate of pressure rise are higher for Al flakes than for atomized aluminum due to the greater surface area of the flakes.

*Table 1. Aluminum dust ignition sensitivity results (Vignes, 2008)*

| Mean diameter (µm) | MEC ($g.m^{-3}$) | MIE (mJ) | MIT (°C) | $P_{max}$ (bar) | $K_{st}$ ($bar.m.s^{-1}$) |
|---|---|---|---|---|---|
| 0.1 | 30 | < 1 | 550 | 8.2 | 364 |
| 0.2 | 30 | 7 | 550 | 9.5 | 656 |
| 7 | 30 | 13 | 900 | 9.8 | 568 |
| 11 | 30 | - | - | 9.1 | 395 |
| 27 | 40 | - | - | 7.5 | 109 |
| 42 | 100 | 17 | 950 | 7.2 | 98 |

*332 - Add inert solids*

Amyotte (2006) reviewed exhaustively the use of inert solid dusts to reduce the risk of dust explosions. He described the various inhibitors and specific parameters that can influence their effectiveness.

For example, Hamdan and Qubbaj (1998) and Sweiss (2006) reported respectively that the MEC and MIE values of combustible oil shale dust can be elevated by adding proportions of inert dust as calcium carbonate, stone, clay and coarse particle size of oil shale. According to Sweiss (2006) an admixed inert dust of 5% by weight of limestone increased the MEC of pure oil shale by 67%, which could improve the process safety. Nevertheless, the results obtained by Dufaud et al. (2009) on the influence of solid inertants on the MEC, MIE and MIT show that the common recommendation of inert solids introduced up to 50 to 80% wt. to eliminate the dust explosion risk should be reconsidered, especially for highly flammable materials.

*333 - Avoid the presence of hybrid mixtures*

Amyotte (2006) and Amyotte et al. (2007) discussed the moderation of hybrid mixtures of flammable gas and explosive dust. The data obtained for the well known example of the underground coal mining industry, where methane usually coexists with coal dust, show the difficulty to control the hazards of hybrid mixtures. Such mixtures can also occur in other industries such as fine chemicals, paints, inks, pharmaceutical, food industries… Pilao et al. (2006) studied the methane - cork dust hybrid mixtures to safe the production of cork stoppers in the cork manufacturing industry. Dufaud et al. (2008) obtained some data for mixtures at pharmaceutical aim, with, as an example, the system niacin (B3 vitamin) dust – diisopropyl ether vapour. Khalili et al. (2010) observed the explosion behaviours of oil cakes and hexane hybrid mixtures in bio-fuels industries. To sum up the trend of these results: i) explosions of hybrid mixtures could be encountered when both the gas/vapour concentration and the dust concentration are below their flammability limits, ii) the ignition probability raises when the gas/vapour concentration increases up to the stoichiometric concentration, iii) for the explosive parameters, the maximum explosion pressure of hybrid mixtures is usually slightly affected relatively with regard of dust air systems, iv) at the contrary the maximum rate of pressure rise is strongly impacted by the joint presence of dust and gas or vapour.

The issue of achieving an inherently safer facility by avoiding of hybrid mixtures formation is not yet a trivial challenge. Amyotte et al. (2007) underlined that safety measures based on the presence of an explosive dust alone can be entirely inadequate when applied to hybrid mixtures. At present, the best way to reduce the potential risk associated to hybrid mixtures consists, in terms of inherent safety, to prevent the occurrence of the explosion by the use of an inert gas, for example nitrogen, carbon dioxide and rare gases. But this is not applicable when the combustible gas is compulsory in the process. The elimination or prevention of ignition sources is also a relevant action.

*334 – Control the storage conditions*

Moderation could also involve processing a material under less hazardous conditions. Traoré et al. (2009) have notably demonstrated that, depending on their chemical nature, the equilibrium relative humidity and thus the moisture content of powders could inhibit or promote the dusts ignitability and explosion severity. As a consequence, the control of the storage conditions, especially the temperature and relative humidity, is essential to ensure the stability of the powders.

**34 - Simplification**

The idea of the simplification principle is to make the process equipment robust enough to withstand process upsets and other undesired events as for example pressure or shock resistant design. Containment is an attractive option since it is a passive barrier and avoids the problem of relief disposal. That is why the concept of error tolerance is often considered as a sub principle of simplification. It is not usually practicable for the whole of a dust handling plant particularly with large plants. Nevertheless, containment is applicable in small scale units and on certain equipment. Amyotte et al. (2007) analysed the example of a hammer mill used in a wood processing facility to accomplish size reduction of sawdust and wood chips; the equipment was designed and built strong enough to withstand the overpressure resulting from a dust explosion originating inside the unit. When the powder dust is highly toxic complete and reliable containment is absolutely necessary. Avoiding the use of exhaust ducts at the exit of rupture discs could also be a solution to improve the exhaust flow rate and thus protect the vessel.

## 4. Conclusion

While the basic principles of inherent safety are generally accepted and despite their potentials benefits, there are still some problems limiting inherent safety practice. The main difficulty consists in the lack of systematic routines to implement these inherent safety principles into reality. Khan and Amyotte (2003) reviewed the literature to explain why inherent safety is not yet a routine practice for contributing to the risk reduction and suggested some ways to make routines. Amyotte and Khan (2002) proposed a framework for dust explosion prevention and mitigation based on the hierarchy of examining inherently safer options before add-on and procedural safeguards. However, inherently safer design should be promoted to contribute to the safety of processes for production, treatment and handling of combustible powders, dust and hybrid mixtures. To achieve this, Eckhoff (2009) emphasized the importance of knowing and using powder/particle science and technology when striving to the inherently safer process design in industries having a dust explosion hazard.

The principles of inherent safety should obviously take the current legislation into account. Conversely, the definition of new normative barriers based on these principles could also improve the management of the dusts explosion risk (Munoz, 2007).

## References


Amyotte P.R. and Khan F.I., 2002, An inherent safety framework for dust explosion prevention and mitigation, Journal of Physics IV France, 12(7) 189-196.

Amyotte P.R., 2006, Solid inertants and their use in dust explosion prevention and mitigation, Journal of Loss Prevention in the Process Industries, 19, 161-173.

Amyotte P.R., Basu A. and Khan F.I., 2003a, Reduction of dust explosion hazard by fuel substitution in power plants, Trans IChem, 81, part B, 457-462.

Amyotte P.R., Khan F.I. and Dastidar A.G., 2003b, Reduce dust explosions the inherent safer way, Chemical Engineering Progress, 98, 36-43.

Amyotte P.R., Pegg M.J. and Khan F.I., 2009, Application of inherent safety principles to dust explosion prevention and mitigation, Process Safety and Environment Protection, 87(1), 35-39.

Amyotte P.R., Pegg M.J., Khan F.I., Nikufu M. and Yingxin, 2007, Moderation of dust explosion, Journal of Loss Prevention in the Process Industries, 20(4-6), 675-687.

Bollinger R.E., Clark D.G., Dowell A.M., Ewbank R.M., Hendershot D.C., Lutz W.K., Meszaros S.I. and Wixom E.D., 1996, Inherently safer chemical processes – A life cycle approach, Center for Chemical Process Safety, AIChE, New York.

CCPS, 2005, Guidelines for safe handling of powders and bulk solids, Center for Chemical Processes Safety, AIChE, New York.

Dastidar A.G., Nalda-Reyes B. and Dahn C.J., 2005, Evaluation of dust and hybrid mixture explosion potential in process plants, Proc. Safety Progress, 24(4), 294-298.

Dufaud O., Perrin L. and Traoré M., 2008, Dust/vapour explosions: Hybrid behaviours?, Journal of Loss Prevention in the Process Industries, 21(4), 481-484.

Dufaud O., Perrin L., Dubut F., Bideau D., Traoré M. and Laurent A., 2009, From Dust to dusts: solid/solid hybrid mixture explosions, 8th World Congress of Chemical Engineering, Montreal.

Eckhoff R.K., 2003, Dust explosions in the process industries, 3rd edition, Gulf Publishing Elsevier, Boston.

Eckhoff R.K., 2005, Explosion hazards in the process industries, Gulf Publishing Company, Houston.

Eckhoff R.K., 2009, Understanding dust explosions. The role of powder science and technology, Journal of Loss Prevention in the Process Industries, 22, 105- 116.

Frank W.L., 2004, Dust explosion prevention and the critical importance of housekeeping, Process Safety Progress, 23(3), 175-184.

Hamdan M.A. and Qubbaj A., 1998, Inhibition effect of inert compounds on oil shale dust explosion, Applied Thermal Engineering, 18(5), 221-229.

Jacobson M., Cooper A.R. and Nagy J., 1965, Explosibility of metal powders. Report of investigation 6516, Bureau of Mines, U.S. Department of the Interior.

Khalili I., Dufaud O., Perrin L., François H. and Putier F., 2010, Hybrid mixtures explosion: Case study of oil cakes and hexane mixtures in bio-fuels industries, 13th International Symposium on Loss Prevention in the Process Industries, Bruges.

Khan F.I. and Amyotte P.R., 2003, How to make inherent safety practice a reality, The Canadian Journal of Chemical Engineering, 81, 2-16.

Kletz T.A., 1998, Process plants: a handbook for inherently safer design, Taylor and Francis, 2nd edition, Philadelphia.

Kong D., 2006, Analysis of a dust explosion caused by several design errors, Process Safety Progress, 25(1), 58-63.

Mintz K.J., Bray M.J., Zuliani D.J., Amyotte P.R. and Pegg M.J., 1996, Inerting of fine metallic powders, Journal of Loss Prevention in the Process Industries, 9(1), 77-80.

Muñoz F., 2007, Evaluation of safety barriers through the MADS/MOSAR methodology: case study of the Colombian mining, INPL, Ph.D thesis (in French).

Nifuku M., Koyanaka S., Ohya H., Barre C., Hatori M., Fujiwara S., Horiguchi S. and Sochet I., 2007, Ignitability characteristics of aluminium and magnesium dusts that are generated during the shredding of post-consumer wastes, Journal of Loss Prevention in the Process Industries, 20, 322-329.

Pilão R., Ramalho E. and Pinho C., Explosibility of cork dust in methane/air mixtures, Journal of Loss Prevention in the Process Industries, 19(1), 17-23.

Sweiss F., 2006, The effect of admixed material on the minimum explosible concentration of oil shale, Journal of Loss Prevention in the Proc. Ind., 19, 701-704.

Traoré M., Dufaud O., Perrin L., Chazelet S. and Thomas D., 2009, Dust explosions: How should the influence of humidity be taken into account?, Process Safety and Environmental Protection, 87(1), 14-20.

Vignes A., 2008, Evaluation of ignition and explosion risks of nanopowders: a great way to manage industrial safety risks, INPL Nancy, Ph.D thesis (in French).