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RECURSIVE OPERABILITY ANALYSIS AS A TOOL FOR ATEX CLASSIFICATION IN PLANTS MANAGING EXPLOSIVE DUSTS

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Safety and prevention in workplaces are important issues, especially regards to risks with serious consequences for health and infrastructures, such as dust explosions, which have caused several industrial accidents during the last centuries and, actually, represent a critical issue in the industrial framework. The current European legislation, referred to as ATEX directive, identifies ATEX zones as parts of the plant where explosive atmospheres can be generated. In this work, a modified version of the classic Recursive Operability Analysis method, specifically tailored to define with an automatic procedure the ATEX zones related to flammable dust clouds, is proposed. The method is fast and effective, allowing for an automatic generation of fault trees from which the probability of occurrence defining the specific ATEX zone type can be estimated. This technique was successfully implemented in a chemical plant dedicated to the mixing of inert powders with a stearate powder, a hazardous dust classified as strongly explosible. The extent of all the ATEX zones identified within the plant was simulated with the ALOHA software, treating the dispersed dust cloud of stearate as a dense gas cloud. From the results, it was possible to identify not only type and extension of all the ATEX zones but also either the most critical parts of the plant or the most dangerous activities (e.g. human errors in the use of the forklift was found to account for about 97.7% to explosion probability in this type of plant).

1. Introduction

Dust explosions are among the most critical accidents in the industrial panorama, involving food, pharmaceutical, and fine chemical plants. According to official reports, only in the first half of 2020, 26 dust explosions have been recorded worldwide ("Combustible Dust Incident Reporting"), with 4 casualties, almost a hundred injured, and huge economic losses. From the analysis concerning accidents involving explosive dusts in the U.S.A., the trend over the period 2016-2019 have shown that 30 dust explosions per year occur ("Combustible Dust Incident Reporting") almost constantly. For such phenomena, prevention and protection are extremely important and can be achieved with a proper risk assessment, whose results imply either the use of specific equipment in the plant or the implementation of organizational/procedural modifications (Abbasi and Abbasi, 2007). A risk assessment for dust explosions must follow the guidelines proposed by dedicated standards: Directive 2014/34/EU and Directive 94/9/EC are the main standards used in Europe (often referred to as ATEX directive); while, in the U.S.A., the NFPA standards such as the NFPA 654 ("Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids") are recommended. For what concerns the ATEX directive, it is required to evaluate, at first, the explosive properties of the involved dust, such as deflagration index K_{st} (Copelli et al., 2019), Minimum Ignition Energy (MIE), Lower Explosible Limit (LEL), Minimum Ignition Temperature of a dust cloud (MIT) or of a layer (LIT) (Eckhoff, 2003). Once explosive dusts have been characterized, the ATEX directive suggests to identify all the possible ignition sources and the so-called ATEX Zones, that represent the areas of the plant where an explosive atmosphere can be generated (that is, a dust cloud above the LEL). The distinction among the zone types is based upon the likelihood of the undesired event and the degree of ventilation of the workplace. For dusts, conversely with respect to gases, no specific indications, or models for the identification of these zones are recommended, leaving a wide margin of operability to analysts. For this reason, in this work, a procedure to evaluate the ATEX Zones for combustible dusts is presented. The proposed method is mainly based on the Recursive Operability Analysis with Cause-Consequences Diagrams (ROA-CCD) (Contini et al., 2016). At first, a risk assessment of the plant is carried out with this method, identifying all the possible accidental scenarios. The novelty of this approach consists in using the probabilities of occurrence for the Top Event “Formation of an explosive atmosphere” to define 20, 21 and 22 ATEX Zones inside the plant. Such probabilities are estimated through the numerical solution of the corresponding Fault Trees, which are automatically generated thanks to the structure of the ROA-CCD technique. Once zones 20, 21, and 22 have been identified, the analysis is completed with an estimation of the extent of all the identified areas, that is where there is a dust concentration (in air) above the LEL. The proposed approach has been finally implemented to perform the ATEX zone identification in a chemical plant where stearate is the most dangerous involved substance. Such a compound is highly explosive, highlighting the need for a plant risk assessment. From results, zones 21 and 22 were identified and characterized, allowing for the selection of proper ATEX equipment for a safer process.

2. Methods and case study

The proposed method is a modified version of the ROA-CCD analysis (Contini et al., 2016). Such a method is an evolution of the classical ROA (Piccinini and Ciarambino, 1997), which has been reported in the literature as a good method to perform a risk assessment on chemical plants, or a base to define new risk analysis techniques (Barozzi et al., 2020). The main advantage of this method is the automatic generation of the Fault Trees, which are a Quantitative Risk Analysis tool. The method starts with filling in the classic ROA Table, represented in Table 1. The table is compiled as in an HazOp analysis, but a recursive structure can be recognized: starting from process variable deviations (Node-Deviation-Variable, see Table 1), the consequences can be both a Top Event (TE) or an additional deviation (for example, a high temperature can cause high pressure inside equipment). If this is the case, the following table rough (Record, Rec) will consider the last consequence as the new deviation to be analyzed, leading to new consequences. The analysis continues until either each process variable deviation has been considered or at least one Top Event has been detected. From each record of a ROA table, Cause-Consequence-Diagrams (CCDs) can be generated, and by matching all the CCDs, a Fault Tree for a specific TE can be identified.

Table 1: ROA-CCD table (Barozzi et al. 2020)

Rec	NDV	Causes	Consequences due to protections failure	Plant state with protections working correctly	Protections			Notes	TE
					Manual		Automatic safety systems actions		
					Alarm (optical/acoustic)	Operator actions on components			
	1	2	3	4	5	6	7		

The novelty presented in this work consists in using the information provided by a ROA-CCD analysis for evaluating the ATEX zone types within a plant managing combustible dusts. The idea is based on the following consideration: ATEX zones can be defined according to Nederlandse Praktijk Richtlijnen (NPR), as a percentage of the working time within an explosive atmosphere can be generated (NPR-7910), as reported in Table 2.

Table 2: ATEX 153 Zones, according to NPR-7910

Percentage of the operating time	Type of release	ATEX Zone (dust)
>10%	Continuous	20
0.1-10%	Primary	21
<0.1%	Secondary	22

Fault Trees can be easily used to define this value by considering as mission time the time required to perform a working cycle. In such a way, the probability of occurrence can be used to define the percentage of the operating time required for the definition of the ATEX Zone. The trick used to speed up the analysis is that ROA-CCD analysis must consider as TEs only those ones implying the “formation of an explosive atmosphere” within the plant. To get such a condition, both the deviation “high concentration” of the flammable dust in the air (that is, the dust concentration must be above the LEL) and the triggering event “presence of an ignition source” must be analyzed. Finally, it is important to estimate the extent of an ATEX zone (that is the spatial extension) around the epicenter of the dust cloud formation. The application of this method can be

summarized in the following steps: 1) general information recovery (P&ID, dust types, ignition sources..); 2) determination of the dusts explosive parameters; 3) application of the ROA-CCD method; 4) generation of the Fault Trees for all the TEs representing the formation of an explosive dust cloud; 5) definition of the ATEX zone type by solving the FTs with a mission time equal to a single process cycle; 6) determination of the extension of the ATEX zone.
Software is required to perform both the numerical solution of Fault Trees and the estimation of the extent of ATEX zones. In this work, OpenFTA 1.0 (Formal Software Construction Ltd., Cardiff, UK), and ALOHA® (Cameo® software suite) were used for the solution of Fault Trees and the extension of the dust cloud with concentrations above LEL, respectively.

The case study considered in this work is a plant dedicated to the mixing of different dusts which are then granulated using micronized water. The most dangerous component is constituted by the stearate which finds several applications in the process industry due to its low toxicity and cost. Properties of such stearate in terms of granulometric distribution and explosive potential were determined experimentally, and the results are shown in Table 3 and Table 4, respectively.

Table 3: Granulometry of the stearate sample

Diameter	Mass fraction
>250 μm	4%
100-250 μm	67%
63-100 μm	21%
<63 μm	8%

For what concerns explosive properties, the MIE is very low (below 3 mJ), indicating a hazardous compound. Such stearate belongs to the St Class 2, which indicates a compound associated with violent explosions. The P&ID of the mixing plant has been reported in Figure 1.

Table 4: Explosive properties of the stearate

Properties	Value	Reference
K_{st}	228 bar·m/s	EN 14034-2:2006+ EN 14034-1:2004
P_{max}	7.1 bar	EN 14034-1:2004
Minimum Igntion Energy (MIE)	1-3 mJ	BS EN ISO IEC 80079-20-2
Lower Explosive Limit (LEL)	18±1 g/m³	BS EN 14034-3:2006

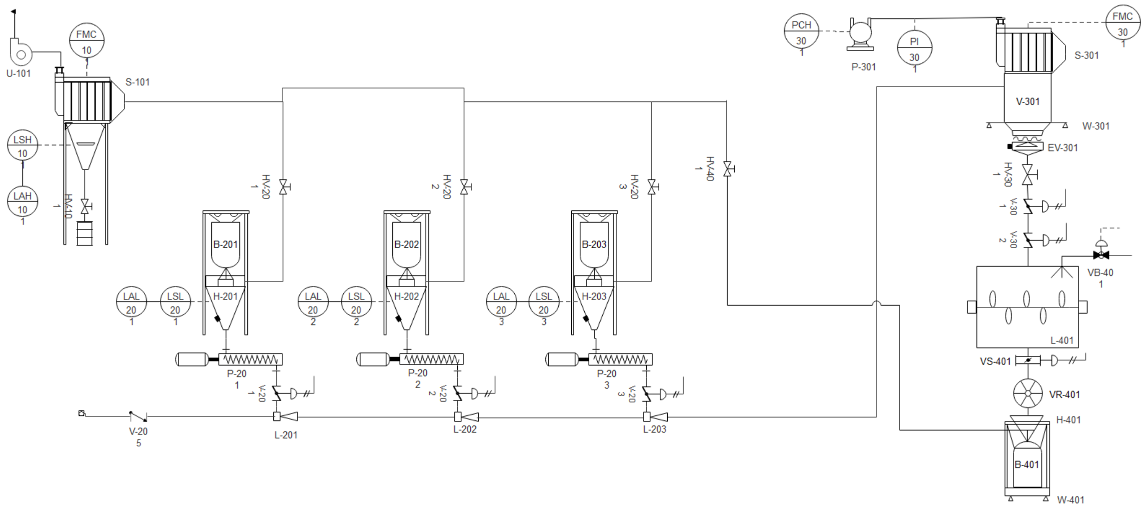

Figure 1: P&ID for the plant processing the stearate

The plant is constituted by 3 dust lines, where powders are loaded with big bags (lines 201-202-203). The stearate is loaded through line 201. During the process, each line works separately: each component is loaded independently into vessel V-301 with the activation of a vacuum pump P-301. Vessel V-301 is equipped with a baghouse S-301 installed to avoid a dust flow inside the vacuum pump, which would eventually wear it.

Once all the dusts are loaded into V-301 (loading is controlled with a mass balance W-301), valves EV-301, V-301 and V-302 are opened and the product is formed inside L-401, where a rotating mixer allows the formation of a homogenous granulate, with the addition of micronized water through VB-401.

When the process is finished, L-401 discharges the product in a big bag B-401, which is finally sent to storage. A detailed list of all components indicated in Figure 1 has been reported in Table 5. A crucial part of the working cycle is the preparation of the big bags which contain about 750 kg of dust. Each big bag is placed on its dedicated hopper and make operative according to a specific procedure: at first, operators put the big bag above the hopper with the use of a forklift; then, the bag is fixed with the use of steel support hooks, and its bottom is opened and connected to the hopper (granting a vertical flow of dust to the screw pumps). As it will be observed later, several issues may occur during such operations, leading to potential leaks of dust.

In order to carry out the analysis, the system has been divided in 4 nodes, which are indicated by the labels in Figure 1: node 1 is the baghouse for all lines, node 2 comprises all the lines dedicated to the powders loading (stearate, 201), node 3 is the pre-loading of all components in V-301 and, node 4 is the mixing equipment where the final powder is produced and sent to storage.

Table 5: List of components involved (xxx refers to a generic node, when multiple components are present)

ID	Description	ID	Description	ID	Description
HV-xxx	Hand valve	B-xxx	Big-bag	U-101	Fan
V-xxx	Check valve	EV-xxx	Solenoid valve	P-301	Vacuum pump
L-xxx	Flow deflector	VB-xxx	Water valve	PI-301	Pressure indicator
H-xxx	Vibrating hopper	P-xxx	Screw pump	V-301	Pre-mixer
LAL-xxx	Low alarm level	S-xxx	Baghouse	W-301/401	Mass balance
LSL-xxx	Low level switch	FMC-xxx	Flow controller	L-401	Mixer

3. Results and discussion

ROA-CCD method was applied to the whole plant and two families of TEs were identified: 1) a plant shutdown state, due to either issues during the dusts loading into V-301 or the blockage of the L-401 rotating mixer, and 2) the formation of an explosive atmosphere. Due to the target of the work, only the second TE family will be reported, as it leads to the definition of the ATEX Zones. An explosive atmosphere of stearate can occur in both node 2 and node 3, where the dust is available in significative amounts. Table 6 reports the specific records including the identification of explosive stearate clouds in the plant. The deviation considered is hC, which stands for high concentration of dust (>LEL) in the air, and the causes are: 1) human error, a defective bag (B-201) or worn support hooks for what concerns node 2; 2) valves (HV-301, V-301 and V-302) case rupture for node 3. Human error is intended as a bad execution of the big bag lifting procedure, which can result in a tearing of the bag due to a misuse of the forklift. The relative Fault Trees are presented in Figure 2. The structure is pretty simple, due to the absence of whatever protective means.

Table 6: ROA-CCD analysis for the desired Top Events

Rec	NDV	Causes	Consequences due to protections failure	Plant state with protections working correctly	Protections			Notes	TE
					Manual		Automatic safety systems actions		
					Alarm (optical/ acoustic)	Operator actions on components			
2.7	2.1hC	Human error OR B-201 OR Hooks	Formation of an explosive atmosphere	-	-	-	-	-	TE1
3.7	3hC	HV-301 OR V-301 OR V-302	Formation of an explosive atmosphere	-	-	-	-	-	TE2

In this phase of the work the event “presence of an ignition source” was considered as having unavailability equal to 1; therefore, it was not reported within the ROA Table. The solution of the Fault Trees requires an estimation of the duration of a process cycle. The time required for a complete cycle can be calculated as it follows: preparation (30 mins); big bags loading (30 min); automatic loading of dusts (60 min) within V-301; mass balance checking (10 min); dust transfer and mixing in L-401 (90 min); product collection (20 min). A stearate bag is supposed to last for 7 product syntheses, hence a whole cycle will include a single big bag loading step and 7 product syntheses, for a total mission time of about 24 hours. Unavailability of components have been calculated according to a Poisson distribution, based upon failure rates recovered from dedicated literature. Broken valves have been associated with a failure rate of $1\cdot10^{-8}$ 1/y (Lees, 2005), and the wearing of support steel hooks has a failure rate of $3.42\cdot10^{-7}$ 1/h (Lees, 2005). The presence of a defective bag has no straight reference, and it was assumed that 1 bag every 100,000 present a manufactory fault, leading to a probability of $1\cdot10^{-5}$ for a complete cycle. The probability of human error has been set to $1.2\cdot10^{-2}$, according to a literature database (Bello and Colombari, 1980).

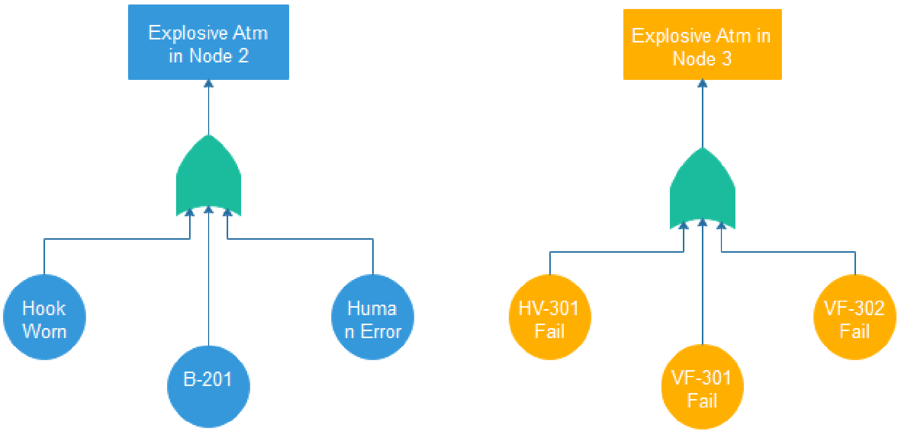

Figure 2: Fault Tree for the event “Formation of an explosive atmosphere”

The final probability of the formation of an explosive atmosphere in the whole plant over a complete 24 h cycle is equal to 1.3%. This result accounts for all the possible causes even though, in order to define the respective ATEX Zones, it is necessary to split the contribution of each node (as it can be seen in Figure 2). The most critical procedure is the big bags lifting above the hoppers, which is responsible for the probability of occurrence of an explosive atmosphere in node 2 (1.23%). Human error with the managing of the forklift shows a relative importance of 97.7%. Otherwise, node 3 brings a negligible contribution as the main causes that can lead to a dust dispersion are the rupture of all the valves on the line connecting V-301 to L-401, which is a rare event. Thus, the declaration of ATEX Zone types comes straightforward: according to NPR-7910, Node 2 is a 21 type, and node 3 is a 22 zone. To increase process safety, it will be necessary to install equipment with a specific ATEX marking (group II, 2D, and 3D in this case). Finally, to provide a more complete analysis, the extent of the different ATEX zones should be determined. In accordance with the results of the analysis, such a calculation was developed for the 21 zone only, as 22 zone for node 3 is necessary located within a narrow span (cm) from the equipment. Dust cloud formation is a complex phenomenon to be modeled (Eckhoff, 2003), therefore simplifications must be introduced. The dispersion was simulated using ALOHA®, which is a software for pollutant dispersions and toxic releases simulation recommended by EPA, but it is not designed to simulate a dust dispersion. To estimate the extent of a dust dispersion using ALOHA®, some assumptions must be made. As the most likely accident is a drop of dust from the big bag due to a human error, that is the big bag tearing generated by a misuse of the forklift, the most likely event is a dispersion of the stearate which falls on the ground and it is then dispersed in the surroundings. Hence, it is reasonable to simulate this event as a heavy gas which is released locally. For the simulation, a virtual dust flow of 1 kg/min released over 10 minutes has been considered. Workplace air conditions are the following: room temperature 25 °C, relative humidity 50% and 4.3 air changed per hour, according to plant data. Results are shown in Figure 3: until 4.1 meters, a dust cloud above the LEL, with a maximum concentration equal to 35.4 g/m³ can be generated.

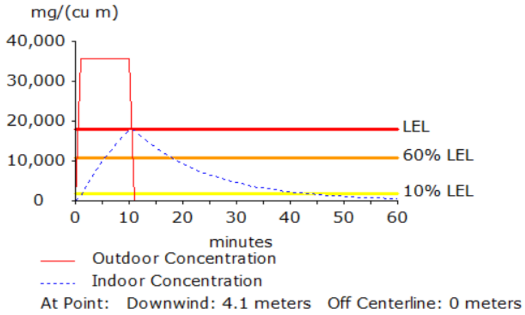

Figure 3: ALOHA simulation for a stearate dust cloud in the big bag location

Hence, the ATEX zone 21 is located on the stearate big bag location, and its extension covers an area of 4.1 meters radius.

4. Conclusions

Identifying the correct type of ATEX zone is a crucial part of a risk assessment for dust explosions. Current standards do not indicate a specific procedure or method to be followed to accomplish such a task. The proposed method is quite rigorous, simple and effective to be applied, in accordance with the main advantages of ROA-CCD. The method requires a simple modification of the original method, which refers to the identification of the TE “Formation of an explosive atmosphere”, which is associated with the deviation “high concentration” and the basic event “presence of an ignition source”. The ATEX zone type is then identified by solving the dedicated Fault Trees considering as mission time a whole production cycle.

From the application of the case study, which is a process that uses stearate, it is clear that the main factors that can lead to an explosive atmosphere in node 2 (1.23%) are represented by the loading of big bags from operators (relative importance of 97.7%). For this reason, to improve process safety, two solutions are recommended: updating the plant by implementing proper ATEX equipment or modify the big bag loading line. A solution may be the implementation of a sliding rack to move them above the hoppers. In this way, human errors may be substantially reduced. Identifying the extent of a dust cloud is also an important factor in the identification of hazardous areas. In this case, a very simple model was applied, but it can be useful for future applications considering more complex models, to provide more detailed and precise accidental scenarios.

References

Abbasi, T., Abbasi, S.A., 2007. Dust explosions–Cases, causes, consequences, and control. Journal of Hazardous Materials 140, 7–44. https://doi.org/10.1016/j.jhazmat.2006.11.007

Barozzi, M., Copelli, S., Scotton, M.S., Torretta, V., 2020. Application of an enhanced version of recursive operability analysis for combustible dusts risk assessment. International Journal of Environmental Research and Public Health 17. https://doi.org/10.3390/ijerph17093078

Bello, G.C., Colombari, V., 1980. The human factors in risk analyses of process plants: The control room operator model ‘TESEO.’ Reliability Engineering 1, 3–14. https://doi.org/10.1016/0143-8174(80)90010-4

Combustible Dust Incident Reporting, n.d. . Dust Safety Science. URL https://dustsafetyscience.com/2020-report/ (accessed 1.20.21).

Contini, S., Contini, P.M., Torretta, V., Cattaneo, C.S., Raboni, M., Copelli, S., 2016. Comparison of classical and “cause consequence diagrams” Recursive Operability Analysis: The T2 Laboratories accident. Chemical Engineering Transactions 53, 109–114. https://doi.org/10.3303/CET1653019

Copelli, S., Barozzi, M., Scotton, M.S., Fumagalli, A., Derudi, M., Rota, R., 2019. A predictive model for the estimation of the deflagration index of organic dusts. Process Safety and Environmental Protection 126, 329–338. https://doi.org/10.1016/j.psep.2019.04.012

Demichela, M., Piccinini, N., Ciarambino, I., Contini, S., 2003. On the numerical solution of fault trees. Reliability Engineering & System Safety 82, 141–147. https://doi.org/10.1016/S0951-8320(03)00142-X

Eckhoff, R.K., 2003. Dust Explosions in the Process Industries. Elsevier. https://doi.org/10.1016/B978-0-7506-7602-1.X5000-8

Lees, F., 2005. Lees’ Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control. Elsevier.

Piccinini, N., Ciarambino, I., 1997. Operability analysis devoted to the development of logic trees. Reliability Engineering & System Safety 55, 227–241. https://doi.org/10.1016/S0951-8320(96)00111-1