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exLOPA for explosion risks assessment

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Abstract

The European Union regulations require safety and health protection of workers who are potentially at risk from explosive atmosphere areas. According to the requirements, the operators of installations where potentially explosive atmosphere can occur are obliged to produce an explosion protection document. The key objective of this document is the assessment of explosion risks.

This paper is concerned with the so-called explosion layer of protection analysis (exLOPA), which allows for semi-quantitative explosion risk assessment for process plants where explosive atmospheres occur. The exLOPA is based on the original work of CCPS for LOPA but takes into account some typical factors appropriate for explosion, like the probability that an explosive atmosphere will occur, probability that sources of ignition will be present and become effective as well as the probability of failure on demand for appropriate explosion prevention and mitigation means.

Keywords: Explosive atmospheres; Layers of protection; Fire/explosion; Risk assessment

1. Introduction

Industry, particularly the process industry, is often confronted with problems where explosive atmospheres endanger safety and health of the personnel. A number of reported incidents with serious results for personnel and equipment confirm the meaning of that problem [1]. Historically, fire and explosion are the predominant causes of chemical plant losses and adoption of effective measures for prevention, protection and mitigation of fire and explosion requires high priority.

The explosive atmospheres can occur inside the equipment as a result of normal process conditions (indoor) and outside due to abnormal processes and work practices as a result of failure of protection of the shell of the equipment and releases of flammable, explosive or oxidizing substances (outdoor). Depending on the type of the substance involved and the size of the release, the phenomena may be considered for major accident hazards regulations (SEVESO regulation) [2] or for atmospheric explosion regulations (ATEX regulations) [3,4]. In fact it is difficult to distinguish between an area of application of the SEVESO and the ATEX regulations. Both may lead to major hazard accidents, however the SEVESO may produce on- and off-side unwanted effects with possible domino effects, whereas the ATEX accidents are definitely connected with local on-site effects, especially for workers and property.

The ATEX directives, which apply to all potentially explosive atmospheres caused by gas, dusts and mists, and apply to all equipment, not only to electrical ones, require the industry sector to identify and evaluate hazards and risks associated with those explosive atmospheres. They require employers to assess the risks of explosion and to provide an appropriate worker protection against explosions. The employer is to demonstrate that he has taken all organizational and/or technical measures to reduce risks from dangerous substances as far as reasonably practicable. This simply necessitates a risk assessment and an Explosion Protection Document based on that must be prepared. By conducting a risk assessment the employer is able to identify hazards arising out of it, and in connection with work where an employee handles dangerous substances, and can assess the subsequent risk to employees.

This paper presents the application of the Layer of Protection Analysis, developed for process industry, to assess explosion risk assessment for the workers employed in the area where an atmospheric explosion can occur. The method called exLOPA is based on the original work of CCPS [5], but takes into account only typical factors appropriate for explosion, like the probability that an explosion atmosphere will occur, the probability that sources of ignition will be present and become effective, as well as the probability of failure on demand for appropriate explosion prevention and mitigation means.

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This paper is limited to the explosion of dispersed flammable substances (gases, vapor, dusts and mists) in mixture with air or another gaseous oxidant agent. Other types of explosion (explosive substance, decomposition or physical explosion) are not applicable to this method.

2. Development of the basic tools for explosion risk assessment

2.1. Definition of risk in terms of the ATEX directive

Many monographs, papers, and publications deal with explosion phenomena [6–9]. However, due to the complex nature of these phenomena, there are very few works on the explosion risk assessment. There are many various definitions of risk. Most of them define the risk as “the possibility of an unwanted event”, which is expressed by the product of probability P_n of a hazardous event and the extent of its damage S_n.

$$R_n = P_n S_n$$

In order to determine the risk of any process or activity, it is necessary to assess both parameters. Missing one of the components does not allow for risk assessment.

However, each technological process or activity is associated with the use of particular safety measures, which can essentially reduce the level of risk. The actions of the safety measures (success or failure) are not represented in the above risk definition. Moreover, they may affect one component of risk (probability) or the second (consequence) or both components. Therefore, there is a need to include in the above definition the probability of failure of safety measures (F_{SMn}) in order to evaluate the risk.

$$R_n = P_n S_n F_{SMn}$$

where:

$$P_n = P_{atex} P_{IG}$$

Taking into account the explosion phenomena, a hazardous event means an explosion event, which requires assessment of the occurrence of explosive atmosphere (P_{atex}), which coincides with the presence of an ignition source (P_{IG}), whereas S_n means the consequences of explosion in terms of losses for humans, property and environment as well as the action of appropriate safety measures. In such a way the explosion risk assessment can be expressed as the following product:

$$R_n = P_{atex} P_{IG} S_n F_{SMn}$$

This is illustrated by an explosion risk triangle presented in Fig. 1. For particular components of this triangle there are additional conditions imposed, e.g., the occurrence of explosive concentration (LEL/UEL), capability of an ignition source to ignite an explosive mixture (MIE) and failure of both controls for an explosive mixture and ignition source.

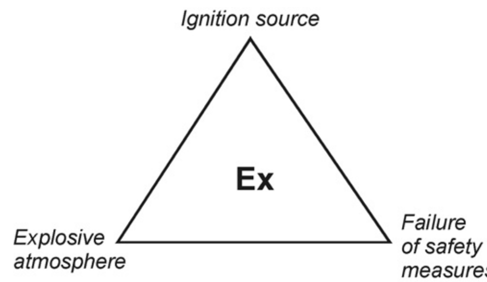

Fig. 1. Explosion risk triangle.

The occurrence of an explosive mixture may happen due to different leak sources in normal operational practice or abnormal situations, mostly due to an accidental release of a substance as a result of failure of the protection shell of the equipment. It may happen in outdoor plants (open space) or in indoor plants (closed space). Outdoor leaks tend to disperse in the atmosphere, whereas indoor leaks tend to result in a build-up of a flammable mixture in a particular closed space. In many cases during normal process practice, not only an explosive atmosphere but also ignition sources are formed. Virtually all industrial facilities are affected, since hazards from explosive atmospheres arise in a wide range of processes and operations. Table 1 provides some examples of the process operation, which normally may create an explosion and/or fire with possible consequences for workers.

A review of the investigated accidents shows that it is not simple to find generalized schemes for possible results of the contacts between the explosive atmosphere, ignition source and reaction of safety measures. The general event tree presented in

Table 1
Possible accident scenario connected with explosive atmospheres

Type of operation	Type of ATEX scenario
Handling of gases/dusts/liquid, e.g., pneumatic transport	Electrostatic charging with possible ignition and internal explosion
Filling of tanks, filling and discharges from conical pills of bulk goods, filtering	As above
Sampling from atmospheric tanks containing flammable liquids	Ignition of explosive atmosphere due to different sources (especially due to electrostatic charging) and internal explosion followed by tank fire
Adiabatic compression and decompression	Electrostatic discharges
Exothermic chemical reaction	Failure of cooling system and runaway chemical reaction with thermal explosion
Heating processes or mechanical equipment (e.g., pumps)	Initiation of decomposition processes and of overheating of mechanical elements
Services operation (grinding, hot work, cleaning and washing, etc.)	Mechanical sparks, hot gas or electrostatics may ignite the explosive atmosphere with possible effects for workers
Failure of protection shell and release of gas/liquid with simultaneous failure of ignition control system or explosion atmosphere control (e.g. ventilation)	Leakage of flammable substance, formation of explosive atmosphere due to different sources (e.g., malfunctioning of electrical equipment), followed by fire or explosion with consequences for workers depending on the amount of released substance
Accidental release of liquids with low auto-ignition temperature (AIT)	Self-ignition and fire

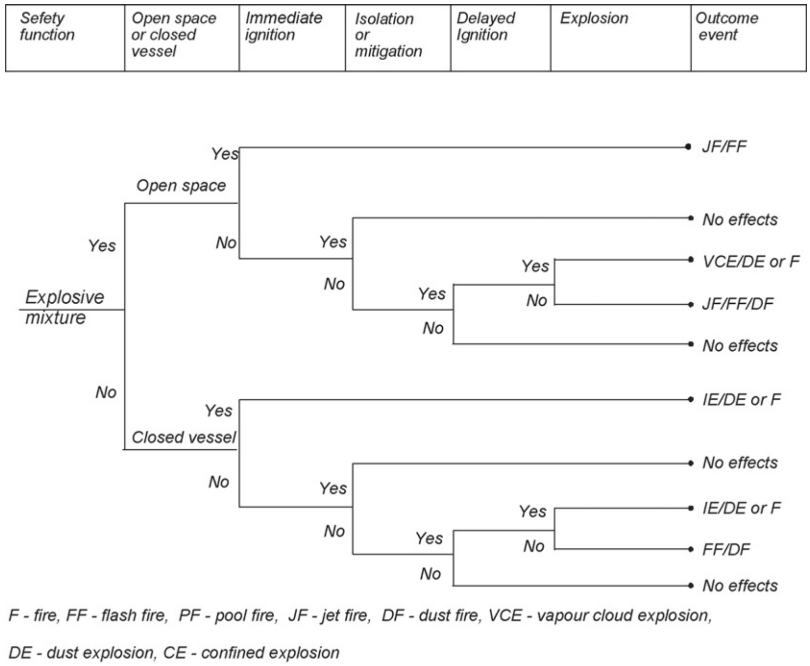

Fig. 2. Explosion scenarios.

Fig. 2 shows different outcome events depending on the type of explosive mixture (gas or dust), the place of this contact (open or closed space), type of the ignition source, presence of the possible prevention, protection and mitigation means. Each path on this event is characterised by an appropriate sequence of events with the frequency associated with this. If safety functions are known, the frequency of particular outcome can be assessed based on the quantitative principle of the event tree.

In the case of a particular outcome event, workers are at risk from the physical effects of combustion in the form of heat radiation, flames, pressure waves and flying debris and from harmful products of the combustion reaction and depletion of the breathable oxygen in the ambient air. This underlines an importance of ensuring safe working environment for workers which demands that potential explosion hazards be tackled at source whenever possible.

2.2. *The occurrence likelihood of explosive atmospheres*

Flammable atmospheres may occur and spread into different areas and there may be different probabilities for the existence of potentially explosive atmospheres formed by gas–air or dust–air mixtures in a particular location of the process plants. It is a difficult job to judge the range (size) of these atmospheres and their existence probability. For this purpose we apply the standard EN-60079 procedure concerning the classification of hazardous area used over time in industry, for specifying suitable protected electrical equipment (zoning) [9]. On this basis, the proportion of time in the year when a flammable atmosphere may be expected to be present and subsequently the likelihood of a potentially explosive atmosphere occurring can be described. The procedure is an objective of national standards and installation rules. Most of the countries following this standard established three-zone systems for areas hazardous due to combustible gas– or vapor–air mixtures as well as due to combustible dust–air mixtures in industrial plants (except coal mining). Table 2 provides an appropriate description of the classification systems. Each zone is characterized by the persistence which may be roughly estimated from 1000 up to 1 h/year depending on the area classification. The probability of explosive atmospheres may be assessed on this basis by means of approximation of the order of magnitude. This is given in Table 2.

Table 2
The occurrence likelihood of the explosive atmospheres

Classification of hazardous areas		Description of existence		Persistence time (h/year)	Frequency per year used in exLOPA
Gas/vapor	Dust				
0	20	Will persist permanently or for a long period or frequently	In normal operation	>1000	1
1	21	Likely to occur in normal operation (occasionally)	Also in the case of foreseeable faults	>10	10^{-2}
2	22	Unlikely (not expected in normal operation)	Even in of rarely occurring faults	<10	10^{-3}

The above description indicates that the hazardous area classes 0/20 and 1/21 may be considered as normal sources of explosive atmosphere, whereas area class 2/22 represents an abnormal hazardous area due to different causes like possible failure of protective enclosure, operational error or maintenance errors as well as surroundings of area 1/21.

It should be noticed that hazardous area classifications are not based on a very scientific foundation and they are essentially empirical and possibly conservative.

This approach is certainly a very rough and limited simplification, especially for particular explosive mixtures, heavier than air and even more for dust-air explosive mixtures where properties of dusts and other conditions have a major impact on the possible range of explosive zone and its frequency. Moreover, this area classification procedure applies for electrical sources of ignition only, but we suggest to extend it to the other sources of ignition. However, the area classifications are legal standard requirements and the data are available in all branches of industry and we believe that they may be used for rough but fast assessment of the likelihood of explosive atmospheres and subsequently explosion risk assessment. On the contrary, a detailed analysis would be required which concerns the dispersion calculations as well as reliability analysis of all systems which is a quite complex task, not easy to perform by all people in industry itself.

2.3. The likelihood of the presence of effective ignition sources

The identification and assessment of effective ignition probability in the explosive atmosphere is a key step in the explosion risk assessment. The issue is quite complex due to the different nature of ignition sources, location of explosive atmosphere (indoor or outdoor), effects of fuel type and concentration (magnitude of explosive atmosphere) and type of mitigation measures. In fact, there is no reliable model to include all these aspects.

Standard EN 1127-1 [10] distinguishes 13 types of ignition sources presented in Table 3a. There are some ignition sources that are of particular importance in operational practice of process plants.

In order to assess the likelihood of a presence of effective ignition sources in a certain process we have applied an expert opinion based on the following check list:

Table 3a
List of possible ignition sources

Common: in process industry (control ignition parameter)	Special: rarely met in process industry
Hot surfaces (MIT)	Lightning
Flames and hot gases (MIT)	Stray electric currents
Mechanical sparks (MIE)	HF electromagnetic radiation
Electrical equipment (MIE)	Optical radiation
Static electricity (MIE)	Ionising radiation
Chemical reaction (thermal instability) (Tex)	Ultrasonic
	Adiabatic compression and shock waves

Table 3b
The likelihood of the presence of effective ignition sources, P_{EFF}

Category	Description, example	Range of ignition probability	Probability used in exLOPA
Certain (permanent)	Operational type, e.g., electrostatic charges when pouring, mixing, pumping or filtering or open flames from burner	Up to 1	1
Occasional	Due to occasional failure of control ignition parameters, e.g., hot surfaces from damaged surface of a boiler	0.1–0.01	10^{-1}
Rare	Due to very rare failure of control ignition parameters, e.g., failure of intrinsically safe electrical equipment (Exi)	0.01–0.001	10^{-2}

1. What are the types of ignition source present?
2. Whether the ignition energy of present particular source is greater than the minimum ignition energy (MIE) of the explosive atmosphere (effective ignition source)?
3. How often an identified ignition source can occur?

The first question can be answered on the basis of current industrial practice and engineering judgment, the second question requires some additional data or further experimental studies and the third one is connected with operational sources or with the frequency of failure of the ignition control measures—linked ignition source. In this aspect we rank approximately the ignition sources into three categories and assign the appropriate value of ignition probabilities. This is given in Table 3b.

We know that this is a quite rough estimation: however, a more detailed one requires a lot of further analysis and experiments which would go far beyond the scope of this paper.

2.4. Safety measures for atmospheric explosion

The safety measures should respond to fire and explosion hazards and eliminate or minimize as much as possible the risks for workers possibly occurring in hazardous plants or activities.

Precautions against vapor/dust explosions or fire fall into a three-layer category, namely, prevention, protection and mitigation layers. Each layer may consist of a different number of safety measures called independent protection layers (IPL). In order to be considered as an IPL, a measures (system, device or action) must be effective, independent and auditable [5].

The aim of the prevention layer is to ensure that the conditions under which an explosion becomes possible never occur. The protection layer aims to limit the effects of explosion or fire, which it is assumed to occur. The response layer will mitigate

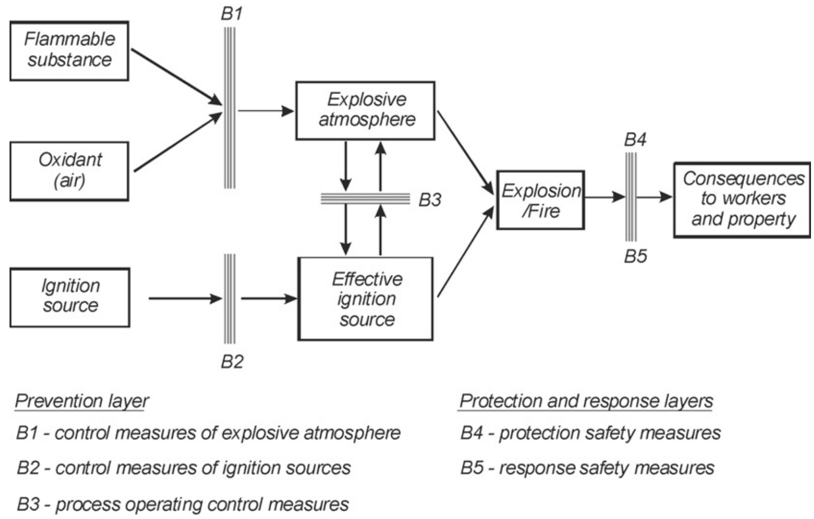

Fig. 3. Explosion safety measures.

the consequences of explosion or fire. Fig. 3 illustrates explosion safety measures acting as a safety barrier.

All above layers are typical barriers for the development of the hazardous event with the aim to exclude or diminish fire and/or explosion as far as possible.

Each barrier has its own probability of failure on demand (PFD). Similarly to the LOPA, ex LOPA has provided the predominated set of PFD values for particular safety measures, so one can select the values that best fit the scenario being analyzed. Table 4 provides the typical range of PFD values for appropriate

Table 4
Probability failure on demand (PFD) of explosion prevention and mitigation measures

Type of the safety measure	Probability of failure on demand—literature	PFD used for exLOPA
Control measures of formation of hazardous explosive atmosphere (B1)		
Use of substitutes for flammable substance (inherent safe design)	10^{-1} to 10^{-4}	10^{-2}
Failure of the protection enclosure:		
Under pressure	10^{-5} to 10^{-7}	10^{-6}
Atmospheric	10^{-3} to 10^{-5}	10^{-3}
Limiting the concentration (remaining outside the explosion limits) e.g., ventilation	10^{-1} to 10^{-3}	10^{-1}
Inerting	10^{-1} to 10^{-3}	10^{-1}
Gas or spark monitoring (detecting)	10^{-1} to 10^{-3}	10^{-1}
Management means (housekeeping)	No exact value	
Control measures of ignition source (B2)		
Safe operating conditions	10^{-1} to 10^{-2}	10^{-1}
Ignition control in electrical equipment	10^{-1} to 10^{-2}	10^{-1}
Ignition control in non-electrical equipment	10^{-1} to 10^{-2}	10^{-1}
Electrostatic control	1 to 10^{-2}	10^{-1}
Organizational measures	No exact value	
Process operating control measures (B3)		
Safe operating conditions	10^{-1} to 10^{-2}	10^{-1}
Safe working procedures	10^{-1} to 10^{-2}	10^{-1}
Mitigation means (B4–B5)		
SIS failure	10^{-1} to 10^{-4}	10^{-2}
Venting	10^{-2} to 10^{-4}	10^{-2}
Suppression system	10^{-1} to 10^{-3}	10^{-2}
Fire detection	10^{-1} to 10^{-2}	10^{-1}
Fire fighting	10^{-1} to 10^{-2}	10^{-1}
Flame/detonaters arresters	10^{-1} to 10^{-3}	10^{-2}
Containment	10^{-1} to 10^{-4}	10^{-2}
Isolating system	10^{-1} to 10^{-3}	10^{-1}

Table 5
Qualitative matrix for consequence severity assessment

Severity category	Description
I. Negligible	Very minor or no injury with no lost time
II. Small	Minor injury, no lost time
III. Medium	Single injury with short losy time (reversible effects)
IV. Large	Serious injuries—irreversible effects
V. Catastrophic	Fatality or multiple serious injuries

safety measures met for explosion prevention and mitigation. The list is not exhausted and may be filled-up by specific safety solutions. Due to variations in design, construction, operation and maintenance, the PFD value will be different between facilities and each organization should establish its own data.

3. Severity of explosion

The severity of an explosion or fire is described by the damages (or consequences) occurring due to the impact of the explosion or fire scenario. This is a very complex task, which is usually based on the application of fire/explosion effect models, applicable to different release sources in outdoor and indoor plant. Major release as a source of the explosive atmosphere is considered by the QRA method where the severity of consequence may be modeled by means of any available software (e.g., PHAST) [11]. This is a very time- and expense-consuming exercise with a high level of uncertainty.

In the chemical and refinery industry, where flammable gases, liquids and solids are converted and processed in many different processes, each point of the plants may be such a source of an explosive atmosphere. There is no chance to predict everything. Therefore, exLOPA takes into account the estimation of the severity of consequences using matrix categorization based on the level of human harm for each particular explosion scenario. Table 5 provides the consequence categorization with an appropriate description. This is a purely qualitative judgment in which past experience, knowledge, and expert opinion are used with some advantages and disadvantages. However, based on our experience, the industry people well understand this approach.

4. The basis of exLOPA

Generally exLOPA is based on the original work of CCPS/AIChE on LOPA [5]. The overall exLOPA process is illustrated in Fig. 4. This should be considered as a general overview without limitation of its applicability.

4.1. Accident scenario identification

This task is usually accomplished using suitable formal techniques of hazard identification, and expert's assessment with support from the results of historical data on accidents that occurred in the past. The analysis should cover three questions: the existing sources of hazardous explosive atmosphere (ATEX), and the effective source of ignition, which could occur at the

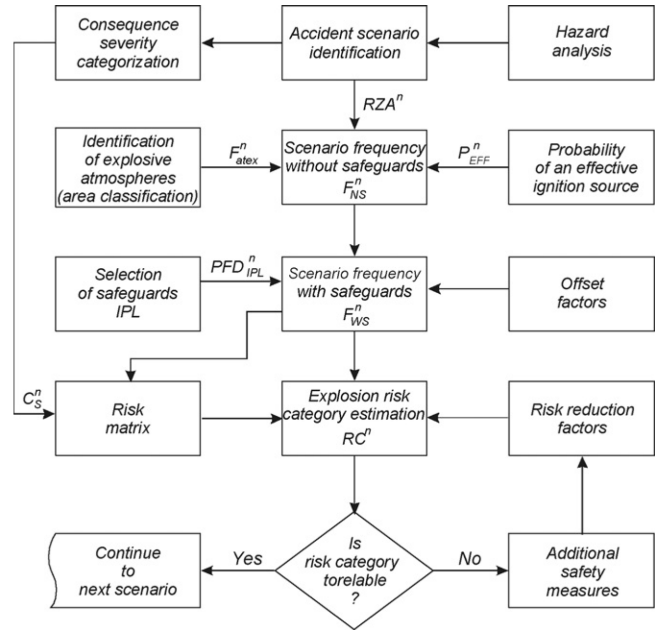

Fig. 4. The exLOPA flowsheet.

same time as well as the action of protective and mitigation measures. In practice, it is done by working systematically with a check list. The exLOPA is applied only to one-accident scenario, which is used to represent the worst case scenario and it may be considered as an indoor representative accident scenario RAS(in) (inside the process equipment) or outdoor explosion scenario RAS(out). The scenario of the accident consequences severity (C_S^n) can be assessed on the basis of estimation of the potential harm to workers by means of severity matrix (Table 5). It is worth noting that the continuous volume of 10 l of explosive atmosphere in a confined space must always be regarded as a hazardous explosive atmosphere, irrespective of size of the room [12] whereas minimum explosive concentration for dusts is about 0.035 kg/m^3 of a cloud.

4.2. Scenario frequency without safeguards (F_{NS})

The frequency of the "*n*" scenario, F_{NS}, which may causes the C_{S}^n consequences can be expressed as follows:

$$F_{\mathrm{NS}}^n = F_{\mathrm{atex}} P_{\mathrm{EFF}}^n$$

where F_{atex} is the frequency of occurrence of explosive atmosphere, P_{EFF} the probability of occurrence of ignition source, and *n* the number of explosive accident scenario.

4.3. Scenario frequency with safeguards (F_{WS})

The frequency of the "*n*" scenario with "*j*" safeguards, F_{WS}, which may cause the *C* consequences can be expressed as follows:

$$F_{\mathrm{WS}}^n = F_{\mathrm{NS}}^n \prod_{j=1}^{jn} \mathrm{PFD}_{\mathrm{IPL}}^{jn}$$

where PFD is the probability failure on demand of a particular independent protection layer (IPL).The data for IPL may be offset taking into account special consideration, e.g., quality of safety management.

4.4. Risk level estimation and assessment

The frequency of each individual scenario, F_{WS}^{n}, and associated severity consequences C_{S}^{n} were used for risk estimation and risk assessment based on the developed risk matrix shown in Fig. 5.

The scenarios with TNA and NA risk level require the necessary risk reduction action. It concerns addition of the independent protection measure (IPL), improvements of the existing safety measures (decrease of $\mathrm{PFD_{IPL}}$), or a more detailed analysis, including quantitative risk assessment (QRA). The analysis is ended with the estimation of the risk reduction factors, due to proposed additional safety measures, on risk level, and checking again if a new value of risk is admissible for each individual accident scenario. The results of analysis are recorded on the worksheet presented in Fig. 6.

Consequence category / Frequency [1/year]	I (negligible)	II (minor)	III (medium)	IV (major)	V (catastrophic)
A ($10^{0}-10^{-1}$)	TA	TNA	NA	NA	NA
B ($10^{-1}-10^{-2}$)	TA	TNA	TNA	NA	NA
C ($10^{-2}-10^{-3}$)	A	TA	TNA	TNA	NA
D ($10^{-3}-10^{-4}$)	A	TA	TA	TNA	TNA
E ($10^{-4}-10^{-5}$)	A	A	TA	TA	TNA
F ($10^{-5}-10^{-6}$)	A	A	A	TA	TA

Fig. 5. Explosion risk matrix.

Plant: Filling station	Filling worker Tank 1b	Explosive scenario Ex (indoor) / **Ex (outdoor)**
Hazardous substance: Petrol 95: F+, R12, R18, T, R45, Cancerogenic cat. 2	**Scenario description**: unloading hose failure, outdoor release, ignition due to electrostatic charges, possible fire or explosion with harmful consequences to workers or clients	
Severity of consequences C_s: (I, II, III, IV,V)	Release of about 100 kg of petrol	**Category C_s: IV**
Atmospheric explosive (atex)		
Area classification- immediate vicinity of feed opening	Class 1	**Frequency F:** **10^{-2}[1/year]**
Initiating event: failure of unloading hose (100 unloadings per year within 2 hours)	Correction for the “time at risk” due to non-continuous operation: 200hr/8000 [hr/year]=$2.5\mathrm{x}10^{-2}$	**Frequency with “time at risk”,** **$F_{atex}=10^{-2}\mathrm{x}2.5\mathrm{x}10^{-2}$** [1/year] =
		$F_{atex}=2.5\mathrm{x}10^{-4}$[1/year]
An effective ignition source		
Electrostatic charges	Very low value of MIE of petrol (<0.2mJ)	**Probability P_{EFF}: 10^{-1}**
Explosion frequency without safeguards (F_{NS}) F_{NS}= **F_{atex}x P_{EFF}[1/year]**		**$2.5\mathrm{x}10^{-5}$[1/year]**
Independent Protection Layers (IPL)		
Explosion atmospheric protection measures, B1		**Probability failure on demand, PFD**
Human error		10^{-1}
PFD_{B1}		**10^{-1}**
Prevention of ignition sources (B2)		
Protection against electrostatics		**10^{-1}**
PFD_{B2}		**10^{-1}**
Operating control (B3)		
N/A		
PFD_{B3}		N/A
Protection means (mitigation) (B4 and B5), $PFD_{B4,B5}$		
Fire fighting		No impact
$PFD_{B4,B5}$		N/A
Total PFD for all IPL **P_Z**= PFD_{B1}x PFD_{B2}x PFD_{B3} $PFD_{B4,B5}$		**10^{-2}**
Scenario frequency with safeguards (F_{WS}) **$F_{WS}=F_{BZ}$ x P_Z [1/year]**		**$2.5\mathrm{x}10^{-7}$[1/year]**
Risk level assessment R (A, TA, TNA, NA)**:TA**		**Risk assessment: TA** (no further action is required)
Additional safety measure: NA		**Risk reduction factors: NA**

Fig. 6. The exLOPA worksheet.

5. Summary

The paper presents the application of Layer of Protection Analysis, called exLOPA, for fast realization of the ATEX 137 directive concerning risk assessment of workers employed in potentially explosive atmospheres. The simplified method, which may be considered as semi-quantitative, takes into account some typical factors appropriate for explosion, like the probability that an explosive atmosphere will occur, the probability that sources of ignition will be present and become effective, as well as the probability of failure on demand of appropriate explosion prevention and mitigation means. This is applied to particular explosion scenarios. The hazardous area classification scheme which identifies location where an flammable atmosphere can exist on the process plant is extended to determine the likelihood of explosive atmospheres, and an expert's opinion is proposed to select the existing ignition source. The reliability of layers of protection as a barrier to prevent undesired explosion event and protect workers is also taken into account. The proposed methodology allows for a fast estimation of the risk of explosion to workers employed in hazardous explosive atmospheres.

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