CHEMICAL ENGINEERING TRANSACTIONS
VOL. 77, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano

ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977087

Integrated Explosion Risk Assessment for the Workplace in a Process Plant

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The improvement of health, safety and protection of workers at risk from explosive in the workplace is governed by the European ATEX Directives requiring the employer to carry out a risk assessment for possible explosion scenario. In order to determine explosion risk, the recently proposed methodology ExLOPA requires the identification of the explosion scenario and its structural elements, conventionally by applying different Process Hazard Analysis methods. This paper presents a novel strategy based on the combination of an expert system for explosion scenario identification (ExSys), with subsequent application of ExLOPA method. An expert system (ExSys) employs values from ad-hoc prepared engineering databases to identify the explosion loss event tailored for the selected target process and the given workplace. Subsequently, an explosion barrier model is developed, to provide data for a representative explosion scenario, which is finally used for explosion risk assessment by the ExLOPA methodology. The proposed technique supports and extends the application of the Layer of Protection Analysis especially for safety assurance assessment of risk-based determination for chemical, petrochemical, pharmaceutical, energy, food, wood and other process industries and related services.

1. Introduction

Notwithstanding the ongoing trend towards inherent safety, raw materials in petrochemical and process plants (e.g. flammable hydrocarbons) are often impossible to be replaced by inherently safer as evidenced by explosion and fire accident statistics (Fabiano and Currò, 2012). It is generally acknowledged that risk assessment is the most effective way to design safety and security safeguards in order to provide safe workplaces and protect the environment. It also concerns workplaces where explosion atmosphere may occur. This aspect is governed by the European Directives 1999/92/EC (ATEX 137) and 2014/34/EU, which require the employer to perform the risk assessment for possible explosion at a workplace. Layer of Protection Analysis is an amply applied tool that analyses cause-consequence pair, estimating initiating cause probability on an order of magnitude basis and severity qualitatively and that is currently applied also to emerging risk (Fabiano et al., 2018). An earlier work by Morkowski (2007) suggested applying the methodology called explosion layer of protection analysis (exLOPA), which allows for semi-quantitative explosion risk assessment for process plants where explosive atmospheres occur. However, in order to apply ExLOPA we need to identify explosion scenario and its structural elements. This task can be adequately fulfilled by different Process Hazard Analysis methods, even if these techniques require extensive experience, efforts by teams of experts. Additionally, PHA techniques imply significant time commitments, especially for complex chemical process units and for branches of industry where risk management is still under development. In order to simplify the overall process, this paper presents a novel strategy that is a combination of an expert system for explosion scenario identification (ExSys) with subsequent application of ExLOPA method.

Paper Received: 1 December 2018; Revised: 18 April 2019; Accepted: 15 July 2019

Please cite this article as: Markowski A., Wasowicz P., Fabiano B., 2019, Integrated Explosion Risk Assessment for the Workplace in a Process Plant, Chemical Engineering Transactions, 77, 517-522 DOI:10.3303/CET1977087

2. The explosion scenario model structure - what Expert System should consider

The explosion event is a key element in explosion risk assessment. General model of an explosion event is presented in Figure 1. When it comes to the explosion phenomena there are typical events and conditions leading to explosion, i.e. occurrence of explosive atmosphere in presence of an ignition source. The last item show large uncertainties in its evaluation and limitations in the possibility of differentiating between immediate and delayed ignition (Pesce et al., 2012). Additionally, the model takes into account preventive layers and protection layers including action of appropriate safety measures (B1-B5). In other words, the conceived model indicates all necessary events and conditions that should be used in developing the expert system.

2.1 Explosive atmosphere hazard factors

Explosive Atmosphere, decrypted as ATEX, is determined by assessing explosion hazard factors. It concerns the set of interrelated technical and technological properties, which may form the explosive atmosphere.
In order to correctly identify the relevant factors, the following knowledge databases are used:

- type of the operational space where explosive atmosphere may occur (4 classes selected),
- type of the apparatus or equipment involved (5 classes),
- type and of process operation (18 classes),
- physical state (5 classes),
- type and properties of the flammable medium involved (12 classes)
- technical source of emission (7 classes),
- type of maintenance and supervision (4 classes).

Analysis is based on the classification of the above indicated factors into an appropriate number of classes, e.g. for “apparatus” factor there are five classes selected: process container, piping, pump, transporter, separator. Classes selected by experts are combined together providing the general description of the ATEX.
Based on the above information an expert may find out about the type, location and any related data of potential explosive atmospheres with reference to a given workplace. A coding system allows for easy identification of the hazard factors of explosion atmosphere. These data are used in the next step of ExSYS method.

2.2 Explosion event list (LEE)

Explosion event (EE) may occur if explosive atmosphere - ATEX - meets an effective ignition source IG_{EFF}.
To this purpose we use two databases:

- database on emission sources able to form explosive atmospheres (19 different classes);
- database on ignition sources (13 different classes with additional specifications).

Combination of data concerning the earlier identified ATEX with data describing the sources of emission and the presence of a specific ignition source allow determining the Explosion Event (EE) in terms of qualitative description of an explosive event (what, where and when) and in terms of semi-quantitative approach.

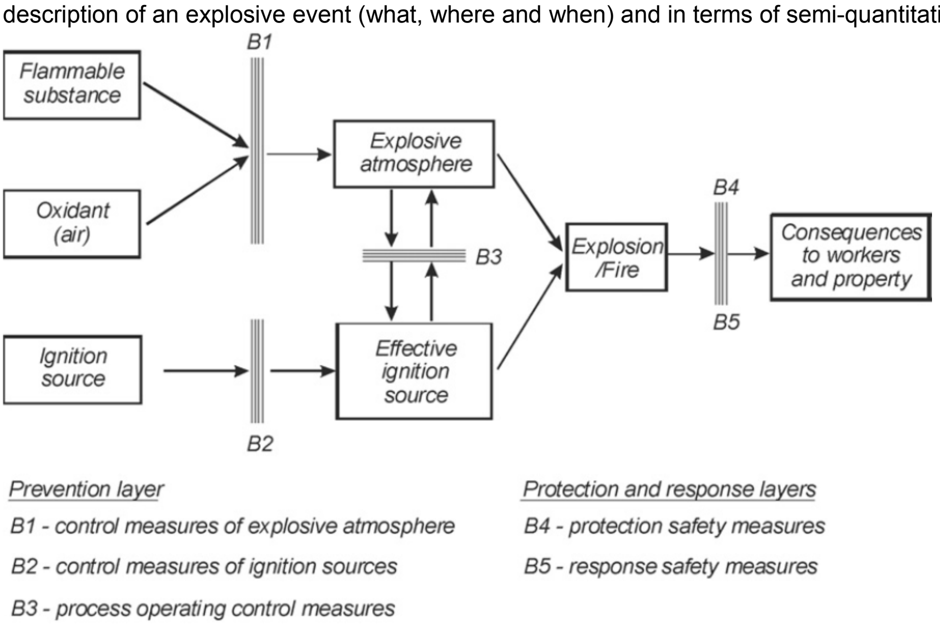

Figure 1: Conceptual model of the Explosion Event (EE)

The latter one concerns a rough estimate of the amount of flammable medium contained in explosive atmosphere consequence (C_S) and the frequency of occurrence demonstrated by the category of emission grade, K_{ATEX} based on logic rules: if X and Y then Z. The (C_S) is expressed in term of five semi-quantitative categories (I-V), where category C (I) means neglected losses and C(V) – catastrophic. Similarly the K_{ATEX} is expressed in terms of three semi-quantitative grade categories K_{ATEX} (I, II, III), where category K_{ATEX} (I) represents the continuous emission of flammable medium and K_{ATEX} (III) secondary emission. The second database provides information on the type and its ignition probability K_{IG}, which occurs in a given workplace. It is similarly categorized into 3 categories (I, II, IIII). Combination of K_{ATEX} and K_{IG} allows semi-quantitatively describe the Explosion Event (EE) representing the frequency of an unmitigated explosion event (without any safety barriers). There may be a number of such events forming a chain (list) of explosion events (LEE), depending on explosion hazard factors. This is an input into ExLOPA Data.

2.3 Representative explosion event (REE)

In order to simplify the analysis the set of EE is reduced to the selected number of events called a representative explosion event, REE. This is understood as a selected explosion event which is typical for each identified explosive atmosphere with highest consequences that is considered plausible and reasonably creditable. The selection of REE is based on the following principles:

1. the explosion events with extremely low value of K_{ATEX} (III category) and K_{IG} ((III category) may be eliminated, whereas the highest values of K_{ATEX} (I category) and K_{IG} ((I category) must be taken into account;
2. careful selection of the emission which is closely connected with most creditable release size and most creditable severity of consequence;
3. grouping and replacing some EE with representative ones having similar inventory, operating condition location and type of the medium.

The major decision must be based on the rough assessment of the category of emission grade of explosive atmosphere (K_{ATEX}) and the category of probability of effective ignition source (K_{IG}). The selection matrix is shown in Figure 2. The conditional allocation of REE must be supported by historical data as well by expert opinion. The output of this step is a list of representative explosion events (LREE). This is input into ExLOPA Data**.**

2.4 Representative explosion scenario (RES)

RES is selected from the list of REE taking into account the functions of the multilayer of safety barriers designed for particular explosion event, as well as an available historical data and other contributing events. Multilayer safety explosion barriers typically encountered in a process plant were presented before (Markowski, 2007).

In order to identify RES, an appropriate safety barrier must be checked and verified for REE and subsequently used to build up an explosion scenario model using the simplified event tree logic diagram. The idea of such a diagram is shown in Figure 3.

It should be observed that there are a number of outcome cases but just the paths representing the failure of all safety functions attributed to barriers B1-B5 are taken into account. The decision on the choice between a major accident (RES1) and a catastrophic one (RES2) should be based on the quality of the safety system involved. This is fundamental data which closes the generation of explosion scenarios needed to apply ExLOPA. The validation of selected RES could be done using historical data provided by the company involved or statistics from scientific literature and open sources. The output of this step is a set of safety barriers (IPL) to be utilized as an input into ExLOPA Data**.**

K_{ATEX} (Grade of emission category)	K_{IG}(Ignition probablity category)		
	I present frequently	II rare	III very rare
I (continuous releases)	REE	REE	REE (CONDITIONAL)
II (primary releases) periodically	REE	REE (CONDITIONAL)	NO REE
III (secondary) infrequent	REE (CONDITIONAL)	NO REE	NO REE

Figure 2: Selection matrix for Representative Explosion Event (REE)

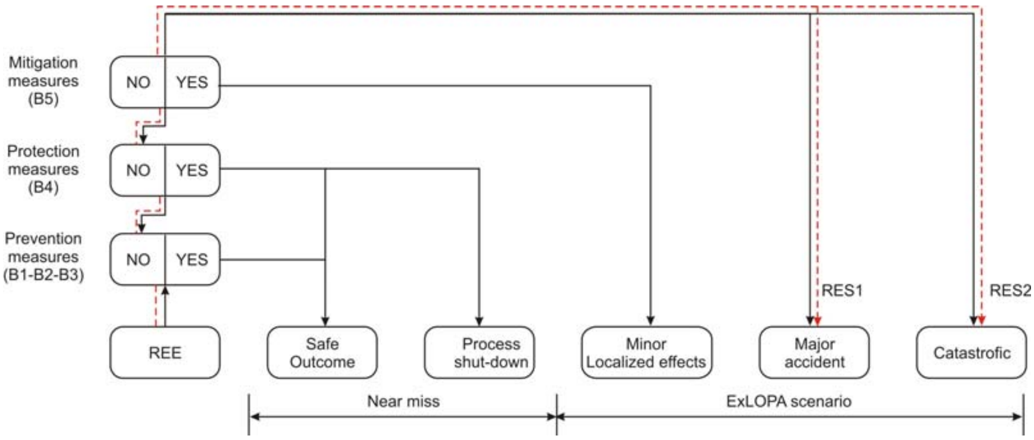

Figure 3: Modelling framework for Representative Explosion Scenario (RES)

3. An expert system for generating accident scenarios (ExSys)

An expert system attempts to use knowledge provided by one or more human experts within a specific problem domain to help in decision making, or to resolve some specific problems. The conceived ExSys consists of both knowledge database and knowledge engineering that transfer knowledge to the user to help in selecting accident scenario. In our case, the knowledge database comprises different databases shown in the previous section. The process of accident scenario generation is shown in the step-wise flowsheet of the ExSys concept schematically depicted in Figure 4 and summarized in the following.

- Step 1. Description of potential explosive atmosphere ATEX

Description of the potential explosive atmosphere EXAT is worked out with the help of seven databases called "Explosion hazard factors". The combination of certain numbers of explosion hazard factors is obtained, which describe in details the explosion atmosphere possibly occurring within a particular plant. Each such an identified ATEX may have some potential for explosion and will go to the next stage of the Expert system ExSys.

- Step 2. Description of an explosion event.

Each identified potentially explosive atmosphere is further analyzed in detail taking into account databases concerning the emission sources as well as databases concerning the ignition source. In such a way we can identify the possible explosion event EE without activating a safety barrier. The event doesn't take into account any existing or design safety barriers.

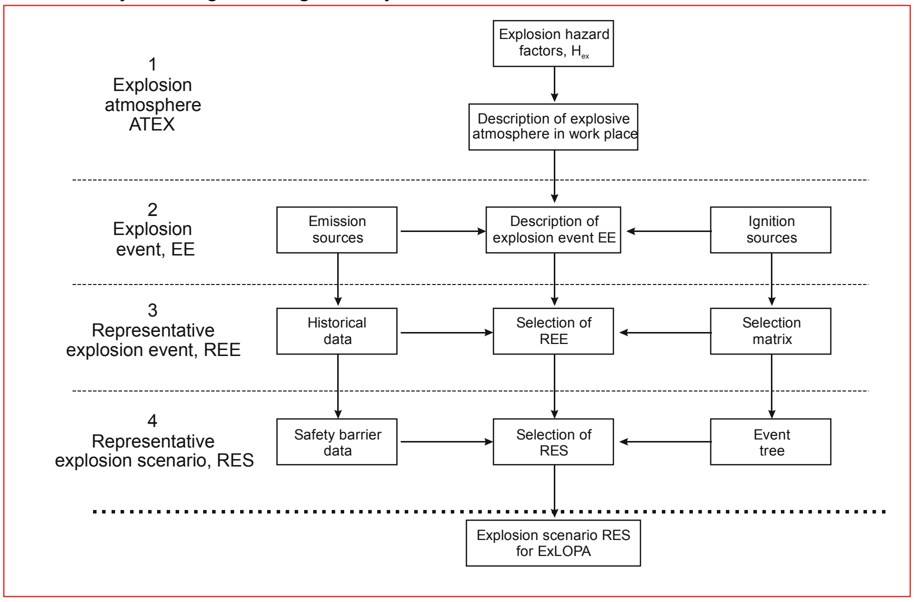

Figure 4: Logic diagram for the selection of explosion scenario ExSys

- Step 3. Selection of representative explosion event REE

The list of described explosion events, LEE is further analyzed in order to reduce it to the list to the most creditable events REE. The selection matrix is shown in the already mentioned Figure 2.

- Step 4. Selection of representative explosion scenario RES

REE analysis doesn't take into account the existing safety barriers. These data are necessary for the selection of a representative explosion scenario RES, starting from each identified REE. As previously outlined in section 2.4., the event tree principles are applied with the use of safety barrier database.

4. ExSys information for ExLOPA analysis

4.1 ExLOPA

As previously outlined, LOPA can be defined as a simplified risk assessment method. It provides an evaluation the risk of accident scenario and its comparison with risk tolerance criteria to decide whether existing safeguards are adequate, and if some additional safeguards are needed.
ExLOPA is based on the original work of CCPS (2001) and the explosion phenomena characteristics.

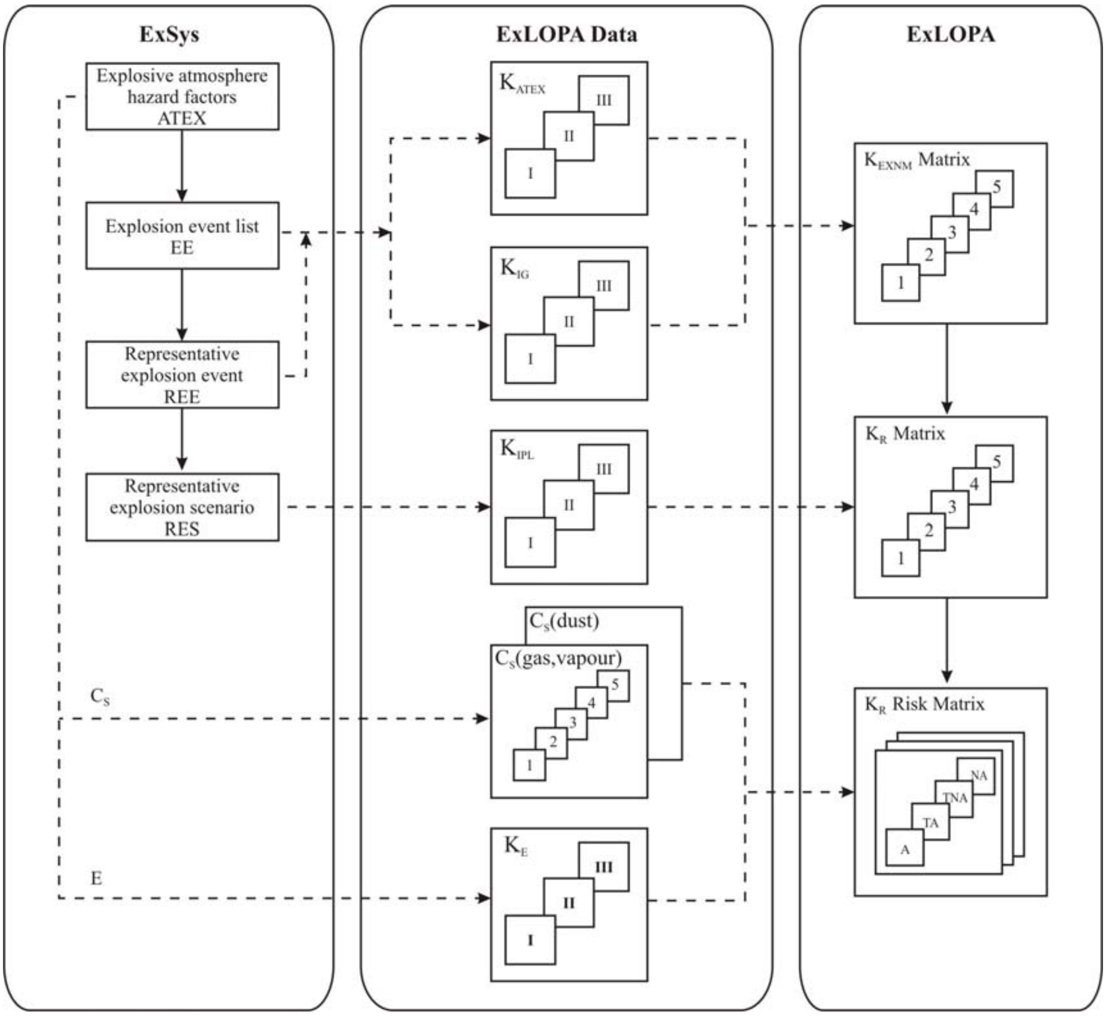

Figure 5: Relationship between ExSys and ExLOPA information

The explosion risk R_n can be expressed according to the general relation provided by Eq(1):

$$R_n = f\,[(P_{ATEX}\,,\, P_{IG}\,,\, F_n\,),\, C_S,\, E\,] \tag{1}$$

where:
P_{ATEX} = probability of atmospheric explosion occurrence; P_{IG} = probability of effective ignition source occurrence;
C_S = explosion consequence; Fn = probability of failure of the safety system; E = exposure index for workplace.
ExLOPA simplifies the analysis replacing all numerical values for the components required to calculate the risk with one from the below appropriate semi-quantitative categories:
$R\sim K_R(A,TA,TNA,NA)$; $P_{ATEX}\sim K_{ATEX}(I,II,III)$; $P_{IG}\sim K_{IG}(I,II,III)$; $Fn\sim K_{IPL}(I,II,III)$, $E\sim K_E(I,II,III)$.
At last, the resulting expression for explosion risk in ExLOPA analysis is provided by following Eq. (2):

$$K_R = f(K_{ATEX}, K_{IG}, K_{IPL}, K_E) \tag{2}$$

All the above categories are provided by the ExSys and gathered into ExLOPA Data. The ExLOPA analysis uses the above data to determine the category of frequency of unmitigated explosion, K_{EXNM}, the category of frequency of mitigated explosion, K_{EXM}, and finally the category of risk, K_R. For the complete description of the ExLOPA semi-quantitative categories and frequencies the reader is addressed to the original paper of Markowski (2007).

4.2 ExSys info for ExLOPA

ExSys includes all information necessary for ExLOPA procedure. Figure 5 shows the relevant Ex-Sys information and the ExLOPA information in graphical form. Solid lines show the sequence of the ExSys or ExLOPA development. Dotted lines show the conceptual flow in transferring Ex-Sys information towards ExLOPA.

5. Conclusions

From a methodological point of view, we can draw the following conclusions:

- The paper presents a comprehensive approach to risk assessment of particular major accident scenario using the combination of two techniques: an expert system ExSys for identification of the structure of accident scenario and ExLOPA method for explosion risk assessment.
- This technique can speed up process hazards analysis by quickly taking into account the numbers of creditable possible scenarios.
- The idea of ExSys-ExLOPA technique may be used primarily for the preparation of the Prevention Explosion Document as required by ATEX regulation.

The developed framework is currently under validation and comparative testing in real process plants, in order to test its capabilities and conservative degree, compared to existing tools, for ensuring consistent application of ATEX Directive.

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