Lisi Roberto

Milazzo Maria Francesca
University of Messina, Messina, Italy

Maschio Giuseppe
University of Padova, Padova, Italy

Quantitative assessment of explosion risk in workplaces

Keywords

risk assessment, explosion, safety, workplace, ATEX

Abstract

The Directive 99/92/EC deals with the safety and health protection of workers potentially exposed at explosive atmospheres. The application of this Directive requires the assessment of specific risks due to the presence of potentially explosive atmospheres. These can generally be originated by releases of flammable substances typical of industries classified at major hazard, but they often could be generated also in all other industries where flammable materials are handling. Risk assessment of explosive atmospheres is required in both the cases, to this purpose, in this article a quantitative approach has been proposed. The paper describes the main aspects of the methodology, based on a probabilistic risk assessment, and finally its application to a case-study.

1. Introduction

Explosive atmospheres can be originated by releases of flammable gases, mists or vapours or by combustible dusts. If there is enough substance, mixed with air, then a source of ignition is sufficient to cause an explosion.

Explosions can cause loss of life as well as serious injuries and significant damage on structures. Preventing releases of flammable substances and the formation of ignition sources are the most widely used ways of reducing the risk. The use of the correct equipment can help greatly in achieving these aims.

In the framework of the General Directive 89/391/CE [2], concerning the application of measures to promote the improvement of the safety and health of the workers, the *places potential characterized by explosion hazard* have assumed particular attention. In this context the term ATEX (from the French language and means *Atmospheres Explosibles*) is the name commonly given to the framework for controlling explosive atmospheres and the standards of equipment and protective systems used to this purpose.

Concerning the control of explosion risk two European Directives exist: the Directive 99/92/EC or ATEX 137 and the Directive 94/9/EC or ATEX 95 [3]-[4].

The Directive ATEX 137 also known as *ATEX Workplace Directive* regards the minimum requirements for improving the health and safety protection of workers potentially exposed at risk from explosive atmospheres.

The Directive ATEX 95 also known as *ATEX 95* or the *ATEX Equipment Directive* concerns the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres.

To increase the safety of the workers and prevent the explosions, during 2003, the European Committee has realized and, on purpose, compiled an official guide defined of *good practice* for the correct application of the newer directives related to the safety of the workers regarding the risk due to the presence of explosive atmospheres. The Directive 99/92/EC has been adopted in Italy, it has been integrated in the main Italian regulations concerning the safety and health protection in the workplace [5]-[8]. The D.L 626 (1994) [5] has recently been

improved and substituted with the D.L. 81 (2008) [8].
The Italian regulation concerning safety and health protection in the workplace includes specific norms for the protection of workers against the explosions. According to this legislation employer has the obligation to prevent the formation of explosive atmospheres adopting all the technical-organizational measures required, this can be done taking into account the evaluation of the potential presence of explosive atmospheres in workplaces. When the formation of such flammable clouds can not be avoided, the ignition must be prevented and the damages potentially caused by an explosion must be reduced to the least. The employer has to classify the areas in which is possible the formation of explosive atmospheres. Then the *document of evaluation of the risk due to explosive atmospheres* (in this work named *document of evaluation of the ATEX risk*) has to be redacted and, periodically, updated. Such document must undergo to the least requisites fixed by the decree law mentioned before [8] and must include a section in which the risk is evaluated using specific methodologies. Measure to avoid the formation of explosive atmospheres and ignition sources must also be indicated, finally the characteristics of the equipments used in the workplace must be specifies.
Safety Reports include the risk assessment related to the explosions of great magnitude for industries classified at major hazard. The estimation of the risk due to explosions, characterized by lower magnitude, which could potentially involve workplace, is included in the document of the risk assessment of the workplace and in the document of evaluation of the ATEX risk. The approach applied for the explosion risk assessment in the workplaces is generally qualitative [1] or semi-quantitative [17]. The application of a qualitative method often causes an underestimation of the risk associated with the explosion of flammable clouds originated by small releases, particularly, in confined places.

2. Methodological approach

In this work a quantitative procedure for the evaluation of the explosion risk has been proposed. It is based on a probabilistic risk assessment. It requires:

- the knowledge of the workplace and the process which takes place in the establishment;
- the identification of risk, this includes the identification of the physical-chemical properties (gas, liquid, dust) and the hazardous characteristics of the flammable substances (flammability and volatility) and, also, the detection of potential sources of release;
- the probabilistic analysis and the consequence estimation.

A flow-chart of the procedure has been drawn in *Figure 1*.

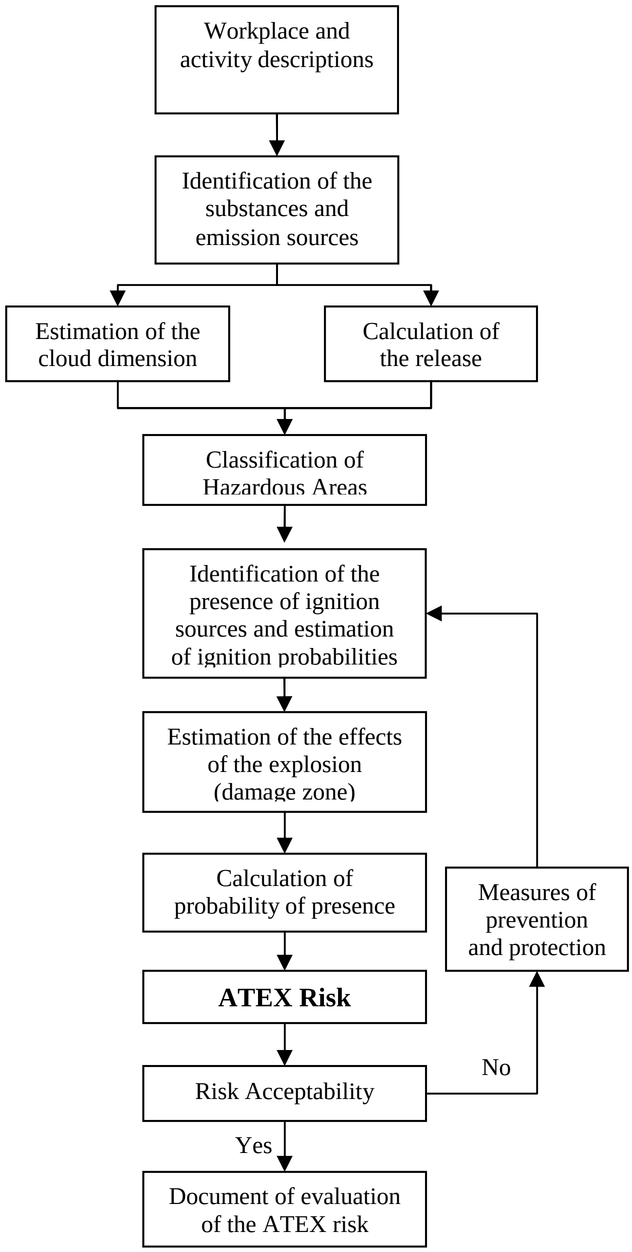

Figure 1. Flow-chart for the evaluation of risk due to the presence of explosive atmospheres.

The application of the procedure starts with detailed knowledge of the analyzed system. After the description of the workplace and the activity, it is necessary to classify the hazardous areas. The classification can be done taking into account the quantity of substances released and the probability of release. The risk evaluation will be possible after

the quantification of the probability of ignition, the potential damage caused by the explosion and the probability of presence of workers. The procedure will be completed with the evaluation of the acceptability of the risk. The analysis gives an risk index (ATEX risk) which, eventually, permits to define the necessary changes to reduce the risk level. The use of a quantitative approach for risk analysis allows an improvement of the overall safety levels. At the same time, in the case of industries not classified at major hazard, the method permits to avoid the underestimation of the risk associated with explosive atmospheres and to identify the correct preventive and protection measures for each case.
The risk assessment has to be done analyzing the establishment relatively to the following phases: under the normal conditions of operation, during the starting and out of service phases and, also, during malfunction of the plant.

2.1. Explosive atmospheres and classification of the areas

An explosive atmosphere is defined as a mixture of flammable substances with air, under atmospheric conditions. If an ignition has occurred, combustion spreads to the entire unburned mixture. Atmospheric conditions are commonly referred to ambient temperatures and pressures. This means temperatures of – 20 °C to 40 °C and pressures of 0.8 to 1.1 bar.
Many workplaces may contain or have activities that produce potentially explosive materials. Flammable substances can be grouped into four categories: liquids, gases, dusts and solids.
Liquids give off flammable vapour and are classified as:

- *Extremely flammable*: liquids having a flash point lower than 0 °C and a boiling point (or, in the case of a boiling range, the initial boiling point) lower than or equal to 35 °C.
- *Highly flammable*: liquids which have a flash point below 21 °C.
- *Flammable*: liquids which have a flash point higher than 21 °C.

The class *Gases* comprises gases liquefied. These are usually stored under pressure in cylinders and bulk containers. Uncontrolled releases can readily ignite or cause the cylinder to become a missile.
Dusts can be produced from many solid materials such as coal, wood, grain, etc. A cloud of combustible dust in the air can explode violently if ignited.
Solids include materials such as plastic foam, packaging, and textiles which can burn fiercely and give off dense black smoke, sometimes poisonous.
The classification of the areas has the purpose to establish the presence of zones characterized by explosion hazard, in which technical and organizational provisions must be adopts with the aim to make negligible the risk due to the presence of explosive atmospheres. In order to classify the areas, the establishment must be divided in units and it is necessary to define the zones where flammable substances can be release due to the normal operation of the plant, deviations of process or during the maintenance activities.
The methodology EN 60079-10 (CEI 31-30) [16] must be used for zone classification. The method needs to be applied together with two guidelines: Guide CEI 31-35 and Guide CEI 31-35/A [12]-[13]. These two guides give special features for determination of the type of the zone and its extension. The norm EN 60079-10 identifies the following hazardous zones:

- Zone 0: area where the presence of an explosive atmosphere is continuous.
- Zone 1: area where an explosive atmosphere is likely to occur in normal operating conditions.
- *Zone 2:* area where an explosive atmosphere is unlikely to occur in normal operating conditions or occurs infrequently for short periods of time.

EN 60079-10 does not give any indications on the release probability that should be taken as reference in the process for decision of classification. The Guide CEI 31-35 gives the indications shown in *Table 1*.

Table 1. Probabilities and durations of explosive atmospheres.

Zone	Probability – P (year^{-1})	Duration – t (hour/year)
0	P > 0.1	t > 1000 h
1	$0.1 \geq P > 10^{-3}$	10 h < t < 1000 h
2	$10^{-3} \geq P > 10^{-5}$	0.1 h < t < 10 h

2.2. Probability of the effectiveness of the ignition source

The presence of an explosive atmosphere is not enough to burn, an ignition is necessary. An important phase of risk analysis is the ignition sources identification. The standards UNI EN 1127-

1 [18] lists the following main causes of ignition of flammable atmospheres:

- Hot surfaces;
- Flames and hot gases or particles;
- Mechanical sparks;
- Electrical network;
- Wandering electrical currents;
- Cathode protection;
- Static electricity;
- Lightning;
- Heating cables;
- Radio-frequency waves (frequency $10^4 \div 3{\cdot}10^{12}$ Hz);
- Electromagnetic waves (frequency $3{\cdot}10^{11} \div 3{\cdot}10^{15}$ Hz);
- Ionizing radiations;
- Ultrasounds;
- Adiabatic compressions and bump waves;
- Exothermic reactions.

In order to quantify the probability of occurrence of each ignition source, literature data or, preferably, specific studies for the plant under analysis can be used. Methods, such as historical analysis, fault tree analysis, FMEA or FMECA, or specific analytic procedures, could also be applied to assess the probability or the likelihood of effectiveness of each ignition source listed above.

2.3. Consequences of the explosion

The consequences of the explosion must be estimated for each emission source identified through the classification of the areas and for each unit of the establishment.
An explosion is a release of energy during a sufficiently small time, following the release of energy, a pressure wave (perturbation) starts to propagate in the space. This phase consists in the estimation of the overpressure vs. the distance from source (the point where ignition occurs). The complexity of the phenomenon would require a fluidynamic study through appropriate simulation code. The purposes of the work and the time available for the risk analysis force to the use of simplified methods/models which give the pressure peak vs. the distance.
Many simplified models for the estimation of the overpressure originated by an explosion are available in [10], [14] and [19]. The most diffused methods are the *equivalent TNT model* and the *equivalent piston model*. Both the methods described above allow to quantify the distance where the pressure wave reaches the value of 0.03 bar. Such value of overpressure is the threshold limit causing reversing lesions.

2.4. Presence of workers

The presence of personnel in workplace depends on the number of people working in the potential damage zone and on their probability of presence.
The number of workers involved in a potential explosion can be calculated using the damage zones obtained through the consequence analysis. The probability of presence is calculated according to the worker task (for example shift-workers, head-shifts, maintenance staff). Thus the presence of workers p_w is calculated using the equation (1):

$$p_w = \left(A_i / A_{est} \right) p_i \qquad (1)$$

where A_i is the impact zone of the explosion, A_{est} is the whole area of the establishment and p_i is the probability of presence of personal in the establishment.

3. Risk assessment

Risk calculation is the most important step of the whole procedure of *Figure 1*. In this work the equation (2) has been proposed for the calculation of the risk index associated with the potential presence of explosive atmospheres, R_{ae} (ATEX risk):

$$R_{ae} = p_e \cdot p_a \cdot p_w \qquad (2)$$

where p_e is the probability of release of flammable substance from an emission source, p_a is the probability of presence of an ignition source and p_w is the presence of workers in the impact area.
The estimation of the ATEX risk does not complete the analysis, it must be judge according to the risk acceptability criteria.

4. Application

The methodology proposed in this paper has been applied to a real establishment. The case study is a petrochemical plant (confidential). The area of the establishment is approximately 400 hectares and consists of 15 manufacturing plants, 10 of auxiliary service, 4 of air pollution protection, 2 of water pollution protection, fire alarm systems, a wide area for the movement of products and general service areas (offices, control room, lunch room, laboratories, etc.). In order to assess the risk the establishment has been divided into 27 units. *Figure 2* shows the layout of a unit of the establishment.

This is the desulphuration plant, which comprises 2 reactors a number of storage tanks, the gas/liquid separation drum, etc.

4.1. Classification of the areas

Each unit the process has been studied. All the flammable substances handling and all potential emission sources (SE) have been identified. Then the quantity of substance released and the probability of formation of an explosive atmosphere have been calculated. Using these data the classification of areas has been carried out. results of The classification of the areas for a part of the unit of *Figure 2* has been given in *Figure 3*. The part under analysis is the gas/liquid separation drum.
The following step is the identification of potential ignition sources (SA). Reconnaissance of the workplace and interviews to the workers have permitted to exclude some potential sources of ignition listed in [14]. Nine potential sources of ignition have been taken into account: 1) hot surfaces, 2) flames and hot gases or particles, 3) mechanical sparks, 4) electrical system, 5) cathodic protection, 6) static electricity, 7) lightning, 8) electric-overload due to clouds, 9) heating cables. For each SA the likelihood of ignition has been calculated using historical analysis and fault tree analysis or, sometimes, specific calculation procedures.
Subsequently, for each SE the effects of explosion due to the presence of at least a SA have been calculated.

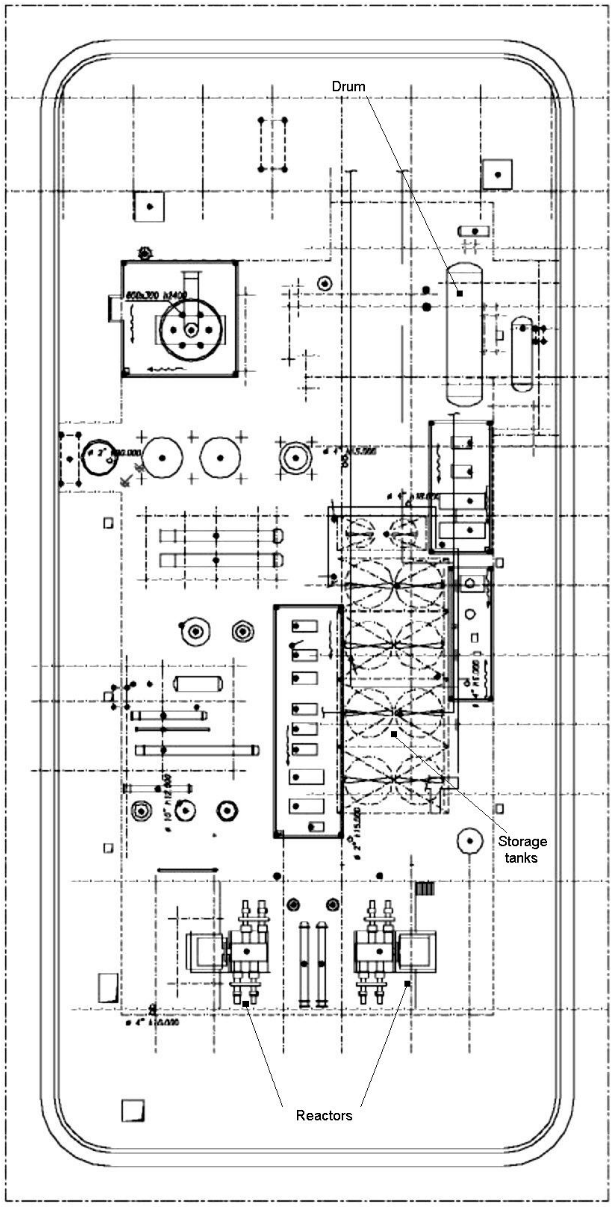

Figure 2. Layout of a unit of the establishment.

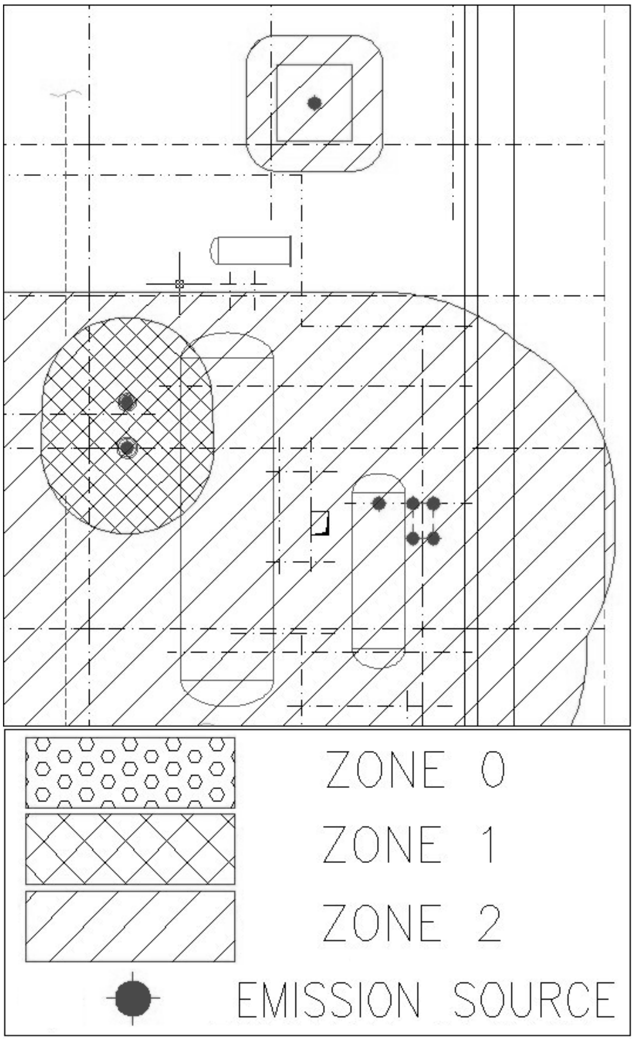

Figure 3. Classification of the areas in the unit of the case-study.

4.2. Consequence assessment

The consequences analysis has been done using a simulation code based on the models described in the previous section. The information required for the consequences assessment, using both the method, are the flow rate Q (kg/s) of the released substance and the *distance of permanence* of the cloud d_z (m). To define this last parameter it is necessary to note that after the release the cloud exists for a certain time in the area and, in presence of ignition sources, can potential cause an explosion. The *distance of permanence* indicates the maximum dimension of the explosive cloud. The consequence analysis permits to define the damage zone, that is a circle whose ray is the distance between the centre of the explosion and the point where the pressure reaches the value of 0.03 bar.

The application of the TNT model is very simple, it is based on the estimation of *equivalent mass of TNT* (m_{TNT}) for a certain explosion, using equation (3), and then on the calculation of the *distance* (x), using specific correlation such equation (4):

$$m_{TNT} = \eta \cdot \frac{\Delta H_C}{4{,}196 \cdot 10^6} \cdot m_{cloud} \qquad (3)$$

$$x = m^{1/3} e^{\left[3.5031 - 0.724 \ln O_p + 0.0398 \left(\ln O_p\right)^2\right]} \qquad (4)$$

where m_{TNT} is the equivalent mass of TNT (kg), η is a yield factor, ΔH_C is the enthalpy of combustion of the explosive (kJ/kg), m_{cloud} is the mass of the explosive (kg), x is the distance (feet) and O_p is the overpressure (psi).

Since the algorithm of the simulation code, available in the laboratory of the Department of Industrial Chemistry and Material Engineering of the University of Messina, is based on equation the TNT method, this approach has been applied for the validation of the procedure. *Figure 4* shows the results of the consequence assessment for an emission source.

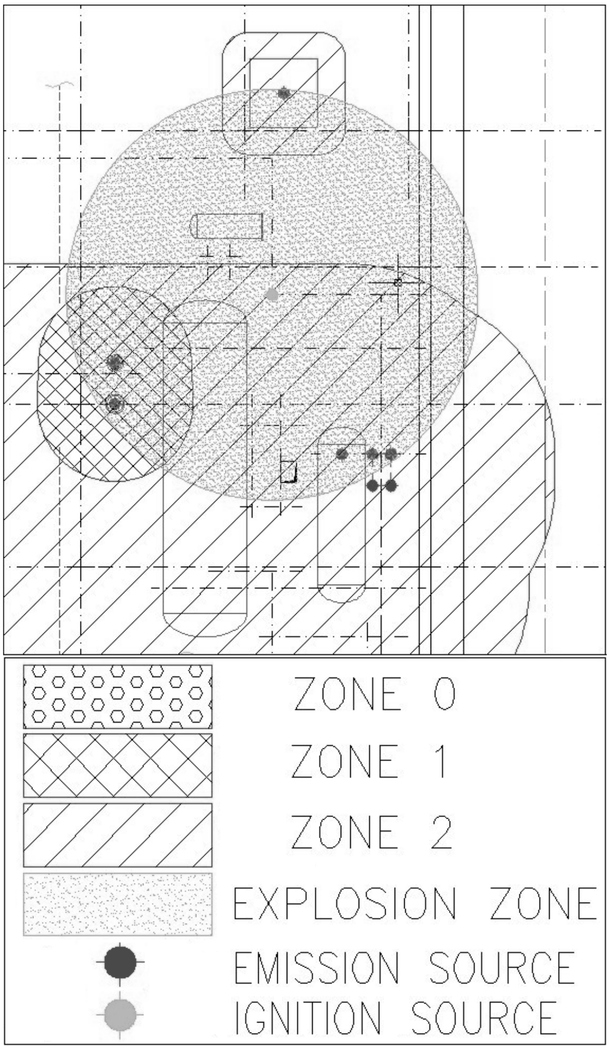

Figure 4. Results of the consequence analysis.

4.3. Presence of workers

The presence of the personnel has been calculated taking into account three different worker tasks. *Table 2* shows the probability of presence for shift workers, head-shifts and maintenance staff.

Table 2. Probability of presence of workers.

Task	Probability of presence p_i
shift worker	0.91
head-shift	0.33
maintenance staff	0.11

4.4. Risk assessment

Given the values for the probability of release of flammable substances, of presence of ignition source and the presence of workers, the risk has been evaluated according to equation (2).
The graph of *Figure 5* shows the values of the index risk R_{ae} calculated for each emission source of the unit of *Figure 2*. The graph shows how is simplified the identification of critical points where actions to reduce the risk are necessary.

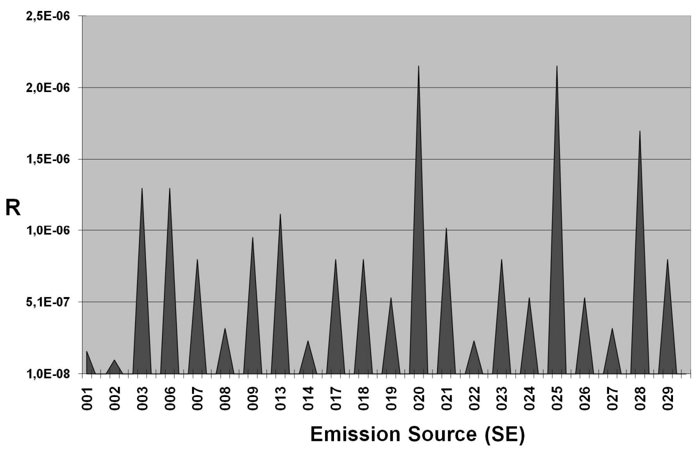

Figure 5. Index risk R_{ae}.

In this paper the same threshold values used to judge the risk acceptability in industries at major risk have been applied. Safety Reports of such industries analyze also explosions.
Explosions analyzed in the Safety Reports are originated by great releases of flammable substances and, consequently, they impact on large areas. For establishments not at major risk, the explosions have a smaller impact area and involve only the workers. Since both the type of explosions can be studied in the same way it is opportune to uniform the approaches of risk evaluation this work represents a first attempt to achieve this aim.
It has already mentioned, that in order to adopt measures of prevention and protection, the calculation of the risk must be combined with the judgment about the risk level. Unfortunately the Italian normative does not defined acceptability criteria for industries classified at major hazard, the risk judgment is made referring to the threshold values of frequency and consequences reported in [9]. Concerning the explosion risk, in this work, it has been proposed to refer to the risk acceptability criterion adopted in the United Kingdom and described in [11] and [15]. The threshold values of risk are:

$R_{ae} < 10^{-6}$ *the risk is acceptable;*

$10^{-6} < R_{ae} < 10^{-4}$ *it is necessary to reduce the risk as low as technically and economically possible;*

$R_{ae} > 10^{-4}$ *the risk is not acceptable.*

According to this criterion and this analysis, based on the risk assessment and combined with on-site inspections, the necessity of further implementation of protective and preventive measures can be verified. In order to make this objective a detailed check-list has been drawn.

5. Conclusion

The proposed methodology permits to identify the critical points in the system (technical and procedural) and decreases the exposure of the workers as low as possible. In particular the quantitative approach allows to not underestimate the risks for the exposed workers. The quantitative evaluation of the explosion risk also allows to obtain an improved effective in the prevention and protection interventions adopted by the company.
A tool for the risk assessment has been created, it permits to repeat the calculations and a faster verifications of the possible improvement of the measures of risk prevention and mitigation for the system under analysis.
Finally through the quantitative analysis it is possible a detailed study of the accidental scenarios due to small releases. For industries at major risk a detailed analysis of such events is essential because they can represent potential sources of domino effects.

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