CHEMICAL ENGINEERING TRANSACTIONS Volume 17, 2009
Editor Sauro Pierucci
 ISBN 978-88-95608-01-3 ISSN 1974-9791
DOI: 10.3303/CET0917053

A novel framework for the quantitative assessment of risk due to major accidents triggered by lightnings

Elisabetta Renni, Giacomo Antonioni, Sarah Bonvicini, Gigliola Spadoni, Valerio Cozzani
Dipartimento di Ingegneria Chimica, Mineraria e delle Scienze Ambientali, Alma Mater Studiorum - Università di Bologna, via Terracini n.28, 40131 Bologna, Italy

The analysis of past accident databases evidences that lightning events are the more frequent cause of technological accidents triggered by natural events in chemical and process plants. Severe fires, mainly affecting storage farms, are the most frequent final scenario associated to such events. In the present study, a quantitative methodology for the assessment of the risk due to major accidents triggered by lightnings is presented. The methodology was developed within a common framework for the quantitative assessment of risk due to external hazard factors in chemical and process plants. The procedure also allows the identification of the credible scenarios that may be associated to the different modes of structural damage and then the identification of critical equipment items.

1. Introduction

The analysis of external events which can lead to chemical accident implies the consideration of the potential threat of natural hazards in the hazard analysis, and carrying out preventive measures in case an accident occurs. It is important to consider this kind of accidents in the conventional risk analysis because they have the potential to trigger severe final scenarios, since they may cause multiple and simultaneous failures of process equipment. Thus the cascading events are more likely to occur during a natural disaster than during normal plant operation.
In the present study the attention is focused only on the impact of lightning events. Several accidents occurred in the last decades in industrial sites evidenced that typology of natural phenomena may cause severe damages to equipment items, resulting in losses of containment, thus in multiple and extended releases of hazardous substances (ARIA 2006, MHIDAS 2001, NRC 2007). The lightning events may cause damages to plants due to the release of high amounts of hazardous compound. Furthermore, the risk due to lightning seems to be increasing because of the climate changes causing an increase in the frequency of heavy storms.

2. Quantitative risk assessment procedure for accidental scenarios induced by lightnings

2.1 Introduction to the procedure

The development of a general and unified framework for the assessment of the risk due to Natech events could be useful, since there are different kinds of natural events and

Please cite this article as: Renni E., Antonioni G., Bonvicini S., Spadoni G. and Cozzani V., (2009), A novel framework for the quantitative assessment of risk due to major accidents triggered by lightnings, Chemical Engineering Transactions, 17, 311-316 DOI: 10.3303/CET0917053

the consequences of their impact on the industrial sites can vary depending on the natural phenomena. In order to have a single approach for any type of natural event, a procedure for the assessment of the contribution of Natech events to standard industrial risk indexes beside the QRA (quantitative risk analysis) needs to be elaborated. Figure 1 shows the example of flowchart of the general procedure to assess the industrial risk generated by natural events (Antonioni et.al 2007, Cozzani et al. 2007).

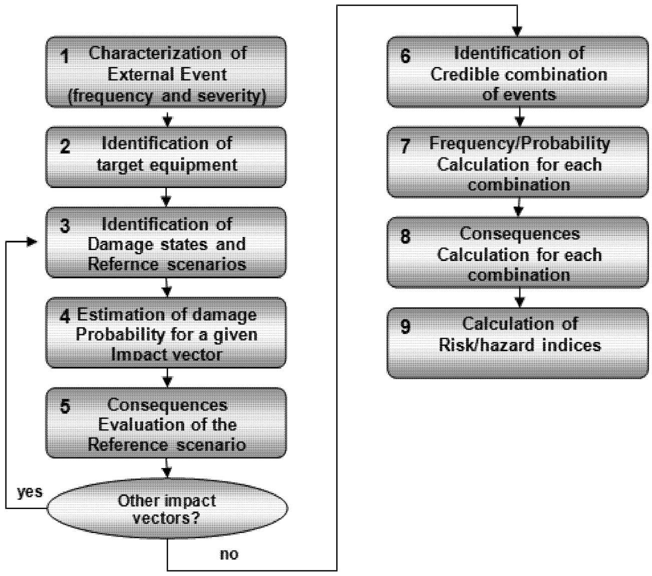

Figure 1 Flowchart of the procedure developed for the assessment of accidental scenarios triggered by lightnings involving industrial plants.

The procedure shown in figure 1 has a general framework but two of the steps (the first and the fourth) need that specific parameters are input to considered the specific natural event. Applying in the fourth step specific sub-models for damage probability it is possible to obtain the quantification of the value of the industrial risk indexes, but data on the vulnerability of equipment items target of the natural event are needed. Due to the lack of these models, in the case of a lightning event it is not yet possible to obtain a precise quantification of the hazard and risk associated to these events, but a preliminary identification of possible damage to equipment and of the consequences of the release of hazardous materials is possible.

2.2 Lightning expected frequency

The first step for assessing risk due to lightning is to evaluate the expected frequencies and consequences of primary events that are in this case lightnings. Both terms are often available on the basis of many historical data. For a lot of geographical locations they cover a wide range of time, so it is not difficult to predict the frequency (e.g. on yearly basis) of a generic lightning of any kind of current intensity. The frequency is quantified by the lightning ground flash density (N_g) measured in number of flashes for year for squared meters and given by national lightning detecting networks. More difficult is to assign a frequency to a lightning event with a given current intensity, because this intensity can be expressed in a qualitative way or missing. Hence, according to probabilistic risk assessment methods, an expected frequency in the form of Eq. 1 must be used in order to apply the procedure. This equation relates the frequency of a lightning (lighting event frequency f_I) to its current intensity I:

$$f_{I_i} = f(I_i) \qquad \text{Eq. 1}$$

In general I_i with $i = 1,\ldots,N_I$ represents the discretization of all possible lightnings' current intensity in the plant area. The historical data show the relation above is well approximated trough a frequencies' log-normal distribution:

$$P(I) = \frac{1}{\sqrt{2\pi}\,\sigma_{\log I}} \int_0^I \frac{1}{I} \exp\left(-\frac{1}{2}\left(\frac{\log I - \log \bar{I}}{\sigma_{\log I}}\right)^2\right) dP \qquad \text{Eq. 2}$$

With: I equal to 25 kA and $\sigma_{\log I}$ equal to 0.39.

Eq. 2 is often available in a graph (Figure 2) reporting P (%) as function of I for different time intervals. Hence, discretizing this curve in some intervals at constant I is possible to obtain vector f_{Ii}.

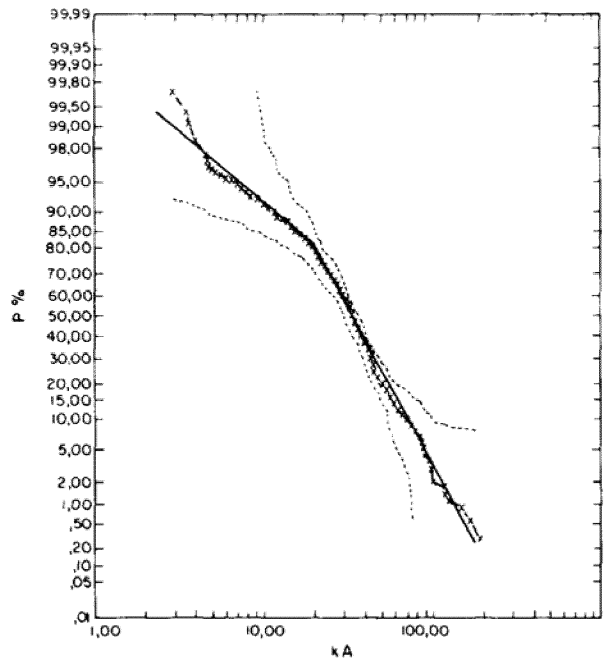

Figure 2 Cumulative statistical distribution of peak value of current intensity for downward negative strokes.

The lightning severity needs to be quantified by two parameters: current intensity and strokes number in order to consider the different impact modalities of the lightning. These parameters can be given by meteorological studies. The value of the severity parameters makes possible to quantify the current intensity and voltage, thus to calculate the overall current acting on the storage/process equipments.

2.3 Identification of critical equipment items

The second step of the quantitative risk assessment procedure is the identification of target equipment. In order to identify the critical equipment items, the four following categories of equipment were defined, having a progressively increasing hold-up: 1) reactors and heat exchangers; 2) columns; 3) piping; 4) vessels (process and storage). The credible scenarios identified for each vessel category as a possible consequence of lightning impact were thus associated to the different storage or operating conditions. This analysis was carried out for three main substance categories: i) substances toxic for human health; ii) substances hazardous for the environment; and iii) flammable substances. However the scenario severity depends both on the substance quantity, on its reactivity, solubility and toxicity. Therefore, on the basis of the characteristics and of the expected severity of the scenarios associated to the each equipment category, it was possible to identify the more critical categories of process equipment, and to rank the hazard associated to each critical category of equipment assigning a degree of severity increasing from 1 to 4, as shown in table 1.

In the third step it is necessary to identify the damage states and reference scenarios and to evaluate their consequences (step 5): this kind of evaluation is the same usually carried out in the "traditional" risk analysis thus it is possible to use the standard event trees.

Class of critical equipment items	*Gas liquefied*	*Liquid (cryogenic, evaporating, stable)*	*Gas*
vessels	4	4	3
piping	4	3	2
columns	4	2	1
Reactors and heat exchangers	3	2	1

Table 1 Matrix for the identifying the more critical equipment item for different storage conditions.

In order to obtain the data of vulnerability and to get a possible correlation between natural event severity and effects on the equipment items, a starting point can be the historical analysis of past accidents. In fact, the review of records on industrial accidents triggered by lightnings can allow the identification of:

- the categories of equipment more frequently involved in these events
- the more recurrent damage modalities
- the associated scenarios
- a possible correlation between the severity parameter of the natural event and the vulnerability of the equipment items in order to develop simplified models

The available information is often fragmented and not very detailed. In most cases the reference to the damage of equipment items is only expressed in general terms, without specifying which modalities led to the loss of containment. In many records only the presence of the release is reported without indicating if the leakage came from a hole in the pipelines or from shell failure in a storage tank. It was possible only to understand the equipment typologies more vulnerable in a chemical plant and their more frequent damage state (failure of flanges and connections, shell fracture, impact with/of adjacent vessels, etc.). Anyhow the EN 62305 Normative (*Protection against lightnings)* offers a first methodology to evaluate the lightning effects for chemical and process equipment items. This was used to obtain a first classification of the possible release modes from equipment items. The release modes identified were used to perform a complete consequence assessment using standard methodologies available from conventional QRA techniques. The only modification applied was to consider a probability equal to 1 for the immediate ignition of the release in the event trees applied to identify the final scenarios.

2.4 Frequencies of accidental scenarios following lightning events

If the expected frequency of a lightning event having a given I is known, the expected frequency of a reference scenario involving a single equipment item may be calculated as follows:

$$f(R)_k^i = f_i \cdot P(DS_j)_k^i \qquad \text{Eq. 3}$$

where $f(R)_k^i$ is the expected frequency of the reference scenario involving the kth equipment item following a lightning event having a I value equal to I_i; f_i is the expected frequency of the ith I value; and $P(DS_j)^i_k$ is the expected probability of the jth damage state of unit k following a lightning event having a I equal to I_i. Since different lightning may be considered as mutually exclusive, the overall expected frequency of the reference scenario R involving equipment k may be calculated as follows:

$$f(R)_k = \sum_{i=1}^{n} f_i \cdot P(DS_j)_i^k \qquad \text{Eq. 4}$$

where n is the total number of elements of the I vector defined above. However, the damage of more than one unit may follow the lightning event. Thus, the overall scenarios that may follow the lightning event are given by a single reference scenario (if a single equipment item is damaged) or by a combination of reference scenarios (if several units are simultaneously damaged). Thus, the actual overall scenarios that may follow a lightning event in a process plant are all the possible combinations of the reference scenarios associated to each of the critical equipment items identified in step 2 of the procedure. If m critical items were identified and an index r is arbitrarily associated to each different reference scenario considered in the procedure, each overall scenario that may follow the lightning event may be identified by a vector S having s elements ($1 \leq s \leq m$):

$$S_{I,t} = \lfloor r_{1,t}, \ldots . r_{s,t} \rfloor \qquad \text{Eq. 5}$$

where the elements of the vector are the indexes of the reference scenarios that take place in the t-th combination of s scenarios considered, $S_{s,t}$. The probability of the scenario $S_{s,t}$ may thus be calculated from the probabilities of each of the reference scenarios considered in the combination:

$$P_{s,t}^i = \prod_{j=1}^{m} \left[1 - P_j^i + \delta(j, S_{I,t})(2 \cdot P_j^i - 1)\right] \qquad \text{Eq. 6}$$

where P^i_j is the probability of each reference scenario considered, obtained from the probabilistic damage models, and the function $\delta(j, S_{s,t})$ equals 1 if the jth event belongs to the t-th combination, 0 if not. The overall expected frequency of the $S_{s,t}$ combination may thus be obtained combining Eq. (4) with Eq. (6):

$$f_{s,t} = \sum_{i=1}^{n} f_i \cdot P_{s,t}^i \quad \text{Eq. 7}$$

It is easy to verify that Eqs. (6) and (7) may be reduced to Eq. (4) if a single reference scenario is considered (*m* equal to 1). On the other hand, if *m* is higher than 1, the total number of different scenarios that may be generated by a lightning event with a given *I* is:

$$v_i = 2^m - 1 \quad \text{Eq. 8}$$

The total number of scenarios that need to be assessed in the quantitative analysis of the risk caused by lightning events, *v*, is given by the sum of all the scenarios considered for each element of the *I* vector:

$$v = \sum_{i=1}^{n} v_i = n(2^m - 1) \quad \text{Eq. 9}$$

Obviously, this may be reduced by the application of cut-off criteria based on the calculated frequency and/or the conditional probability (Eq. (6)) of the scenario.

3. Conclusions

In this study a procedure for the qualitative assessment of industrial risk caused by lightnings was developed. The methodology defined allows the identification of the possible modes of structural damage of equipment items and to define the credible scenarios that may be associated. The analysis of past accidents highlighted the possible hazards due to lightning-induced releases and showed the criticality of such accidents in the presence of cascading events. The possibility to estimate by the present approach the probability of severe scenarios involving multiple plant units is of fundamental importance to assess the criticality of lightning events for the integrity of the plant and for the safety of the nearby area.

References

[1] ARIA (2006) Analyse, Recherche et Information sur les Accidents, French Ministry of Ecology and Sustainable Development

[2] Major Hazard Incident Data Service (MHIDAS) (2001) AEA Technology, Major Hazards Assessment Unit, Health and Safety Executive, UK

[3] US National Response Centre (2007), Database of chemical and oil spills

[4] R. B. Anderson, A. J. Eriksson, 1980, A summary of lightning parameters for engineering applications, in Proc. CIGRE, no. 33-06

[5] G. Antonioni, V. Cozzani, G. Spadoni (2007), A methodology for quantitative risk assessment of major accidents triggered by seismic events, Journal of hazardous materials 147, 48-59

[6] Campedel M., Cozzani V., Garcia Agreda A., Salzano E., (2008) Extending quantitative assessment of industrial risk to earthquakes effects, Risk Analysis, Issue 5, Vol. 28, 1231-1246

[7] CEI EN 62305-2 (2006), Protection against lightning: Risk management

[8] US Environmental Protection Agency (1997), *Lightning Hazard to facilities handling flammable substances,* EPA 550-F-97-002c