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Reduction of NaTech Risk Due to Lightning by the Use of Protection Systems

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Several accidents that occurred in the last decades evidenced that the impact of natural events in industrial plants may trigger accidental scenarios involving the release of relevant quantities of hazardous substances. Severe scenarios typical of the process industry, as fires, explosions, toxic releases, and water pollution were reported as the consequence of natural events in industrial areas. The specific features of technological accidents triggered by natural events were recently recognized, and these scenarios are now indicated as NaTech (natural-technological) accidents. The screening of past accident databases points out that NaTech scenarios are quite common in industrial facilities.
Past accident analysis evidences that lightning is one of the most common initiator event for fires in oil refineries and tank farms. In most facilities, simple lightning protection measures, such as grounding or lighting rods, are implemented to reduce the risk due to lightning strikes. However, several accidents suggest that these measures may not be sufficient to retain the structural integrity of the equipment. In the present study a procedure for the determination of the mitigation effect due to lightning rods on storage tank farms is proposed. A statistical method was developed to evaluate the failure frequency of tanks due to lightning strikes. The model includes both the assessment of lightning impact probability and of tank damage conditional probability given the lightning impact. The method then considers the effect of lightning rods placed at given distances from the equipment items and calculates the reduction of the failure frequency due to attraction competition between the rods and the equipment.
The procedure was implemented in a GIS-based software tool for the calculation of individual and societal risk. The method allows the assessment of the effect of lightning protection in terms of individual risk reduction.

1. Introduction

The occurrence of technological accidents triggered by natural events in process industries was analyzed by Rasmussen (1995) that examined the MHIDAS (SRD) and FACTS (TNO) databases reporting past industrial accidents. The study indicates that 3-5% of past industrial accidents have natural events as causative factors. As shown by the mean of the historical analysis of past accidents (Renni et al., 2010a) and by the development of a dedicated methodology *for NaTech risk assessment* (Renni et al., 2010b) the plant items more vulnerable to lightning impact are storage tanks. The study of Argyropoulos et al. (2012) confirms that lightning is a major accident initiator and evidences the necessity of an effective lightning protection system for hydrocarbon storage tank parks. Fires were evidenced as the main final scenario caused by the impact of lightning on process equipment (Renni et al., 2010a). Past accident analysis evidences that structural damage to the equipment directly struck by lightning is the more frequent cause of loss of containment accidents, that usually result in severe consequences, also due to the high ignition probability of flammable substances in these scenarios (that resulted as high as 82% in the analysis of past accidents (Campedel et al., 2008)). Furthermore, the resulting fire has potential to trigger a cascading effect on nearby equipment, leading to severe accident escalation or domino effect (Landucci et al., 2009; Tugnoli et al. 2012b).

Previous studies addressed the specific assessment of lightning damage and impact probability (Renni et al., 2009) within the more general framework of NaTech hazard (Cozzani, 2010) and risk quantitative assessment due to NaTech events (Antonioni et al., 2009). Specific contributions focused on providing tools for the inclusion of NaTech-related threats in risk assessment practice (e.g. Tugnoli et al., 2012a; Landucci et al.,2012). In the present study, a Monte Carlo model was developed for the assessment of lightning capture and damage probability. The model was applied to the analysis of the effect of specific protection barriers on lightning impact frequency.

Metal tanks with fixed metal roofs and horizontal metal tanks are generally protected from damage by direct-stroke lightning and ignition of their contents if all metal components are in electrical contact (i.e. bonded). However, there can be internal sparking at the liquid/gas interface within the tank if the tank suffers a direct lightning strike (API RP 2003, 2008) or the puncture of the vessel if the shell thickness is low. There is general agreement that such ordinary protection systems are not able to protect a process item from the effects of a direct lightning strike (Cooray, 2010) In order to protect critical equipments or storage tanks from the lightning hazard, several typologies of specific lightning protection systems can be adopted. In this study, the reduction of the failure frequency due to the installation of protection masts was assessed, as suggested by (Borghetti et al,, 2010).

2. Capture Model

A “capture model” is needed to assess the frequency of lightning impact on a process vessel of known geometry. The model relates the geometrical features of the equipment to the lightning strike probability. The capture model was developed using a Monte Carlo method to assess the probability of strike given the geometry. The procedure is based on the generation of a large number of lightning events with the associated parameters as lightning current amplitude and stroke location coordinates x and y. It is assumed that the parameters of the randomly generated events follow the log-normal probability distributions (Anderson and Eriksson, 1980) for negative and positive strokes. The lightning peak current intensity $\boldsymbol{I_p}$ statistically follows a log-normal distribution characterized by a mean value $\boldsymbol{\mu_{ln}}$ and a standard deviation value $\boldsymbol{\sigma_{ln}}$. The model is applied to an area, $\boldsymbol{A}$ (1 km^2), in which the presence of a single or of multiple equipment units of given geometrical characteristics (diameter, length or height, wall thickness) is assumed. First the polarity of the flash is randomly determined (according to statistics 90% of flashes are negative and 10% are positive) then the peak current intensity of the lightning $\boldsymbol{I_p}$ and the coordinates of the impact position ($\boldsymbol{x}$ and $\boldsymbol{y}$, which identify the striking point in a fixed domain, in the absence of attraction made by structures) are randomly generated for every simulation. Every simulated lightning is captured by the target equipment unit if the distance between the equipment and the strike location is lower than lateral distance r, calculated by the use of the electro geometric model - EGM (IEEE Std. 1410, 2004). The method for the calculation of the lightning attraction radius at the ground ($\boldsymbol{r}$) for a generic lightning event of intensity $\boldsymbol{I_p}$ and a generic structure of height $\boldsymbol{h}$ starts from the calculation of the maximum attraction distance for the structure (Love, 1973):

$$r_s = 10 \cdot I_p^{0.65} \tag{1}$$

where $\boldsymbol{r_s}$ is the attraction distance or lightning final jump (m), and $\boldsymbol{I_p}$ is the peak current intensity of the lightning (kA). The attraction distance from the ground, $\boldsymbol{r_g}$, may be calculated as a fraction of $\boldsymbol{r_s}$:

$$r_g = 0.9 \cdot r_s \tag{2}$$

The attraction distance, $\boldsymbol{r}$, may thus be obtained as follows:

$$\begin{cases} r = \sqrt{r_s^2 - (r_g - h)^2} & h < r_g \\ r = r_s & h \geq r_g \end{cases} \tag{3}$$

where $\boldsymbol{h}$ is the structure height, $\boldsymbol{r_s}$ is the final jump distance and $\boldsymbol{r_g}$ is attraction distance from the ground. The lightning is captured by the equipment if the distance between the equipment and the strike location is lower than the capture distance at ground, $\boldsymbol{r}$. Usually all the real equipment units are placed in an industrial plant with many other different structures surrounding the unit of concern. Buildings, tanks, trees, columns, flares, etc. can attract lightning strike as the equipment under investigation does. In this case every lightning strike must be allocated to one structure among all the units in the area under investigation. The attraction distance equations of the EGM (Eqs. 1-3) are used for each object included in the layout considered. If two or more structures are capable to capture the same lightning, for each structure, *j*, the height at which the lightning is attracted can be calculated as:

$$z_j = \sqrt{r_s^2 - d_{sl,j}^2} + h_j \quad (4)$$

Where Z_j is the capture height, $d_{sl,j}$ is the distance between the structure and the strike location and h_j the height of a generic structure *i*. The structure with the highest capture height, Z_j, is considered to be struck by the lightning.

Lightning frequencies are often available on the basis of historical data. For wide areas, mainly in Europe and in the US, there are historical data covering a wide range of time and, consequently, it is not difficult to predict the frequency, for example on yearly basis, of a generic lightning. As an example it is possible to obtain the value of the lightning ground flash density (n_g) measured in number of flashes per year per square kilometres, in Italy from the Italian lightning detection network SIRF (2009).

The following equation provides an assessment of expected annual capture frequency for a generic unit *j* in the installation:

$$f_{capture,j} = \frac{n_{captured,j}}{n_{tot}} \cdot n_g \cdot A \quad (5)$$

where $n_{captured,j}$ is the number of simulated lightning captured by the j-th unit, n_{tot} is the number of simulations.

3. Damage frequency calculation

The developed damage model takes into account the evaluation of loss of containment events caused by lightning strike that hits the equipment shell. At the attachment point material melting and erosion may occur due to the large heat input as well as due to a concentration of resistive heating due to the high current densities. In order to be conservative it was assumed that all the energy developed at the arc root contributes only to melting, neglecting the heat lost by vaporization. The radius of the melted volume may be compared to the thickness of the equipment, assuming a hemispherical volume for the melted zone. In the case of atmospheric storage tanks the shell thickness is usually low and it is likely that perforation occurs. The chosen reference damage state is a 10mm hole diameter in the vessel. The approach is based on the correlations provided by the European Standard Protection Against Lightning EN 62305 (2006). A detailed description of the procedure for the damage probability assessment is reported elsewhere (Necci et al., 2012). The failure frequency is obtained as follows:

$$f_{dam} = f_{capture} \cdot P_{dam} \quad (6)$$

Where f_{dam} is the annual damage frequency and P_{dam} is the damage probability.

4. Results

4.1 Case study description

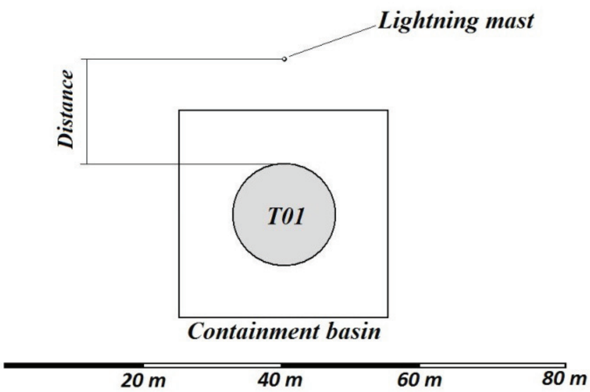

Figure 1: Lay-out considered for the case study layout: 1,000 m^3 tank, lightning mast and a 30 m side containment basin. A variable distance comprised between 2.5 m and 5 m was considered for the mast.

The model developed allows the quantitative assessment of lightning capture and damage frequencies for a vessel of known geometry. The capture model also allows the assessment of the effectiveness of the protection systems. For the sake of brevity, the results will be illustrated by a case-study. A specific representative case-study was selected to assess the methodology and the effectiveness of lightning protection systems. The capture and failure frequencies for a 15m diameter and 6m height cone roof atmospheric storage tank (*T01*) were calculated. The tank was assumed to contain 750 m^3 of gasoline. First, failure and capture frequencies were calculated for a single tank in an open flat field. Then frequencies were assessed for the tank in the vicinity of a lightning protection mast, positioned at a variable distance (Figure 1).
It is useful to define an index that indicates the mitigation effect on the expected number of lightning captured by the unit of concern, due to the presence of other structures in the surroundings. This index depends on the layout and on the topography of the site considered, and it is calculated by Eq.7. The index represents the ratio between the lightning capture frequency of the unit in its specific layout and the capture frequency that the same unit would have in an open flat field:

$$LI = \frac{f_{captured,j}}{f_{capture,j,solo}} \qquad (7)$$

Where ***LI*** is the layout index and $\boldsymbol{f_{capture,j,solo}}$ is the capture frequency of equipment *j* in an open flat field.
In figure 2 the LI against the distance between tank T01 and the protection mast is reported for different mast heights. It is important to observe that the probability of lightning strike on the equipment of concern can be reduced of more than one order of magnitude.

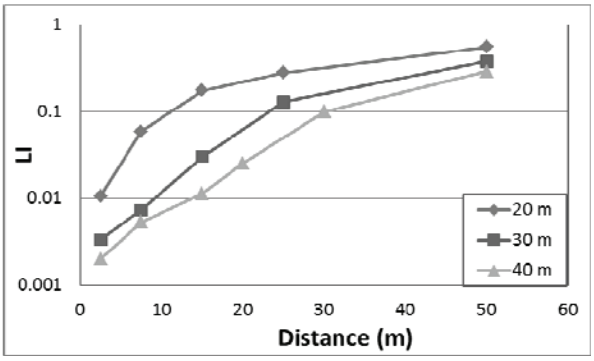

Figure 2: The lay-out index, LI, with respect to distance, considering a mast at a distance of X__Xm having height comprised between 20 and 40 m.

4.2 Individual risk due to lightning impact
Three possible releases were considered: two release modes were considered as a consequence of conventional “internal” failure causes:

- Catastrophic rupture, with an expected frequency of 10^{-5} events/year
- Leak from a vessel (diameter 10 mm), with an expected frequency of 10^{-4} events/year

Failure frequencies were derived from the TNO Purple book (Uijt de Haag and Ale, 1999). With respect to lightning strikes, a leak from a vessel (diameter 10 mm) was considered as the result of lightning impact. An expected frequency of $3.3 \cdot 10^{-4}$ events/y was calculated for the event by the above approach.

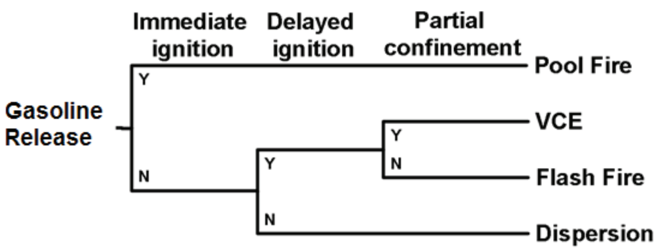

Figure 3: Final outcomes assumed for the release scenarios considered

The final outcomes assumed for the release scenarios considered are shown in figure 3. Only in the case of lightning the immediate ignition probability is considered equal to 1.
In figure 4 local-specific individual risk contours are calculated for the lay-out considered by the ARIPAR software (Antonioni et al., 2007). The figure clearly evidences that the iso-risk curves corresponding to values equal or lower than 10^{-6} are not affected by considering lightning-induced releases.

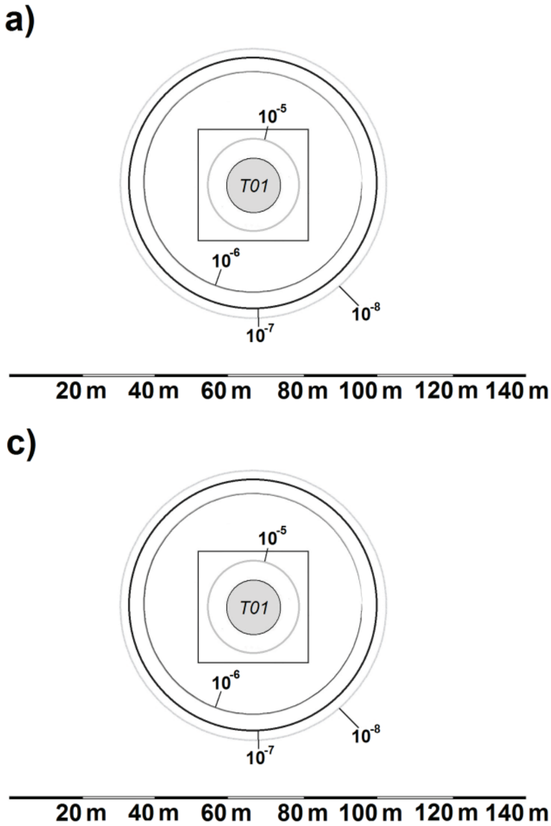

Figure 4: Individual risk contours calculated for the case-study. (a) Not considering lightning-induced scenarios; (b) Considering lightning induced scenarios and no specific lightning protection; (c) considering lightning-induced accidents and a 40 m height protection rod placed at 15 m from the structure

Actually, these curves are mostly influenced by the low-frequency catastrophic release considered, due to "internal" causes. When lightning is considered (Figure 4-b), a zone where individual risk is higher than 10^{-4} events/y is present, due to the rather high frequency estimated for lightning-induced pool fires. Protection rods result in a dramatic decrease of lightning impact, as evident from Figure 4-c. Individual risk is always lower than 10^{-4} events/y and the zone where values are higher than 10^{-5} events/y is strongly reduced.

5. Conclusions

A model was developed to calculate lightning capture and damage frequencies on storage tanks. The model, applied within a more general methodology developed for the quantitative risk assessment for NaTech events, allowed the calculation of individual risk due to lightning impact and the assessment of the performance of specific protection systems. The results shows how the lightning attraction frequency and thus the lightning NaTech risk can be reduced of orders of magnitude by the use of one (or more) lightning protection masts.

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