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# RISK ASSESSMENT OF MAJOR ACCIDENTS TRIGGERED BY LIGHTNING EVENTS

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The analysis of major industrial accident databases indicates that lightning events are the most 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 lightning 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 the identification of critical equipment items.

## 1. INTRODUCTION

The analysis of external events which may lead to chemical accidents requires the assessment of the potential threats due to natural hazards. The assessment of hazards due to external events may as well allow the implementation of preventive measures or the planning of mitigation actions in case an accident occurs. When the presence of a relevant hazard is identified, it is important to consider accidents triggered by natural events in quantitative risk analysis since they have the potential to initiate severe final scenarios, resulting in multiple and simultaneous failures and in the release of hazardous substances. As a matter of fact cascading events are more likely to occur during a natural disaster than during normal plant operation.

In the present study the attention is focused on the impact of lightning on process equipment. Several accidents that occurred in the last decades in industrial sites indicate that this type of natural phenomenon may cause severe damage to equipment items, possibly resulting in loss of containment and/or in multiple and extended releases of hazardous substances (ARIA 2006, MHIDAS 2001, NRC 2007). This may lead to water pollution and to dispersion of hazardous substances in the ground, as well as to fires and explosions. Furthermore, the risk of lightning is increasing in several areas around the world due to climate change causing an increase of heavy storms.

The hazard due to lightning in industrial sites is well known. However, no detailed methodology exists in order to assess the risk due to accidents triggered by lightning. Moreover, recent improvements both in the analysis of lightning events and in the collection and analysis of lightning data allow the development and the implementation of more comprehensive methodologies for the assessment of lightning impact and damage probability.

The present contribution affords the development of a specific procedure for the quantitative risk assessment of major accidents triggered by lightning. The methodology was developed in the framework of the enhancement of

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methods for the quantitative risk assessment of NaTech (Natural events triggering technological accidents) scenarios.

## 2. QUANTITATIVE RISK ASSESSMENT PROCEDURE FOR ACCIDENT SCENARIOS INDUCED BY LIGHTNING

### 2.1 Framework

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 the consequences of their impact on the industrial sites can vary depending on the natural phenomena considered. The aim of such framework development should be to elaborate a procedure for the assessment of the contribution of Natech events to standard industrial risk indices to support and expand conventional QRA (quantitative risk analysis). Figure 1 shows a flowchart of the general procedure to assess the industrial risk generated by natural events (Antonioni et al. 2007, Cozzani et al. 2007).

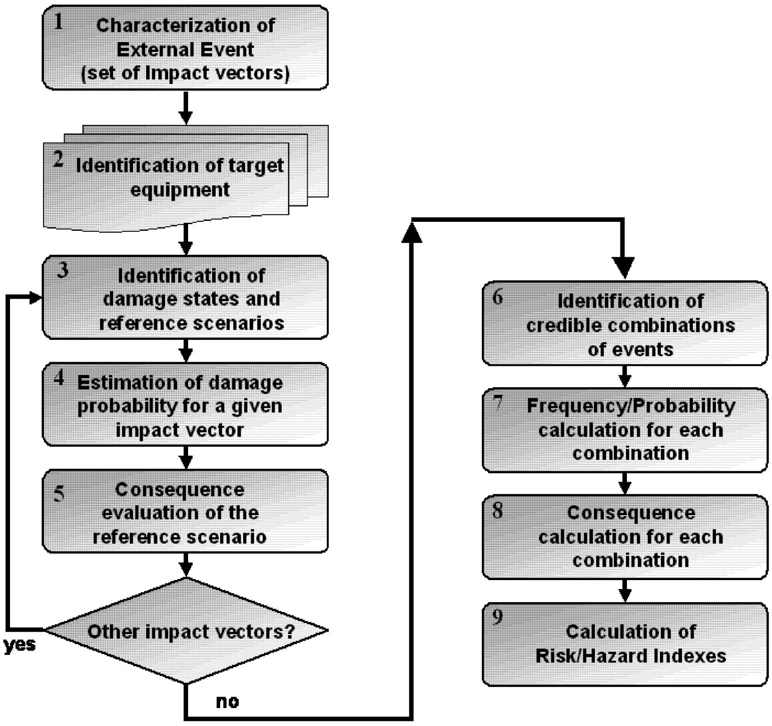

Figure 1: Flowchart of the procedure developed for the assessment of accident scenarios triggered by lightning involving industrial plants.

The procedure shown in Figure 1 is a general framework but in two steps (the first and the fourth) some specific parameters need to be inserted for the natural event considered. Applying in the fourth step specific sub-models it is possible to arrive at the quantification of the industrial risk indices, but knowledge on the vulnerability of every equipment item that is target of the natural event is required. In the case of lightning, a methodology was developed to obtain a precise quantification of the hazard and risk associated to these events; moreover, simplified vulnerability models were obtained by using correlations between the severity of lightning event and the damage state (Renni et al. 2010b).

## 2.2 Characterization of the lightning event

The characterization of the lightning event, Step 1 in the flowchart in Figure 1, requires the assessment of the frequency and severity parameters of the possible events. These parameters are usually available from national lightning detection networks. The Italian lightning detection network, called SIRF, consists of 16 sensors positioned on the Italian territory (SIRF 2009). They detect the electromagnetic field emitted by any cloud-ground lightning, providing raw data (EM field vector, time, etc.). Data coming from each sensor are received and elaborated by the central analyzer which calculates, in few seconds, the impact's geographic coordinates, the time of the impact and the electric parameters of each lightning event (current amplitude, electrical charge, polarity, number of strokes, etc.). For many geographical locations these data cover a wide time range, 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 per year per square meter and is given by national lightning detecting networks. 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.

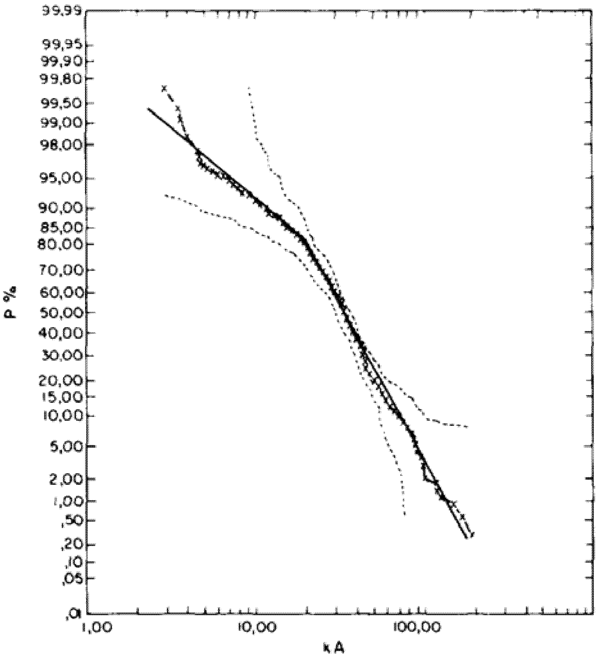

Figure 2: Cumulative frequency distribution of lightning current amplitudes (subdivision of the cumulative frequency division into two regimes, namely, a "shielding" regime comprising currents below 20 kA and a "back-flash" regime comprising those currents in excess of 20 kA, according to the approach proposed by Anderson and Eriksson, 1980).

Equation (1) relates the frequency of a lightning (lighting event frequency $f_I$) to its current intensity $I$:

$$f_{I_i} = f(I_i) \qquad \textbf{(1)}$$

The current intensity $I_i$ (with $i = 1,\ldots, N_I$, where $N_I$ represents the total number of recorded intensity values) is the discretization of all possible current intensity of lightning events in the plant area. The historical data show the relation above is well approximated trough a log-normal distribution of frequencies:

$$P(I)=\frac{I}{\sqrt{2\pi}\cdot\sigma_{log\,l}}\int_0^I\frac{I}{l}exp\left(-\frac{1}{2}\left(\frac{log\,l-log\,\bar{l}}{\sigma_{log\,l}}\right)^2\right)dP \tag{2}$$

with $I = 25$ kA and $\sigma_{\log I}$: = 0.39.
Equation (2) is often available as a plot reporting the probability $P$ (%) as function of $I$. An example is reported in Figure 2. Hence, by discretizing this curve in some intervals at constant $I$, it is possible to obtain vector $f_{li}$.
The severity parameter of a lightning event can be expressed using the electrical charge (or the current amplitude) provided by the detection networks mentioned above. In such way, it is possible to correlate the physical damage of a lightning strike on a chemical equipment item to the mechanical and thermal effects of lightning by using the electrical charge (Renni et al., 2010a).
Thermal effects linked with lightning charge are due to the resistive heating caused by the circulation of an electric current flowing through the resistance of a conductor like a metallic storage tank. Thermal effects are also relevant due to the heat generated in the root of the arcs at the attachment point and in all the isolated parts involved in arc development (e.g. spark gaps). Guidance is given in the European Normative *"Protection against Lightning*"( EN 62305-1 (2006)) in order to evaluate the temperature rise of conductors subjected to the flow of a lightning current. More specific damage types are discussed in Section 3.

### 2.3 Identification of critical equipment items

The second step of the quantitative risk assessment procedure (Figure 1) is the identification of the target equipment. In order to identify the critical equipment items, the four following categories of equipment with a progressively increasing hold-up were defined: 1) reactors and heat exchangers; 2) columns; 3) piping; 4) vessels (process and storage). The credible scenarios identified 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.

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Table 1: Matrix for identifying the most critical equipment items for different storage conditions.

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

### 2.4 Identification of damage states and reference scenarios

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 assessment is the same usually carried out in the "conventional" industrial risk analysis; thus it is possible to use the standard event trees.
In order to obtain information on the vulnerability and to get a possible correlation between natural event severity and the effects on the equipment items, a starting point is the analysis of past accidents. In fact, the review of records on industrial accidents triggered by lightning allowed the identification of:

- the categories of equipment most frequently involved in these events;
- the more recurrent damage modes;
- the release states associated to the most significant release scenarios that may follow structural damage caused by lightning (instantaneous release of the complete inventory (R1), continuous release of the complete inventory in ten minutes (R2), continuous release from a hole having an equivalent diameter of 10 mm (R3).

Table 2 shows the results obtained from the analysis of 172 records regarding storage tanks that are the most frequent equipment items involved, due to their design and the high hold-up. (Renni et al. 2010a).

Table 2: Damage modes and release states considered for storage tanks damaged by lightning based on the analysis of 172 accident records (n.s.: not specified).

| Type of damage | Number of records | Release state |
|---|---|---|
| Electrical device malfunctions | 9 | -- |
| Explosion | 36 | n.s. |
| Pipeworks detachment | 1 | R3 |
| Pool fire | 116 | R2 or R1 |
| Roof fire | 10 | R1 |

## 2.5 Frequencies of accident 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:

$$f(R)_k^i = f_i \cdot P(DS_j)_k^i \tag{3}$$

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

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

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 ($1 \le s \le m$):

$$S_{l,t} = \lfloor r_{1,t}, \ldots\ldots r_{s,t} \rfloor \tag{5}$$

where the elements of the vector are the indices 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:

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

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 *j*th 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):

$$f_{s,t} = \sum_{i=1}^{n} f_i \cdot P_{s,t}^{i} \qquad \textbf{(7)}$$

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:

$$\nu_i = 2^m - 1 \qquad \textbf{(8)}$$

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

$$\nu = \sum_{i=1}^{n} \nu_i = n\left(2^m - 1\right) \qquad \textbf{(9)}$$

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. THEORETICAL ANALYSIS OF POSSIBLE DAMAGE DUE TO LIGHTNING

The information available on lightning damage to industrial equipment is fragmented and not very detailed. In most cases the reference to the damage of equipment items is only made 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 the rupture of pipeworks or from shell failure in a storage tank. Through the accident analysis it was only possible to understand the most vulnerable equipment types in a chemical plant and the more frequent damage states caused by lightning impact (failure of flanges and connections, shell fracture, impact with/of adjacent vessels, etc.). For this reason, no simplified equipment model is available in the literature. Depending on the physical effects of lightning, different damage types are possible. All credible damage states were analyzed theoretically and for each a frequency was assumed on the basis of the physical phenomenon involved. Three possible modes of lightning effect were assumed: resistive heating, attachment point thermal damage and flammable vapours ignition.

The resistive heating can lead to an increase of the temperature until values at which the yield strength admissible for steel is very low. The thermal effect of lightning strikes on objects can be simulated by transient heat conduction in solids. The 3-D transient temperature distribution in metals struck by different lightning currents is determined using a computer program based on the volume technique, developed in Metwally et al. (2003). The temperature field within the material is obtained upon solving the energy equation subjected to the appropriate boundary and initial conditions. The results are presented in Metwally et al. (2003).

Due to the lightning arc attachment, a certain amount of erosion of the metal will occur. For the high current pulse there is usually an insignificant amount of erosion because of the short duration of the pulse. However a long duration, or continuing current, may last for a sufficiently long time to burn through thin metal sheets or cause hot spots on the back of thicker metal sheets.

With respect to flammable vapour ignition, sites of hydrocarbon storage tanks are classified zones, according to standards (NFPA 780, 1997). Figure 3 shows a typical sketch indicating zone classification in the proximity of

such vessels. In Division 1 zone a spark with sufficient energy is enough to create a fire while in the Division 2 zone additional conditions for a fire are required (e.g. a perforation in the tank roof).
Usually, even if there is no burn-through, the temperature rise inside of a fuel tank may exceed a critical value and the fuel may ignite, thereby causing a tank fire that may cause extensive damage to the entire tank and its surroundings. In fact, a 600-700 μJ spark represents a 50% ignition probability, where the minimum acceptable hazard limit of energy is 200 μJ.

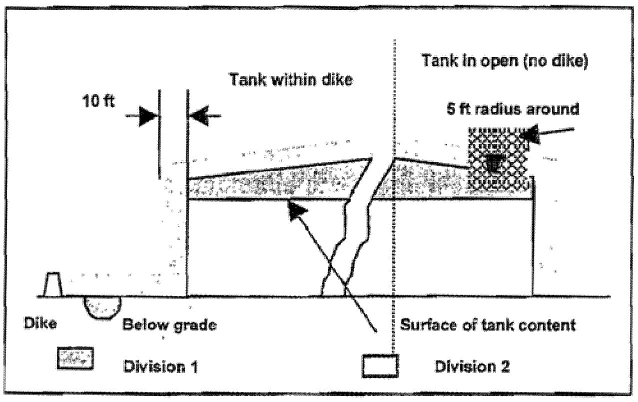

Figure 3: Schematic indicating zones classification of a hydrocarbon storage tank (adapted from Mariani et al. 2000).

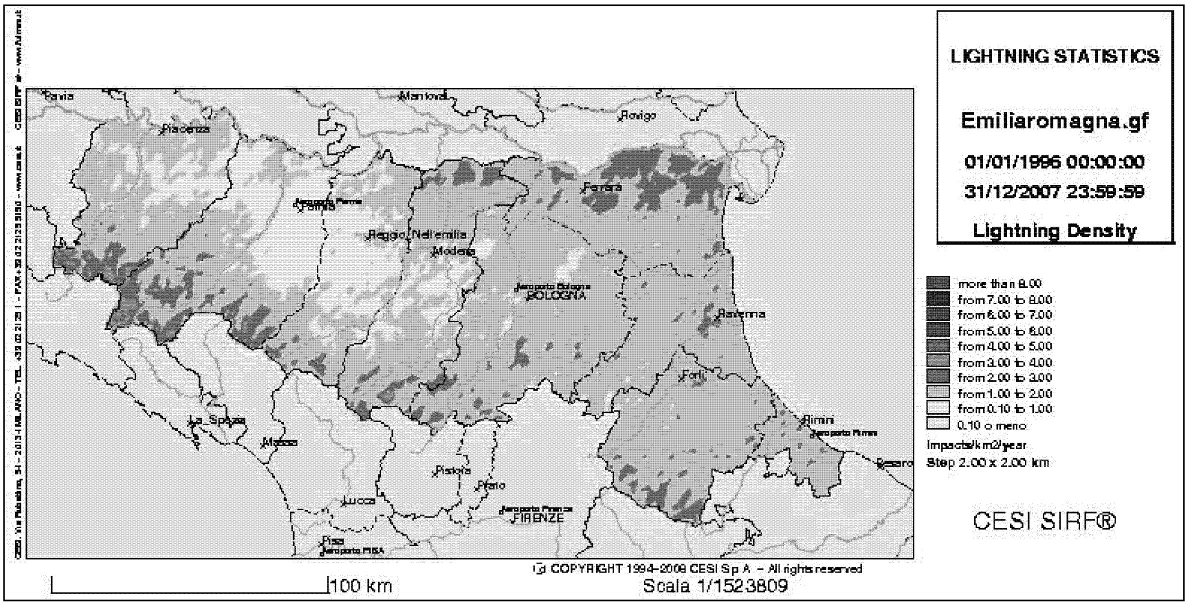

Figure 4: Lightning density map for the Emilia Romagna region (SIRF 2008).

## 4. CASE STUDY: APPLICATION OF THE PROCEDURE DEVELOPED

The developed methodology was applied to a simple case study. Since the most vulnerable equipment items were found to be atmospheric steel storage tanks (Renni et al. 2010a), an atmospheric storage tank containing gasoline located in the port area of Ravenna (Italy) was considered. The geographical location is important since it affects the lightning frequency.

The frequency of lightning considered for the case-study was provided by the lightning density map reported in Figure 4. The data shown in this map were collected and provided by the national network SIRF (SIRF 2008). As shown in Figure 4, the value of the lightning frequency near Ravenna is between 2 and 3 impacts per square kilometer per year. This frequency value is a starting point in order to assess the probability of accidents triggered by lightning.

The geometrical specifications of the tank considered are reported in Table 3. A Monte Carlo simulation capable to generate a random lightning strike referred to the specific lay-out considered was applied. By this method it was possible to determine the damage probability considering the number of lightning events capable to burn through the thickness of the tank (creating a hole and therefore a release state) out of the total number of simulated lighting events. The capability of a lightning event to cause damage was correlated to its electrical charge by using the relation provided by the Normative EN 62305 that links the electrical charge of a lightning to the melted volume on the attachment point. By applying this correlation a damage probability equal to $3 \cdot 10^{-2}$ was calculated. A hemispherical melted volume was assumed and resulted equal to $1.7 \cdot 10^{-6}$ m$^3$. An "equivalent" diameter of the resulting hole equal to 18.2 mm was thus calculated. The final consequences of the release scenario were then determined using a conventional model for a continuous liquid release from a hole. The final events expected to follow the release were identified by the event tree technique, taking into account, when applicable, the possible scenarios deriving from substances reacting with water possibly present in cases of severe storms. A simplified event tree for a flammable liquid release is shown in Figure 5. If there is an immediate ignition, very probable in these cases because of the sparks and other static sources, the final scenario will be a pool-fire. More details about the damage evaluation methodology are reported elsewhere (Renni et al., 2010b).

Table 3: Atmospheric cone-roof tank selected for the case study.

| Volume (m$^3$) | Diameter (m) | Height (m) | Thickness (mm) | Roof Height (m) |
|---|---|---|---|---|
| 10000 | 30 | 14 | 6.5 | 3.35 |

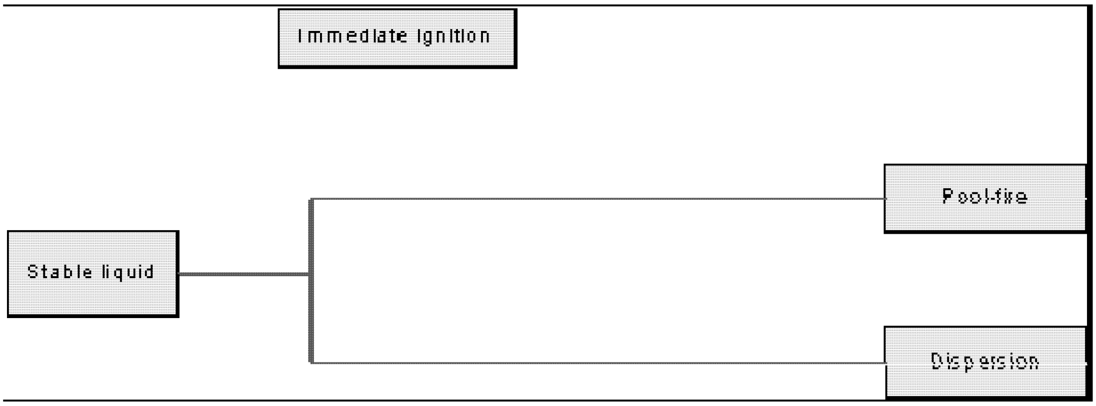

Figure 5: Event tree for a continuous release of a flammable liquid.

In order to investigate the vulnerability of pressurized tanks to lightning as well, a preliminary analysis of existing pressurized tanks was considered. Table 4 shows some sample geometries of pressurized tanks reported in literature (Lees, 1996).

Table 4: Geometrical sizes of reference pressurized storage tanks (L=length, D=diameter).

| **Volume ($m^3$)** | **L/D** | **D (m)** | **L (m)** | **Thickness (mm)** | **Volume ($m^3$)** | **L/D** | **D (m)** | **L (m)** | **Thickness (mm)** |
|---|---|---|---|---|---|---|---|---|---|
| 5 | 1.88 | 1.6 | 3 | 11 | 25 | 1.88 | 2.3 | 4.4 | 15 |
| 10 | 6.32 | 1.2 | 7.7 | 9 | 50 | 6.32 | 2.1 | 13.2 | 14 |
| 20 | 6.32 | 1.5 | 9.7 | 10 | 100 | 6.43 | 2.8 | 18 | 18 |

The value of the melted volume is the same found in the case of atmospheric storage tank (about 9mm), since it depends only on characteristics of the lightning event obtained by the Monte Carlo simulation. Thus, comparing such value to the shell thickness for which indicative values are reported in Table 4, it becomes clear that the tank perforation due to lightning impact is unlikely for pressurized tanks, since the shell thickness is higher than the radius of the hemispherical melted volume caused by the lightning strike.

## 5. CONCLUSIONS

In this study a procedure for the risk assessment due to lightning events on chemical facilities and flammable storage was developed. The methodology defined allows the identification of the possible modes of structural damage of equipment items and to define the credible release 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 triggering cascading events. By using this approach it was possible to assess the probability of severe scenarios involving hazardous material releases. This methodology can represent an effective approach to assess the danger of lightning events to the integrity and safe operation of an industrial plant.

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