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Accident Scenarios Caused by Lightning Impact on Atmospheric Storage Tanks

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In recent years, severe natural events raised the concern for the so-called NaTech (natural-technological) accident scenarios: technological accidents caused by the impact of a natural event on an industrial facility or infrastructure. 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 historical analysis of accidental scenarios triggered by lightning shows that the impact of a lightning on an atmospheric storage tank might be the initiating event of a severe accident. The analysis of past accident evidences that several alternative damage mechanisms and accident scenarios may follow lightning impact. Although lightning hazard is well known and is usually considered in the risk analysis of chemical and process plants, well accepted quantitative procedures to assess the contribution of accidents triggered by lightning to industrial risk are still lacking. In particular, the approaches to the assessment of accident scenarios following lightning strike are mostly based on expert judgment. In the present study, a detailed methodology is presented for the assessment of quantified event trees following lightning impact on an atmospheric tank. Different damage mechanisms have been considered in order to assess the frequencies of loss of containment due to lightning strikes. The results were used in a case study to assess the overall risk due to lightning impact scenarios in typical lay-outs of tank farms of oil refineries.

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 that collect past industrial accidents files. The study indicates that 3-5% of past industrial accidents have natural events as causative factors. As shown by 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: in particular it evidences the vulnerability of hydrocarbon storage tank parks to the respect of lightning. 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 most frequent cause of loss of containment accidents (Chang and Lin, 2006), 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 (Tugnoli et al. 2012b). Therefore the problem of vessel integrity (Landucci et al. 2009) should be also analyzed, in order to understand the risk related to lightning.

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

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assessment due to NaTech events (Antonioni et al., 2009). Specific contributions have recently 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). The present study is aimed at the development of a detailed methodology for the assessment of quantitative risk assessment (QRA) following lightning impact on an atmospheric tank.

2. The lightning hazard

Different damage mechanisms have been considered in order to assess the frequencies of loss of containment due to lightning strikes. Lightning can cause indirect damage to process equipment due to the ignition of flammable vapors present near or inside specific process equipment items, such as floating roof tanks and other atmospheric tanks. In particular, rim-seal fire scenarios may be triggered by lightning in floating roof tanks, while confined explosions may follow the lightning-induced ignition of flammable atmospheres inside process or storage equipment. For this reason storage metal tanks are always protected for the arc formation by providing that all metal components are in electrical contact (i.e. bonded). However, 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).

The developed structural damage model takes into account the evaluation of loss of containment events caused by lightning strike that hits and perforates 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 (CEI EN 62305-1, 2006; Necci et al., 2013).

3. Expected frequencies for the reference scenarios

For the seek of simplicity, this method assumes that the bonding and earthling systems can protect the tank from electric currents generated by indirect strikes, thus only direct strikes to storage tank are considered. The failure frequency is obtained as follows:

$$f_{scenario} = f_{capture} \cdot P_{scenario} \tag{1}$$

Where $f_{capture}$ is the annual expected frequency for direct strikes on the target equipment, $f_{scenario}$ is the annual occurrence frequency and $P_{scenario}$ is the probability for the specific scenario. Figure 1 summarizes the main mechanisms of lightning damage to process equipment obtained from the analysis of past accidents (Renni et al., 2010). As shown in the figure, lightning can cause indirect damage to process equipment due to the ignition of flammable vapours present near or inside specific process equipment items, such as floating roof tanks and other atmospheric tanks. In particular, rim-seal fire scenarios may be triggered by lightning in floating roof tanks, while confined explosions may follow the lightning-induced ignition of flammable atmospheres inside process or storage equipment, mainly in the case of storage tanks vented to the atmosphere. Flammable vapours may be ignited by lightning either at vent points or by electric arc at junction points where the metallic shell is not continuous, as in the case of flanges (Metwally et al., 2003). These event trees can be compared to the diagram used in conventional risk analysis for the consequences of a flammable liquid accidental releases (Figure 2).

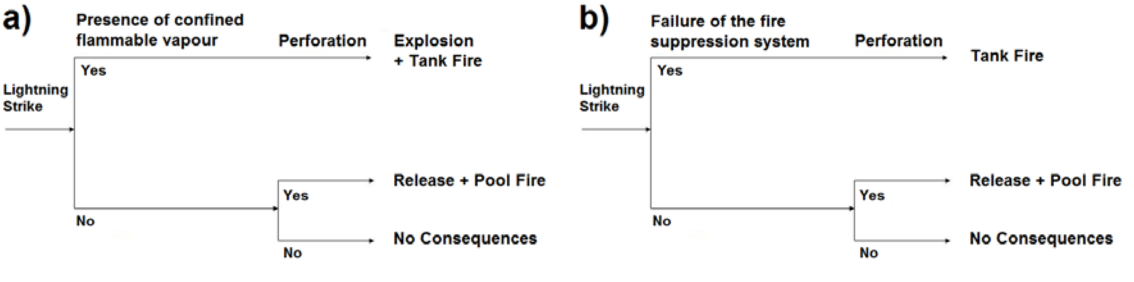

Figure 1: Event tree for atmospheric storage tanks containing flammable liquids due to lightning strikes: a) Fixed Roof ; b) Floating Roof

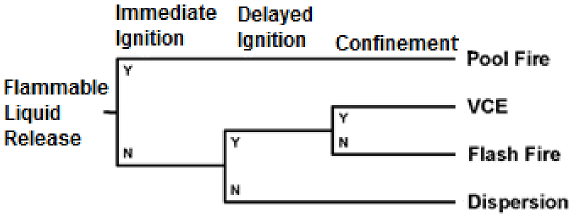

Figure 2: Event tree for the catastrophic rupture of atmospheric storage tanks containing light flammable liquids, used in conventional risk assessment

3.1 The frequency of lightning strikes on storage tanks

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 strike 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 model is applied to an area, 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. Every simulated lightning is captured by the target equipment unit if the distance between the equipment and the strike location is lower than the lateral capture distance r, calculated by the use of the electro geometric model - EGM (IEEE Std. 1410, 2004). A detailed description of the use of EGM to assess capture probability is reported elsewhere (Borghetti et al., 2007).

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. In order to obtain lighting frequencies, it is possible measure the value of the lightning ground flash density (n_g) expressed 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:

$$f_{capture,j} = \frac{n_{captured,j}}{n_{tot}} \cdot n_g \cdot A \tag{2}$$

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

3.2 The probability of fire escalation from rim seal fire to full surface fire

In case a lightning strike hits directly on a floating roof storage tank filled with flammable material, the ignition of the flammable vapour at the rim-seal takes place in most of the cases. In this condition the fire suppression system turns on and stops the fire. However, there is the possibility that this system is not available or that it fails, allowing the fire to burn the seal and causing the roof sinking into the flammable liquid. For this particular scenario mechanism we assume the ignition probability of the seal equal to 1 and the tank vulnerability equal to the Probability of Failure on Demand (PFD) of the fire suppression system. A preliminary study on fire suppression systems suggests that this protection has a unreliability that varies from 1/50 to 1/100, depending on the system typology.

3.3 The probability of confined explosion of fixed roof storage tanks

In general, fixed roof storage tanks containing flammable liquids have a system that provides gas to the empty space to maintain the inside pressure at a constant level and avoid structural collapse. In order to neglect the formation of a flammable mixture of gas in the vapour space, the gas is not atmospheric air, but an inert gas. In case the system that provides the inert gas has a leak to the atmosphere, a valve is left open or for any reason the system fails to provide the inert gas, air can enter in the vessel and generate a flammable mixture with the liquid vapour. A lightning that hits a tank containing a flammable atmosphere generates a confined explosion that results in the roof failure and in a full surface fire of the tank. The probability of this scenario following the lightning impact is equal to the complement to one of the reliability of the inertization system. Preliminary data available for such systems indicate that the unreliability ranges between 1/100 to 1/1000, depending on the tank size and on substance features.

3.4 The perforation probability of tank shells

In order to be conservative it was assumed that all the energy developed at the arc root contributes only to melting. 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 approach is based on the correlations provided by the European Standard Protection Against Lightning EN 62305 (2006). The damage probability is defined as the fraction of lightning strikes capable to create a hemisphere of melted metal, whose radius is larger than the shell thickness. Thus the damage probability related to this specific mechanism is dependent by the shell thickness only. A detailed description of the procedure for the damage probability assessment is reported elsewhere (Necci et al., 2013).

4. Modelling the consequences

In order to appreciate the contribution of lightning-induced accidents to industrial risk and to compare it with the risk due to conventional events (e.g. component failures, operator errors, etc.), a Quantitative Risk Analysis (QRA) was carried out. The particular issues of the releases following the impact of lightning are discussed in this section. The first difference with the classical consequence analysis is that the probability of immediate ignition is set to 1 for every release scenario caused by lightning. Furthermore the modelling of the tank fire scenario requires particular attention since it is among the more frequent scenarios, as reported also in past accident records.

4.1 Tank Fire

The tank fire scenario is modelled as a regular pool fire, but its height from the ground is set to the height of the tank and its diameter is assumed as the same of the tank. This scenario has more limited consequences than a classical pool fire scenario with respect to operators or exposed population, that generally are at the ground level and thus more distant from the fire. However this scenario is relevant due to possible accident escalation to the other equipment items within the plant. Tall structures can suffer relevant heat radiation during the tank fire, which may cause structural collapse and domino effects (Cozzani et al., 2005).

4.2 Release from a molten hole in the vessel

The perforation of vessel shell caused by lightning is followed by the immediate ignition of the flammable liquid, due to the very high temperature of the hole edges. It was proved that a reasonable size for the holes formed in lightning impact is 10 mm (Necci et al., 2013). The final outcome of this scenario in the case of an atmospheric vessel is usually a pool fire. As ignition always occurs as the release starts, the size of the pool fire may be calculated from the burning rate at the surface of the pool and the release rate.

5. Case Study

The site under investigation was located in Ferrara (Italy) in order to select the meteorological data set. Eight atmospheric storage tanks are considered in this case study: four floating roof tanks and four fixed roof tanks. Both conventional release scenarios (Figure 2) and lightning induced release scenarios (Figure 1) were considered. Figure 3 shows the lay-out considered and the local-specific individual risk contours, calculated by the ARIPAR software (Antonioni et al., 2007). The individual risk curves corresponding to a value of 10^{-4} and 10^{-5}, calculated by the mean of the lightning hazard are slightly larger than the same curve calculated in the by the conventional methodology. The figure clearly evidences that the iso-risk curves corresponding to values equal to or lower than 10^{-7} are not affected by considering lightning-induced releases, because they are caused by accidental scenarios that have not lightning as initiating factor. Tank specifications and scenario frequencies are reported in table 1.

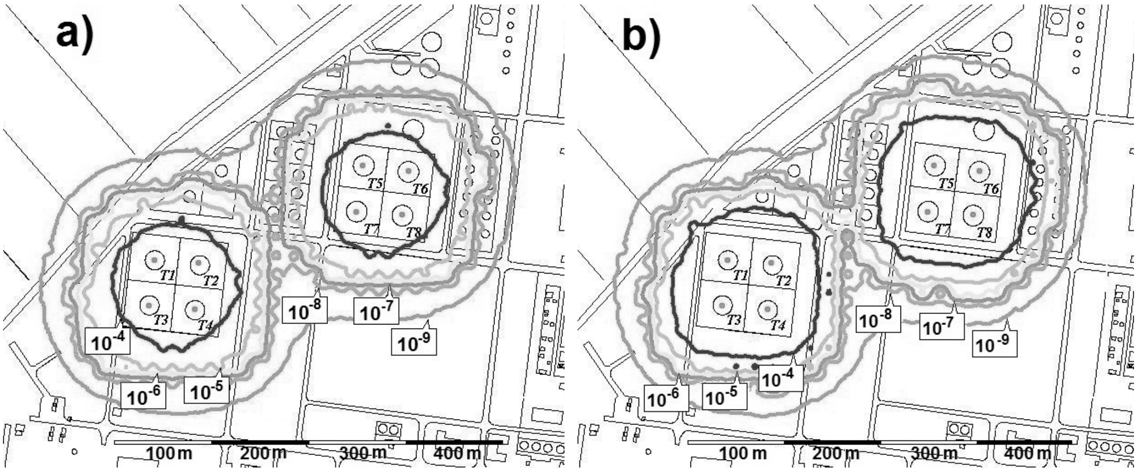

Figure 3: Individual risk curves calculated for the case study considered; a) individual risk due to conventional scenarios; b) individual risk including lightning scenarios

Table 1: Case study features

Vessel features	**Floating Roof**	**Cone Roof**
Tank ID	**T1-T4**	**T5-T8**
Nominal capacity (m^3)	6511	5200
Diameter (m)	24	25
Height (m)	14.4	11
Shell thickness (mm)	12.5	11
Substance contained	Gasoline	Benzene
Inventory (metric ton)	3656	3415
Lightning Capture Frequency (IEEE Std. 1410, 2004)	1.0 E-02	1.0 E-02
Fire Suppression System PFD	1.0 E-02	-
Presence of Confined Flammable Mixture	-	5.0 E-03
Perforation Probability (Necci et al., 2013)	1.0 E-04	9.0 E-04
Lightning Pool Fire Frequency	1.0 E-06	9.0 E-06
Lightning Tank Fire Frequency	1.0 E-04	5.0 E-05
Conventional Catastrophic Rupture Frequency (Uijt de Haag and Ale, 1999).	1.0 E-05	1.0 E-05
Conventional Leak Rupture Frequency (Uijt de Haag and Ale, 1999)	1.0 E-04	1.0 E-04
Immediate Ignition Probability (Uijt de Haag and Ale, 1999).	6.5 E-02	6.5 E-02
Delayed Ignition Probability (Uijt de Haag and Ale, 1999).	9.0 E-01	9.0 E-01
Confinement	1.0 E-01	1.0 E-01
Conventional Leak Pool Fire Frequency	8.5 E-05	8.5 E-05
Conventional Catastrophic Pool Fire Frequency	6.5 E-07	6.5 E-07
Conventional Catastrophic Flash Fire Frequency	8.0 E-06	8.0 E-06
Conventional Catastrophic VCE Frequency	8.0 E-07	8.0 E-07

6. Conclusions

The hazard due to lightning strike and the damage mechanisms of storage tanks filled with flammable materials have been discussed. The two more probable accidental scenario are tank fire and pool fire. The frequency of the lightning-induced accident scenarios can be higher than the frequency of the accident scenarios used in conventional QRAs, but the overall severity of the scenarios in general is limited, if escalation effects do not take place. The tank fire scenario has the potential to induce escalation effects on nearby equipment. The individual risk calculated by the inclusion of the lightning hazard evidences higher risk values than the individual risk calculated by the standard methodology, in the vicinity of the atmospheric tanks considered in the case study.

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