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Equipment Failure Probability due to the Impact of Lightning

Amos Necci[a], Giacomo Antonioni[a], Elisabetta Renni[a], Valerio Cozzani*[a], Alberto Borghetti[b], Carlo Alberto Nucci[b], Elisabeth Krausmann[c]

[a]Alma Mater Studiorum – Università di Bologna, Dipartimento di Ingegneria Chimica mineraria e delle Tecnologie Ambientali, Via Terracini 28, 40131 Bologna, Italy
[b]Alma Mater Studiorum – Università di Bologna, Dipartimento di Ingegneria Elettrica, Viale Risorgimento 2, 40136 Bologna, Italy
[c]European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, via E. Fermi 2749, 21027 Ispra (VA), Italy
valerio.cozzani@unibo.it

The historical analysis of accidental scenarios triggered by lightning shows that the impact of a lightning on a process plant might be the initiating event of a severe accident. The analysis identifies the most common damages to the equipment as either immediate ignition of flammable atmospheres or structural damage with subsequent release. However, the available information on lighting damage to industrial equipment is fragmented and not very detailed. The aim of the present study is to define a failure model for reference equipment categories following lightning impact. Starting from the analysis of lightning damage, the possibility of equipment damage is assessed on the basis of lightning characteristics. The probability of failure is evaluated as the probability to find, in impacting lightning strikes, the minimum energy necessary to cause the loss of containment of the selected equipment. Probability distribution functions available for lightning characteristics, used together with the lightning capture frequency, allow the development of a failure probability model for reference equipment categories.

1. Introduction

The phenomenon of lightning has been studied for years with aim of protecting various tall structures. The study by Anderson and Eriksson (1980) was focused on the determination of statistical distribution of lightning characteristics for electrical power engineering applications. They are indeed a valuable source for the assessment, by statistical methods, of the protection measures to be adopted also for buildings (CEI EN 62305-1, 2006). The lightning strike probability of a given structure may be evaluated by the application of the Monte Carlo method and by using a lightning capture model assumed to be adequate for the specific structure (Borghetti et al., 2007). For example, the so called Electro Geometric Model is often adopted for the statistical estimation of the lightning performance of overhead electric power lines.
The effect of natural events on the process industries has been carried out by Rasmussen (1995), analysing the data bases Mhidas (SRD) and Facts (TNO). The study indicates that between 1 % and 5 % of accidents in industrial activity have natural events as causative factor. For fixed installations, 80 % of natural triggering causes has atmospheric origin whilst the remaining fraction has mostly geological origin. According to Rasmussen (1995) and Chang and Lin (2006) lightning strikes may be

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considered responsible of a large percentage of accidents initiated by natural events for process or storage installations, which are located in a region characterized by a significant value of annual flash density. As shown by Renni et al. (2010a, 2010b), the plant items more vulnerable to lighting threats are storage tanks. The study by Argyropoulos et al. (2012) confirms that lightning is a major accident initiator and evidences the necessity of a effective lightning protection system for hydrocarbon storage tank parks. A detailed model for the description of potential lightning damage is still missing in the literature. The study by Cozzani (2010) was aimed to the determination of a methodology for the risk assessment of technological disasters triggered by natural events (Na-Tech). Renni et al. (2009) is aimed at the assessment of the lightning-triggered accidental scenario frequencies, on the basis of the lightning capture frequencies of different equipment categories. In the present study a method for the prediction of the damage probability on a generic equipment is described. A structural damage of the tank may be followed by a release and by the ignition of flammable substances, resulting in final consequences as fire or explosion**.** It is important to remark the particular severity of the effects of this natural event, which may induce a domino effect ending in a scenario with much more severe consequences. The LOC (loss of containment) event due to the impact of a lightning may, itself, take place simultaneously in more than one unit, resulting in significant release of hazardous substances.

2. Mathematical Model

2.1 Arc effects on equipments

Lightning is a high energy density phenomenon that can cause many different types of damage in an industrial plant. Due to the very high current intensity, lightning generates an electromagnetic pulse that may damage the electric instruments that act on the plant control (Renni et al., 2010b). The electric arc is a source for the ignition of any flammable gas/air mixture, eventually present in a plant; especially the flammable cloud that usually forms just above the floating roof tanks.

The point of junction between the lightning and the equipment is subjected to an electric arc characterized by a very high energy density that heats the striking point and its close surroundings. Temperature can arise to very high values in a few milliseconds, with the possible melting or even vaporization of the stroked material resulting in a small hole in the target equipment. The hot spot is furthermore a possible ignition source for the flammable substances.

The predicted damage frequency ($\boldsymbol{f_{damage}}$) to process equipment may be evaluated as the product between the lightning capture frequency ($\boldsymbol{f_{capture}}$) of the equipment and the damage probability ($\boldsymbol{P_{damage}}$), which depends on the type of equipment and on the substance hazardous properties

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

Floating roof tanks may present a cloud partly within flammable range above the roof surface. The lightning impact produces immediate ignition of the flammable cloud, starting a rim seal fire, with high chances to damage the tank roof. In this case, the roof sinks in the flammable liquid ending in a tank fire scenario. A flammable atmosphere may be present also inside equipments, where ignition sources should be prevented, such as fixed roof tanks breathing to the atmosphere.

In absence of flammable atmospheres, lightning may still be a source of danger. In case of inert tanks or tanks filled with non-flammable substances (including pressurized tanks), the high energy of lightning flashes is able to melt or even evaporate construction materials as steel, aluminium or copper (González and Noack, 2008). The volume of the molten metal is dependent by the lightning event energy. This phenomenon involves any type of equipment, in particular atmospheric and pressurized tanks with low vessel thickness. Furthermore this damage mechanism is independent by the flammable properties of the substance, so even toxic releases are possible. The LOC probability can be determined as the probability to be stroked by flashes with at least the necessary energy to generate a fixed diameter of the melted pool – e.g. the standard hole diameter of 10 mm proposed in Purple Book (Uijt and Ale, 1999). The leakage scenario of atmospheric tanks filled with liquid hazardous substances may be followed by a pool fire scenario for flammable liquids, or by an atmospheric dispersion for toxic compounds. The leak scenario for pressurized or liquefied gases may end up either in jet fire or pool fire scenario for flammable substances or in an atmospheric dispersion of a toxic substance.

2.2 Erosion modelling

Several theoretical models have been developed for the calculation of the erosion volume on metal surfaces at the attachment point of the lightning channel. In spite of the very high temperature of the arc channel, the temperature at the arc spot is limited to values below or at most up to the boiling point of the electrode material. The main heating at the attachment point is produced by the charged particles (electrons and positive ions) which impinge on the metal surface and transfer their kinetic energy, gained because of their acceleration through the voltage drop region (González and Noack, 2008). Since in the real cases, very large uncertainties are still present concerning the lightning stroke properties, it is extremely difficult to predict the duration and the intensity of the heating power of a lightning arc discharging through a solid structure. For the seek of simplicity, in Std. EN 62305 the power associated to the electric arc is evaluated as a function of the product between the lightning current intensity (***i***) and the cathode-or-anode voltage drop ($\boldsymbol{u_{a,c}}$). The energy (*W*) produced by the electric arc is the integral in time of this product or simply by the product between the voltage drop and the electric charge (***Q***) if the voltage drop is assumed to be constant:

$$W = \int u_{a,c} i dt = u_{a,c} \int i dt = u_{a,c} Q \tag{2}$$

The model appears to be adequate for thin metal skins (CEI EN 62305-1, 2006). The typical value of $\boldsymbol{u_{a,c}}$ is lower than few tens of volts. With the simplified assumption of neglecting heat dispersion, all the energy developed at the arc root is used for melting:

$$V = \frac{u_{a,c} Q}{\gamma} \frac{1}{C_w (T_s - T_u) + c_s} \tag{3}$$

where ***V*** is the melted volume, **γ** is the material density, $\mathbf{C_w}$ is the material thermal capacity, $\mathbf{T_s}$ is the melting temperature, $\mathbf{T_u}$ is the ambient temperature and $\mathbf{C_s}$ is the latent heat of melting. The resulting volume of molten metal is in general characterized by a hemispherical shape. For a metal skin width ***w***, if the molten hemisphere radius $\boldsymbol{r_{hs}}$ is larger than ***w***, the molten volume shape is a slice of a sphere, of radius $\boldsymbol{r_s}$, thickness ***w***, and minor radius ***r***:

$$r_s = \sqrt{\frac{V}{\pi w} + \frac{w^2}{3}} \tag{4}$$

$$r = \sqrt{\frac{V}{\pi w} - \frac{2w^2}{3}} \tag{5}$$

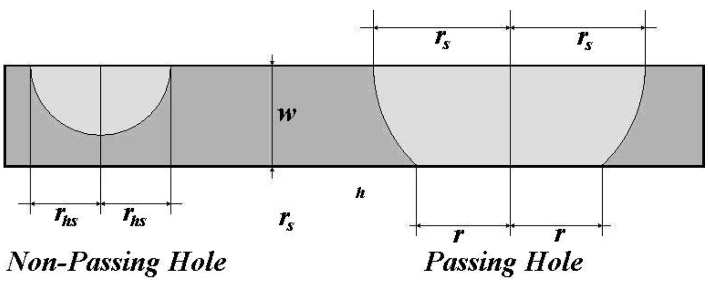

Figure 1: Geometry of the melted pool

Figure 1 illustrates the two different situations: $\boldsymbol{r_{hs}} < \boldsymbol{w}$, without a passing hole and $\boldsymbol{r_{hs}} > \boldsymbol{w}$ with the realization of a passing hole. The value of the effective diameter $\boldsymbol{D_{hole}}$ is calculated assuming that the melted volume is entirely removed by the shell, i.e. as the double of minor radius ***r***.

3. Probability assessment

The lightning property that is responsible of the lightning damage is the flash overall electric charge. As mentioned the lightning characteristics usually adopted in the literature are those collected by Anderson and Eriksson (1980). The lightning characteristics are provided for two different types of flashes and strokes: positive and negative. Both lightning peak current ***I*** and electric charge ***Q*** statistically follow a log-normal distribution characterized by mean value μ and standard deviation value ***σ***. The lightning current parameters are statistically related one to another by a correlation coefficients.. As a first approximation, we assume that the set of flashes that hit the considered tank are characterized by the same statistical distributions provided in Anderson and Eriksson (1980).
For a fixed hole diameter, D_{hole} and shell thickness, ***w***, the melted volume, ***V*** can be calculated from equation (7), where equation (6) is solved for ***V***, assuming $r=D_{hole}/2$, while the minimum lightning electric charge, Q_{min}, required for melting a volume ***V*** of metal, is determined from equation (7), resulting from equation (3) solved for Q and assuming a value of 30 V for $u_{a,c}$:

$$V = \pi w \cdot \left(\frac{2w^2}{3} + \frac{D_{hole}^2}{4} \right) \tag{6}$$

$$Q_{\min} = \frac{V\gamma \left(C_w (T_s - T_u) + c_s \right)}{u_{a,c}} \tag{7}$$

The resulting value of Q_{min} is introduced in the cumulative distribution function (cdf) of the lightning charge, $cdf(Q_{min})$, both for the case of positive flashes and for the case of negative flashes. The complement to 1 of the ***cdf*** is the probability to experience lightning with electric charge equal to or higher than Q_{min}:

$$P\left(Q_{\min}\right)_{pos-neg} = 1 - cdf\left(Q_{\min}\right)_{pos-neg} \tag{8}$$

Thus for a single value of Q_{min} two values of probability exist: one for positive flashes and one for negative flashes. The overall probability, which in turn is the damage probability, is the average of the positive and negative flashes probabilities, weighted with the expected ratio between the number of positive and negative flashes with respect to the total set of lightning events:

$$P_{damage} = P\left(Q_{\min}\right) = \Psi_{pos} \cdot P\left(Q_{\min}\right)_{pos} + \Psi_{neg} \cdot P\left(Q_{\min}\right)_{neg} \tag{9}$$

where Ψ_{pos} is the ratio of positive flashes and it is set equal to 0.1, whilst Ψ_{neg} is the ratio of negative flashes and it is set equal to 0.9. In order to provide the expected annual number of treating events the molten volume model can be introduced in a Monte Carlo simulation procedure, which implements the lightning capture model of the structure as described in (Borghetti et al., 2010). The annual number f_{damage} of expected dangerous events can be calculated as follows:

$$f_{damage} = f_{capture} \cdot P_{damage} = \frac{n_{captured}}{n_{tot}} n_g A \cdot \frac{n_{damaged}}{n_{captured}} = \frac{n_{damaged}}{n_{tot}} n_g A \tag{10}$$

Where $n_{damaged}$ is the number of events that causes a passing hole with diameter larger than the chosen D_{hole}, $n_{captured}$ is the total number of lightning events assumed to strike onto the target equipment, n_{tot} is the total number of lightning events assumed to strike inside the considered area ***A*** around the plant and n_g is the annual flash density of the region where the plant is located. In the following section the results obtained by applying equations (6)-(9) are presented.

4. Results

In Figure 2 the probability of charge responsible of a D_{hole} larger than the selected minimum hole diameter (10 mm, 20 mm and 30 mm) is reported against the shell thickness (***w***). The logarithm of the probability depends linearly with the shell width for the three diameters considered. The three curves are almost parallel.

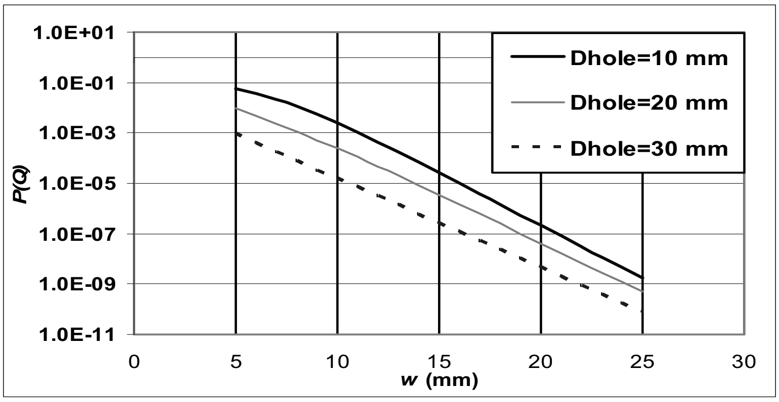

Figure 2: Damage probability versus the shell thickness for three different hole diameters.

Table 1: Damage probabilities for different atmospheric tanks

Volume (m^3)	D (m)	H (m)	*w* (mm)	P_{damage}
100	4.4	7	5	$5.75 \cdot 10^{-02}$
250	7.7	7.5	5	$5.75 \cdot 10^{-02}$
500	7.8	11	6	$3.69 \cdot 10^{-02}$
750	10.5	9	7	$2.13 \cdot 10^{-02}$
1000	15	6	9	$5.41 \cdot 10^{-03}$
2500	16	13	13	$1.74 \cdot 10^{-04}$
5200	25	11	19	$5.49 \cdot 10^{-07}$

Table 1 reports the application of the method for the assessment of failure probability for atmospheric storage tanks with different sizes and thicknesses. ***D*** is the tank diameter, ***H*** is the tank height and ***w*** the plate thickness. For this kind of equipment the higher damage probability is of the order of 10^{-2} when the shell thickness has a value of 5 mm.

Table 2: Damage probabilities for different pressurized horizontal tanks

Volume (m^3)	D (m)	L (m)	*w* (mm)	P_{damage}
10	1.6	4.5	11	$1.05 \cdot 10^{-03}$
	1.2	7.7	8	$1.12 \cdot 10^{-02}$
20	2.15	4.05	14	$6.84 \cdot 10^{-05}$
	1.9	7.2	12	$4.35 \cdot 10^{-04}$
	1.5	9.7	10	$2.45 \cdot 10^{-03}$
25	2.3	4.4	15	$2.64 \cdot 10^{-05}$
	1.7	10.5	11	$1.05 \cdot 10^{-03}$
50	2.9	5.5	19	$5.49 \cdot 10^{-07}$
	2.7	10	17	$3.83 \cdot 10^{-06}$
	2.1	13.2	14	$6.84 \cdot 10^{-05}$
100	3.9	5.8	25	$1.79 \cdot 10^{-09}$
	3.2	12	21	$7.95 \cdot 10^{-08}$
	2.8	18	18	$1.45 \cdot 10^{-06}$
250	5	9.4	32	$1.94 \cdot 10^{-10}$
	3.8	24	24	$4.57 \cdot 10^{-09}$

Table 2 reports the application of the method for horizontal pressurized storage tanks of cylindrical shape with different size and hold-up. The shell width of this tank category is directly dependent by its diameter dimension (***L*** is the vessel length). The higher damage probability is of the order of 10^{-2} when the shell thickness is equal to 8 mm, but this thickness usually applies to small inventory vessels and the in LOCs (loss of containment) with a minor severity. Pressurized storage tanks generally have larger values of shell thickness than atmospheric tanks and are thus less vulnerable to lightning erosion.

5. Conclusions

The hazardous events due to lightning have been discussed. In particular the calculation of perforation probability due to metal melting at the lightning attachment point is presented. A linear trend of the logarithm of the damage probability with respect to the shell width of the equipment is observed. The damage probability has been calculated for a set of atmospheric and pressurized storage tanks. Due to the higher shell thickness, pressurized tanks appear less vulnerable to lightning damage.

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