Reliability Engineering and System Safety 115 (2013) 91–99

Contents lists available at SciVerse ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A model for process equipment damage probability assessment due to lightning

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

[a] *Alma Mater Studiorum – Università di Bologna, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Via Terracini 28, 40131 Bologna, Italy*
[b] *European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, TP 720, Via E. Fermi 2749, 21027 Ispra (VA), Italy*
[c] *Alma Mater Studiorum – Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione, Viale Risorgimento 2, 40136 Bologna, Italy*

ARTICLE INFO

Article history:
Received 3 December 2012
Received in revised form
9 February 2013
Accepted 21 February 2013
Available online 4 March 2013

Keywords:
Major accident hazard
NaTech
Lightning
Damage probability
Risk assessment

ABSTRACT

In recent years, severe natural events raised concern about so-called NaTech accident scenarios: technological accidents caused by the impact of a natural event on an industrial facility or infrastructure. Lightning strikes are one of the most important triggers of NaTech scenarios. Moreover, previous studies showed that lightning strikes are among the main causes of loss of containment (LOC) of atmospheric storage vessels containing hazardous materials. Although the lightning hazard is well known, 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 lightning strike probability and to the damage caused by lightning strike are mainly qualitative or semi-quantitative and are mostly based on expert judgment. In the present study, a quantitative methodology for the assessment of the equipment damage probability due to lightning is presented. The lightning severity was quantified by means of probability distribution functions of two parameters: peak current intensity and lightning charge. Through the application of a Monte Carlo simulation the expected frequency of lightning strikes on the equipment and the equipment damage probability were determined. The results of the equipment damage model were validated by available experimental data on metal perforation in simulated lightning strikes. The results of the validated Monte Carlo simulations were fit to empirical functions obtaining a simplified model suitable for use in a quantitative risk assessment framework.

1. Introduction

The impact of natural disasters on industrial facilities or infrastructures may trigger severe technological accidents due to the release of hazardous substances. These so-called NaTech (Natural-Technological) accident scenarios were analyzed in detail by several authors [1–17]. A study of Rasmussen [14] indicated that natural events cause around 3% of industrial accidents. Lightning strikes resulted responsible for 61% of accidents initiated by natural events in process or storage installations. The analysis of a set of industrial accidents caused by lightning highlighted the potential severity of such events, in particular in storage sites and tank farms of chemical and process plants [18]. Specific studies of accidents involving tanks indicated that lightning strikes are among the most frequent causes of loss of containment [19,20].

Several technical standards require the adoption of specific protection measures against lightning in industrial sites [21–23]. However, while these provide for adequate protection of buildings, protection measures and systems complying with up-to-date standards for process and storage equipment, such as grounding systems or bonding, can protect equipment from indirect lighting currents but they are not sufficient to prevent damage in the case of a direct lightning strike [23]. This is evident from the almost constant frequency of tank fires caused by lightning events [18]. Effective protection of tank farms may be obtained by installing a network of dedicated lightning rods [24], but the cost of this specific protection system can be high, suggesting its use only when a particularly high risk exists. Thus, the development of quantitative models to assess the risk due to lightning impact on process equipment is of fundamental importance to understand both the relevance of the contribution of these accidents to the overall risk of an industrial site, and to allow a cost-benefit analysis to support decision making concerning the installation of dedicated protection measures.

The lightning hazard is strongly dependent on the geometrical parameters of the equipment (height, diameter, shell thickness,

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[*] Corresponding author. Tel.: +39 051 2090240; fax: +39 051 2090247.
E-mail address: valerio.cozzani@unibo.it (V. Cozzani).

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http://dx.doi.org/10.1016/j.ress.2013.02.018

etc.) and on the site layout, that influence both the capture probability and the equipment damage probability following lighting impact. In the present study the issue of equipment damage following a lightning strike was investigated. A description of the lightning damage dynamics on process and storage equipment is introduced and a method for the prediction of the associated damage probability is presented. Equipment damage was estimated by identifying a critical volume of molten metal needed to cause equipment perforation due to the impact of a lightning flash. A model was developed and validated by using experimental data available in the literature to estimate the molten volume as a function of the statistical distribution of the lightning charge. The damage probability of equipment was obtained by using Monte Carlo simulations based on the probability distribution function of the lightning current characteristics (e.g., Borghetti et al., [24–26]). In particular, in this study the probability function of the total charge of lightning flashes and its correlation with the probability distribution of first stroke amplitudes was used. From the results of the Monte Carlo simulations a simplified model was inferred. The simplified model appears suitable for quantitative risk assessment studies.

2. Model for lightning damage

2.1. Effect of lightning strikes on process equipment

Fig. 1 summarizes the main mechanisms of lightning damage to process equipment obtained from the analysis of past accidents [18]. As shown in the figure, 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, mainly in the case of storage tanks vented to the atmosphere. Flammable vapors 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 [27].

However, a direct damage mechanism is also possible, due to the perforation of the equipment shell. The high energy of lightning flashes is able to melt or even to evaporate construction materials like steel, aluminum, copper or composite materials [28]. The volume of the molten metal depends on the lightning energy. The present study focused on this direct damage mechanism. As highlighted in several analyses of past accidents, the direct damage mechanism triggered a significant number of major accidents [18,20,21,23,29].

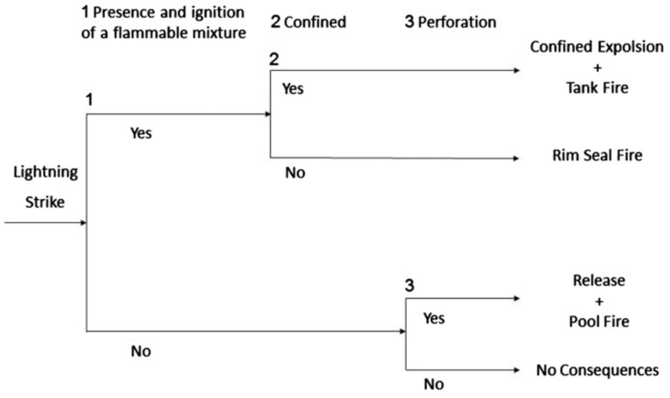

Fig. 1. Event tree following lightning strike on a process equipment item.

2.2. Arc erosion modeling

The electric arc formed by a lightning is a phenomenon having a high energy density. In the case of a lightning strike, the temperature of the strike point increases abruptly due to the high plasma temperature and by resistive heating. The temperature can reach very high values (even exceeding 15000 °C) in a few milliseconds [22]. The high temperature generated can melt (or even vaporize) part of the metal shell, causing a hole that may result in loss of containment usually leading to a major accident.

In order to model the damage induced by lightning strike, a model for lightning arc erosion is required. According to conventional theory on welding processes [30], the electric arc is defined as a discharge of electricity between electrodes. The arc is typically formed by three regions: the cathode region, the arc column region and the anode region. Each region is characterized by a specific voltage drop, and the voltage drop at the cathode and at the anode should be of the order of the excitation potential of the electrode material (of the order of 10 V). The flowing current can have any value above a minimum, which varies between 0.1 A and 1 A, depending on the electrode material.

Several theoretical models are available for the calculation of the erosion volume on metal surfaces at the attachment point of the arc channel [22,30–32]. 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 [30,32]. The heating at the attachment point is mainly 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. The current density, the arc spot radius and the voltage drop at the electrode are thus the most important parameters to consider for the assessment of the heat transferred to the electrode. An important contribution to the overall heat transferred to the area around the arc spot is due to heat radiation from the arc channel [32].

González and Noack [32] theoretically and experimentally described that positive strokes are characterized by the unsteady behavior of the arc spot. The fast and short displacement of the arc spot over the sheet surface near the original attachment point spread the molten volume rather than making it deeper in the case of positive strokes. Negative long strokes are instead characterized by a stable behavior. The resulting molten volume zone has shown to be deeper than wide, indicating a better transport in the axial direction.

Due to the variation and uncertainties related to the lightning current 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 sake of simplicity, in Standard CEI EN 62305 [22] the power associated to the electric arc (W) is evaluated as the product of the lightning current intensity, i, multiplied by the cathode or anode voltage drop, $u_{a,c}$. The typical value of $u_{a,c}$ is in the range of 10–20 V. The cathode or anode current drop is dependent on the current intensity amplitude and on the arc length, duration and polarity. A value between 13 and 17 V is suggested for this parameter in the literature [32].

The energy (E) released by the electric arc is the time integral of the power associate to the electric arc over the total duration of the strike. If the voltage drop is assumed constant, this becomes equal to the voltage drop multiplied by the electric charge [22]

$$E = \int W dt = \int u_{a,c} i dt = u_{a,c} \int i dt = u_{a,c} Q \tag{1}$$

where t is time and Q is the electric charge of the lightning. If heat dispersion to the surroundings is conservatively neglected, all the energy transferred to the solid material at the lightning attachment