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Quantitative Evaluation of the Safety Barriers to Prevent Fired Domino Effect

Francesca Argenti, Gabriele Landucci*

Dipartimento di Ingegneria Civile e Industriale - Università di Pisa, Largo Lucio Lazzarino, 56126, Pisa, Italy
gabriele.landucci@unipi.it

A simplified methodology was developed for the assessment of fire protection barriers and to support the Quantitative Risk Assessment (QRA) of industrial facilities. Given a generic fire scenario, the aim of the methodology was to evaluate the probability of fire damages on industrial equipment both considering the availability and effectiveness of the protective barriers. Fire protections for industrial equipment were first classified, and then literature reliability data were used to build a dataset of Probability of Failure on Demand (PFD) for each protection type. Next, the effectiveness was determined from specific studies and surveys available in the literature. For passive protections, the effectiveness evaluation was based on the protective barrier response to fire. A case study was presented and discussed in order to exemplify the methodology implementation and to show the potential application in simplified QRA studies.

1. Introduction

In the framework of chemical and process industry, accidental fires may lead to damages to equipment with severe consequences and possible accident escalation (Bagster and Pitblado, 1991; Lees, 1996; Khan and Abbasi, 1998; Cozzani et al., 2009; Antonioni et al., 2009).
When equipment are exposed to fire, the heat received by radiation and convection is then conducted through the insulation layer (if present) and through the equipment shell to the wall inner surface, which heats up causing heat exchange into the lading by convection and radiation (Roberts et al., 2000; Birk, 2006; Landucci et al., 2009; Paltrinieri et al., 2009). These processes take time to develop and to increase the wall temperature of the impacted equipment before a critical exposure condition is reached, jeopardizing the structural integrity of the target and leading to a loss of containment (Bagster and Pitblado, 1991; Lees, 1996; Birk, 2006). Therefore, a time lapse (namely, the "time to failure" TTF of the exposed equipment) exists between the fire starting and the eventual equipment failure and consequent escalation; during this time lapse mitigation actions can be taken. In the majority of industrial facilities, protection systems and procedural emergency measures are adopted for preventing escalation, reducing the frequency or mitigating the consequences of escalation scenarios.
Hence, the analysis of fire protection systems and safety barriers action needs to be included in the procedures of escalation probability evaluation, in order to support Quantitative Risk Assessment (QRA). In the following, a simplified methodology for the assessment of fire protection barriers is presented and applied to a case-study.

2. Methodology

2.1 Overview of the methodology

The main steps of the methodology are summarized in the flowchart reported in Figure 1.
The presence of active and passive barriers, as well as the adoption of procedural measures, was taken into account and barrier performances were quantified by the application of event tree analysis (Lees, 1996). Once the event tree analysis has been carried out starting from the considered primary fire, the methodology allows describing and characterizing the possible final scenarios in case of success and failure of all implemented active and passive fire protections.

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Two main types of final scenarios were considered possible: unmitigated fire escalation scenario (no protection systems present or all protection systems unavailable) and mitigated fire escalation scenario (effective action of protection systems and reduced escalation frequency and consequences). Each identified scenario was characterized in terms of associated time to failure of the exposed equipment and frequency.

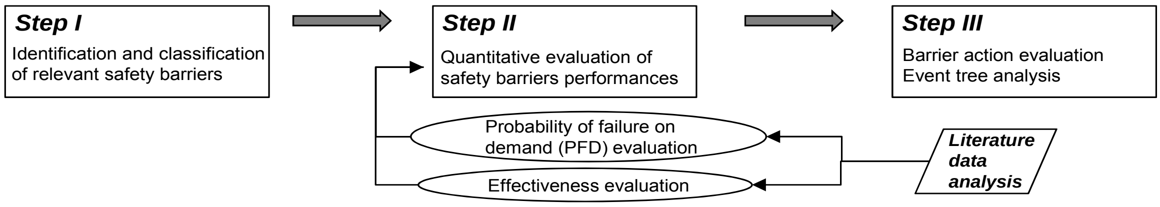
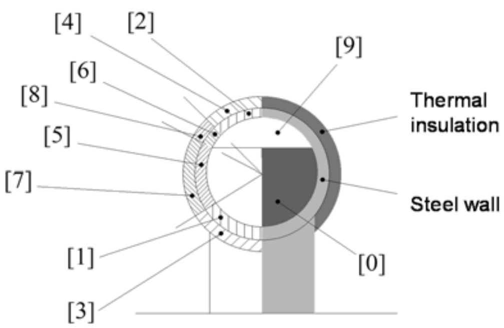


Figure 1: Overview of the methodology developed in the present study.

2.2 Determination of fired equipment resistance

As mentioned in Section 1, the fired equipment “time to failure” (TTF) is a key parameter in the determination of target resistance and its evaluation represents an issue of fundamental relevance in the risk assessment of escalation scenarios caused by fire (Landucci et al., 2009). In the literature, very complex and time consuming approaches based on Finite Elements Modelling (FEM) are available for the accurate calculation of the equipment TTF (Birk, 2006). However, simplified models have to be preferred in the framework of QRA procedures for escalation assessment, where computational time optimization is of the utmost importance considering the high number of accidental scenarios to be analysed (Cozzani et al., 2009; Khan and Abbasi, 1998).

In the specific contest of QRA of complex industrial installations, Landucci et al. (2009) suggested a simplified approach and developed related tools for the straightforward assessment of vessel time to failure: in particular, a simplified lumped parameters model, based on a ‘thermal nodes’ approach, was used for characterizing the behaviour of equipment exposed to fire and for evaluating equipment TTF. Figure 2 summarizes the key-aspects of the lumped parameters model, which allows evaluating the dynamic evolution of the pressure and of the liquid, vapour and wall temperatures, considering the presence of an eventual layer of fireproofing material and the activation of a pressure relief device. Those parameters are used for the TTF evaluation, implementing a simplified failure criterion. More details on the validation and development of the model are reported elsewhere (Landucci et al., 2009).



[0]	Liquid space
[1]	Vessels wall in contact with the liquid phase but not in the zone impinged by the flame
[2]	Vessels wall in contact with the vapour phase but not in the zone impinged by the flame
[3]	Insulated material layer (if present) at the level of the liquid phase but not in contact with the flame
[4]	Insulated material layer (if present) at the level of the vapour phase but not in contact with the flame
[5]	Vessels wall in contact with the liquid phase and in the zone impinged by the flame
[6]	Vessels wall in contact with the vapour phase and in the zone impinged by the flame
[7]	Insulated material layer (if present) at the level of the liquid phase and in contact with the flame
[8]	Insulated material layer (if present) at the level of the liquid phase and in contact with the flame
[9]	Vapour space

Figure 2: Thermal nodes definition for the lumped parameters model applied in the present study.

2.3 Quantification of escalation probability

According to the approach suggested by Landucci et al. (2009), the time to failure associated to each final scenario was used to directly calculate the probability of escalation (EP), which corresponds to the damage probability of the equipment exposed to fire. Vulnerability models based on probit equations (Lees,1996), which are extensively adopted in QRA, were used for this purpose:

$$Y = a + b \ln(TTF) \quad (1)$$

in which: Y is the probit; TTF is the time to failure, which takes into account the severity of the fire scenario (radiation mode, radiation intensity) and the vessel resistance to fire conditions (vessel geometry, vessel failure conditions); “a” and “b” coefficients were derived comparing the TTF to the characteristic times required to implement effective emergency operations and procedures. In the present work, the values of “a” and “b” were selected on the basis of a survey of the times needed for the arrival of internal emergency teams in different locations of extended storage farms of existing oil refineries. It was shown that only in 10% of cases the cooling of an exposed structure could start in less than 5 min and in 90% cases in less than 20 min. Thus, assuming a log-normal distribution of failure probability, the escalation probability EP was set equal to 0.1 (Y = 3.71) for TTF equal to 5 minutes, and it was set equal to 0.9 (Y = 6.27) for TTF equal to 20 minutes. On this basis, the probit function coefficients were calculated, obtaining a = 9.25 and b = -1.85 in Eq. 1.

2.4 Assessment of active and passive barriers: availability and effectiveness

Among industrial and process facilities, the implementation of risk management strategies relies on multiple safety layers (CCPS, 2001): process design (including inherently safer concepts), safety instrumented systems, passive and active devices, safety shutdown systems and response plans. Layers of Protection Analysis (LOPA) is a simplified form of risk assessment that may be adopted for assessing the value of protection layers for a well-defined accident scenario (Lassen, 2008). For the probabilistic assessment of fired escalation scenarios, LOPA results incomplete, since it describes only the worst case option (failure of all protections) (CCPS, 2001). Therefore, in the present work, an event tree analysis was carried out in order to consider both success and failure of all the mitigation systems and to identify an enlarged set of final scenarios (Lees, 1996).

The quantification of the event tree branches was performed through the analysis of the performances of safety barriers, considering two main aspects (see Step II in Figure 1):

- availability → the presence of a barrier does not necessarily imply it will perform its mitigation function; therefore, an estimate of typical Probability of Failure on Demand (PFD) of the protection system was carried out;
- effectiveness → the presence of passive protections or the proper actuation of active protections do not guarantee that the mitigation action will be performed successfully: depending on the type of barrier, effectiveness of the mitigation action needs to be quantitatively evaluated as the reduction of primary fire intensity (e.g., fire heat load) or as the increase in target resistance obtained due to the specific protection system.

The quantitative evaluation of the protection systems effectiveness is a crucial step introduced in the presented methodology. In fact, it allows a deeper investigation on the safety barriers performances as it covers another key aspect related to the analysis of fired equipment: it expresses the mitigation action of barriers in terms of variation of physical parameters, thus in relationship with the physical modelling of the fire attack or the target equipment resistance and behaviour. Despite the relevance of analysing these aspects, a generic procedure and consolidated methods to quantify the effectiveness of a generic fire protection system are still lacking in the literature. Therefore, for each type of protection system, a specific approach and a dedicated parameter was defined to describe the contribution of effectiveness.

3. Application to a case-study: LPG storage facility

3.1 Definition of the case-study

A LPG storage facility was taken as a reference in the definition of a case-study. The possible escalation of a jet fire due to a breach in a transport pipeline was considered. As a consequence of the jet fire, a 100 m^3 LPG storage tank is fully engulfed by the fire (estimated received heat flux I = 200 kW/m^2). For the sake of simplicity, the other equipment items in the facility were considered as not affected by the primary fire, and only the LPG vessel was analysed as target. The presence of all typical protection systems for this type of facility (Lees, 1996) was taken into account.

The frequency of occurrence of the primary fire scenario was determined: a frequency of 10^{-7} events/year for a continuous release of flammable gas resulting from a full bore rupture of a 100 meter long pipeline (DN >150 mm) and a probability of 0.5 for immediate ignition were considered, according to the guidelines of TNO Purple Book (Uijt de Haag and Ale, 1999).

3.2 Identification of relevant safety barriers for scenario mitigation

In the case of the horizontal pressurized vessel storing LPG, fire exposure protection is provided by: i) adoption of active fire protection, in particular an object-specific water deluge system; ii) application of fireproofing materials on the vessel shell and installation of a pressure relief device (passive fire protections).

A water deluge system uses many spray nozzles arranged in a grid pattern to distribute the water evenly over the LPG vessel (according to technical standards NFPA 58 and NFPA 59). Release of the deluge systems shall be possible both locally and remotely at the control station, where the operating status of the systems is monitored. WDS prevents heat from damaging equipment and supporting structure while a fire is being extinguished. A generic passive protection device is a system or a barrier which does not require either power or external activation to trigger the protection action (Lees, 1996; Landucci et al., 2009). Passive fire protection (PFP) systems are usually based on the implementation of a set of barriers aimed at delaying the target vessel failure, hence providing additional time for the implementation of active protections or of mitigation measures (Paltrinieri et al., 2009, Cozzani et al., 2009). More specifically, the pressure relief device is aimed at limiting the vessel internal pressure by the control of the vapor pressure increase due to the rise in the liquid temperature (Lees, 1996; Birk, 2006; Roberts et al., 2000), while fireproofing materials are able to delay the temperature rise of the protected structural elements (Di Padova et al., 2011; Tugnoli et al., 2012).

4. Results and discussion

4.1 Analysis of protection barriers performances

Since active fire protections are complex systems, the evaluation of PFD was accomplished through the application of fault tree analysis (Lees, 1996). A survey on the industrial schemes for WDS was carried out, determining a reference WDS scheme for the present study. Hence, fault tree analysis was applied evaluating the PFD values reported in Table 1.
Passive fire protections (PFP) can be instead considered as single components, hence a conservative reference value of PFD was derived from specific literature (CCPS, 2001). The adopted PFD values are reported in Table 1.

Table 1: Adopted PFD values for active and passive fire protections

Fire Protection	Abbreviation in Table 2	Type of protection	PFD	Source
Water Deluge System	WDS	Active	4.3×10^{-2}	(calculated)
Pressure Relief Valve	PRV	Passive	1.0×10^{-2}	CCPS, 2001
Fireproofing coating	PFP	Passive	1.0×10^{-3}	CCPS, 2001

Concerning the determination of water deluge systems effectiveness in protecting LPG storage vessels, a survey in the literature was carried out for a preliminary assessment of active protection systems. Experimental studies by Shirvill (2004), Roberts (2004a,b), Hankinson and Lowesmith (2004) on small and medium scale pressurized vessels engulfed by fire and provided with WDS, allowed obtaining data on the percentage reduction achieved in the incident thermal radiation levels caused by the fire and the decrease in the rate of temperature rise of the vessel, compared with the case without deluge operating. In the present work, a numerical parameter was hence introduced (intensity reduction factor, namely φ) in order to estimate the WDS effectiveness. This factor represents the reduction in the incident radiation intensity (namely, I) obtained due to the presence of the activated deluge system. The selection of a conservative value of 0.5 for the intensity reduction factor parameter was made on the basis of the results of the abovementioned experimental studies (Shirvill, 2004; Roberts, 2004a,b; Hankinson and Lowesmith, 2004) hence obtaining as follows the reduced intensity (I_{WDS}) in case of available WDS system:

$$I_{WDS} = \varphi \times I \quad (2)$$

Therefore, for the scenarios in which the unsuccessful actuation of water deluge system is taken into account, the total radiation intensity I of the fire is considered; while in case of successful actuation of water deluge system the reduction of I up to I_{WDS} (Eq.2), is instead accounted for the evaluation of target equipment TTF.
The effectiveness of fireproofing may be evaluated as the degree by which the target resistance is enhanced thanks to their presence: the higher the time to failure of the target is, the more effective PFP are. Hence, effectiveness evaluation was integrated in the physical modelling of target equipment behaviour, i.e., applying the thermal nodes model for the TTF estimation (see Section 2.2). The thermo-physical data of the PFP were derived from previous studies (Gomez-Mares et al., 2011).
An example of the results obtained with the lumped parameters model is shown in Figure 3, comparing the response of LPG vessel protected only by a fireproofing layer (thus, no WDS or available PRV) (Figure 3a) with the case with no protection systems (Figure 3b). The figure shows the dynamic evolution of the internal pressure, internal vapour and liquid temperature; moreover maximum vessel wall temperature is presented evidencing the vessel time to failure.
As is can be seen, fireproofing of the vessel is an effective strategy against fire exposure as it allows reducing the temperature and thus the pressure rise in the vessel; in this way, the failure is significantly delayed (up to about 2 hours compared to a TTF of few minutes in the case of unprotected vessel).

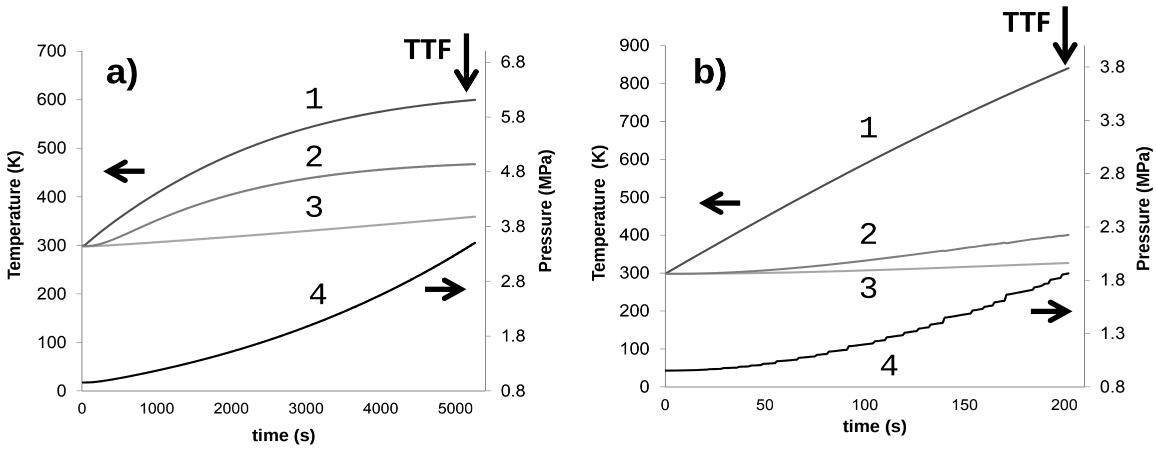


Figure 3: Example of results obtained with the lumped parameters model: prediction of the fire response for the LPG vessel considered in the present study, evidencing the time to failure for two scenarios; (a) vessel protected only by fireproofing; (b) unprotected vessel; 1: maximum vessel shell temperature; 2: vapour temperature; 3: liquid temperature; 4: pressure; TTF = Time to Failure.

4.2 Probabilistic assessment and evaluation of escalation frequency

Table 2 shows the possible escalation scenarios, identified with the application of an event tree analysis and associated to the LPG vessel engulfed by the jet-fire ("Primary Fire"). Each final scenario identified in the Table was characterized through the evaluation of final frequency and modified escalation probability (considering the mitigation action provided by the barriers), function of the time to failure TTF.

Table 3 shows the results, and also the base-line value of frequency evaluated for the scenario in which no layer of protection was considered (e.g., frequency of LPG vessel rupture in absence of fire protection systems). The results confirm that the scenario deriving from the failure of all implemented safety barriers (scenario 1) is the less credible one while the scenario deriving from the successful action of all safety barriers (scenario 8) has the highest frequency of occurrence.

Table 2: Definition of reference escalation scenarios associated to the failure of the LPG vessel.

ID scenario	Description
Base-line	Vessel exposed to fire in absence of any protection system
1	The failure of all the possible installed protection system is taken into account
2	The failure of only WDS and PRV is considered, while PFP is available
3	The failure of only WDS and PFP is considered, while PRV is available
4	The failure of only WDS is taken into account; PRV and PFP are available
5	The failure of PRV and PFP is considered, while WDS is available
6	The failure of only PRV is considered, while WDS and PFP are available
7	The failure of only PFP is considered, while WDS and PRV are available
8	The three protection layers (PFP, PRV and WDS) are available and effective

Table 3: Results of the case study: final scenarios frequency and associated escalation probability (EP).

ID scenario	TTF value (s)	Probit value (Eq. 1)	EP from Probit	Modified EP	Frequency (y^{-1})
Base-line	202	4.99	4.941×10^{-1}	-	2.47×10^{-6}
1	202	4.99	4.941×10^{-1}	2.141×10^{-7}	1.07×10^{-12}
2	5262	2.37	4.218×10^{-3}	1.826×10^{-6}	9.13×10^{-12}
3	202	4.99	4.941×10^{-1}	2.119×10^{-5}	1.06×10^{-10}
4	5477	2.33	3.834×10^{-3}	1.643×10^{-4}	8.22×10^{-10}
5	372	4.49	3.066×10^{-1}	2.933×10^{-6}	1.47×10^{-11}
6	10215	1.83	7.699×10^{-4}	7.358×10^{-6}	3.68×10^{-11}
7	372	4.49	3.066×10^{-1}	2.904×10^{-4}	1.45×10^{-9}
8	10568	1.81	7.006×10^{-4}	6.629×10^{-4}	3.31×10^{-9}

Furthermore, it may be interesting to compare the value of frequency of unmitigated escalation scenario in the case of unprotected vessel (base-line scenario) to the frequency associated to the same scenario deriving from the failure of all implemented safety barriers (scenario 1).

This comparison clearly shows that the frequency of the unmitigated scenario results to be reduced by more than five orders of magnitude by simply considering the presence of unavailable barriers. Hence, it was highlighted that an accurate and more realistic evaluation of escalation probability given a primary fire needs to include a specific analysis of the action of implemented fire protection barriers.

5. Conclusions

A simplified methodology for the assessment of fire protection barriers was presented. The methodology was aimed at the evaluation of fire damages probability to process equipment, in order to consider the action of mitigation barriers. The application of the methodology through a case-study allowed for a straightforward assessment of the probability of escalation events caused by fire in industrial facilities. The presented methodology might be successfully integrated in procedures for the quantitative assessment of domino contribution to risk indexes calculated in Quantitative Risk Analysis (QRA) of complex industrial installations, as it provides support element for the estimation of fired escalation frequency and the estimation of escalation scenarios risk contribution.

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