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Quantitative Assessment of Safety Barrier Performance in the Prevention of Cascading Events

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Abstract

The prevention of high-impact low-probability (HILP) events in industrial clusters or complex industrial areas where critical infrastructures are present critically depends on the presence and the performance of safety barriers that may have the potential to prevent escalation. In recent years a set of tools and models were developed for the quantitative assessment of risk due to cascading events and domino scenarios. The aim of the present study is the integration of tools for risk assessment with a specific approach allowing a detailed assessment of safety barrier performance. A LOPA (layer of protection analysis) based methodology, aimed at the definition and quantification of safety barrier performance in the prevention of escalation was developed. The method allowed the quantitative characterization of alternative mitigated and unmitigated escalation scenarios. Data were collected on the more common types of safety barriers aimed at the prevention of fire escalation. An example of application was developed, allowing the quantitative assessment of risk mitigation of cascading events triggered by fire escalation based on the assessment of safety barrier performance.

1. Introduction

The specific feature of escalation caused by fires is the time lapse which exists between the start of secondary events with respect to the start of the primary fire. This time lapse is usually indicated as time to failure (*ttf*) (Landucci et al. 2009a). In fact, while equipment damage caused by overpressure or fragments projection is almost instantaneous (Lees 1996, Tugnoli et al. 2014), the damage mechanism of equipment exposed to fire is such that time is needed before the temperatures of the shell and of the internal fluid are able to jeopardize the structural integrity of the target vessels (Landucci et al. 2009b). The *ttf* represents a key parameter to describe the resistance of equipment to external fires and depends on both the characteristics of the primary fire scenarios and the features of the secondary equipment involved in the fire (Khan & Abbasi 1999, Lees 1996).

In most cases, both factors may be modified by the installation of mitigation barriers and by appropriate emergency measures. The awareness of the hazards posed by domino effect led to the introduction of several technical standards that recommend the use of protective systems or barriers to reduce the possibility of fire escalation.

Cascading events and domino scenarios caused by the escalation of industrial fires were responsible of severe accidents in chemical and Oil&Gas industrial facilities (Cozzani et al. 2009, Khan & Abbasi 1999, AIChE CCPS 2000). Past accident data analysis shows that the secondary targets more frequently affected by escalation were pressurized tanks, atmospheric tanks, process vessels and pipelines (Reniers & Cozzani 2013, Darbra et al. 2010). Therefore, an accurate assessment of escalation probability needs to include the analysis of the available fire protection systems and safety barriers (AIChE CCPS 2001a) of such process items. However, an exhaustive approach to the quantitative assessment of the performance of all categories of protection layers (passive, active, procedural) relevant to the prevention or mitigation of fired domino effect is still lacking.

The present study aims at the integration of a systematic quantitative analysis of safety barrier performance with probabilistic models for the assessment of escalation developed in previous studies (Landucci et al. 2009a). A methodology to assess the performance of safety barriers in the prevention of escalation was developed. The performance of active, passive and procedural safety barriers was assessed considering both availability and effectiveness, by adopting a LOPA (layer of protection analysis) approach. Equipment vulnerability models based on probit functions (Lees 1996) were integrated with the LOPA results. Modified escalation probabilities, including the influence of safety barriers, were thus obtained. The approach allowed assessing the reduction in escalation probability provided by each protection layer as well as by the overall system of safeguards implemented. The application to a case-study allowed the exploration of the features and potentialities of the methodology.

2. Theoretical approach

2.1 Procedure for the assessment of escalation probability accounting for safety barriers

The methodology developed to integrate safety barrier performance in the escalation probability assessment is shown in Figure 1.

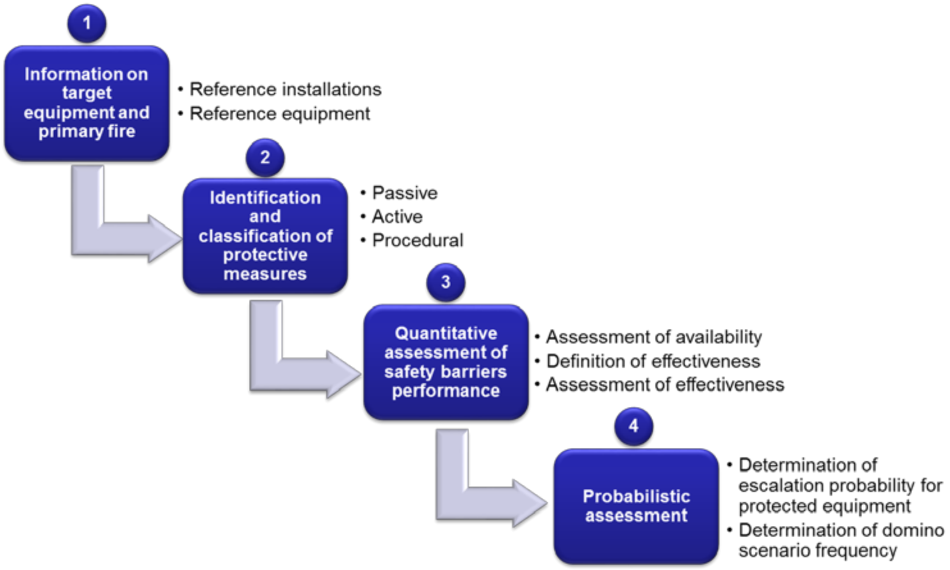

Figure 1. Overview of the methodology.

The first and preliminary step is aimed at gathering information about the equipment item under analysis and the primary fire scenario affecting the equipment and potentially triggering the domino chain.

The second step consists in the identification and classification of the safety barriers available to prevent fire escalation on the equipment item of interest (Lees 1996, AIChE CCPS 2001a).

As third step, a quantitative assessment of safety barrier performance should be carried out, obtaining barrier availability and effectiveness. This step is detailed in Section 3.

In the final step, an event tree is built to assess escalation probability with respect to each equipment item classified as a relevant secondary target, also considering the action of safety barriers. A top-down approach starting from the primary fire (e.g., pool fire, torch or jet fire, etc.) affecting the target is adopted to obtain the event tree. The characterization of the primary fire is needed as a preliminary step to the quantification of the event tree: it requires to determine the expected duration of the primary fire, the heat load and the type of exposure (distant radiation, partial impingement or full engulfment). Intermediate events related to the performance of safety barriers are then defined using specific logic gates and operators.

Event tree quantification allows accounting for the probability of unmitigated escalation and, if relevant, of one or more partially mitigated or delayed escalation scenarios. Being aware that the type of fire protection systems strongly depends on the features of the site and equipment under analysis, a repository of data for safety barriers frequently applied to prevent escalation triggered by fire was prepared in order to support and to demonstrate the application of the proposed methodology.

2.2 Classification of standard technical safety barriers

Different types of safety barriers are effective in delaying or preventing escalation. The three categories (De Dianous & Fievez 2006, AIChE CCPS 2001b) of i) active protection systems, ii) passive protection systems and iii) procedural and emergency measures were taken into account according to different procedures in the quantitative assessment of escalation probability.

Active fire protection systems more relevant in escalation prevention can be divided into two different categories (Lees 1996, Dennis & Nolan 1996, De Dianous & Fievez 2006):

a) Systems for the delivery of fire-fighting agents (such as water or water-based foam), which are designed to mitigate fire exposure of the target or to provide effective control of the primary fire and prevention of fire spread in nearby units;
b) Emergency Shutdown Systems (ESD) and Emergency Depressurization Systems (EDP), which are designed to isolate and empty the target vessel, reducing the potential loss and consequent damage connected to the large inventory.

In the framework of escalation prevention, the application of fireproofing materials constitute a relevant and effective passive safety barrier aimed to delay the increase of the vessel wall temperature (Gomez-Mares et al. 2012a, b). Pressure Safety Valves (PSVs) are a further widely applied passive safety barrier to limit the vessel internal pressure by the control of the vapor pressure increase due to the raise of the liquid temperature. More details on the performance of PFP systems and on the underlying fundamental phenomena are reported elsewhere (Lees 1996, Droste & Schoen 1988, Landucci et al. 2009b).

Procedural measures include the relevant operating procedures with respect to escalation prevention. Emergency measures represent the coordinated response to a major accident scenario, in which different roles and functions are to be performed by different actors (local authorities, fire brigade, emergency teams, etc.) (Lees 1996, TNO 2004).

2.3 Assessment of safety barriers success probability

The quantitative assessment of safety barrier performance is routinely carried out by standard assessment techniques as the layer of protection analysis (LOPA) approach. However, the specific framework of escalation prevention requires a tailorized approach to be developed.

In the present study, the evaluation of safety barriers performance was aimed at quantifying:

- *availability*, defined as the probability of failure on demand (PFD) of the safety barriers;
- *effectiveness*, defined as the probability that the safety barrier, once successfully activated, will be able to prevent the escalation.

The quantification of effectiveness, not carried out in a standard LOPA assessment, is of particular importance in the assessment of escalation prevention, since several barriers are known to be able to delay but not to prevent escalation.

2.4 Calculation of escalation probability

Considering the application in the framework of a conventional QRA, a modified event tree analysis (Schüller et al. 1997) was selected to consider the actual performance of the safety barrier. For any type of equipment item exposed to a primary fire, an event tree may be built to describe all the possible events in the case of success and/or failure of the implemented safety barriers. Intermediate events related to the performance of safety barriers were defined as parts of the event trees.

More specifically, three specific gates and associated operators, shown in Figure 2 were used to consider the actual availability and effectiveness of safety barriers:

a) a simple composite probability (gate type “a”): availability, expressed as the probability of failure on demand, is multiplied by a single probability value expressing the probability of barrier success in the prevention of the escalation;
b) a composite probability distribution (gate type “b”): availability, expressed as the probability of failure on demand, is multiplied by a probability distribution expressing the probability of barrier success in the prevention of escalation, thus obtaining a composite probability of barrier failure on demand;

c) a discrete probability distribution (gate type “c”): depending on barrier effectiveness, three or more events may originate from the gate describing barrier performance: barrier success (no escalation), barrier failure (unmitigated escalation), and one or more partially mitigated scenarios (partial or delayed escalation).

The quantification of the event tree based on the specific gates illustrated in Figure 2 allowed the straightforward calculation of the final probability of escalation. It is worth to remark herein that the data needed for the quantitative assessment of the event tree and to apply the logic operators shown in Figure 2 are specific of the barrier assessed and may also be influenced by site-specific procedures related to barrier degradation and/or maintenance. Section 3 reports a repository of data to apply the event tree shown in Figure 2.

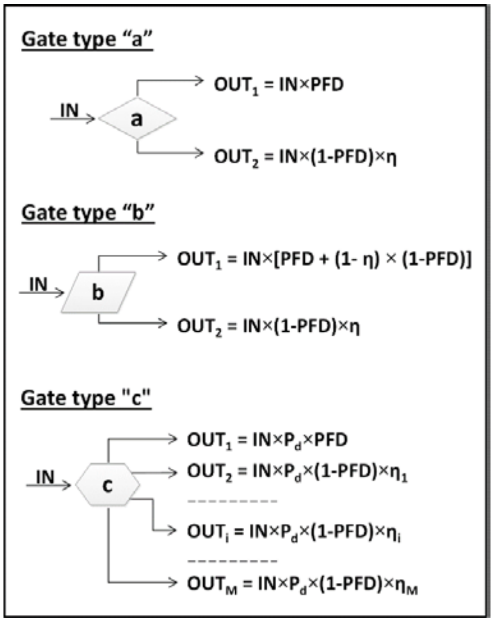

Figure 2. Definition of gate types and associated operators. *PFD*: probability of failure on demand; η: efficiency; P_d: equipment failure probability; *M*: number of possible final scenarios for type “c” gate.

3. Safety barrier performance assessment

3.1 Data repository

A specific availability and effectiveness analysis was carried out for protection systems against fire escalation. Data repository is based on the identification of Reference Installations (RIs) which are categories of installations where common standards or practice apply to the selection and design of fire protection barriers, and of macro-categories of reference target equipment within each RIs. Identified RIs included refinery tank farms, LPG storage facilities and offshore Oil&Gas rigs for hydrocarbon extraction. Table 1 reports a data repository based on the collection of specific technical documentation and standards. More details on data collection are reported elsewhere (Landucci et al. 2015).

3.2 Active barriers

Since active fire protections are complex systems, the evaluation of PFD, and thus of system availability, was achieved through the application of fault tree analysis (FTA) (Lees 1996, Schüller et al. 1997), which requires a detailed knowledge of the system components and architecture.

The “beta factor method” (Schüller et al. 1997) was used for taking into account dependency and common cause failure assuming a constant value of β = 5%. Further details on the reliability data values selected for the analysis and their sources together with the FTA results and their validation for each system considered can be found elsewhere (Argenti & Landucci 2014).

The successful activation of active fire protection systems does not guarantee that the escalation is actually prevented. Hence, the evaluation of system effectiveness through quantitative parameters was required to finalize the analysis of the performances of foam-water sprinkler systems and water deluge systems.

Table 1. Repository of PFD and effectiveness for the protection systems considered in the present study.

Protection system	**Gate type**	**PFD**	**Effectiveness (η)**	**Reference Equipment**
Foam-water sprinkler system	b	5.43×10^{-3}	0.954	Atmospheric vessel
WDS	a	4.33×10^{-2}	1	LPG vessels
WDS	a	2.24×10^{-2}	1	Horizontal separators
ESD system	a	3.72×10^{-4}	1	Horizontal separators
Pressure Safety Valve (PSV)	a	1×10^{-2}	1	Any
Fireproofing coating	a	1×10^{-3}	1	Any
Emergency intervention	c	1×10^{-1}	0;1*	Any

* Depending on the comparison between *ttf* and *tfm*

For sprinkler systems, a conservative value of effectiveness was derived from sprinkler systems performance data and statistics, such as the ones compiled by the US National Fire Protection Association, the Australian Fire Protection Agency, the UK Fire Offices’ Committee and other national authorities (see extended set of references provided by Landucci et al., 2015).

Sprinkler systems effectiveness parameter (namely, η) was defined as the probability of success in controlling the primary fire, i.e. the fraction of case histories in which correct activation of the system resulted in effective action in controlling the fire: the lowest value reported in the literature (η = 0.954) was selected. A gate type “b” was thus associated to sprinkler systems in escalation event trees (see Fig. 2 for the use of PDF and η in gate type “b”).

In order to quantify the effectiveness of water deluge systems (WDS), the numerical parameter φ, which represents the reduction in the heat load due to heat radiation (Q_{HL}) obtained due to the presence of the activated deluge system, was introduced. Through the parameter φ, the reduced heat load in case of WDS effective activation (Q_{WDS}) is estimated as follows:

$$Q_{WDS} = \varphi \times Q_{HL} \tag{1}$$

A conservative φ value of 0.5 (corresponding to a 50 % reduction to the incident heat load on the vessel) was selected on the basis of the results of the experimental studies conducted by Shirvill (2004), Roberts (2004), Hankinson & Lowesmith (2004) to investigate the performance of WDS in protecting horizontal pressurized vessels. A gate type "a" (see Fig. 2) was associated to the presence of WDS in escalation event trees. In case of failure of WDS system, the full heat load is supposed to affect the Reference Target Equipment; on the contrary, in case of WDS availability, a value of η equal to 1 is considered and the heat load is reduced of 50 %. Both mitigated and unmitigated heat load values were then implemented in specific correlations for the assessment of the time to failure of the target equipment (see Eq. 2 and Section 3.3).

Since the ESD system activates in order to stop the leakage that feeds the primary fire, the effectiveness of this ESD system is related to system maximum response time. Also in this case gate type "a" was considered (see Fig. 2): in case of successful activation of the safety barrier, an isolation time of 3 minutes (AIChE CCPS 2000, Lees 1996) and efficiency equal to 1 ($\eta=1$, see Fig. 2) were assumed.

3.3 Passive barriers

Passive protection systems perform a mitigation action: in particular, they reduce the physical effects induced by the fire exposure on the target, which result in an increase in the time to failure (*ttf*).

Concerning availability, the order of magnitude of the PFD was conservatively derived from specific literature on LOPA (AIChE CCPS 2001b). Concerning effectiveness, this parameter was evaluated for PFP as the degree by which the target resistance is enhanced due to PFP presence through the calculation of the *ttf* of the protected vessel. The gate type "a" was adopted for passive fire protections (see Fig. 2). In case of failure of PFP systems, the *ttf* was estimated as a function of the heat load by the use of simplified correlations for vessels integrity expressed in the following form:

$$ttf = 0.0167 \times \exp\left(cV^{d} + e\ln(Q_{HL}) + f\right) \tag{2}$$

in which *ttf* is expressed in minutes, Q_{HL} is the heat load (kW/m^2) actually received by the target equipment (which may be substituted by Q_{WDS} in presence of effective activation of WDS system, see Eq. 1), V is the vessel volume (m^3). The coefficients (c, d, e, f) are reported in Table 2 for the more common types of process and storage equipment.

Table 2. Summary of the coefficients used in the time to failure (*ttf*) correlations

Item	**Coefficients for Equation 2**			
	f	***e***	***d***	***c***
Pressurized vessel	0	-0.95	0.032	8.845
Atmospheric vessel	9.877	-1.13	1	-2.667×10^{-5}

Since previous studies (Droste & Schoen 1988, Di Padova et al. 2011, Landucci et al. 2009b, Tugnoli et al. 2012) demonstrated that the presence of a PSV alone is not sufficient to delay significantly the target time to failure, the unprotected vessel time to failure correlation given in Eq. 2 was conservatively applied also in the cases of available PSV with unitary efficiency.

On the contrary, since the presence of a protective fireproofing layer showed to be able of delaying the vessel failure, in case of availability of this barrier an efficiency equal to 1 was considered and a further term (namely ttf_c) was added to the *ttf* estimated for the unprotected vessel as follows:

$$ttf_p = ttf + ttf_c \tag{3}$$

where ttf_p is the time to failure in presence of thermal protection. A simplified assessment of ttf_c is proposed herein: a conservative value of 70 minutes is used if high performance materials (such as intumescent coatings, vermiculite spray and fibrous mineral wool) specifically designed to withstand severe fire conditions are adopted. On the opposite, if common insulating materials (glass wool, rock wool, etc.) not designed for fireproofing applications are used for equipment protection, ttf_c is set equal to zero.

3.4 Procedural barriers

In case of fire, emergency response can be provided by internal and/or external emergency teams (Lees 1996, AIChE CCPS 2001a). These teams can be composed of experts or fire-fighters as well as of volunteers or workers who receive a specific training. Hence, the PFD of emergency team intervention might vary depending on the skills and the level of preparedness of emergency responders (Lees 1996, AIChE CCPS 2001a, De Dianous & Fievez 2006). However, in the present study the PFD was estimated using the conservative value associated to human errors in LOPA literature (AIChE CCPS 2001b).

The effectiveness of emergency team response was quantified defining a time scale for emergency intervention that was used for a direct comparison with the time available for mitigation, represented by the time to failure (*ttf*) of the target vessel. Three reference times were defined:

- *tta* (*time to alert)*: maximum time required to start the emergency operations, defined as the time needed for the fire to be detected and the alarm to be given;
- *tsm* (*time to on-site mitigation)*: maximum time required to start the pre-planned response actions to be put in place by personnel and with resources available on site;
- *tfm (time for final mitigation)*: characteristic time of an effective intervention of external emergency teams, defined as the maximum time required by the external emergency team to provide and keep constant, by means of suitable equipment and vehicles, the amount of water which is required for primary fire suppression or effective cooling action on the target.

For the sake of brevity, reference values were adopted herein to quantify the *tta* and *tsm* of each reference installation (RI), as derived from surveys and fire brigade guidelines (Hobert & Molag 2006) and reported in Table 3. However, it is worth to remark that these parameters are site-specific and need to be assessed for the site considered.

A simplified calculation procedure is proposed to the assessment of the time for final mitigation (*tfm*). The procedure focuses on the calculation of the required amount of water for mitigation, which is one of the predominant factors affecting the value of *tfm* (Hobert & Molag 2006).

Two different relationships were used to estimate the required amount of water depending on the firefighting strategy adopted in preventing escalation: Eq. 4 is proposed to describe the case of intervention aimed to directly suppress the primary fire, while Eq. 5 is proposed to consider the target exposure protection strategy:

$$G_w = w_S \times A_{fire} \tag{4}$$

$$G_w = w_{EP} \times A_{target} \times SF \tag{5}$$

where G_w = amount of water required for primary fire suppression; A_{fire} (m^2) = area of pool surface, or any other surface characteristic of the fire geometry; A_{target} (m^2) = cross sectional area of the target vessel; w_{EP} = 12.2 L min^{-1} m^{-2} (NFPA 2009) required water application density for target exposure protection; w_s = 10.0 L min^{-1} m^{-2} (NFPA 2009) required water application density for fire suppression; and SF = 3 safety factor (Hobert & Molag 2006). Then, the overall time lapse required to provide and keep constant the prescribed amount of water was calculated as the sum of literature values for:

- time to alert external emergency team;
- time to redirect call, time for fire fighters turn-out and driving time, which can be referred to as an overall response time;
- time to carry out equipment deployment and other extra set-up operations, which depends on the type and number of fire fighting vehicles involved in the operations.

Clearly enough, in the case of offshore platforms, *tfm* was set equal to *tsm* because no additional time is required for water supply and deliver apart from fire-fighting equipment deployment time, and no external aid is contemplated in emergency plans nor can be provided in a reasonably short lapse of time.

In order to establish the value of barrier effectiveness, the *tfm* value was compared to the *ttf* of each target. The gate type "c" was used in the escalation event tree for procedural barriers involving emergency team intervention (see Fig. 2). The following three alternative scenarios were identified:

- OUT_1: if the emergency response is not activated or not available, the escalation will occur;
- OUT_2: the emergency response is activated but *tfm* results higher than *ttf*; in other words, emergency team actions come too late to prevent escalation ($\eta=0$) and a mitigated scenario result;
- OUT_3: the emergency response is activated and *tfm* is lower than *ttf*, so the mitigation action is successful and the fire escalation prevented ($\eta=1$).

In order to quantify the gate output for gate type "c", according to the operator described in Figure 2, the estimation of fired equipment damage probability (P_d) is needed together with external emergency team availability and effectiveness.

Table 3. Suggested values for time parameters characterizing emergency response and evaluated probit coefficients for Eq. 6, in which *ttf* is expressed in minutes.

Parameter	**Refinery tank farm**	**LPG storage facility**	**Offshore installation**
tta (min)	5	5	3
tsm (min)	20	20	10
tfm (min)	Calculated (Section 3.4)	Calculated (Section 3.4)	*tfm = tsm*
Probit coefficient *a*	9.261	9.261	8.616
Probit coefficient *b*	-1.85	-1.85	-2.126

It is worth to notice that at this point of the event sequence, the target equipment damage probability is a function of the actual target equipment fire exposure conditions resulting from the primary fire. The effects of primary fire might have been mitigated to a certain extent by the installed active and passive protection systems, already taken into account in the development of the event tree.

The values of parameters *tta* and *tsm* related to the effectiveness of internal procedural measures were used in the determination of the coefficients of probit functions that allow to obtain P_d as a function of the *ttf* (expressed in minutes), following the approach presented by Landucci et al. (2009a):

$$Y = a + b\ln(ttf) \tag{6}$$

where Y is the probit value which allows to directly obtain P_d and *a, b* are the probit coefficients. Table 3 reports the coefficients to be applied in Eq. 2 and 6 for the identified reference installations (RIs).

It is worth to remind that the performance data obtained during the present study were gathered from the analysis of literature sources and from fault tree analysis based on generic reliability data for the single components of safety barriers. Therefore, the use of site specific data, when available, is strongly suggested to improve the estimates. Nonetheless, these data can be used as benchmark values to assess the expected performance.

4. Case-Study definition

Fire escalation probability assessment based on expected safety barrier performance data reported in the present study was carried out considering a sample layout derived from that of an existing storage tank park located in the premises of refinery. The layout is shown in Figure 3.

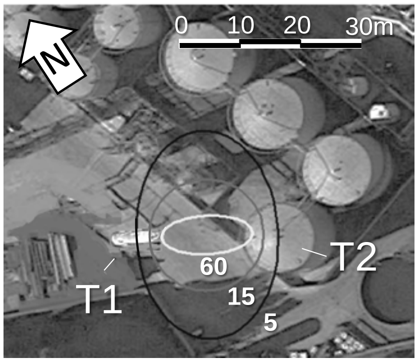

Figure 3. Layout considered in the case study and heat radiation contours (in kW/m^2) associated to the jet fire from tank T1.

In order to simplify the case study, only two equipment items are considered: the pressurized tank T1, storing LPG and the atmospheric tank T2, containing gasoline. The relevant data on the equipment items present in the layout are summarized in Table 4, which exemplifies the level of detail concerning the information required to apply the proposed methodology.

Table 4. Features of the equipment considered for the case study. The layout is reported in Figure 3.

Item	**Tank T1**	**Tank T2**
Type	Pressurized	Atmospheric
Substance	Propane	Gasoline
Capacity (m^3)	25	407
Diameter (m)	2.2	12
Length/height (m)	6	3.6

A 10-mm equivalent diameter leak from tank T1 is supposed to cause a jet fire impacting on tank T2. In order to simplify the case study, only one release position and the orientation were considered. The frequency of the primary scenario was assumed equal to 5×10^{-6} y^{-1}, as derived from Purple Book (Uijt de Haag & Ale 1999). The consequences of jet fire were evaluated using conventional literature integral models (Lees 1996). A single set of meteorological parameters and a uniform wind direction were to calculate the consequences of the jet fire (wind velocity of 5m/s, stability class D) for the sake of simplicity. According to the heat flux contours shown in Figure 3, vessel T2 is exposed to a heat load of $60kW/m^2$.

The relevant safety barriers considered in the analysis were: i) foam-water sprinkler systems; ii) pressure relief valve; and iii) emergency teams intervention.

5. Results and Discussion

The escalation event tree shown in Figure 4 was drawn for the tank T2 (see Fig. 3); then, the quantification of its branches was carried out applying the operators shown in Figure 2 and using the reference performance data concerning the safety barriers listed above and the installation type “refinery”, as summarized in Tables 1-3.

The *tfm* parameter was calculated in accordance with the simplified calculation procedure described in Section 3.3. More specifically, it was considered that emergency teams would give support in providing sufficient target exposure protection and cooling. A required water rate of about 600 m^3/h was derived by applying Eq. 5. Hence, it was therefore reasonable to assume that the refinery water main could provide the required water rate, as long as two fire engines reach the fire area. The *tfm* value was calculated as equal to 32 minutes by summing up the time to alert the external emergency teams (5 minutes as given in Table 3) and fire engines arrival and deployment time (12 minutes and 15 minutes respectively), as derived from (Hobert & Molag 2006).

Several final outcomes were identified, deriving from all possible combinations of success and failure of implemented safety barriers. The frequency of occurrence of all the identified scenarios are reported in Table 5.

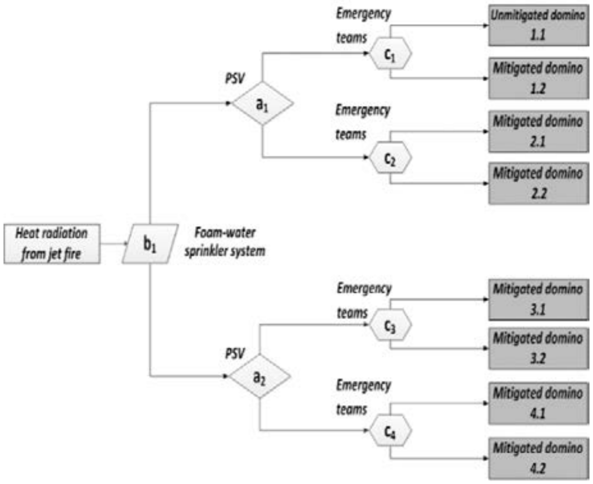

Figure 4. Event tree for the probabilistic assessment of domino events resulting from jet fire impingement on T2 considering the action of relevant safety barriers.

Table 5. Probabilistic assessment of final domino events for target T2. UD = unmitigated domino; MD = mitigated domino.

Final Event ID	**Final event Calculated Probability**	**Final event Frequency (y^{-1})**	**Type of resulting scenario**
1.1	4.98×10^{-5}	2.49×10^{-10}	UD
1.2	4.48×10^{-4}	2.24×10^{-9}	MD
2.1	4.93×10^{-3}	2.47×10^{-8}	MD
2.2	4.44×10^{-2}	2.22×10^{-7}	MD
3.1	4.25×10^{-5}	2.12×10^{-10}	MD
3.2	3.82×10^{-4}	1.91×10^{-9}	MD
4.1	4.21×10^{-3}	2.10×10^{-8}	MD
4.2	3.79×10^{-2}	1.89×10^{-7}	MD

If safety barriers were not considered as in simplified literature approaches (Landucci et al. 2009a), a time to failure of approximately 3 minutes would have been obtained for T2 and then used for the assessment of a provisional unmitigated escalation frequency equal to 4.87×10^{-6} y^{-1}. According to the results of the case study, the frequency of occurrence of an unmitigated domino scenario (represented by the upper most branch of the event tree in Fig. 4), showed a reduction of four orders of magnitude if the implementation of all relevant protection layers is instead considered.

In the considered case-study, the interruption of domino chain was considered not possible. This was mainly due to the severe exposure condition to which atmospheric tank T2 was subjected, leading to an extremely short time to failure of targets compared to the time required by external emergency teams to provide a sufficient water rate. It can be observed that the major contribution to the frequency of domino scenarios (both mitigated and non-mitigated) was due to the frequency of mitigated scenarios (4.61×10^{-7} y^{-1}). Therefore, a more realistic description of the actual escalation potential and a more precise estimate of related frequencies were allowed by accounting for safety barriers. In fact, applying the developed methodology it was possible to distinguish between mitigated and unmitigated final scenarios and to assess their credibility. Furthermore, it was possible to quantify the changes in the overall frequency of domino scenarios due to the presence and action of different protection layers.

6. Conclusions

A methodology for the probabilistic assessment of fire escalation leading to domino scenarios was developed taking into account the role of safety barriers. The methodology allowed considering the actual performance of safety barriers in preventing and mitigating escalation. A repository of reference data made available benchmark data for a comparison of actual to expected barrier performance. Finally, the analysis of a case study pointed out the importance of considering barrier performance in the evaluation of fire escalation probability in the assessment of domino scenarios, allowing for a more precise estimate of the frequency related to cascading events triggered by fire.

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