Journal of Hazardous Materials A139 (2007) 209–219

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Prevention of domino effect: From active and passive strategies to inherently safer design

Valerio Cozzani [a], Alessandro Tugnoli [a], Ernesto Salzano [b,*]

[a] *Dipartimento di Ingegneria Chimica, Mineraria e delle Tecnologie Ambientali, Università degli Studi di Bologna, viale Risorgimento 2, 40136 Bologna, Italy*

[b] *Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, via Diocleziano 328, 80125 Napoli, Italy*

Received 27 January 2006; received in revised form 10 June 2006; accepted 13 June 2006
Available online 16 June 2006

Abstract

The possible application of an inherent safety approach to the prevention of domino accidents was explored. The application of the inherent safety guidewords to the definition of effective actions for the prevention of domino events was analyzed. Due to the constraints originated by the conventional approach to process design, the “limitation of effects” guideword resulted the more effective in the identification of inherent safety actions to avoid domino events. Detailed design criteria for the improvement of layout in the framework of inherent safety were identified and discussed. Simple rules of thumbs were obtained for the preliminary assessment of safety distances and of critical inventories with respect to the escalation of fires and explosions. The results evidenced that the integration of inherent safety criteria with conventional passive or active protections seems a promising route for the prevention of severe domino accidental scenarios in chemical and process plants.

Keywords: Domino effect; Escalation inherent safety; Inherently safer design; Safety distances; Major accident hazards

---

1. Introduction

A domino accident (also known in the literature as escalation or knock-on event) may be defined as an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events. Four elements characterize this phenomenon:

- a primary accidental scenario, which triggers the domino event;
- the propagation effect following the primary event, due to the physical effects (“escalation vectors”) caused by the primary event on secondary targets;
- one or more than one secondary accidental scenarios, involving the same or different plant units;
- an “escalation” effect, that is an increase of the overall severity of the domino event with respect to that of the primary accidental scenario.

Accidents in which a domino effect takes place are among the more severe events that may affect industrial processes and storage sites. Hence, strong efforts should be addressed by the safety management to the prevention of domino accidental scenarios, which is currently mainly pursued by active and passive safety strategies.

The passive safety approach consists in the proper design of physical barriers and protection systems (e.g. thermal insulation of process equipment) whose effect, when needed, is available without any external intervention. This strategy is widely used for the reduction of accident consequences, although the cost of passive protection systems may be relevant [1]. Active strategies to prevent escalation events are usually considered less reliable in the hierarchy of safety but, at least for some primary scenarios as pool or jet fires, these approaches may be effective (e.g. sprinklers protecting pressurized storages), and are often compulsory in the national legislation of several countries as well as in international design standards.

Although the two approaches cited above are of great relevance, it is of fundamental importance to explore the possibility of an inherent safety approach to the prevention of domino accidental events. It is well known that an inherent safety approach is

---

* Corresponding author. Tel.: +39 0817621922; fax: +39 0817622915.
E-mail address: salzano@irc.cnr.it (E. Salzano).

0304-3894/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2006.06.041

Table 1
Escalation vectors and escalation criteria for the definition of escalation radius for different primary scenarios

Primary scenario	Escalation vector	Escalation criterion	Escalation radius
Fireball	Heat radiation	Engulfment	Fireball radius
Jet fire	Heat radiation	15 kW/m^2	Distance at which heat radiation equals threshold value
Pool fire	Heat radiation	15 kW/m^2	Distance at which heat radiation equals threshold value
Vapour cloud explosion (VCE)	Overpressure	16 kPa	Distance at which peak pressure equals threshold value
BLEVE	Overpressure	16 kPa	Distance at which peak pressure equals threshold value
	Fragment projection	Fragment impact	Maximum projection distance
Mechanical and confined explosion	Overpressure	16 kPa	Distance at which peak pressure equals threshold value
	Fragment projection	Fragment impact	Maximum projection distance

based on actions aimed to achieve process safety by a reduction of the hazard. More details on the definition of inherent safety and on the potential advantages coming from this safety strategy are reported in the literature [2,3].

An inherent approach to domino prevention may be easily applied in early plant design, taking into account the possibility of domino events during layout definition. In this case, escalation events may be avoided simply by introducing appropriate safety distances between the more hazardous process units (those having large inventories of flammable or toxic substances) and other process installations. However, distances between process units are usually defined on the basis of industrial practice and simple guidelines or rule of thumbs, without specific reference to the prevention of domino events [4]. Several methods were proposed for the assessment and the comparison of inherent safety of alternative processes, mainly based on the calculation of safety indexes [5–10]. However, most of these methods do not include the assessment of possible domino events. Moreover, none of the methods used for inherent safety assessment includes consequence-based criteria to consider the actual hazard posed by escalation [10]. Thus, the possibility of an inherent approach to escalation prevention, based on layout definition during early design, is seldom taken into account, and no well accepted procedure or guideline is available. Moreover, the possibility of an inherent approach to escalation prevention in existing plants, where layout modifications are usually not possible and only limited changes may be introduced, has never been explored.

The present study focused on the development of tools for the prevention of domino scenarios by an inherent approach in new and existing plants, aiming to the development of simplified criteria for the assessment of safety distances and of critical inventories with respect to the escalation of fires and explosions. The analysis was extended to the primary scenarios listed in Table 1 on the basis of the results of the analysis of about 100 domino accidents performed in a previous study [11].

2. Prevention of escalation events by an inherent safety approach

The theory of inherent safety was systematized by several authors [1,3,12,13]. Kletz [3] was among the first to recognize that any action towards inherently safer design of process plants may be sketched by five well-known guidewords: *intensification* (minimization), *substitution*, *moderation* (attenuation), *simplification* and *limitation of effects*. These guidewords may be applied to identify and define inherent safety actions aimed to escalation prevention, although it is worth noting that the basic conceptual framework represented by these guidewords is sometimes difficult to turn out in practice, and not all these concepts may be applied at the stage of process design in which the assessment of escalation possibility should be afforded.

As a matter of fact, inherent safety assessment should be applied in the early stages of process design to obtain best performances, although the effectiveness of application of inherent safety measures throughout the life of the plant was demonstrated [12]. However, in the case of domino effect prevention, the assessment of escalation requires the analysis of the possible primary scenarios and of the possible domino targets, and thus may not be carried out in detail before the preliminary design of equipment. On the other hand, at this stage, limited changes may be introduced in the process, although the layout definition still leaves some degrees of freedom. Even less modifications are possible on existing plants. The feasibility of inherent safety actions addressed to the prevention of domino effect and classified by the above listed guidewords should thus be carefully evaluated, taking into account the above-defined framework.

The guide word *intensification* is mainly referred to the reduction of the inventory in single equipment items or of the number of equipment items. Since the inventory involved is often a significant parameter in determining the escalation of a primary scenario (e.g. for BLEVEs or VCEs), the minimization of quantities stored or processed is an effective measure for the reduction of hazard, though the revision of equipment design is needed. Also actions related to *moderation* would lead to important reduction in escalation possibilities. The use of less hazardous conditions, as the shift to safer storage technologies (as, in general, the use of cryogenic instead of pressurized storages), is effective in reducing on one hand the hazard of the primary event, on the other the vulnerability of equipment to escalation as well as the severity of the possible secondary scenarios. However, also in this case the revision of equipment design and mainly of storage strategies is required. Thus, actions falling under the *intensification* and *moderation* guidewords, when introduced specifically for escalation prevention issues, may be considered mainly for equipment items having relevant inventories, as storage tanks (e.g. reducing storage capacity or changing storage conditions). Their application will actually lead to complex design modifications that are hardly acceptable in the final stages of plant design. Similarly, *substitution* of substances with others having less hazardous proprieties, and *simplification* of processes, although effective in reducing the possibilities of escalation, would require relevant modification in process design, that are scarcely applicable in the stage of layout definition during plant design or in existing plants. Indeed, the actions identified by these guidewords require, in general, important process modifications or changes in plant design, usually not affordable in the stage of layout definition during plant design or in existing plants. Thus, actions related to the *moderation*, *intensification*, *substitution* and *simplification* guidewords are usually hardly applicable to the prevention of escalation, and should be considered in other steps of process development.

Finally, *limitation of effects* is sometimes considered as a "minor" guideword, as it accepts that a negative effect will somehow take place. However, in the perspective of escalation, this guideword should assure that no secondary event will be caused by domino effects, thus pursuing the prevention of domino accidents by an effectively inherent approach. It may be concluded that the application of an inherent safety approach to the prevention of escalation events will mainly lead to identify actions that fall under the *limitation of effects* guideword, specific to the prevention of damage and of escalation. The identification of these actions will be discussed in the following sections, taking into account the features of the primary scenarios likely to trigger escalation events.

3. Escalation vectors, safety distances and escalation radii

Escalation sequences for atmospheric and pressurized equipment are only possible when highly energetic primary scenarios occur. Table 1 shows the primary scenarios that are likely to trigger escalation effects, and the escalation vectors identified for each scenario. The list of primary scenarios included in Table 1 was derived from the analysis of more than 100 domino case-histories performed in a previous study [11], and was extended to comprehend all the categories of accidental scenarios that were responsible of at least an escalation event. Definition, model details and physics of the scenarios listed in Table 1 are widely described elsewhere [14–16]. Table 1 reports also the physical effects responsible of escalation identified for each scenario, which may be defined as the escalation vectors of the scenario. The intensity of each escalation vector (the escalation radius) depends on the total amount of energy (or substance) which is possibly released from the primary system of containment (reactor, storage tank, etc.), and may be defined as the maximum distance at which escalation effects may be considered credible. This may be estimated on the basis of the threshold values for escalation determined for the more vulnerable categories of process equipment. The threshold values adopted in the present approach were derived from recent studies [11,17–20], and are reported in Table 1.

Table 2 shows the safety distances that may be identified for different categories of target equipment on the basis of the specific escalation thresholds listed in the table [11,18]. The safety distances and the threshold values reported in the table are specific to escalation assessment, thus they were derived also taking into account the severity of the secondary scenarios that are likely to follow the damage of the primary equipment [11,20]. To better understand the data in Table 2, it must be recalled that F is the strength factor of explosion as reported in the multi-energy method (MEM) [21], M_f is the flame Mach number in the Baker–Sthrelow–Tang method [22] and R is the Sachs energy-scaled distance ($R = r(E/P^0)^{1/3}$, where r is the effective distance, P^0 is the ambient pressure and E is the explosion energy calculated by means of the total combustion heat of the flammable cloud). It is also important to evidence that Tables 1 and 2 report general results that are not affected by substance-dependent parameters.

The possible inherent strategies to reduce the probability of domino events will be discussed in detail in the following,

Table 2
Safety distances for escalation

Primary scenario	Escalation vector	Equipment category	Threshold value	Safety distance
Fireball	Heat radiation	Atmospheric	15 kW/m^2	Fireball radius
		Pressurized	50 kW/m^2	0
Jet fire	Heat radiation	Atmospheric	15 kW/m^2	Flame length + 50 m
		Pressurized	50 kW/m^2	Flame length + 25 m
Pool fire	Heat radiation	Atmospheric	15 kW/m^2	Pool border + 50 m
		Pressurized	50 kW/m^2	Pool border + 15 m
Vapour cloud explosion (VCE)	Overpressure ($F \geq 5$; $M_f \geq 0.35$)	Atmospheric	22 kPa	$R = 1.75$
		Pressurized	16 kPa	$R = 2.10$
BLEVE	Overpressure	Atmospheric	22 kPa	$R = 1.80$
		Pressurized	16 kPa	$R = 2.00$
	Fragment projection	Any	Undefined	Undefined
Mechanical and confined explosion	Overpressure	Atmospheric	22 kPa	$R = 1.80$
		Pressurized	16 kPa	$R = 2.00$
	Fragment projection	Any	Undefined	Undefined

R, F and M_f are respectively the Sachs energy-scaled distance, the strength factor as in the multi-energy method [21] and the flame Mach number in the Baker–Sthrelow–Tang methodology [22].

starting from the definition of the escalation vector and of the escalation radii of each accidental scenario.

4. Escalation caused by fires

4.1. Escalation caused by fire scenarios

It is well known that escalation may be caused by fire scenarios due to:

(i) damage of the secondary unit caused by radiation;
(ii) ignition of flammable vapours at the secondary unit due to direct flame impingement or to the heat of the primary fire.

The escalation radius is dependent on the fire intensity, that may be related to the type of fire scenario, to geometrical parameters (release diameter, pool radius, etc.), and to the inventory involved in the fire. The latter is in turn related to the equipment item at which the fire takes place and to the fire prevention measures introduced in equipment design. The estimation of fire intensity starting from the previous parameters is a standard procedure in the consequence assessment of fire scenarios within conventional QRA studies [23]. Thus, the intensity of the escalation vector of each fire scenario may be calculated estimating the distance at which the radiation thresholds reported in Table 1 are obtained. Inherent safety may be achieved reducing the escalation radius and/or limiting the possible escalation effects of fires.

In the chemical and process industry, fires are the more frequent accidental event. Consequently, relevant efforts are usually addressed to the reduction of fire hazards, mainly by avoiding the presence of ignition sources and installing mitigation devices. A number of well-known active and passive systems for fire prevention are typically installed in process plants. The strategies and the details of fire prevention and fire fighting measures are widely discussed in the literature (e.g. see [16,24,25] and references cited therein) and are not reported here for the sake of brevity. However, it is important to remark that several alternative actions may be considered in order to apply an inherent safety approach to the prevention of escalation events caused by fires. The more effective are related to the *substitution*, *intensification* and *moderation* guidewords: using non flammable substances, reducing stored quantities, and shifting to less hazardous storage conditions (in general, lower pressure and lower temperature) are well known measures aimed to the reduction of fire hazard. If these are not applicable or, more frequently, if after the application of these measures an escalation vector is still present, inherent safety may be obtained by *limitation of effects*. The limitation of the effects of the escalation vector should be related to the vulnerability of the possible target equipment. This principle suggests two categories of actions: (i) the proper design of the possible targets of escalation events (e.g. buried or mounded tanks are not exposed to external fire radiation) and (ii) the adoption of appropriate safety distances. A specific study dedicated to the analysis of the behaviour and to the assessment of the time to failure of atmospheric and pressurized vessels exposed to fires [11,18,26] evidenced that safety distances are strongly dependent on target vulnerability and on the primary fire scenario. Nevertheless, conservative envelope correlations were obtained for the time to failure of different categories of unprotected vessels with respect to the radiation intensity and the radiation mode. The primary fire scenario is therefore the key element both in the evaluation of the escalation vector and in the assessment of the safety distances for limitation of effects. Thus, the inherent safety actions applicable to the fire scenarios listed in Table 1 will be separately discussed in the following sections.

4.2. Fireballs

A fireball is a diffusive combustion of a gas cloud originated by the sudden release of relevant amounts of pressurized and/or liquefied gases, followed by ignition. Several models are available for the calculation of the maximum flame diameter, of the duration of the fire and of radiation intensities [15,27]. The fireball diameter and duration mainly depend on the mass released after the vessel rupture, which is usually (and conservatively) assumed to be equal to the whole vessel content.

The fireball duration is usually limited (in general of the order of 5–20 s), and this should be taken into account in order to define the possibility of escalation. However, it must be recalled that the limited duration of the fireball scenario excludes the possibility of active protection systems in the prevention of escalation.

It is well known that the fireball scenario is typical of flammable liquefied pressurized gases, although it is also possible for any flammable pressurized gas. Thus, an inherently safer condition with respect to escalation would be obtained by eliminating this scenario, by changing operating conditions (e.g. introducing low pressure cryogenic storage), or by reducing the escalation radius by limiting vessel inventory.

The results of a study concerning the behaviour of unprotected atmospheric and pressurized vessels exposed to fireball radiation evidenced that the possibility of escalation due to radiation may be reasonably excluded for pressurized vessels, even in the absence of passive protections [11,18]. With respect to atmospheric equipment, escalation resulted as well unlikely, unless a direct engulfment in the flame takes place.

Fig. 1 reports the escalation radius with respect to inventory and mass released from a pressurized vessel containing propane. The plot was obtained using the simple approach recommended by CCPS [15] for fireball radius calculation. In Fig. 1, the separation distances necessary to prevent escalation involving atmospheric equipment are given. Indeed, the upper region is the inherently safer zone, where escalation may reasonably be excluded. On the other hand, the lower region corresponds to the zone where passive protection measures may be required to prevent escalation due to fireball radiation. The figure also evidences the influence of actions towards process *intensification* (thus leading to lower process inventories) on safety distances.

4.3. Jet fires

A jet fire is a turbulent flame that may have a relevant length in the direction of the release. It is well known that escalation is

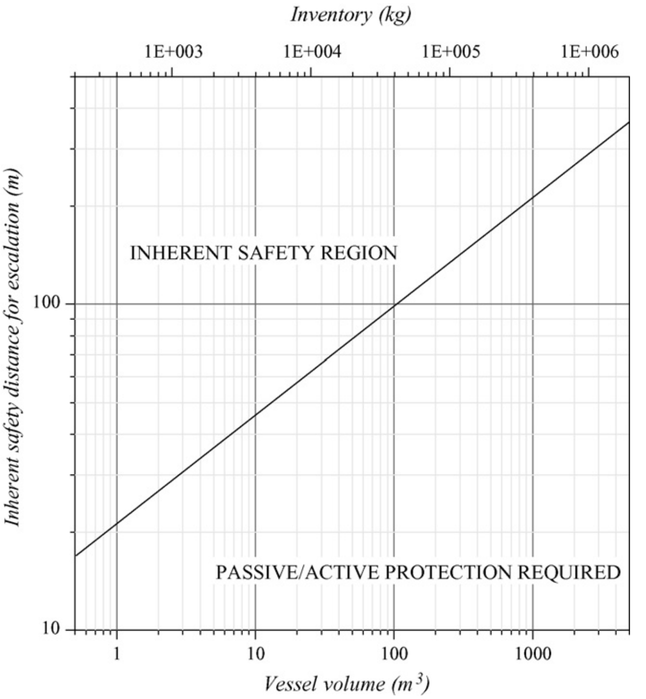

Fig. 1. Escalation radius for fireballs with respect to inventory (=mass released) and to the corresponding volume of a propane vessel, filling level = 80%.

always possible when any fire engulfs or impinges target equipment. Indeed, recent experimental studies confirmed that even in the presence of active mitigation systems (e.g. water deluges) and passive protections (e.g. thermal insulation), hot spots may cause the failure of vessels exposed to jet fires [28–30]. As a consequence, the escalation radius depends mainly on the maximum flame length, i.e. the maximum distance from the flame source at which the damage of the more vulnerable category of unprotected vessels results credible. As shown in Table 1, the escalation vector may be obtained adding a constant distance to the jet flame length, below which the radiation intensities are unlikely to cause an escalation due to vessel damage. Horizontal directions of the flame should be conservatively assumed.

Figs. 2–4 may be used for a preliminary conservative assessment of flame length for the three more common types of jet fires that are likely to take place in industrial installations: (i) jet fires from compressed flammable gases at high pressure and ambient temperature; (ii) jet fires from liquefied gases at ambient temperature (e.g. propane and butane in storage conditions); (iii) jet fires from hot saturated liquids (e.g. butane or higher molecular weight hydrocarbons in process conditions, as in distillation columns or in pressurized batch reactors). The plots were obtained applying the Shell jet fire model [31], extensively described in the TNO “yellow book” and by Lees [15,27]. The model was applied to different hydrocarbons and considering different wind velocities, selecting the worst case results.

An inherently safer condition with respect to escalation may be obtained eliminating or reducing the escalation radius, and/or limiting the possible effects of the event. Pressure is the main operating variable that influences the flame length and thus the escalation possibility of a jet fire. As shown in Figs. 2–4, the flame length is highly dependent on the internal pressure. Temperature may also be an important factor in the case of saturated liquids, since it influences the vapour pressure and thus the severity of the jet fire. However, if the application of the *moderation* guideword to these process variables is not possible or not sufficient to eliminate the hazard, the *limitation of effects* guideword may lead to an effective reduction of the escalation hazard.

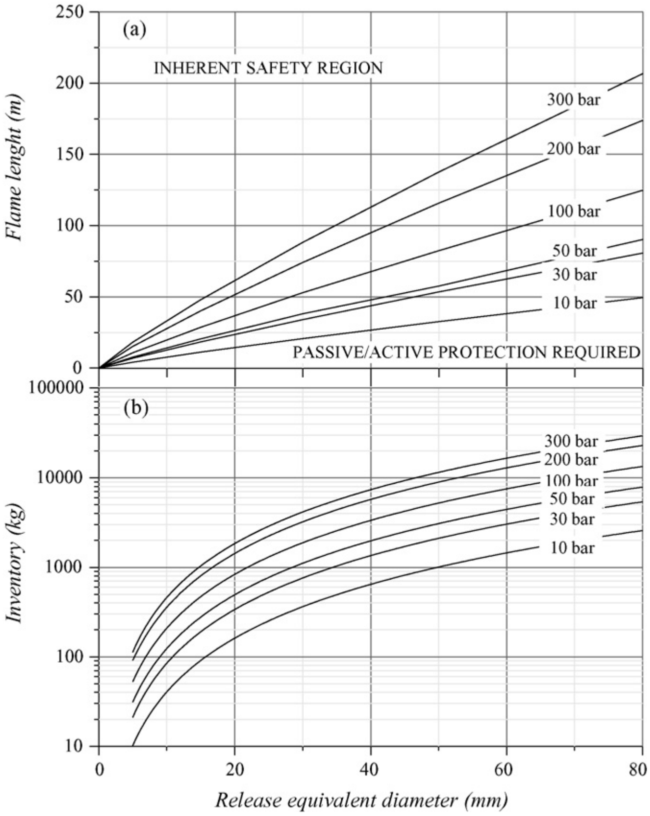

Fig. 2. Jet-fire flame length (a) and critical vessel inventory for a 15 min release (b) with respect to the equivalent release diameter for hydrocarbon gases at ambient temperature and high pressure. To obtain safety distances, 50 m for atmospheric vessels and 25 m for pressurized vessels should be added to the flame length.

Escalation due to jet fire heat radiation only (i.e. target equipment is not directly impinged) is dependent both on radiative heat load and on the duration of the flame exposure. Several criteria were proposed to identify critical heat radiation values for jet fires. In a recent study, the minimum heat loads leading to vessel failure in a critical time (15 min) were estimated for several vessel categories [11,18]. Figs. 2(b), 3(b) and 4(b) report the value of the inventory of the primary vessel above which the jet fire duration is at least equal to the critical time assumed for secondary vessel failure. Thus, the plots in Figs. 2–4 allow on one hand the identification of the range of release diameters that may lead to escalation given the inventory of the primary vessel and the distance of the secondary target. On the other hand, given the maximum credible release equivalent diameter, the data reported allow

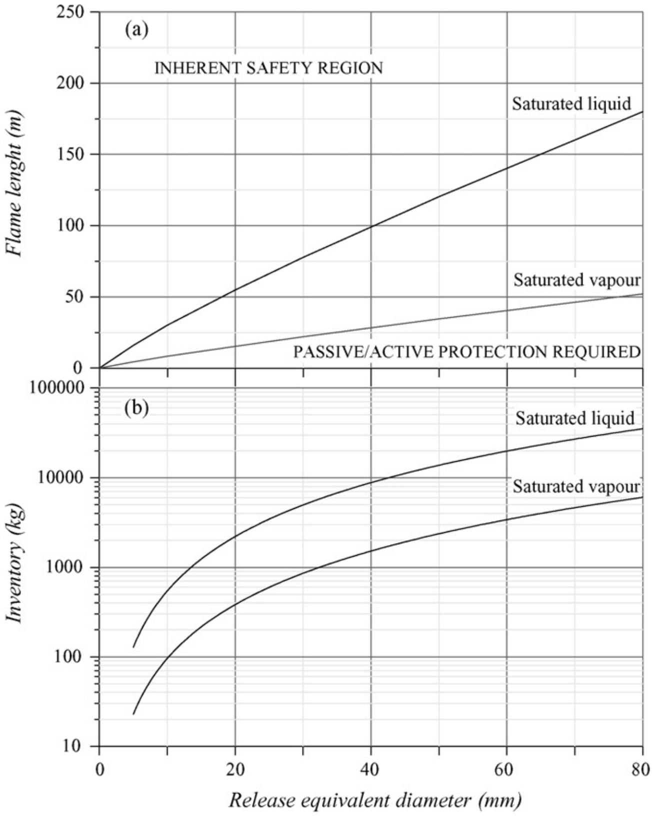

Fig. 3. Jet-fire flame length (a) and critical vessel inventory for a 15 min release (b) with respect to the equivalent release diameter for propane releases at ambient temperature. To obtain safety distances, 50 m for atmospheric vessels and 25 m for pressurized vessels should be added to the flame length.

the identification of the safety distances for the limitation of effects with respect to different categories of secondary vessels (Figs. 2(a), 3(a) and 4(a)), and the critical inventory of the primary vessel, above which the duration of the jet fire may be sufficient to cause the failure of the secondary target (Figs. 2(b), 3(b) and 4(b)).

Thus, the upper sections of Figs. 2(a), 3(a) and 4(a) identify the inherently safe regions of secondary targets with respect to escalation caused by jet fires: escalation involving a secondary target falling in this region may be considered unlikely. On the other hand, the lower region of the figures identifies the region where passive and active protection systems are required. Targets having a distance from the primary event that falls inside this region are not inherently safe, and require the installation of protections to prevent domino accidents, in particular in existing plants. Similarly, Figs. 2(b), 3(b) and 4(b) point out that an inherently safer region may be identified on the basis of vessel inventory with respect to the possibility of generating primary jet fires resulting in escalation.

Finally, it must be recalled that the safety distances obtained from the data in Figs. 2–4 and in Table 2 refer to unprotected vessels, thus may be considered as conservative values. The use of active (fire sprinklers, water curtains) and, preferably, of passive (thermal insulation, fire walls) protection systems may greatly improve the resistance of the secondary targets, thus lowering the probability of escalation.

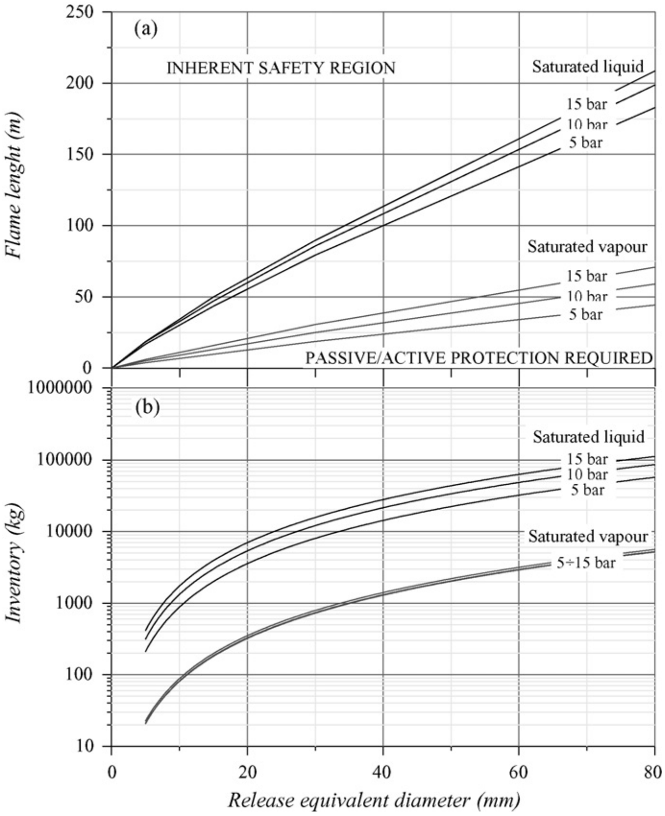

Fig. 4. Jet-fire flame length (a) and critical vessel inventory for a 15 min release (b) with respect to the equivalent release diameter for hot saturated hydrocarbons at high temperature and pressure. To obtain safety distances, 50 m for atmospheric vessels and 25 m for pressurized vessels should be added to the flame length.

4.4. Pool fires

A pool fire is formed by the combustion of the vapour from a pool of a flammable liquid [27,32]. Escalation caused by pool fires is mainly due to the full engulfment of a vessel in the flames, although the stationary radiation caused by the fire may as well cause the failure of a secondary vessel. Therefore, the escalation radius depends on the area of the pool fire and on the distance from the border of the pool fire. As in the case of jet-fires, the escalation radius was assumed as the maximum distance from the flame at which the damage of the more vulnerable category of unprotected vessels (atmospheric storage tanks) is credible. The parameters that mainly influence the escalation radius are two: (i) the surface emissive power of the flame, that in turn depends by the characteristics of the flammable substance that forms the pool and (ii) the pool dimension or equivalent diameter. Pool fires in fixed installations are most likely to take place inside the catch basin of the primary vessel at which a loss of containment takes place. Thus, in the case of severe pool fires, the pool extension may be often coincident with that of the catch basin, if present. In the case of unconfined pool fires, the maximum pool diameter should be considered. A number of literature models are available for the calculation of pool fire radiation and of pool fire radius (e.g. see [15,16,27] and references cited therein), and may be used for the assessment of the escalation radius. The results reported in the present study were obtained using the models reported in the TNO "yellow book" [27]. As shown in Table 2, the escalation radius may be estimated as the maximum radius of the liquid pool added of a constant distance over which the radiation intensity falls below the threshold values discussed above.

Inherently safer conditions with respect to escalation are obtained also in this case eliminating the escalation vector or reducing the escalation radius, and/or limiting the possible effects of the event. Also in this case, provided that the substitution guideword is not applicable, the *moderation* guideword applied to temperature and pressure would be effective at least in the reduction of the ignition probability. However, quite often the liquid forming a pool fire is above the flash point even at ambient conditions. Thus, the *limitation of effects* guideword seems to identify the only effective actions that may lead to the reduction of the escalation hazard.

As for jet-fires, escalation possibility depends on the radiation intensity and on the fire duration. Table 2 shows the safety distances from flame border for pool fire damage of atmospheric and pressurized vessels derived from a previous study [11,18]. In the case of pool fires, the safety distances may be expressed as the distance from the pool border. The presence and a proper design of the catch basins are thus important elements towards inherent safety. Individual catch basins having a high height/surface ratio lead to an inherently safer layout with respect to escalation. This is evidenced in Fig. 5, where the critical inventory for escalation is reported. The figure shows the inventory involved in the pool fire required to obtain a pool fire duration equal to the critical time for escalation (15 min) as a function of the pool surface and of the burning rate of the liquid. The critical inventory was calculated on the basis of literature data for the burning rate [27], assuming a constant area of the pool.

The plot shows conservative results for two categories of flammable liquids: "heavy liquids", having a burning rate lower than 0.055 kg/m^2 s (e.g. kerosene, fuel oil, etc.), and "light liquids", having a burning rate higher than 0.055 kg/m^2 s (e.g. gasoline, *n*-heptane, etc.). Pool fires involving liquefied gases are characterized by higher burning rates (typically higher than 0.078 kg/m^2 s), thus the results obtained for "light" liquids are sufficiently conservative to be extended also to these compounds.

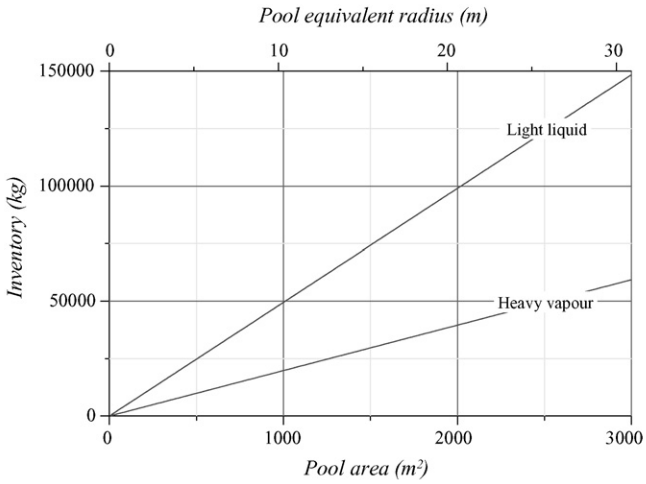

Fig. 5. Critical inventory for pool fire scenarios with respect to catch basin surface area and equivalent radius. To obtain safety distances, 50 m for atmospheric vessels and 15 m for pressurized vessels should be added to catch basin equivalent radius.

As in the case of jet fires, also in Fig. 5 the section below the solid lines may be considered an inherently safer region for the inventory of the primary vessel as a function of separation distances. On the other hand, the upper region of the plot is that where passive or active protection of possible targets is required. Thus, in particular in the case of existing plants, the installation of passive (e.g. thermal insulation, fire walls) or active systems (e.g. sprinklers, fire curtains) are required to protect the possible target vessels that fall in these zones with respect to primary pool fire scenarios.

5. Escalation caused by overpressure

5.1. Escalation caused by overpressure scenarios

It is well known that escalation may be triggered by pressure waves as a consequence of the damage of secondary vessels containing hazardous substances. The interaction of pressure waves with process equipment is rather complex, involving pressure wave reflection, flow separation, drag forces, and being influenced by the mechanical characteristic of equipment. However, in industrial explosions (thus excluding the explosions due to condensed high explosives or nuclear weapons), damages to equipment in the far-field are mainly related to the incident peak overpressure and to the positive impulse, while the effects of the drag forces (the explosion wind) may be neglected. Furthermore, many literature approaches relate the damage intensity to the maximum peak static overpressure only [11,14,18]. As a matter of fact, pressure-impulse data related to equipment damage are lacking and theoretical difficulties arise in the description of the interaction unless ideal and unrealistic blast waves are considered. Thus, a conservative assumption often used in the design criteria is to assume that the equipment damage is mainly related to the peak overpressure. Following this approach, the escalation vector due to overpressure is related to overpressure thresholds above which the damage of the more vulnerable equipment items may be expected. Table 1 shows the threshold values derived from a previous study [11,18] for different overpressure scenarios. Blast waves from confined explosions, i.e. gas, vapour and dust explosions or runaway reactions within equipment, producing blast waves propagating in the external atmosphere through vents and openings (even formed for the partial failure of shell) were not included in the discussion due to low distances run by low-energy blast waves (see Forcier and Zalosh analysis [33] and [11] for further details) and considering the more severe damage usually associated to the contemporary fragment projection and/or jet fire formation.

The escalation radius for each overpressure scenario may be calculated estimating the distance at which the specific threshold reported in Table 1 is obtained by the use of standard literature models [15,23,27]. Inherent safety may be obtained reducing the escalation radius and limiting the possible escalation effects that may be triggered by the blast wave.

A number of active safety devices (alarms, safety interlock system, automatic remote safety valves, water curtains, foam sprinklers) and passive systems (pressure release valves, vents, etc.) are used to prevent the different explosion scenarios possible in the process industry (e.g. see [14,16,24] and references cited therein). An inherent approach may however suggest several possible actions, related to the *substitution*, *intensification* and *moderation* guidewords: using non-flammable or non-volatile substances, reducing stored quantities, and shifting to less hazardous operating conditions (in general, lower pressure and lower temperature that may limit the explosion energy and/or the amount of substance forming a vapour cloud). As in the case of fires, if after possible actions compatible with the process under examination an escalation vector is still present, the *limitation of effects* guideword may suggest further actions leading to an inherently safer plant layout with respect to escalation. However, the features of the primary scenario generating the blast wave are of fundamental importance in the identification of the more effective actions. These will be thus separately discussed in the following for the explosion scenarios listed in Table 1.

5.2. Vapour cloud explosion (VCE)

When partially confined or unconfined gas or vapour cloud explosions (VCE) occur as a primary scenario, large destruction is usually expected in the surroundings due to the heat effects and the blast wave which characterize this scenario. Provided that heat radiation is unlikely to produce damage to equipment, escalation effects are usually caused by the mechanical damage followed by loss of containment of target equipment. The escalation radius is thus related to the distance at which the blast wave peak overpressure equals the threshold value in Table 1. This may be calculated by the standard approach used in QRA [15,23], estimating the explosion energy and evaluating the "strength" of explosion on the basis of plant layout and fuel reactivity, i.e. the "strength factor F" for the multi-energy method (MEM, see [21,34]), or the flame Mach number, M_f, in the Baker–Sthrelow methodology (BS, see [22] for details).

Fig. 6 shows the escalation radius with respect to the estimated explosion energy, and the correspondent fuel air mass and volume, for two categories of target equipment (atmospheric vessels and pressurized equipment). The escalation radius was defined as the threshold distance with respect to the fuel-air cloud border at which damage is expected for the category of process equipment more likely to trigger escalation events (pressurized vessels). The plot was obtained using the threshold values for escalation given in Table 2, starting from the following assumptions: (i) the cloud was considered hemispherical (release at ground level), homogeneous and at stoichiometric concentration; (ii) a mean combustion energy typical of air/hydrocarbon mixtures was assumed (3.6 MJ/m^3 of mixture); (iii) the strength factor and the flame Mach number for the VCE were assumed as for intense deflagration ($F > 7$ and $M_f > 3.5$). The latter assumption is justified comparing the energy-scaled plots for the propagation of blast waves in the region where escalation effects are of concern: either by the MEM or by the BS approaches, no differences may be observed for more intense explosions (i.e. the peak pressures are superimposed whatever is the initial pressure). The mass–volume–energy conversion was obtained considering the total combustion of fuel to water and carbon dioxide.

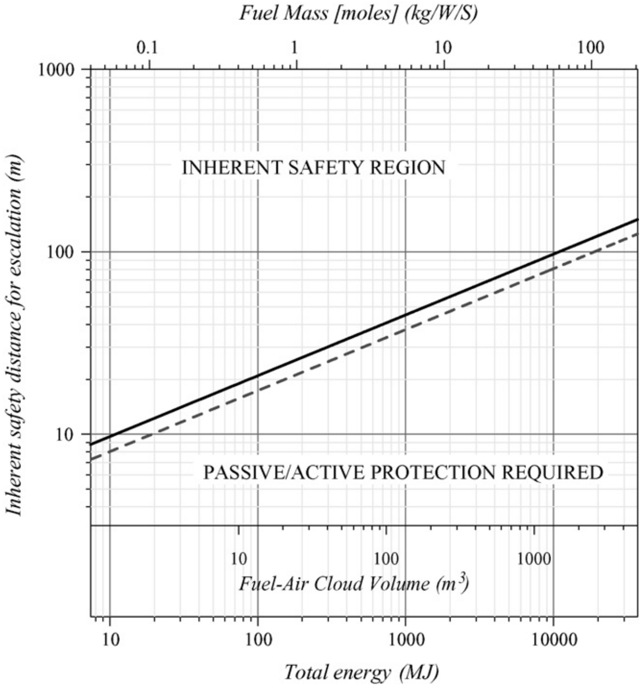

Fig. 6. Escalation radius and inherent safety distances for escalation effects on equipment loaded by VCEs generated by the more common hydrocarbons. (W = molecular weight; S = stoichiometric concentration expressed in volume percent of fuel air mixture). Distances should be calculated from the flammable cloud border. For more reactive fuels a factor 1.2 should be used to correct energy values based on cloud volume. Target vessel—(i) solid line: pressurized; (ii) dashed line: atmospheric.

Quite obviously, several actions may be identified to improve inherent safety by the minimization of the escalation radius. This may be obtained decreasing the explosion energy and the explosion strength. Explosion energy may be reduced by the *substitution* of process substances with less volatile compounds or by the *moderation* of operating conditions (e.g. using lower pressure and temperature), thus minimizing the total fuel available for the explosion. On the other hand, the explosion strength may be reduced again by the *substitution* of substances with less reactive compounds, e.g. gases or vapours with minor specific combustion energy, and/or minor laminar burning velocity. However, also the *limitation of effects* may also be effective in reducing the explosion strength, by a proper layout design, aimed to the reduction of the geometrical congestion and confinement, which strongly affect the violence of explosions.

If an escalation vector is still present after the application of the above-discussed actions that resulted compatible with the process under examination, the *limitation of effects* guideword indicates the necessity of adopting appropriate safety distances in layout design. As in the case of fires, in Fig. 6 the section above the solid lines may be considered as the zone of inherent safety separation distances with respect to the flammable cloud border. On the other hand, the lower region is that where passive protections, as barricades and/or blast wall, should be considered for application.

5.3. Boiling liquid expanding vapour explosion (BLEVE)

The catastrophic failure of a vessel containing a pressurized liquefied gas, due to the external heating of vessel wall or to other causes of overpressure, may result in a sudden evaporation of the vessel content and in the formation of a blast wave. The conditions necessary for the blast wave formation, usually related to a superheat temperature, as well as the procedure for the evaluation of the explosion energy are widely discussed in the literature [15,26]. In the present section, escalation effects triggered by the blast wave originated from the sudden expansion of the vessel content are only considered.

As for vapour cloud explosion, the escalation radius may be defined as the distance from the explosion centre at which damage is expected for pressurized equipment and vessels (see Table 1). A preliminary estimate of the escalation radius may be obtained from Fig. 7, which reports the inherent safety radii for either atmospheric or pressurized target equipment vessels with respect to the explosion energy, starting from the explosion of typical propane vessel with failure pressure of 20 bar, and 80% filling level, as conservative choice. The explosion effects have been calculated from the assumption that the expanding boiling liquid is at the superheat temperature (about 326 K for pure propane) at the moment of failure of vessel shell. Keeping constant the filling level and the initial and final thermodynamic states (corresponding to the expansion from 20 bar to the atmospheric pressure), the correlation of the escalation radius with respect to vessel volume and inventory is also obtained, as the boiling liquid and the vapour specific energies can be scaled to any amount or vessel volume. Eventually, as the pressure threshold values for target equipment and the total available energy for the explosion of both expanding liquid and vapour are known, the effective safety distances are easily obtained (see the methodology given in [15], where specific energy-scaled plot for the evaluation of peak overpressure are also given). To this regard, it’s worth considering that the results obtained for propane are conservative with respect to butane and LPG, as detailed in [26].

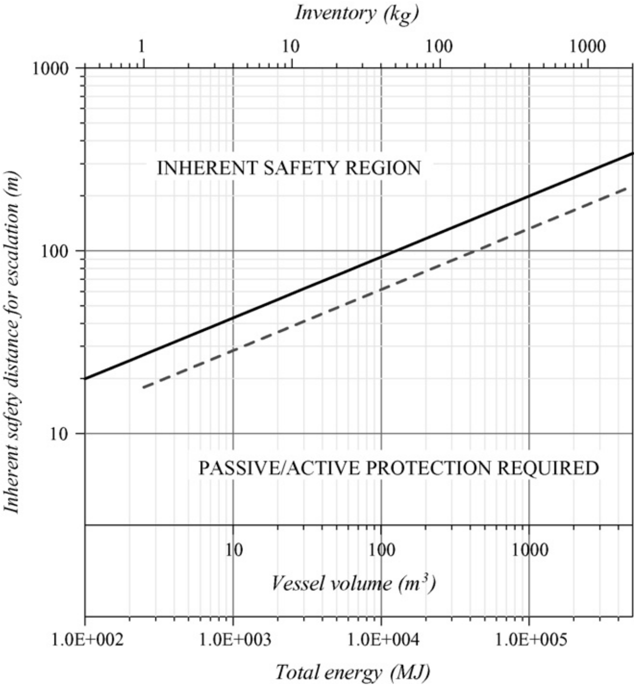

Fig. 7. Escalation radius and inherent safety distances for escalation caused by blast waves produced by BLEVEs with respect to the total explosion energy and to the corresponding volume and mass of a propane vessel having an 80% filling level. Distances must be calculated from the vessel border. Target vessel—(i) solid line: pressurized; (ii) dashed line: atmospheric.

Several actions may be considered in order to eliminate or reduce the escalation radius. The *intensification* and *moderation* guidewords suggest to reduce the vessel volume or to shift to less hazardous storage conditions (e.g. use of lower storage pressure and temperature). If these actions are not applicable to the process of interest, inherent safety may be obtained by the *limitation of effects* guideword. The analysis of Fig. 7 evidences that also in this case the upper region of the plot identifies the zone of inherent safety, where no damage to secondary equipment is expected to be caused by the blast wave. The lower zone of the plot is the region where protection measures are required. As in the case of VCE, the more effective protections are blast walls or barricades, or vessel mounding. However, since the BLEVE is likely to take place after a few minutes of heat loading, active systems as vessel dumping may be effective in the prevention of escalation following the damage of the secondary equipment.

5.4. Mechanical explosion

Mechanical failure of an equipment item, followed by the sudden expansion of the compressed gas phase may result in the generation of a blast wave, which may trigger escalation events. The explosion energy may be estimated by standard literature approaches on the basis of vessel volume and of conservative assumptions for energy calculation, e.g. by using the Brode equation [15,16]. In particular, following conventional approaches, two categories may be introduced for vessel failure pressure [35,36]: low strength equipment behaviour (failure pressure of 0.03 bar g) and high strength equipment behaviour (failure pressure higher than 1 bar g). Also in this case, the escalation vector may be defined as the distance from the explosion centre at which damage is expected for the more vulnerable target category (see Table 1). This is plotted in Fig. 8 with respect to the total explosion energy. The escalation radius may be reduced following the *moderation* guideword, thus considering the adoption of lower operating pressures. Fig. 8 also reports the inherent safety threshold distances for pressurized and atmospheric equipment, whose application is suggested by the *limitation of effects* guideword. Also in this case, the lower region of the plot identifies the zone where passive protection

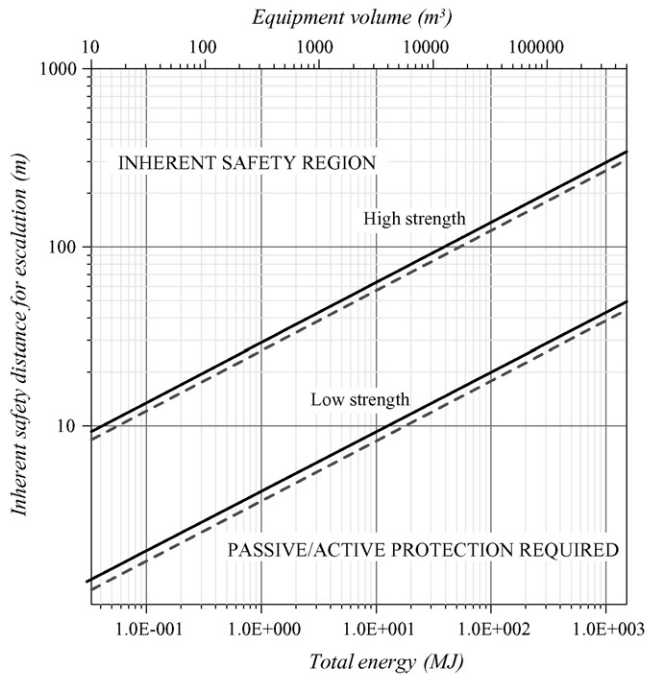

Fig. 8. Escalation radius and inherent safety distances for escalation caused by mechanical explosion of high strength and low strength equipment/enclosures with respect to total explosion energy. Distances must be calculated from the vessel border. Target vessel—(i) solid line: pressurized; (ii) dashed line: atmospheric.

systems, as blast walls or barricades, are required to prevent escalation.

6. Escalation caused by fragments

Fragment projection is among the more frequent causes of domino effect in industrial accidents. The primary scenarios that are likely to generate this escalation vector are BLEVEs mechanical and confined explosions. The escalation radius may be defined as the maximum fragment projection distance for the primary scenario of interest. Several approaches were proposed in the literature for the assessment of fragment projection distances and of damage to process equipment following fragment impact [14,37,38]. In all these approaches, the fragment projection distances are dependent on the initial explosion energy. In many scenarios involving the burst of pressurized vessels, the projection distances may be higher than 500 m. This is in accordance with the experience from past accidents, in which fragment projection up to 800 m was reported [39,40]. Therefore, in the framework of the identification of actions towards inherent safety with respect to escalation events caused by fragment projection, the *limitation of effects* guideword has a limited utility.

As discussed above, no safety distance of practical use in layout design may be identified for fragment projection on a deterministic basis. Actions towards inherent safety should be oriented to the elimination of the escalation vector or to the reduction of its intensity. The *substitution*, *intensification* and *moderation* guidewords may lead to the identification of the more appropriate actions. Among these are: the introduction of vessel having lower volumes and the use of lower operating pressures, that contribute to the reduction of the available explosion energy; the substitution of vessel technology (e.g. the shift from fixed roof to floating roof tanks), that may reduce the possibility of confined explosions leading to fragment projection. However, in most applications, the above listed actions towards inherent safety are effective in the reduction of the escalation radius, but often not sufficient for the complete elimination of the possibility of fragment projection. Thus, conventional actions based on passive protection either of the primary vessel (venting devices, thermal insulation) or of the critical targets (blast walls, mounding, etc.) should be also applied to prevent the escalation due to the projection of fragments.

7. Conclusions

The possible prevention of domino accidents by an approach based on inherent safety was explored. The starting point of the study was the definition of escalation vectors to evaluate the damage possibility of equipment due to a primary accidental event.

Escalation radii may be used to assess the effectiveness of escalation prevention actions, because decreasing these values corresponds to an increase in the inherent safety of the installation and to a corresponding reduction of the cost of safety actions based on active or passive protections. It should be noted that the variation of escalation radii may be obtained by any of the classical inherent safety guidewords. For instance, reduction of inventory is the main issue for the total energy available for explosions and may be applicable either for existing or during early-design layout optimisation phases of process plants.

The detailed analysis of possible escalation scenarios based on escalation vectors allowed the identification of a number of actions to improve the inherent safety with respect to domino accidental events.

In the prevention of escalation due to fires and to blast waves, simple rules of thumbs were obtained, based on plots for the preliminary assessment of safety distances and for the critical vessel inventories.

The results obtained point out that the integration of inherent safety criteria with the conventional passive and active protections seems a promising route for the prevention of severe domino accidental scenarios in chemical and process plants.

References

[1] D.C. Hendershot, Inherently safer chemical process design, J. Loss Prevent. Process Ind. 10 (1997) 151.

[2] D. Edwards, Are we too safe for inherent safety? Trans. IChemE, Part B: Process Safety Environ. Protect. 81 (2003) 399.

[3] T.A. Kletz, Inherently safer design—its scope and future, Trans. IChemE, Part B: Process Safety Environ. Protect. 81 (2003) 401.

[4] J.C. Mecklenburgh, Process Plant Layout, George Goodwin, London, 1985.

[5] D.W. Edwards, D. Lawrence, Assessing the inherent safety of chemical process routes: is there a relation between plant cost and inherent safety? Trans. IChemE, Part B: Process Safety Environ. Protect. 71 (1993) 252.

[6] A. Heikkilä, M. Hurme, Equipment safety as part of inherent safety index for preliminary process design, in: Proceedings of the Ninth International

Symposium on Loss Prevention and Safety Promotion in Process Industries, Barcelona, 1998.

[7] G. Koller, U. Fischer, K. Hungerbuhler, Assessing safety, health, and environmental impact early during process development, Ind. Eng. Chem. Res. 39 (2000) 960.

[8] F.I. Khan, T. Husain, S.A. Abbasi, Safety weighted hazard index (SweHI): a new user-friendly tool for swift yet comprehensive hazard identification and safety evaluation in chemical process industries, Trans. IChemE 79B (2001) 65.

[9] C. Palaniappan, R. Srinivasan, R. Tan, Expert system for the design of inherently safer processes, Ind. Eng. Chem. Res. 41 (2002) 6698.

[10] F.I. Khan, R. Sadiq, P.R. Amyotte, Evaluation of available indices for inherently safer design options, Process Safety Prog. 22 (2003) 83.

[11] V. Cozzani, G. Gubinelli, E. Salzano, Escalation thresholds in the assessment of domino accidental events, J. Hazard. Mater. 129 (2006) 1.

[12] G.W. Carrithers, A.M. Dowell III, D.C. Hendershot, It's never too late for inherent safety, in: Proceedings of the International Conference and Workshop on Process Safety Management and Inherently Safer Processes, Orlando, FL, American Institute of Chemical Engineers, New York, 1996.

[13] F.I. Khan, P.R. Amyotte, Inherent safety in offshore oil and gas activities: a review of the present status and future directions, J. Loss Prevent. Process Ind. 15 (2002) 279.

[14] W.E. Baker, P.A. Cox, P.S. Westine, J.J. Kulesz, Explosion Hazards and Evaluation, Elsevier, Amsterdam, 1983.

[15] CCPS, Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs, AIChE Edition, CCPS, New York, 1994.

[16] F.P. Lees, Loss Prevention in the Process Industries, II ed., Butterworths/Heinemann, Oxford, 1996.

[17] E. Salzano, V. Cozzani, Blast wave damage to process equipment as a trigger of domino effects, in: Proceedings of the 19th Annual CCPS International Conference, AIChE, New York, 2004, p. 101.

[18] V. Cozzani, G. Gubinelli, E. Salzano, Criteria for the escalation of fires and explosions, in: Proceedings of the Seventh Process Plant Safety Symposium, AIChE, New York, 2005, p. 225.

[19] V. Cozzani, E. Salzano, Threshold values for domino effects caused by blast wave interaction with process equipment, J. Loss Prevent. Process Ind. 17 (2004) 437.

[20] E. Salzano, V. Cozzani, A fuzzy set analysis to estimate loss intensity following blast wave interaction with process equipment, J. Loss Prevent. Process Ind. 19 (2006) 343.

[21] A.C. Van den Berg, The multi-energy method—a framework for vapor cloud explosion blast prediction, J. Hazard. Mater. 12 (1985) 1.

[22] M.J. Tang, Q.A. Baker, A new set of blast curves from vapour cloud explosion, Process Safety Prog. 18 (1999) 235.

[23] P.A.M. Uijt de Haag, B.J.M. Ale, Guidelines for Quantitative Risk Assessment (Purple Book), Committee for the Prevention of Disasters, The Hague, The Netherlands, 1999.

[24] D.P. Nolan, Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical and Related Facilities, Noyes Publications, New Jersey, 1996.

[25] A.E. Cote (Ed.), Fire Protection Handbook, 19th ed., National Fire Protection Association, Quincy, MA, 2003.

[26] E. Salzano, B. Picozzi, S. Vaccaro, P. Ciambelli, The hazard of pressure tanks involved in fires, Ind. Eng. Chem. Res. 42 (2003) 1804.

[27] C.J.H. Van Den Bosh, R.A.P.M. Weterings, Methods for the Calculation of Physical Effects (Yellow Book), Committee for the Prevention of Disasters, The Hague, The Netherlands, 1997.

[28] L.C. Shirvill, Efficacy of water spray protection against propane and butane jet fires impinging on LPG storage tanks, J. Loss Prevent. Process Ind. 17 (2004) 111.

[29] T.A. Roberts, Directed deluge systems designs and determination of the effectiveness of the currently recommended minimum deluge rate for the protection of LPG tanks, J. Loss Prevent. Process Ind. 17 (2004) 103.

[30] T.A. Roberts, Linkage of a known level of LPG tank surface water coverage to the degree of jet fire protection provided, J. Loss Prevent. Process Ind. 17 (2004) 169.

[31] G.A. Chamberlain, Developments in design methods for predicting thermal radiation from flares, Chem. Eng. Res. Des. 65 (1987) 299.

[32] CCCPS, Guidelines for Chemical Process Quantitative Risk Analysis, II ed., AIChE, New York, 2000.

[33] T. Forcier, R. Zalosh, External pressures generated by vented gas and dust explosions, J. Loss Prevent. Process Ind. 13 (2000) 411.

[34] J.B.M. Eggen, GAME: development of guidance for the application of the multi-energy method, health and safety executive, Contract Res. Rep. 202 (1998).

[35] NFPA 68, Guide for Venting of Deflagrations, National Fire Protection Association, Quincy, MA, USA, 2002.

[36] NFPA 69, Standard on Explosion Protection Systems, National Fire Protection Association, Quincy, MA, USA, 1997.

[37] M.R. Baum, The velocity of missiles generated by the disintegration of gas pressurised vessel and pipes, J. Pressure Vessels Techn. 106 (1984) 362.

[38] G. Gubinelli, S. Zanelli, V. Cozzani, A simplified model for the assessment of the impact probability of fragments, J. Hazard. Mater. 116 (2004) 175.

[39] P.L. Holden, A.B. Reeves, Fragment hazards from failures of pressurised liquefied gas vessels, IChemE Symposium Series No. 93, 1985, p. 205.

[40] W.E. Westin, Summary of ruptured tank cars involved in past accidents, Report No. RA-01-2-7, Railroad Tank Car Safety Research and Test Project, Chicago, IL, 1971.