CHEMICAL ENGINEERING TRANSACTIONS
VOL. 31, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti

ISBN 978-88-95608-22-8; **ISSN** 1974-9791
DOI: 10.3303/CET1331132

Domino Effects Related to Explosions in the Framework of Land Use Planning

Ernesto Salzano*[a], Giacomo Antonioni[b], Gabriele Landucci[c], Valerio Cozzani[b]

[a] Istituto di Ricerche sulla Combustione, CNR, Via Diocleziano n.328, 80124 Napoli, Italy.
[b] Dipartimento di Ingegneria Chimica, Mineraria e delle Tecnologie Ambientali, Alma Mater Studiorum - Università di Bologna, via Terracini n.28, 40131 Bologna, Italy
[c] Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Via Diotisalvi n.2, 56126 Pisa, Italy.
salzano@irc.cnr.it

The present study analyses the possible escalation due to the damage of industrial equipment containing hazardous materials loaded by pressure waves produced either by an accidental source as a Vapour Cloud Explosion, or by a voluntary external attack such as the explosion of a TNT charge located nearby the industrial facility. The results obtained evidence the similarities and the differences for the two explosion sources in terms of structural damage, loss of containment and of expected impacts on the population. In particular, a specific vulnerability assessment was carried out defining a case-study in order to evidence the different potential impact of domino effect triggered by internal process causes respect to escalation scenarios caused by external acts of interference.

1. Introduction

A large effort has been addressed in recent years to include domino effects in existing risk assessment methodologies, as extensively described in the technical literature and in specific studies (Salzano and Cozzani, 2005, Salzano and Cozzani 2006, Cozzani et al., 2006, Cozzani et al., 2009). Here, it is worth mentioning that the definition of domino effects includes a specific requirement for the primary accidental scenarios, which have to occur outside the physical boundary of the target industrial system. Furthermore, both primary and target installations are typically characterised by the presence of large amount of hazardous substances, to be released due to structural failures.
This requirement involves far-field effects. Indeed, it has been demonstrated that Vapour Cloud Explosion (VCE) is the most hazardous accidental scenario which may affect industrial installations, while fires are in most cases less hazardous due to the possibility of mitigation by protection systems (Paltrinieri et al., 2009.
Quite clearly, voluntary explosive charges may easily trigger the escalation of destructive scenarios. In this case, however, another option has to be included: the explosive charge may be intended to damage the installation but indirect damages to the target equipment may also occur, being another strategic target located in the proximity of industrial equipment.
The present study analyses the possible escalation due to the damage of industrial equipment containing hazardous materials loaded by pressure waves produced either by an accidental source as a VCE, or by a voluntary explosion as the explosion of a TNT charge located in the proximity of an industrial facility. The results obtained evidence the differences between the two explosion sources in terms of structural damage, in terms of loss of containment and in terms of expected impacts on the population.
In order to evidence the potential impact of voluntary acts of interference and to compare it to domino effect escalation scenarios due to internal process causes, a case-study was defined. A reference industrial installation was considered and a vulnerability assessment was carried out.

Please cite this article as: Salzano E., Antonioni G., Landucci G. and Cozzani V., 2013, Domino effects related to explosions in the framework of land use planning, Chemical Engineering Transactions, 31, 787-792 DOI: 10.3303/CET1331132

2. Domino effects and voluntary attacks: a peak overpressure comparison

Dealing with large-scale industrial explosions in the early-design phase needs strong simplifications on explosion sources, incident pressure and target geometry. Whatever the complexity of the model for the source of the explosion, peak overpressure and total duration (impulse) for a triangular shape are typically the only parameters needed for the analysis of the interaction of explosion waves with industrial equipment. However, accidental explosions are typically dynamic in nature, and complex behaviours are observed in real accidents. Furthermore, design pressure and structural parameters (e.g. natural period) of the target equipment may greatly affect the level of damage experienced by the same structure after the wave-equipment interaction.

In the case of domino effect evaluation, these considerations are further complicated by the necessity of predicting the possible loss of containment from the target equipment, since only specific failure modes are relevant in the perspective of Quantitative Risk Assessment (QRA).

Figure 1 sketches the possible mechanism for domino effect escalation and interaction with security issues. The industrial installation or area (the “Installation”) is the analyzed system. Due to any possible accident scenario in the installation, the “industrial domain” is defined as the maximum distance reached by any possible accidental (industrial) scenario due to fire, or explosion or dispersion. That is indicated as a circle with radius r_{max} and it is normally evaluated by considering the worst case assumptions for industrial failure. The choice of r_{max} is however more consistent if based on Maximum Credible Accident (MCA), i.e. an accident that is within the realm of possibility (probability higher than $1{\cdot}10^{-6}$ 1/y) of having a propensity to cause significant damage (including domino effects) or at least one fatality (Kletz, 2001). Within the industrial domain (e.g., for $r < r_{max}$) domino effect scenarios may occur due internal process causes, thus involving secondary equipment, with the need of a specific assessment for the implementation of safety barriers (Tugnoli et al., 2012) and for land use planning purposes, according to the Seveso directive. If security is of concern, an attack with explosive may occur both in the far-field and within the industrial domain, being either intended to affect the industrial system or being directed to the urban system or any possible non-industrial target, hence indirectly hitting the installation.

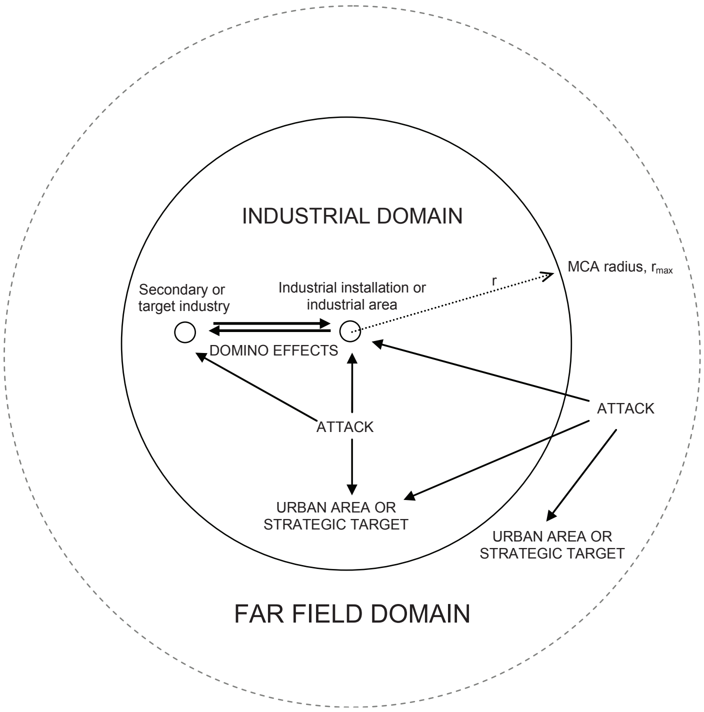

Figure 1. Possible interactions for domino effects and voluntary attacks with industrial domain and its surrounding urban area and/or environment

When far-field attacks are considered, some considerations should be addressed to the mass of explosive needed to reach the target (e.g. the primary installation). Indeed, if considering a minimum overpressure of 7 kPa (Cozzani et al., 2006) as the conservative threshold value for structural damage to process equipment, whatever the primary explosion in terms of duration, and assuming TNT as reference explosive, we can evaluate by the inverse problem the minimum amount of TNT needed with respect to the effective distance for the propagation of shock wave with that intensity, and compare it with r_{max}, by using the well-known mass-scaled plot for point-source explosives (Lees, 1996). This evaluation is plotted in Figure 2, where it is clear that the mass of explosive needed for even such conservative pressure value is absolutely out of reach of terrorist attack for distances higher than about 250 m, for which 2t of TNT are needed. This value can be further limited if considering that the explosive strength is generally evaluated by considering a flat, desert system, which is not the typical situation when either indirect or direct actions are considered. Indeed, buildings, plant walls, urban environment or in many cases the local orography may protect the installation from attack. Eventually, being the industrial domain as the area with $r<r_{max}$ and the near field as $r<<r_{max}$, it can be derived that attacks with explosives are unlikely to produce structural damage to industrial installation in the far-field. The industrial installation is inherently safe for distance greater than 250 m with respect to explosives if loss of containment is considered. This value is absolutely compatible with typical value for VCEs and other typical industrial phenomena.

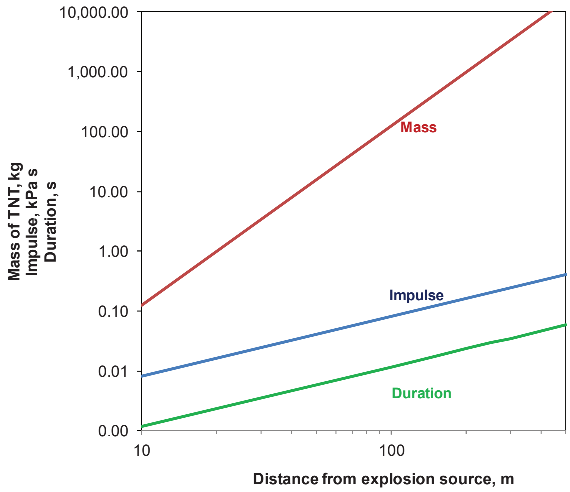

Figure 2. The minimum mass of TNT (kg) needed for the structural damage of industrial equipment, and the correspondent impulse (kPa s) and duration (s), with respect to the distance between the point-source explosion and the installation

3. Domino effects and voluntary attacks: an impulse-based comparison

The use of peak overpressure as the main parameter for the discussion of domino effects and point-source explosions involve a strong simplification of the physical scenario. Another essential input for the analysis of damage is indeed the positive impulse, which is related to the time duration of the shock wave, given the peak pressure.

A typical approximation for pressure (shock wave) is the triangular shape. VCEs last usually 100-200 ms, or more, whereas explosive charges have very short duration and may considered as shock pulse with zero rise time. This difference is essential for the shock wave interaction with industrial equipment, as the ratio of total duration of the explosion (t_d) with the natural period of the structural element (T) identifies the explosion regime, and consequently the level of damage.

Following classical definition (Bowerman et al., 1992), the static regime occurs for $t_d/T > 2$ whereas impulsive regime occurs for $t_d/T << 1$. As discussed in previous papers cited above, the static regime occurs only for VCE, hence a very long explosion, while impulsive regime is fully shown for t_d of the order of 1 ms only, i.e. for explosive charges, whatever the equipment (e.g. large scale tank, atmospheric equipment, pressurized vessel). When static regime occurs, domino effects can be related to peak overpressure whereas, for impulsive regimes, the combination of duration and peak overpressure is necessary for the same structural damage.

Figure 2 shows the calculated impulse with respect to the distance for the point-source explosion of corresponding mass of TNT needed for the structural damage (i.e. 7 kPa), as calculated from mass-scaled impulse plot, similarly to the mass-scaled plot for peak overpressure (Philips 1994). Quite clearly, the data are over-conservative but however they show that for very low amount of TNT (short distance, < 30 m) the time duration is less than 0.01 s and that the duration of TNT shock wave is comparable to VCE for very large amount of TNT only (> 10^4 kg). Table 1 shows the evaluation of the ratio t_d/T for two typical equipment: a steel, atmospheric tank, half filled with fuel and a pressurized cylindrical vessel. Details of the calculation are shown elsewhere (Salzano et al., 2012).

Table 1. The time ratios for two characteristic industrial equipment. V= Vertical; H = Horizontal

Equipment		Fill	Capacity (m^3)	Radius (m)	t_d/T (t_d=0.01 s)	t_d/T (t_d = 0.1 s)
Atmospheric	V	Half	30000	44	0.014	0.141
Pressurized	H	Gas filled	100	2.8	0.019	0.188

Quite clearly, the explosion interaction follows always an impulsive realm. Following simplified Biggs' plots (Biggs, 1964), eventually, it can be derived that in the case of triangular shocked pulse load in the near field produced by TNT, the response ability of equipment decreases by increasing the distance, for the same peak overpressure. Furthermore, unless very large amount of TNT are used, damages are unlikely t_d<<0.01 s and P=7 kPa, if considering ductility ratio greater than 10, which is the typical value for heavy damage to steel structures. The minimum amount of TNT for these effects are however larger than 100 kg and the corresponding safe distance is about 100 m. It's however clear that small variation of pressure may give large variation in the structural response of equipment.

4. Definition of the case-study

In order to apply the outcomes of the present analysis, a case-study was defined considering the industrial facility shown in Figure 3. In particular, a storage section featuring relevant inventories of hazardous chemicals was taken into account. Table 2 reports the features of the storage tanks of the facility (see Figure 3a for the equipment positioning). As shown in Figure 3b, the considered tank farm is located inside an industrial complex surrounded by a residential area.

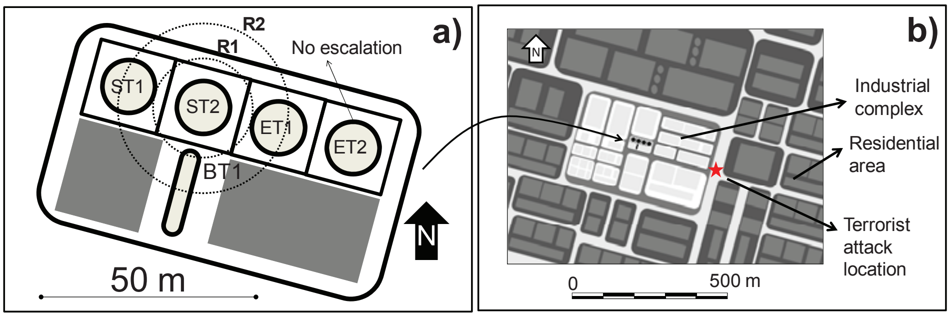

Figure 3. Layout considered in the analysis: a) detailed positioning of the vessels and radiation map of the primary scenario (pool fire from tank ST2) leading to escalation in case of domino effect triggered by internal process causes; b) map of the surrounding area. For radiation threshold definition see Table 2

Table 2. Main features of the storage vessels of the case-study and radiation threshold values considered for the domino effect assessment due to internal process causes

ID	Vessel type	Capacity (m^3)	Radius (m)	Length/height (m)	Stored substance	Filling level	Radiation threshold (kW/m^2)
BT1	Pressurized	250	4	20	1,3-butadiene	80	R1 = 40
ST1	Atmospheric	1000	6	9	Styrene	75	R2 = 10
ST2	Atmospheric	1000	6	9	Styrene	75	R2 = 10
ET1	Atmospheric	1000	6	9	Ethanol	75	R2 = 10
ET2	Atmospheric	1000	6	9	Ethanol	75	R2 = 10

A consequence analysis based on a vulnerability assessment was performed in order to evidence the different potential impact of domino effect triggered by internal process causes respect to escalation scenarios generated by external acts of interference. In particular, the following types of accidents were considered for the case-study:

1) occurrence of only primary scenarios, e.g., associated to each individual tank without considering the possibility of domino effect. The primary scenarios are described in Table 3 for each tank;

2) occurrence of domino effect triggered by internal process causes;
3) "Weak" external terrorist attack with limited quantities of explosive (50 kg of TNT-equivalent) inside the industrial complex;
4) "Severe" external terrorist attack with a high amount of explosive (3,000 kg of TNT equivalent) outside the industrial complex.

Table 3. Primary and secondary scenarios associated to the equipment considered in the case-study.

ID	Primary event	Secondary event – domino effect due to process causes	Secondary event – domino by following external attack
BT1	Jet-fire from 1" hole caused by mechanical impact.	Fireball following the vessel catastrophic rupture	Fireball following the vessel catastrophic rupture
ST1	Confined** pool-fire due to the ignition of liquid released from a rupture in the vessel shell	Confined** pool-fire following the vessel catastrophic rupture	Confined** pool-fire following the vessel catastrophic rupture
ST2	Same as above	- *	Same as above
ET1	Same as above	Same as ST1	Same as above
ET2	Same as above	No escalation	Same as above

* The rupture of this tank leads to fired domino escalation
** A bund is present featuring a total surface of $300 m^2$ and 1.5m height (see Figure 3a).

In the case of domino effect triggered by internal process causes, the pool fire following the rupture of tank ST2 was considered as reference primary scenario, among the ones reported in Table 3, able to affect the other equipment of the tank farm. In order to determine the possible escalation targets, the threshold values for thermal radiation derived by Landucci et al. (2009) and reported in Table 2 were considered. As shown in Figure 3a, not all the equipment are affected by the consequences of the primary fire: the credible secondary scenarios are reported in Table 3 for each tank. Next, the possibility of external terrorist attack is considered supposing that the access to the industrial site is not credible with large amounts of explosive. Thus, only the attack with limited quantities was supposed inside the plant, while the one with higher quantities was considered outside the industrial facility at about 250 m from the storage tanks (see Figure 3b). In the case of the "weak" attack, the TNT-equivalent quantity is able to damage the equipment only inside the storage facility, while in the case of "severe" attack, the TNT equivalent quantity is above the minimum required quantity to cause damages (about 2,000 kg, see Figure 2) thus the escalation scenarios reported in Table 3 were considered.
Once the possible accident scenarios are determined, the consequences were assessed using the conventional TNT model for blast wave assessment (Lees, 1996). In order to obtain a homogenous representation of the accidents impact, a vulnerability assessment was also carried out. Hence, lethality maps (see Figure 4) were obtained considering a reference 1 % death probability value, which was derived applying the probit equations shown in Table 4. More details on the vulnerability assessment and use of probit models are extensively reported elsewhere (Lees, 1996).

Table 4. Probit equations used for the vulnerability assessment

Physical effect	Probit equation	Notes
Radiation	$Y = -14.9 + 2.56 \ln(t_e \times I^{4/3} \times 10^{-4})$	t_e [s] : exposure time; I [kW/m^2]: radiation
Overpressure	$Y = -15.6 + 1.93 \ln(P_s)$	Ps [Pa]: peak overpressure

5. Results and discussion

The results of the vulnerability assessment are reported in Figure 4 for the scenarios described in Section 4, evidencing the potential impact by the 1% lethality contour. The primary scenarios described in Table 3 have limited impact and do not affect the area outside the industrial facility. Figure 4a shows the results obtained for the "weak" terrorist attack. As it can be seen, the affect area is mostly inside the industrial complex, thus with limited effects on the outside population. The fireball associated to tank BT1 is the most severe scenario, but the catastrophic rupture induced by blast leads to a sudden rupture of the vessel at the operative pressure and ambient temperature, thus limiting the amount of energy released after the catastrophic rupture. In the case of domino effect triggered by internal process causes (Figure 4b) the fireball is still the most severe scenario but with a higher impact respect to the previous case. As a matter of fact, the rupture occurs after the liquid heat-up, reaching higher pressure and temperature and thus higher energy potential before the rupture (Paltrinieri et al., 2009). Finally, Figure 4c reports the

vulnerability contour evaluated considering the domino scenarios induced by external “severe” attack. The secondary scenarios are the same of the “weak” attack, thus featuring the same impact. Nevertheless, in this case the attack occurs close to the residential area and the consequences of the explosion directly affect a wider impact zone.
Therefore, a higher escalation severity associated to internal process causes was evidenced, while the effect of the terrorist attack resulted critical for direct impact on population rather than for triggering more severe escalation scenarios.

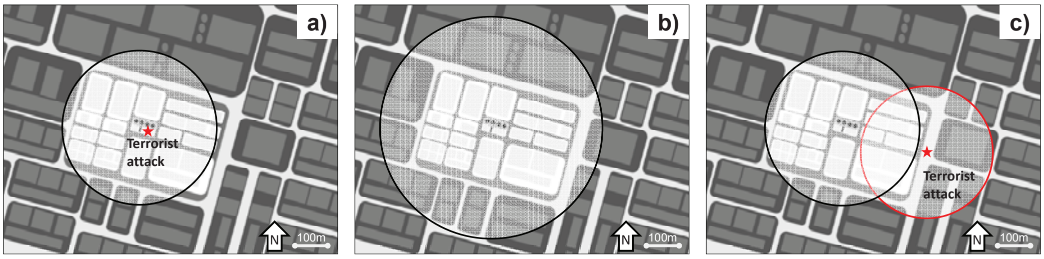

Figure 4. Vulnerability maps (1 % lethality level) obtained for the different accidental scenarios: a) escalation triggered by “weak” terrorist attack; b) domino effect triggered by internal process causes; c) domino effect triggered by “severe” terrorist attack. For scenarios definition, see Table 3

6. Conclusions

In the present study, a comparison between possible domino effect triggered by internal process causes and external attack was carried out focusing on overpressure damages. The differences among damage areas produced by process accidents and voluntary external attacks aimed at causing a domino effect by the damage of process equipment. The results obtained evidenced that escalation triggered by external attack does not result in a relevant amplification of the damage area of the primary attack, unless the intentional interference is carried out from inside the process area where the target equipment are located. Moreover, the damage areas of such intentional attacks were found to be comparable to those of domino events following internal process malfunctions.

References

Biggs J.M., 1964, Introduction to structural dynamics. McGraw-Hill Publishing Company, New York, USA.
Bowerman H., Owens G.W., Rumley J.H., Tolloczko J.J.A., 1992, Interim Guidance Notes for the Design and Protection of Topside Structures Against Explosion and Fire, The Steel Construction Institute Document SCI-P-112/487, Berkshire, UK.
Cozzani V., Gubinelli G., Salzano E., 2006. Escalation thresholds in the assessment of domino accidental events, J. Hazard. Mater., 28, 1-21.
Cozzani V., Salzano E., Tugnoli, A., 2009, The development of an inherent safety approach to the prevention of domino accidents, Acc. Anal. and Prev., 41, 1216-1227.
Landucci G., Gubinelli G., Antonioni G., Cozzani V., 2009, The assessment of the damage probability of storage tanks in domino events triggered by fire, Accid. Analysis Prev., 41, 1206-1215.
Paltrinieri N., Landucci G., Molag M., Bonvicini S., Spadoni G., Cozzani V., 2009, Risk reduction in road and rail LPG transportation by passive fire protection, J. Hazard. Mater., 167, 332-344.
Philips H., 1994, Explosions in the Process Industries: A Report of the Major Hazards Assessment Panel Overpressure Working Party (Major Hazards Monograph). Inst of Chemical Engineers (IChemE), UK.
Salzano E., Cozzani V., 2005, The analysis of domino accidents triggered by vapour cloud explosions, Rel. Eng. and Syst. Saf., 90, 271-284.
Salzano E., Cozzani V., 2006, A fuzzy set analysis to estimate loss of containment relevance following blast wave interaction with process equipment, J. Loss Prev. Proc. Ind., 19, 343-352.
Salzano E., Cozzani V., Kolbe M., 2012, The interaction of accidental explosions with industrial equipment containing hazardous substances, Chemical Engineering Transactions, 26, 159-164.
Tugnoli A., Landucci G., Salzano E., Cozzani V., 2012, Supporting the selection of process and plant design options by Inherent Safety KPIs, J. Loss Prev. Proc. Ind. 25, 830-842.