CHEMICAL ENGINEERING TRANSACTIONS
VOL. 26, 2012

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy De Rademaeker

ISBN 978-88-95608-17-4; **ISSN** 1974-9791

DOI: 10.3303/CET1226033

Probabilistic Assessment of Domino Effect Triggered by Fire: Implementation in Quantitative Risk Assessment

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The present study was aimed at the quantitative assessment of domino effect triggered by fires. A recent methodology based on simplified correlations for the determination of vessel resistance to fire exposure was applied to estimate the damage probability of equipment exposed to fires. The analysis was aimed at evidencing the quantitative contribution due to the domino escalation to a risk profile of industrial facilities. A case study was defined for the application of the methodology obtaining a significant risk increment due to the implementation of domino effects triggered by fire in a Quantitative Risk Assessment (QRA) framework.

1. Introduction

Domino effect was responsible of several catastrophic accidents that took place in the chemical and process industry (CCPS, 2000; Khan and Abbasi, 1999; Lees, 1996). As a matter of fact, severe accidents may arise from the escalation of primary events to trigger secondary scenarios, as well documented in the technical literature and in accident reports. Hence, the European legislation for the control of major accident hazards and for land-use planning in the vicinity of hazardous industrial sites (Seveso-II Directive) requires that all the possible accidental scenarios caused by domino effect are taken into account. In spite of these requirements, coming from the legislation, no well accepted approach exists for the analysis of domino hazards.

The present study was devoted to the analysis of domino scenarios involving one particular type of primary event: industrial fires. In this particular case, a lapse of time is interposed between the occurrence of the primary event, e.g. a steady source of thermal radiation, and the potential escalation due to the failure of secondary equipment (Landucci et al., 2009). On one side, this is critical for the success of potential mitigation actions and, on the other, it may lead to over-conservative estimations of escalation probability if arbitrary threshold values are applied to calculate escalation probability as suggested by several approaches (Cozzani et al., 2005). In the present study, the quantitative assessment of fired domino effect was carried out applying a methodology based on simplified correlations for the determination of fired vessels time to failure (TTF). By this procedure the damage probability is estimated by a probabilistic function that takes into account the calculated TTF with respect to the time required for effective mitigation, that is a function of site-specific factors. The analysis was aimed at evaluating the possible increase in risk profile due to the implementation of

Please cite this article as: Landucci G., Antonioni G., Tugnoli A. and Cozzani V., 2012, Probabilistic assessment of domino effect triggered by fire: implementation in quantitive risk assessment, Chemical Engineering Transactions, 26, 195-200
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domino effect in conventional QRA. For this purpose, a case-study was defined to test the methodology in actual industrial layouts.

2. Methodology for fired domino risk assessment

The flowchart of the methodology applied in the present work for the risk assessment of domino events triggered by fire is reported in Figure 1.

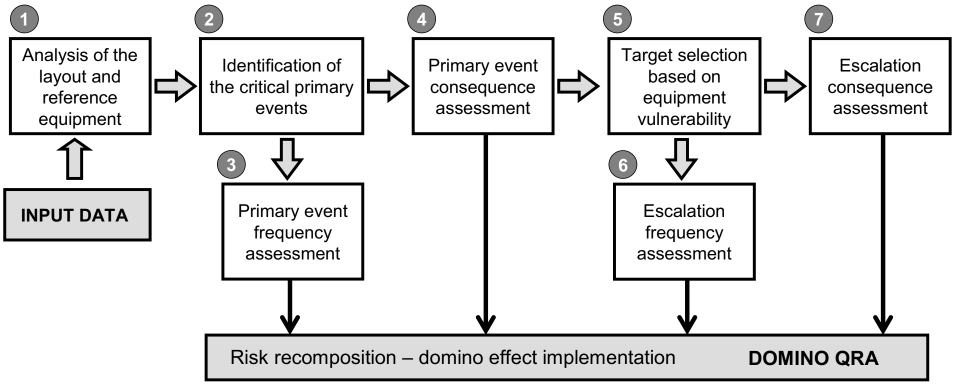

Figure 1: Methodology applied for the risk assessment of domino events triggered by fire

According to Figure 1, the starting point of the methodology is the analysis of the facility considered, aimed at evidencing the reference equipment which may lead to a Loss Of Containment events (LOC) able to generate primary fire events. This preliminary screening is based on a limited set of input data, such as the inventory of hazardous materials, the type of equipment and the operative conditions combined with the analysis of the facility layout.

After the reference equipment identification, the analysis is then focused (steps 2,3 and 4) on the characterization of the primary event, both in terms of expected frequency and consequences assessment. In particular, the approach suggested by “Purple Book” (Uijt de Haag and Ale, 1999) is used to determine the standard LOCs associated to the equipment considered, to which the release frequencies, also reported in “Purple Book”, are associated.

The consequences of the primary LOCs are assessed with a commercial software (Phast^{TM} 6.54), which allows evaluating the thermal heat flux contours, that are then superimposed on the plant layout. On the basis of these results, the secondary targets affected, involved by the primary fires, are identified (see step 5), applying a screening criterion, based on the probabilistic assessment reported by Landucci et al. (2009). In particular, the escalation probability (vessel vulnerability) is estimated by a site-specific probabilistic function that takes into account the time to failure (TTF) of the equipment exposed to fire with respect to the time required for effective mitigation by emergency teams. Given the TTF, the following probit (Pr) correlation is used to estimate the probability of escalation of the vessels exposed to fire:

$$\mathrm{Pr} = a + b \ln(TTF) \tag{1}$$

Where TTF is expressed in minutes and the value of the probit constants (a = 9.25 and b= -1.85) is derived from site specific factors, that take into account the time required for effective mitigation.

In order to have a straightforward TTF estimation, the simplified correlations developed in a previous study (Landucci et al., 2009) and reported in Table 1 are applied to evaluate the vessel resistance and to select the equipment that may trigger the escalation. The more credible secondary scenarios are associated to the identified domino target and assessed (see steps 6,7 in Figure 1). The probabilistic assessment combined with the frequency evaluation of step 3 (see Figure 1) allows determining the expected frequency of escalation. At the same time, also the escalation effects are quantified analyzing the consequences of the domino scenarios with the same computer code (Phast^{TM} 6.54).

Since the conventional models used for consequence assessment in a QRA framework are not able to consider the effects of multiple scenarios, a simplified approach has been used for the representation of the actual consequences of the scenarios. The overall consequences of the domino scenarios, expressed as the probability of death of an unprotected individual, are assumed to be the sum of the death probabilities due to all the scenarios involved in the domino event, with an upper limit of 1. This approach, tough simplified, was found to be acceptable and not over-conservative in the framework of a QRA (Cozzani and Salzano, 2004). Finally, the risk recomposition is performed with the Aripar-GIS software combining all the outcomes of the methodology step as evidenced in Figure 1.

Table 1: Time to failure correlations used in the present study; TTF: time to failure (s); I: radiation intensity (kW/m^2); V: vessel volume (m^3).

Type of fire exposure	Correlation for pressurized vessels
Equipment fully engulfed by the flames	$\ln(TTF) = -1.29\ln(I) + 10.970\ V^{0.026}$ (2)
Distant source radiation	$\ln(TTF) = -0.95\ln(I) + 8.845\ V^{0.032}$ (3)

3. Results and discussion

3.1 Definition of the case study

In order to exemplify the methodology a case study is presented and discussed evidencing the activities carried out in each step. The layout of the case study is reported in Figure 2: a small area of large industrial facility is taken into account.

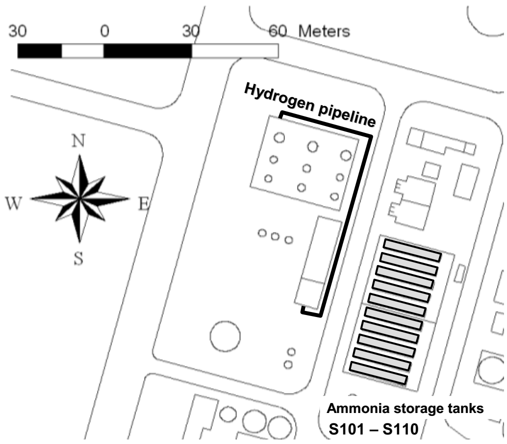

Figure 2: Layout of the considered case study

The necessary input data for the analysis are summarized in Table 2. A hydrogen manifold is located close to an ammonia storage facility. The ammonia storage consists in 10 pressurized vessels (S101-S110) located about 20 far from the hydrogen pipeline. A leak from hydrogen pipeline is supposed to generate a strong jet fire able to impinge one or more pressurized vessels, thus leading to escalation. In order to simplify the case study, only one release position and orientation are considered in the analysis.

3.2 Analysis of the case study

Following the approach reported in Figure 1, the primary event characterization is carried out applying a standard LOC assessment for the primary source. In particular, according to “Purple book” (Uijt de Haag and Ale, 1999), two reference LOCs are associated to pressurized pipelines. The LOCs are described in Table 3 also reporting the correspondent standard frequency. LOC1 is a catastrophic failure supposing the full bore rupture of the pipeline while LOC2 consists in a minor leak (10 % nominal diameter rupture).

Table 2: Features of the considered equipment and input data to the analysis of the case study

Parameter	**Primary source: hydrogen pipeline**	**Secondary sources: ammonia storage vessels (S101 – S110)**
Diameter (mm)	100	3000
Length (m)	110	18
Volume (m^3)	0.86	127 (nominal 100 m^3)
Elevation	1 m	Ground level
Total inventory (kg)	0.5	56000
Operative temperature (K)	293	293
Operative pressure (barg)	6	9
Design temperature (K)	n.r.	323
Design pressure (barg)	n.r.	19.26

Table 3: Characterization of the primary release scenario

LOC	**Description**	**Release diameter (mm)**	**Unit length frequency ($m^{-1}y^{-1}$)**	**Evaluated frequency (y^{-1})**
LOC1	Full bore rupture of hydrogen pipeline	100	$3 \cdot 10^{-7}$	$3.3 \cdot 10^{-5}$
LOC2	10 % nominal diameter rupture of hydrogen pipeline	10	$2 \cdot 10^{-6}$	$2.2 \cdot 10^{-4}$

The release following LOC1 leads to limited consequences (not able to trigger domino escalation). On the contrary, the severe release following LOC2 is able to generate a strong jet fire affecting the neighbour ammonia storage, supposing the immediate ignition of the released hydrogen. No other fire scenarios associated to the release are considered in the study since not able to lead to the domino escalation due to the limited duration. The quantification of the heat fluxes profiles following the primary jet fire is presented in Figure 3. As it can be noticed, four equipment are affected by the primary jet-fire: the first tank (S101) is directly impinged by the flame, while other three tanks are exposed to distant source heat radiation (S102, S103, S104). Table 4 summarizes the impact vector, e.g. the heat load received by each target in the considered fire scenario and the time to failure estimated by applying the correlations reported in table 1, selected on the basis of the type of fire exposure of each vessel.

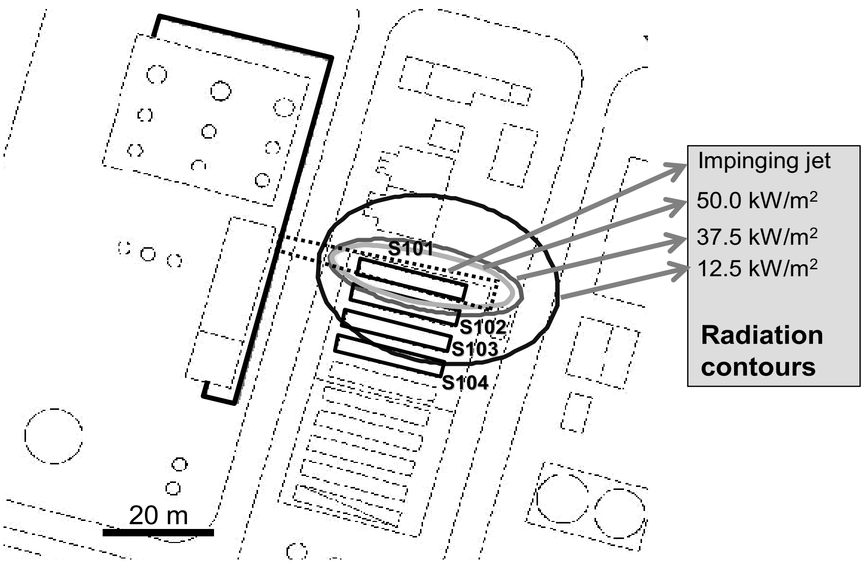

Figure 3: Consequence assessment of the primary jet fire for target equipment identification

Table 4: *Escalation vector and vulnerability assessment of secondary units*

Equipment	Type of fire exposure	Heat load (kW/m^2)	Time to failure (s)	Escalation probit
S101	Full engulfment	74	983	4.07
S102	Distant source radiation	50	1485	3.31
S103	Distant source radiation	25	3400	1.78
S104	Distant source radiation	12.5	7784	0.25

Table 5: Domino combinations above combination probability threshold (10^{-5})

ID combination	Involved targets	Combination probability
1	S101	$1.76 \cdot 10^{-1}$
2	S102	$4.55 \cdot 10^{-2}$
3	S101 and S102	$8.01 \cdot 10^{-3}$
4	S103	$6.41 \cdot 10^{-4}$

Next, on the basis of the evaluated TTFs, the vulnerability assessment is performed calculating the probit for each vessel (see Table 4) by applying Equation 1. Hence, the probability of escalation is first evaluated for each vessel (e.g., single escalation scenarios) by simply converting the probit into probability. It is worth to notice that not only single escalation scenarios might occur, but also the possibility of multiple escalation should be taken into account to have a more realistic picture of the domino chain. Therefore, the following step was the definition of the credible secondary event combinations, fixing a probability threshold below which the combination is not credible. In particular, the maximum number of secondary events was limited considering only combinations having an escalation probability higher than 10^{-5}, thus obtaining the four domino combinations reported in Table 5 with the correspondent escalation probability.

In each case considered, the escalation scenario was the release of the entire inventory of the ammonia storage tank leading to a toxic dispersion. An instantaneous heavy gas release (transitioning to neutral or buoyant during dispersion) with the source located on the ground level was modeled applying the following meteorological conditions: wind speed 2 m/s in F stability class. The approach used to consider the effect of multiple scenarios described in Section 2 was applied for taking into account the damages caused by the escalation combination 3 (thus combining the effect of the escalation of vessels S101 and S102).

Finally, the risk profile due to domino effect escalation following the hydrogen jet fire is reported by the Aripar-GIS software in the map shown in Figure 4, in which the local specific individual risk is reported (in y^{-1}). As it can be seen, due to the massive toxic dispersion, the risk contour of 10^{-7} y^{-1} reaches a distance of about 300 m from the primary event, thus affecting numerous facilities of the industrial area. The map also shows the risk profile of the facility without considering the presence of the domino escalation, thus neglecting the amplification of the consequences and combination of escalation events. As it can be seen from Figure 4, while no significant difference in the higher risk profile (10^{-5} y^{-1} contour) is evaluated, thus very high severity scenarios with and without domino effect result with compatible severity, an increase of the 10^{-6} y^{-1} contour is obtained in the case of domino effect implementation. Moreover, without considering domino effect, the 10^{-7} y^{-1} level is not reached.

Thus, an amplification of the risk profile of the industrial facility is then experienced by implementing domino scenarios, in particular taking into account the potential effect of severe toxic exposure.

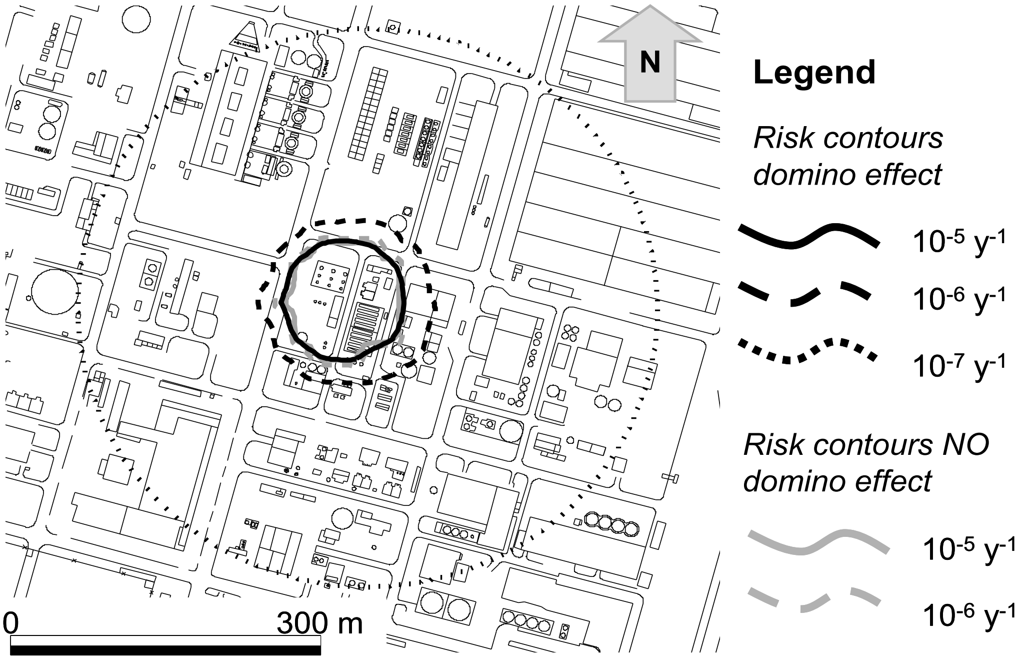

Figure 4 Individual risk curves evaluated for the first case study (risk is expressed in y^{-1}).

4. Conclusion

The present study was devoted to the analysis of domino effect triggered by fire in complex industrial layouts. A methodology was developed based on the results of previous studies on the probabilistic assessment of domino effect. A case study based an actual industrial layout analysis was defined and analyzed in order to test the potentiality of the considered simplified approach. The study evidenced that the increase in the individual risk due to escalation events triggered by fire may give an important contribution to industrial risk, since high severity scenarios may result from the simultaneous damage of several process units.

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