CHEMICAL ENGINEERING TRANSACTIONS
VOL. 36, 2014
Guest Editors: Valerio Cozzani, Eddy de Rademaeker

ISBN 978-88-95608-27-3; **ISSN** 2283-9216
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
DOI: 10.3303/CET1436063

Frequency Evaluation for Domino Scenarios Triggered by Heat Radiation Exposure

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Severe fires may damage process equipment or pipes, leading to accident escalation and domino effect. Several accidents that occurred in the chemical and petrochemical industry presented these features. In order to account for these accident scenarios in conventional Quantitative Risk Analysis (QRA) studies, the more critical step is the availability of reliable models to estimate the probability of escalation given the fire impact mode on industrial equipment. The present contribution was aimed at developing a methodological approach to the assessment of the damage probability of process and storage vessels, identified as escalation targets, with the final aim of quantifying the frequency of accidents triggered by domino effect and the implementation in QRA studies. Efforts were devoted to include in the analysis relevant site-specific factors and to consider the presence of eventual mitigation measures. The developed methodology was applied to a case study dealing with the escalation of a primary fire scenario.

1. Introduction

Domino effect was responsible of severe accidents that took place in the chemical and process industry (AIChE-CCPS, 2000) as demonstrated by past accident data analysis (Gòmez-Mares et al., 2008) and by specific studies (Cozzani et al., 2009). The more critical step in the quantitative assessment of domino hazards is the availability of reliable models to estimate the effects caused by the escalation of primary accidents (Khan and Abbasi, 2001).

In particular, the damage probability of process and storage vessels involved in fires is often calculated by the use of arbitrary threshold values that do not take into account site-specific factors, as the possible mitigation due to passive and active protection systems or effective emergency response (Cozzani et al., 2006). On the other hand, very complex and time consuming approaches are available for the detailed calculation of equipment resistance under the impact of a primary event, requiring a detailed description of vessel geometry and other design data (Manu et al., 2009).

The present study was devoted to the analysis of domino effect scenarios involving accidental fires affecting process equipment by heat radiation. In this 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 fire-induced failure of equipment. This time lapse, usually indicated as time to failure (Landucci et al., 2009a), is critical for the success of potential mitigation actions (Birk, 1988). A simplified approach was developed to the calculation of the damage probability of process vessels, aimed at the frequency estimation of domino accidents triggered by fire. The methodology was based on simplified correlations for the time to failure of vessels. These were obtained from an integrated approach, based on: i) the use of literature experimental data, ii) finite elements modelling (FEM) for complete thermal and mechanical simulations of the behaviour of vessels exposed to fires, iii) a lumped parameters model for vessel failure based on a thermal nodes approach. The analysis was aimed at evaluating the possible frequency of accidents for the implementation of domino effect in conventional Quantitative Risk Assessment (QRA). For this purpose, a case study was defined to test the methodology in actual industrial layouts, both considering pressurized and atmospheric equipment.

Please cite this article as: Argenti F., Landucci G., Antonioni G., Cozzani V., 2014, Frequency evaluation for domino scenarios triggered by heat radiation exposure, Chemical Engineering Transactions, 36, 373-378 DOI: 10.3303/CET1436063

2. Methodology for the evaluation of damage probability

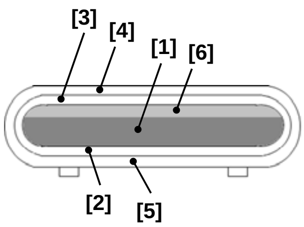
2.1 Overview

The precise evaluation of domino effect triggered by fire represents a complex task. In fact, the proper description and determination of several aspects characterizing fired domino effect, such as flame geometry, modes and severity of fire exposure condition and target equipment resistance to exposure actually arise several difficulties when problem simplification is attempted. A suitable approach could be the adoption of simplified correlations, based on “probit” functions, to evaluate the damage probability of process equipment. By means of probit vulnerability models, the escalation probability is calculated as the damage probability of target equipment, which is directly related to a “dose” amount of physical effect deriving from the impact vector.

If the impact vector is represented by the heat load deriving from the primary fire, the failure of the target equipment may derive from the wall temperature increase and the consequent material weakening, and/or from the increase of internal pressure due to stored fluid heat up (Lees, 1996). This is a relatively slow process: hence, a significant time lapse exists between the primary fire start and the escalation occurrence (between 5 and 30 min, according to past accidents). Consequently, the evaluation of target equipment time to failure (ttf) is a fundamental parameter in the assessment of fired domino accidents. Probit vulnerability models based on the comparison of the target ttf and the characteristic time required for an effective mitigation (tem) were used for the escalation probability assessment. The analysis of protection systems effectiveness leading to tem estimation was performed by applying a LOPA (Layer Of Protection Analysis) approach and vulnerability models, also taking into account the mitigation measures implemented in the specific plant type and industrial site under analysis.

2.2 Evaluation of process equipment resistance to fires

The first step of the methodology was based on the use of sufficiently detailed models for the characterization of fired equipment behavior. For the present study, a model based on thermal nodes approach was developed. The main features of the model are described in the following, while more details can be found elsewhere (Landucci et al., 2009a). In the model, the physical quantities (temperature, pressure, thermal conductivity, density, etc.) were considered homogeneous within the defined wall region, in the liquid and vapour space. A sufficient number of thermal nodes were defined to describe the vessel wall and the stored substance and adopted in the thermal balance formulation. Figure 1 shows the defined thermal nodes for the modelling of vessels coated with a layer of fireproofing material and full engulfment in the flames. The legend in Figure 1 shows the nodes definition.



NODE	DESCRIPTION
[1]	Liquid space
[2]	Vessels wall in contact with the liquid phase impinged by the flame
[3]	Vessels wall in contact with the vapour phase impinged by the flame
[4]	Insulated material layer (if present) at the level of the vapour phase in contact with the flame
[5]	Insulated material layer (if present) at the level of the liquid phase in contact with the flame
[6]	Vapour space.

Figure 1: Nodes definition for a thermally insulated vessel adopted in the lumped parameters model for the time to failure estimation

Although the lumped parameter model allowed a simple determination of temperature and pressure dynamic profiles, a local analysis of temperature distribution within vessel could not be obtained due to model limitations. Therefore, an exhaustive evaluation of thermal stresses within the structure due to heat radiation exposure was not possible. In order to validate the simplified assumptions that were made in the development of the lumped model, model simulation results were validated against those obtained by applying more complex physical models and against literature data. Particularly, a numerical code based on finite element modelling (FEM) was adopted to simulate in detail targets behaviour in severe fire exposure conditions and to obtain an extended dataset used for validation purposes. More information on FEM models are reported elsewhere (Landucci et al., 2009b). The results of validation procedure evidenced that the lumped parameter model allowed estimating conservative but credible ttf values, featuring an average error of 15 %.

2.3 Simplified correlation for the estimation of damage probability

Even if the lumped model requires only a low computational time, its use in the analysis of extended and complex industrial areas, where a huge number of possible escalation targets triggered by fire may be identified, may require a relevant effort. In fact the model, although simplified, requires to define several input parameters for each simulation (e.g. vessel geometrical data, properties of vessel content, radiation mode, etc.). Thus, a further simplified tool to carry out a preliminary assessment of credible domino targets in a complex lay-out was identified in the adoption of simple analytical functions for the evaluation of vessel ttf.

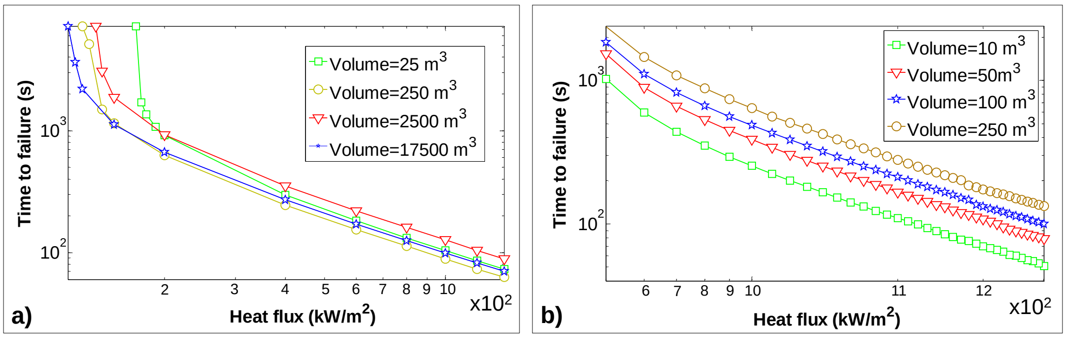


Figure 2: Results of lumped model simulations: time to failure (s) for atmospheric tanks (capacity from 25 to 17500 m^3) and pressurized vessels (capacity from 10 to 100 m^3, design pressure 25 bar) plotted as a function of heat load (kW/m^2).

In order to define simple analytical functions, reference typologies of atmospheric tanks and pressurized vessels were considered according to specifications and operative data from existing industrial installations. The lumped parameter code was used to simulate several tanks types under different fire exposure conditions obtaining an extended data set of ttf values. Figure 2 shows an example of the ttf evaluated for atmospheric vessels exposed to distant source radiation (Figure 2a) and for pressurized vessels fully engulfed by the flame (Figure 2b). Different vessel capacities were analysed.

Interpolating the extended data set obtained by lumped parameter model simulations allowed to determine simplified correlations for ttf evaluation as a function of heat load (I, kW/m^2) and vessel volume (V, m^3), considering different fire exposure conditions. The correlations have the following form:

$$ln(ttf) = cV^d + e\,ln(I) + f \qquad (1)$$

Table 1 reports the coefficients for Eq. 1.

Table 1: Summary of the coefficients to be used in Eq. 1 for the time to failure correlations applied in the present analysis

Type of equipment	Fire exposure condition	Coefficients for Eq. 1			
		c	d	e	f
Pressurized vessel	Flame engulfment	10.970	0.026	-1.29	0
Pressurized vessel	Distant source radiation	8.845	0.032	-0.95	0
Atmospheric vessel	Any	-2.667×10^{-5}	1	-1.13	9.877

2.4 Implementation of fire protection barriers

The proposed correlations led to conservative estimates of target time to failure without considering the mitigation due to protection systems and emergency measures.

Active fire protection systems, such as automatically actuated sprinkler systems or water deluge systems, play an important role in firefighting efforts and significantly contribute to the tem value (accordingly to the previously presented definition). However, active fire protection system often feature a limited availability due to the possible delayed activation or the possible failure of critical component compromising the proper system functioning, often caused by the primary fire itself (Dennis and Nolan, 1996). Hence, in order to provide more reliable and robust safety barriers, passive fire protection systems are also adopted in storage (Di Padova et al., 2011), offshore (Tugnoli et al., 2012) and transport installations (Argenti and Landucci, 2014): in fact, passive protection systems do not require either power or external activation to trigger the protection action. A typical example is represented by the combined adoption of emergency relief devices (Pressure Safety Valves) and fireproofing (Gomez et al., 2012) for pressurized vessels.

Table 2: Thermal properties and maximum operative pressure TC_{max} for commercial coatings.

Type of coating	**TC_{max} (K)**	**Density (kg/m^3)**	**Thermal conductivity (W/mk)**	**Heat capacity (J/kgK)**
Ceramic fibers	1223-1473	192-208	0.066-0.163	1045
Glass wool	473-773	10-100	0.03-0.07	1045
Rock wool	923-1023	30-200	0.03-0.08	920

Therefore, during the development of the methodology, a key issue was the implementation of passive protection systems in the evaluation of protected equipment time to failure. More specifically, passive protections allow delaying the failure of protected equipment with respect to the unprotected configuration. In the present analysis, the increased time to failure of protected equipment (identified in the following as ttf_p) was obtained simply by adding the time to failure of the coating layer (ttf_c) to the time to failure of the unprotected equipment item (ttf), according to the following expression:

$$ttf_p = ttf + ttf_c \tag{2}$$

In the case of fireproofing materials that are commonly adopted for industrial applications (in particular mineral wools), the value of ttf_c was estimated on the basis of the maximum temperature reached by the material itself under fire exposure conditions. A maximum operative temperature (TC_{max}), above which the material loses almost completely its insulating properties, was defined for several typologies of fireproofing coatings. The selected values of TC_{max} together with the physical properties (Malloy, 1969) considered in this study are reported in Table 2. The ttf_c was defined as the time at which the exposed surface of the fireproofing material reached the TC_{max} value. The study evidenced that a considerable delay in the target failure was induced by the presence of the PFP, providing extra time for the deployment of emergency teams and thus for the mitigation and suppression of the primary fire.

2.5 Estimation of damage probability and domino frequency

The present analysis highlighted that more the equipment is resistant to the fire, the less credible is escalation, since a higher time to failure allows longer time for fire protection systems activation and emergency team intervention. This is a peculiar aspect of domino effect induced by fire, in which a lapse of time is interposed between the primary fire and the escalation. This is not the case for other possible domino accident types, such as the ones triggered by fragments projection or overpressure, in which the escalation is almost simultaneous respect to the primary event.

Thus, the probability of damage and escalation was related to the time to failure of the equipment, even in presence of thermal protection, comparing the ttf_p (see Eq. 2) to the characteristic times required for successful mitigation (tem) (see Section 2.1). In the present study, two key times for emergency response were identified: the maximum time required to start the emergency operations (tem_1) and the maximum time required to start the mitigation actions (tem_2). In the absence of site specific data, tem1 was assumed of 5 min and tem2 was assumed of 20 min (Landucci et al., 2009a). Assuming a value of escalation probability equal to 0.1 (probit equal to 3.71) for ttf_p equal to tem1 and equal to 0.9 (probit equal to 6.27) for ttf_p equal to tem2, the following probit was applied in the present study to estimate escalation probability:

$$Pr = 9.25 - 1.857\, ln(ttf_p) \tag{3}$$

where the target equipment ttf_p is expressed in minutes. Clearly enough, in absence of thermal protection ttf_p = ttf in Eq. 3. Once the probit is evaluated, a value of escalation probability, univocally associated to the calculated probit, was also determined (see (Lees,1996) for probit into probability conversion).

Finally, the frequency of occurrence of the secondary event triggered by fire can be evaluated as follows:

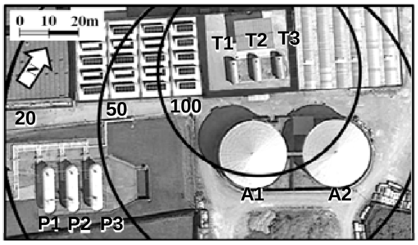
$$f_{second,i} = f_{fire,} P_{E,i} \tag{4}$$

where $f_{second,i}$ is the frequency of occurrence of the secondary accident involving the i-th equipment item of the layout, f_{fire} is the frequency of occurrence of the primary fire triggering the domino chain and $P_{E,i}$ is the probability of escalation given the primary fire impacting on the i-th equipment item of the layout.

3. Application to a case study

3.1 Definition of the case study

With the aim of exemplifying the method developed, a case study was defined and analysed in order to determine the frequency of possible domino events triggered by fire. The layout of the case study, shown in Figure 3, consisted in a section of a storage tank farm including both atmospheric and pressurized storage tanks. The analysis dealt with the LOC event associated to the main connection failure of an acetone road tanker (T2, nominal capacity = 60 m^3) in the unloading station, which was supposed to generate a pool fire. The expected frequency of the considered primary fire scenario was assumed equal to 2.5×10^{-7} y^{-1}, according to literature sources (Uijt de Haag and Ale, 1999). Figure 3 also shows the iso-radiation contours for the considered pool fire. Conventional literature integral models for consequence analysis (Lees, 1996) were applied considering uniform wind direction, stability class D and wind velocity equal to 5 m/s. The pressurized vessels storing chlorine (tanks P1, P2 and P3) were coated with a layer of rock wool.



ID	Design pressure (barg)	Substance	Diameter (m)	Height or Lenght (m)	Thickness (mm)	Insulating coating
A1 A2	0.01	Toxic water solution	24	5.4	10.5	NO
P1 P2 P3	19	Chlorine	3	18	24	YES
T1 T3	2	Water solution	2.6	15	16	NO
T2	2	Acetone	2.6	15	16	NO

Figure 3: Case study definition and features of the considered equipment. The map reports the iso-radiation contours (bold black lines) expressed in kW/m^2 associated to the primary pool fire

3.2 Result and discussion

As it can be seen from the layout depicted in Figure 3, all the vessels in the facility are potential domino targets. The atmospheric tanks A1 and A2 are fully engulfed by fire, while the pressurized vessels are exposed to distant radiation of decreasing intensity moving from P3 to P1. The road tankers T1 and T3 were not considered in the analysis since they did not contain any hazardous materials.

Table 3: Quantitative assessment of the probability and frequency of occurrence of final domino events

Target ID	Heat load (kW/m^2)	ttf (min)	ttf_c (min)	ttf_p (min)	Evaluated probit	Escalation probability	Reference secondary event	Secondary event frequency (y^{-1})
A1	Flame Engulfment[a]	1.24	-	-	8.849	9.999×10^{-1}	Toxic dispersion	2.499×10^{-7}
A2	Flame engulfment[a]	1.24	-	-	8.849	9.999×10^{-1}	Toxic dispersion	2.499×10^{-7}
P1	30	19.76	15	34.76	2.660	9.648×10^{-3}	Toxic dispersion	2.412×10^{-9}
P2	35	17.07	15	32.07	2.810	1.426×10^{-2}	Toxic dispersion	3.565×10^{-9}
P3	48	12.64	15	27.64	3.086	2.779×10^{-2}	Toxic dispersion	6.948×10^{-9}

a) In the case of flame engulfment, a heat load equal to 130 kW/m^2 was considered.

Table 3 summarizes the results of the application of the presented methodology to each single target. On the basis of the heat load caused by the pool fire (see Figure 3), the ttf of uncoated equipment was estimated by applying the simplified correlations (see Eq.1 and Table 1 for the parameters).

Next, the presence of the coating layer was taken into account for the estimation of the ttf_p of vessels P1, P2 and P3 adding the ttf_c contribution to the estimated ttf (see Eq. 2). In particular, a conservative value of ttf_c (e.g. 15 min) was evaluated applying the lumped parameter code and simulating the time needed by the coating to reach the degradation temperature TC_{max} of 1000°C (see Table 2 for material properties).

On the basis of ttf_p, Eq. 3 was applied for probit calculation. Then the probit was converted into escalation probability (see (Lees, 1996) for more details). Finally, the frequency of occurrence of the final events was calculated through Eq. 4. The obtained results confirm that in case of severe fire exposure the escalation is credible leading to high values of escalation frequency. Hence, the evaluated accident propagation trough the rupture of atmospheric tanks containing toxic material (A1 and A2) had the same order of magnitude of the primary pool fire, leading to amplification of the consequences and of the risk profile of the facility. Due to the inherent higher structural resistance and less severe fire exposure conditions, the accident propagation to the chlorine tanks (P1, P2 and P3) was less credible. In fact, the calculated escalation frequency is two orders of magnitude lower than the one of A1 and A2. Moreover, in this latter case, the presence of a heat resistant coating, even if with low protection performances (see Table 2), allowed increasing the ttf_p value.

4. Conclusions

A methodological approach was developed for the frequency estimation of domino accidents triggered by fire. A detailed analysis of fired domino effect was presented to exemplify the procedure for escalation probability evaluation through the use of physical models for the estimation of the time to failure of equipment exposed to fire. Next, the model simulations were used to derive simplified correlations for ttf estimation and then escalation probability determination. In addition, the approach was extended to consider the effectiveness of passive fire protections in delaying equipment heat up and failure. A case-study was defined to exemplify the methodology application. The results obtained evidenced on one side that severe fire scenarios have the potential to cause credible accident propagation and, on the other, that the mitigation action of PFP, aimed at delaying the time to failure of equipment exposed to fire, significantly contribute to the reduction of domino effect frequencies.

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