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# Quantitative Assessment of Domino Effect Caused by Heat Radiation in Industrial Sites

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**Abstract:** Accidents caused by the domino effect or chain of accidents are the most destructive accidents related to industrial sites. The probability of domino effects is increasingly high due to the development of industrial complexes, their proximity, and storage of dangerous substances, transportation networks and population growth. Fires are among the most frequent accidents due to the installations or storage equipment under pressure, and storage of flammable substances. The thermal radiation generated by fire is one of the main factors leading to domino effects and may cause severe consequences on industrial sites, people, structures, environment and economy. This paper presents a methodology for quantitative assessment of domino effect caused by heat radiation on storage areas, a model for the estimation of the human vulnerability is also proposed, individual and societal risk are estimated. The results have proved the importance of domino effect in quantitative risk analysis.

**Keywords:** Domino effect, Cascading events, Risk assessment, Fires, Human vulnerability.

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## 1. Introduction

Accidents caused by the domino effect are those that cause the most catastrophic damage. The consequences of the damage caused are at various levels and may not only affect the industrial sites, but also people, environment and economy. The potential risk of domino effect is widely recognized in the legislation since the first "Seveso-I" Directive (82/501/EEC), the "Seveso-II" Directive (96/82/EC) extended these requirements to the assessment of domino effects not only within the site under consideration, but also to nearby plants.

A recent study (Clini et al, 2009) provides a historical analysis of 261 accidents involving domino effects. This analysis shows that storage areas are the most probable starters of a domino effect (Kadri et al., 2011a). An inventory of the past domino accidents (Abdolhamidzadeh et al, 2010), reveals that the most typical primary incidents for a domino effect sequence are explosions (57%), followed by fire (43%).

The objective of this paper is to present a methodology for the quantitative assessment of domino effect caused by fire to industrial equipments or storage areas and computes the individual/societal risk in the framework of domino effect analysis. Sub-next section is dedicated to the introduction to domino effect assessment. The second section, presents the methodology used for quantitative assessment of domino accidents in industrial sites. The third section uses a case study to illustrate the proposed model and to present typical results. The last section concluded this paper.

### 1.1. Domino effect assessment

Although several studies were dedicated to the detailed analysis of fire damage to industrial equipment (Kadri et al., 2011b). Only few models based on very simplistic assumptions are available for the assessment of equipment damage by fire in the framework of domino effect (Latha et al, and Purdy et al, 1992).

A well known simplified model proposed by (Valerio Cozzani et al, 2006, and Landucci et al, 2009) is based on the probit approach developed by (Eisenberg et al, 1975). The authors have proposed a damage probability model that take into account the categories of industrial equipments, table 1, witch presents the thresholds and probit models for two equipment categories.

The authors (Khan and Abbasi, 1998) have remarked that the intensity of heat radiation of  $37kW/m^2$  is sufficient to cause severe damage in to process equipment in other installations operating under atmospheric conditions.

Table 1: Damage probability models and threshold values for the heat radiation, where  $Y$  is the probit function,  $ttf$  is the time to failure (sec),  $V$  is the vessel volume ( $m^3$ ), and  $Q$  is the amount of heat radiation received by the target vessel ( $kW/m^2$ ) (Cozzani et al, 2006).

Equipment category	Threshold	Correlation
Atmospheric vessels	$15 kW/m^2$	$Y = 12.54 - 1847 \times \ln(ttf)$
	$t \geq 10$ min	$\ln(ttf) = - 1.128 \ln(Q) - 2.66710^{-5} V + 9.887$
Pressurized vessels	$50 kW/m^2$	$Y = 12.54 - 1847 \times \ln(ttf)$
	$t \geq 10$ min	$\ln(ttf) = - 0.947 \ln(Q) + 8.835 V^{0.032}$

The decree of September 29, 2005, regarding to the evaluation and consideration of the probability of occurrence, kinetics, effect intensity and seriousness of the consequences of potential accidents in the risk assessments of classified installations subject to authorization takes into account the threshold values represented in the table 2.

Table 2: Threshold values of thermal dose on people (INERIS, 2005).

Dose ( $[kW/m^2]^{4/3}.s$ )	effects on peoples
600	irreversible effects
1000	lethal effects
1800	significant lethal

Different formulas are used to quantify the heat radiation generated by fire. The radiation from fire ball or pool fire on a receptor body located at a distance  $r$  from the center of this latter may be expressed by the following equation (Van den Bosh et al, 1996):

$$I(r) = \frac{\tau F_s D^2 m_\infty H_C}{16.r^2} \quad (1)$$

Where:  $I(r)$  is the heat radiation flow ( $kW/m^2$ ),  $F_s$  is the fraction of the generated heat radiated from the flame surface,  $m_\infty$  is the combustion velocity per unit surface area of the pool [ $kg/(m^2.s)$ ],  $\tau$  is the atmospheric transmissivity coefficient,  $H_C$  is a combustion heat (kJ/kg),  $D$  is the pool diameter ( $m$ ) ( $D_{max}=5.8 \times m_t^{\frac{1}{3}}$ ,  $m_t$  is the total mass of the fuel in  $kg$ ).

## 2. Methodology

### 2.1. Domino system

A domino system consists in at least of two subsystems, the source subsystem(s) ( $S_1$ ), and the target subsystem(s) ( $S_2$ ) (Fig. 1):

- Source subsystem(s), where on failure may generate a danger (physical effects: thermal load, overpressure, fragments and toxic releases) that may affect other surrounding subsystems, and
- Target subsystem(s) which may be affected by the failure of the sources sub-system(s). Addition to these physical effects, we may include the influence factors (malicious acts, human and organizational factors, safety system and weather conditions) that can influence or aggravate the target system.

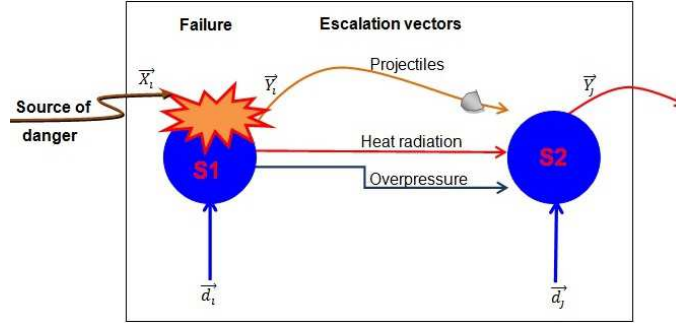


Figure 1: Domino System.

The domino system can be described by the following vector function:

$$\vec{y} = N(\vec{x}, \vec{d}, t) \quad (2)$$

- $\vec{x} = (x_1, x_2, \dots, x_p)^T$  is a real vector (input vector) with  $p$  dimension in a space of physical state at time  $t$ .  $x_i$  may be divided into two types of parameters, random physical parameters (physical effects), and influence factors (intervention system, human factor);
- $\vec{d} = (d_1, d_2, \dots, d_g)^T$  is a real vector (input vector) with  $g$  dimension,  $d_j$  represents the deterministic input parameters of the system (physical characteristics of system like threshold);
- $\vec{y} = (y_1, y_2, \dots, y_k)^T$  is the vector of system output, which is a real vector with  $k$  dimensions,  $y_i$  are random variables depending on the random input.

## 2.2. Failure function and Failure probability

In normal operation, the output values  $y_i$  corresponding to the input parameters of the system are less than the threshold values  $y_{0i}$  respectively. While the value of any output  $y_i$  of system at an entry point  $\vec{x}_i$  is greater than its corresponding threshold value  $y_{0i}$ , the system says failed. Then, the failure function describes the state of the system. The failure function is defined as follows:

$$G(\vec{x}) = \vec{y}_0 - \vec{y} \quad (3)$$

where,  $\vec{y}_0$  is the threshold criterion (defined for each system), and  $\vec{y}$  is the output of target system. If  $(G_i(x, t) < 0)$  then the system says failed. After calculating the failure function, the failure probability  $P_{f_i}$  for each escalation vectors may be calculated by the following equation:

$$P_{f_i} = P(G_i(x, t) < 0) \quad (4)$$

The total failure probability  $P_{F_j}$  for all the escalation vectors that affects the target subsystem ( $S_j$ ) may calculated with the following equation:

$$P_{F_j} = P\left(\bigcup_{i=1}^k \{G_i(\vec{X}) < 0\}\right) \quad (5)$$

### 2.3. Domino effect probability/ Affected zones

While failure probability  $P_{F_j}$  is known for each subsystem, the probability of domino effect and the damage radii (affected zones) may be evaluated for all the system. Also, the probability of each domino scenario (domino sequence) may be calculated as follows:

$$P_{DO_i} = \prod_{j=1}^n P_{F_j} \quad (6)$$

Where  $P_{DO_i}$  is the probability of the domino scenario  $i$ , and  $n$  is the number of the failed sub-systems involving in the domino sequence (caused by the primary event).

### 2.4. Human vulnerability model

Heat radiation can affect not only the industrial equipments but also environment and people. A total number of population ( $N$ ) can be calculated with a density of population  $\rho(t)$ , equal to  $\rho_0$  at  $t = 0$ , and the surface  $S(r) = \pi r^2$ .

Let  $I(r, t)$  be the heat radiation received by the person at distance  $r$  with an exposure time  $t$ . The thermal radiation phenomenon is transient, then it is necessary to integrate the heat flows for each time step as follows:

$$I(r, t) = \int_{t_0}^{t_0+t} I^{\frac{4}{3}}(r, t) dt \quad (7)$$

Thus, the number of people ( $N$ ) affected by heat radiation may be estimated by the following equation:

$$N(t) = \int \rho(t) \cdot P_l(r, t) dS \quad (8)$$

where,  $P_l(r, t)$  is the probability of lethality, which may be assessed by comparing the heat flux  $I(r, t)$  received by a person with threshold value  $I_{th}$  as follow:

$$P_l(r, t) = P(I(r, t) > I_{th}) \quad (9)$$

## 3. The case-study

A case-study has been studied in order to assess domino effect in the case of storage areas. The lay-out considered in the analysis, the type of equipments and their inventory are shown in the figure 2. We assume that a primary scenario has caused the failure of one tank. The latter can generate three escalation vectors, and may affect the surrounding equipment and personnel. Some simplifications are used in the present study, only the head radiations has been considered, all tanks are spherical, and a homogeneous distribution of population was assumed, with a density  $\rho = 10^{-3}$  person/ $m^2$ . Finally, in order to estimate the societal risk, the effect to personnel is neglected if the probability of lethality falls below  $10^{-4}$ .

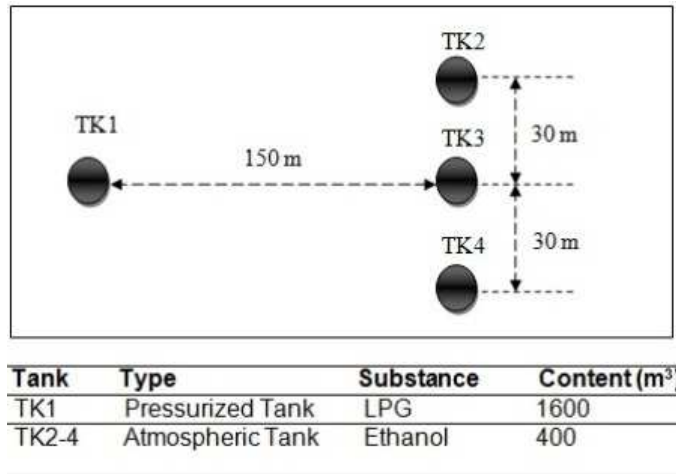


Figure 2: Lay-out and equipment characteristics for the case study.

### 3.1. Effects on surrounding equipments

The influence parameters used in this study are presented in the table 3. The failure probabilities  $P_{F_j}$  for each tank are represented in the table 4. The radius of the zone affected by the effects of heat radiation resulting from the failure of TK1 is 841 m with failure probability  $P_F = 10^{-6}$  ( see fig. 3). The figure 4 represents the affected zones generated by the rupture of the tanks,  $Z1$  (destruction zone) and  $Z2$  (destruction possible zone) estimated for the failure probability  $P_F = 0.9$  and  $10^{-2}$  respectively.

Table 3: The influence parameters used in the case-study,  $R$ : spherical tank radius,  $\mu = 0.5 \times \ln(2R \times D_{max})$ ,  $\sigma = 0.26 \times \ln(\frac{D_{max}}{2R})$ .

Deterministic parameters	Random parameters
$H_{C_{LPG}} = 46.333$ (MJ/Kg)	$\tau \sim U(0.2, 0.8)$
$m_{\infty_{LPG}} = 0.099$ [Kg/(m <sup>2</sup> .s)]	$F_s \sim N(0.265, 0.0821)$
$H_{C_{Ethanol}} = 29.7$ (MJ/Kg)	$D \sim \text{Log-N}(\mu, \sigma)$
$m_{\infty_{Ethanol}} = 0.015$ [Kg/(m <sup>2</sup> .s)]	

Table 4: Failure probability.

Failed tank	Target tank	$P_{F_j}$
TK1	(TK2-4, TK3)	(0.256, 0.268)
TK2-4	(TK1, TK3)	$(2.056 \times 10^{-5}, 0.284)$
TK3	(TK1, TK2-4)	$(3.865 \times 10^{-5}, 0.284)$

### 3.2. Effects on Human vulnerability

To study the human response to the effects of heat radiation, the failure of TK1 is assumed as the initiating event. The results of the effect of heat radiation on the population in function of exposure time is represented in the table 5.

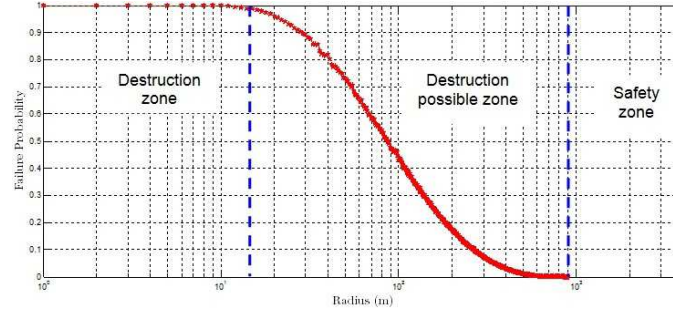


Figure 3: The failure probability resulting from the rupture of TK1.

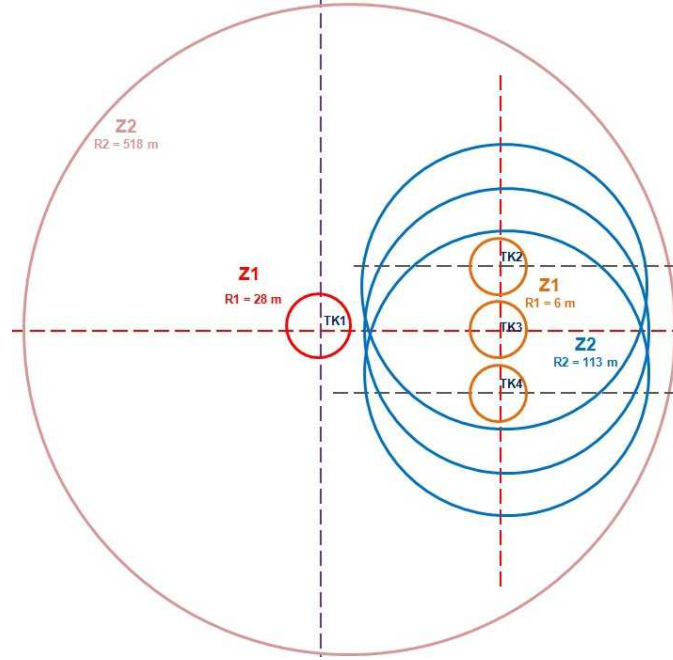


Figure 4: The affected zones Z1 and Z2.

Table 5: Number ( $N$ ) of the person affected by the thermal radiation,  $t_e$ : exposure time (sec),  $I_{th}$ : dose ( $[\text{kW}/\text{m}^2]^{4/3} \cdot \text{s}$ ).

Effets	Dose ( $I_{th}$ )	$t_e$ (sec)	$N$	Distance (m)
Irreversible effects	600	(60 , 30)	(918 , 590)	(1882, 1462)
Lethal effects	1000	(60 , 30)	(599 , 390)	(1552 , 1202)
Significant lethal	1800	(60 , 30)	(364 , 241)	(1212 , 927)

## 4. CONCLUSION

A quantitative method for the assessment of domino effects has been developed in this paper. It allows to quantify the effect of the escalation vectors (physical effects) in industrial plants. A human vulnerability model to the heat effects has been also developed to estimate the individual and societal risks.

Based on this method, we can evaluate the failure probability for each subsystem (unit), after, the probability of domino effect may be evaluated for all the system. The three areas defined in this study may be useful in the choice of safe distances between industrial equipments.

For a better estimation of the failure probability and  $ttf$  of the target, we must assess both i) the failure

probability of the target due to the high pressure accumulation and, ii) the failure probability due to the material failure (based on the mechanical properties), also, we can compare the time emergency response (mitigation time) with the *ttf*. These are being modeled for a forthcoming paper (Kadri et al., 2011c).

The analysis above, shows the importance of giving much more importance to studying this phenomenon (cascading events). Hence, domino effects need more scientific investigations.

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