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# The Quantitative Assessment of Risk Caused By Fire and Explosion in Chemical Process Industry

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**Abstract-** In the field of risks analysis, the domino effect has been documented in technical literature since 1947. The accidents caused by the domino effect are the most destructive accidents related to industrial plants. Fire and explosion are among the most frequent primary accidents for a domino effect due to the units under pressure and the storage of flammable and dangerous substances. Heat radiation and overpressure are one of major factors leading to domino effect on industrial sites and storage areas. In this paper we present a method for risk assessment of domino effects caused by heat radiation and overpressure on industrial sites. This methodology is based on the probabilistic models and the physical equations. It allows quantifying the effect of the escalation vectors (physical effects) in industrial plants, the three areas defined in this study may be useful in the choice of safe distances between industrial equipments. The results have proven the importance of domino effect assessment in the framework of risk analysis.

***Keywords*****:** *Domino effect; Quantitative risk assessment; Explosions; Fires; Storage areas.*

## 1. Introduction

The accidents caused by the domino effect are those that cause the most catastrophic consequences. The consequences of these latter are at various levels and may affect not only the industrial plants, but also people, environment and economy. The probability of domino effect is increasingly high due to development in industrial plants, the proximity of such establishments and their inventories of dangerous substances. The potential risk of domino effect is widely recognized in the legislation since the first "Seveso-I" Directive

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(82/501/EEC), which required the assessment of domino effects in the safety analysis of industrial sites whose activities are subject to this directive. Furthermore, the "Seveso-II" (96/82/EC) extended these requirements to the assessment of domino effects not only within the site under consideration, but also to nearby plants [1].

An inventory of the past domino accidents [2], reveals that explosion are the most frequent cause of domino effect (57%), followed by fires (43%). A study of 225 accidents involving domino effects [3], shows that storage areas are the most probable starters of a domino effect (35%), followed by process plant (28%). Also, the most frequent accident sequences are explosion-fire (27.6%), fire-explosion (27.5%) and fire-fire (18%).

To address the problem posed by the assessment and/or analysis of domino effects in industrial sites, several methods and software tools have been developed [4, 5, 6, 7]. An analytic methodology for the quantitative assessment of industrial risk due to accidents triggered by seismic events has been developed [8]. This procedure is based on the use of available data (historical data) to assess the expected frequencies and magnitude of seismic events. A method for assessing domino effects based on Monte Carlo simulation has been developed by [9]., the authors developed an algorithm, which is based on conducting several hypothetical experiments to simulate the actual behavior of a multi-unit system.

Recently, a review of methodologies and software tools used in the literature to the study of the cascading events [10], shows that, in the last decade, the available methodologies for the assessment of domino effects caused by heat load and overpressure to process equipments are based on the probit models [11, 12, 13].

The objective of this article is to present a methodology for the quantitative assessment of domino effects caused by heat radiation and overpressure to industrial/chemical plants and storage sites. Next-subsection is dedicated to a brief definition of the domino effect and its main features, potential sources of domino effects and the propagation process. Next, brief analysis of previous works is presented. In the third section we present a methodology for quantitative assessment of domino accidents in industrial sites. The fourth 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 and escalation*

There is no generally accepted definition of what constitutes domino effects in the context of accidents in the industrial plants, although various authors have provided suggestions [14, 15, 16, 17]. A domino accidental event may be considered as an accident in which a primary event propagates to nearby equipment (units), triggering one or more secondary events resulting in overall consequences more severe than those of the primary event [18].

The concept of escalation is a process that promotes the degradation of property (materials, equipments, systems industrials, ecosystems) and injury to people during development of the domino effect (increase damages). Thus, in the industrial field, we consider that any event spreading from equipment and/or industrial unit to another or from one site to another site should be classified as a domino event.

According to the case histories concerning past domino accidents, all the accidental sequences where a relevant domino effect has took place have three common features [19]:

- A primary accidental scenario, which initiates the domino accidental sequence;

- The propagation of the primary event, due to an escalation vectors, generated by the physical effects of the primary scenario, that results in the damage of at least one secondary target;

- One or more than one secondary accidental scenarios or events, involving the same or different plant units causing the propagation of the primary event.

### *1.2. Potential sources of domino effects*

Potential sources of domino effects are of different nature and are also linked to various initiating events. In general, they are distinguished by the nature of risks, from natural or anthropogenic. In the latter category, there are technological and organizational risks (unintentional) and the risks of malevolence (intentional), knowing that the purpose of study of domino effects takes into account the combination of these two risks. It is therefore possible to propose the decomposition of the nature of risks as follows:

a) Natural origins (geological origins and/or atmospheric mainly) [18, 20, 21]:

- Climate origin: forest fires, runoff and floods, avalanches, hurricanes and tornadoes, storms;

- Geological origin: landslides and earthquakes, tsunamis, volcanic eruptions and other natural emissions (gas, etc.).

b) Human origins (organizational and malevolence) [22, 23, 24]:

- Organizational origin: Humans failures (incorrect human action, lack of human action), defects in design, procedures and/or organizational;

- Malevolence origin, thefts, sabotage and/or revenge action, damage of any kind attacks. These actions may touch or affect the material, but also the personal or sensitive information.

c) Technological origin (fire, explosion and toxic releases):

- Fire: pool fire, flash fire, fireball and jet fire;

- Explosion: confined vapor cloud explosions (CVCE), boiling liquid expanding vapor explosion (BLEVE), vented explosion, vapor cloud explosion (VCE), dust explosion and mechanical explosion;

- Toxic chemicals release: from process or storage sites and transportation accidents.

These risks can be combined which significantly complicates the analysis. Sometimes, the very different nature of risks involves varied propagation processes. This also leads to the exploitation of different analysis methods (deterministic, probabilistic and quantitative methods).

### *1.3. The propagation process*

The propagation process is directly related to the potential source and the initiating event, but also to its immediate environment (field of danger). It is described by a physical-chemical process, but also informational whose evolution conditions are guided by features such as: physical (atmospheric, geological,

hydrological) and material (buildings, sites, facilities, roads,...), ecological (vegetation, animals), informational (detections, observations and information systems) and human (individual behavior, organization and logistics, local demography). For more detailed about the propagation of danger from potential source to a potential target and the concepts of "source" and "target" and systemic approaches, it is advisable to refer to references [25, 26].

## 2. Domino effect analysis

In the framework of domino effect analysis, the risk of explosion and fire, characterized by the possibility of an accident in an industrial site may lead to damage and serious consequences for the surrounding process equipment, people, goods and environment. These latter can generate four main events that may affect and/or cause the failure of the surrounding process equipments/units [27] :

- Overpressure/blast waves;
- Heat load;
- Projection of fragments (missiles);
- Toxic release.

Table 2. Probability models and threshold values for the heat radiation, Y is the probit function, ttf is the time to failure (sec), V is the vessel volume ($m^3$), and I is the amount of heat radiation received by the target vessel ($kW/m^2$) [36]

| *Equipment category* | *Threshold* | *Correlation* |
|---|---|---|
| *Atmospheric vessels* | $15kW/m^2$<br>$t \geq 10\ min$ | $Y = 12.54 - 1.847 \times ln\ (ttf)$<br>$ln(ttf) = -1.128 \times ln(I) - 2.667 \times 10^{-5}V + 9.887$ |
| *Pressurized vessels* | $50\ kW/m^2$<br>$t \geq 10\ min$ | $Y = 12.54 - 1.847 \times ln\ (ttf)$<br>$ln(ttf) = -0.947 \times ln(I) + 8.835 \times V^{0.032}$ |

Although several studies were dedicated to the assessment of domino effect caused by fires and explosions, only few models based on very simplistic assumptions are available for the assessment of equipment damage caused by heat load and overpressure in the framework of domino effect. The more simple approach proposed for the assessment of damage to equipment caused by fires and explosions. Several authors propose to consider zero probability of damage to equipment if the physical effect is lower than a threshold value for damage, and to assume a probability value of one if the physical effect is higher than a threshold value for damage [28,29, 30, 31].

A quantitative study, however, of the domino effect has been made by [32]. They have described possible approaches for quantifying the consequences of domino effects resulting from events giving rise to thermal radiation. A first approach evaluating the frequency accidental explosions was proposed by [33]. They provided a methodology for predicting domino effects from pressure equipment fragmentation.

A simplified model proposed by [34].allows to assess the damage probability of process equipment caused by blast wave. The model is based on "experimental" evaluation of equipment displacement with the subsequent

deformation and breakage of connections. The author defines the "probit function" (Y) relating equipment damage to the peak static overpressure ($P^0$) as follow:

$$Y = a + b \times \ln (P^0) \quad (1)$$

where $Y$ is probit function for equipment damage, P^0is peak static overpressure (Pa), $a$ and $b$ are the probit coefficients.

The probit approach has been followed by [35, 36], the authors have been published articles in which they analyzed and reviewed the existing models to develop a probabilistic model for damage evaluation of specific categories of industrial equipments.

The damage probability model proposed by the authors takes into account four categories of industrial equipments (atmospheric vessels, pressurized vessels, elongated vessels, and small equipments). The probit coefficients and thresholds for overpressure damage probabilities for four equipment categories are represented in the table 1.

Table 1. Probit coefficients for different equipment categories [36]

| **Equipment category** | **a** | **b** | **Threshold** |
|---|---|---|---|
| Atmospheric vessels | -18.96 | +2.44 | 22 kPa |
| Pressurized vessels | -42.44 | +4.33 | 16 kPa |
| Elongated equipments | -28.07 | +3.16 | 31 kPa |
| Small equipments | -17.79 | +2.18 | 37 kPa |

To estimate the time to failure *ttf* of industrial equipments exposed to fire. A well known simplified model proposed by [37] is based on the probit approach. The authors proposed damage probability models that take into account the categories of industrial equipments. Table 2 presents the thresholds and probit models for two equipment categories.

A methodology for domino effect analysis has been developed by [4] and, some applications in [38, 39]. The authors have cited that the intensity of heat radiation of 37 kW/m$^2$ is sufficient to cause severe damage to process equipment in other installations that operate under atmospheric conditions. Also, a peak overpressure of 70 kPa is enough to cause severe damage to process equipment and may generate new accidents, either associated to new explosions or new events involving fires.
A systematic procedure for the quantitative assessment of the risk caused by domino effect to industrial plants has been developed by [19]. This methodology aims to calculate the propagation probability of primary scenarios, the expected frequencies of domino events, and allowed to estimate the contribution of domino scenarios to individuals as well as societal risk.

On industrial sites/storage areas, the heat load and overpressure generated by BLEVE explosions of tanks containing gas or highly pressurized liquids are threats to other surrounding equipment and can lead to successive explosions and fires. Several studies have been done on modeling the impact of BLEVE explosions on industrial installations [40, 41, 42, 43, 44].

Boiling liquid expanding vapor explosions (BLEVEs) are among the diverse major accidents which can occur in process industries. It is usually associated with the explosion of tanks containing flammable liquids (LPG). Therefore, to the effects of the BLEVE, one must add those corresponding to the

fireball often occurring immediately after the explosion. On the whole, then, the physical effects from this type of explosion are usually i) thermal radiation, ii) overpressure (blast) and ii) fragments projection. The BLEVEs mechanism, the causes and consequences are presented by [45, 46].

Different formulas are used to quantify the heat radiation generated by fire. The radiation from fireball 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 [47]:

$$I(r) = \frac{\tau F_s D^2 m_\infty H_c}{16r^2} \tag{2}$$

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 [ $kg/(m^2.s)$], τ, is the atmospheric transmissivity coefficient, $H_c$is a combustion heat (kJ/kg), D is the pool diameter.
In experiments with explosives framework, the equivalent mass of TNT ($m_{TNT}$) was used to evaluate the effects of potential damage of a quantity of fuel (hydrocarbon) given. The combustion energy available in a cloud of steam was converted into an equivalent mass of TNT (kg). $m_{TNT}$ may be evaluated assuming that an exploding fuel mass behaves like exploding TNT on equivalent energy basis. Hence, the equivalent mass of TNT is estimated by using the following equation [48]:

$$m_{TNT} = \frac{\mu m \Delta H_c}{E_{TNT}} \tag{3}$$

where μ is the explosion efficiency (0.03 to 0.1), m is the mass of fuel involved in the explosion (Kg), $\Delta H_c$ is the energy of explosion of the flammable gas (energy/mass) (MJ/kg), $E_{TNT}$ is the energy of explosion of TNT (MJ/kg).

In an explosion, the peak overpressure may be estimated using the following equation:

$$P^0(r) = \frac{1616\left[1+\left(\frac{z_e}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{z_e}{0.048}\right)^2}\cdot\sqrt{1+\left(\frac{z_e}{0.32}\right)^2}\cdot\sqrt{1+\left(\frac{z_e}{1.35}\right)^2}} \tag{4}$$

where $P^0(r)$ is the peak of overpressure (kPa), and is atmospheric pressure (101.3 kPa), $z_e$ is a scaled distance ( $m/kg^{\frac{1}{3}}$ ) which may be estimated using an equivalent mass TNT ($m_{TNT}$) as follow:

$$z_e = \frac{r}{m_{TNT}^{\frac{1}{3}}} \tag{5}$$

where *r* is distance from the center of the explosion. Note that, $z_e$ can be calculated by setting the threshold of peak of overpressure for each equipment categories.

## 3. Methodology

An industrial site and storage areas contains many storage equipments/units under pressure that may be subjected to an external and/or internal incident. The escalation vectors (physical affects) generated after a unit rupture (explosion), may affect the surrounding units, building, personnel and environment. If the affected targets are damaged, these latter, may also explode and generate another threats to other surrounding facilities and so on. This accident chain is a domino effect and may lead to catastrophic consequences in an industrial plant.

### *3.1 Domino system*

We define a domino system as a system which consists at least of two subsystems ($S_1, S_2$), a source subsystem and a target subsystem (see Fig. 1):

- A source subsystem: its failure may generate a danger (physical effects) that may affect other surrounding subsystems (heat load, overpressure, fragments, toxic releases), and

- A target subsystem: it may be affected by the failure of sub-system sources. In addition to these physical effects, we may include the influencing factors that can influence or aggravate the target system damage (malicious acts, human and organizational factors, intervention system and weather conditions).

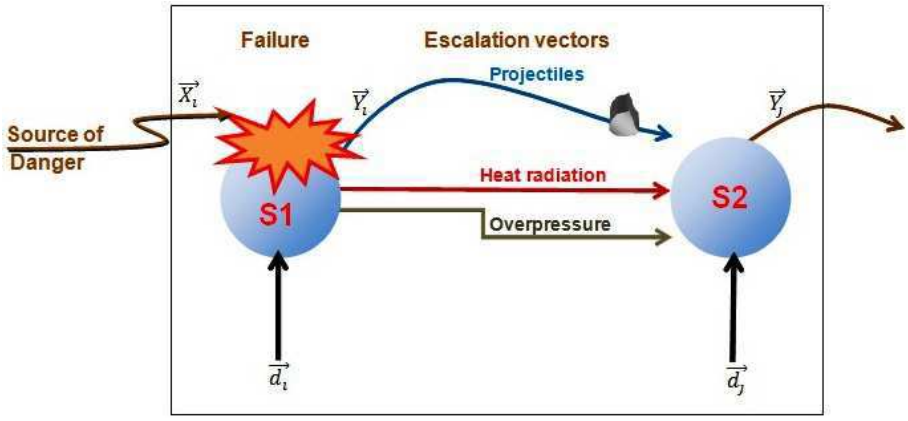


Fig.1: Domino system.

In the case of domino effect analysis, the failure of a subsystem depends on the dynamic characteristics of the escalation vectors (input vector), threshold values and the aforementioned influence factors. Then, the domino system can be described by the following vector function [49, 50]:

$$\vec{y} = N(\vec{x}, \vec{d}, t) \tag{6}$$

- $\vec{x} = (x_1, x_2 \dots, x_p)^T$: 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 and 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 thresholds);

- $\vec{y} = (y_1, y_2 \dots, y_k)^T$: is the vector of system output with $k$ dimensions, $y_i$ is random variable depending on input parameters.

### *3.2 Representation of system states*

An industrial system composed of several subsystems $(S_1, S_2, \dots, S_n)$. In the framework of domino effect analysis, each unit can be characterized by the following three main states [51, 52]:

$$S_i \begin{cases} State1, run\ state \\ State2, affected\ state \\ State3, failure\ state \end{cases}$$

- **State 1:** In normal operation, the output values corresponding to the input parameters of the system are less than the threshold values respectively. In this state, the unit may be affected by the escalation vector(s) generated by a primary event,
- **State 2:** While the intensity or the value(s) of escalation vector(s) is equal to its corresponding threshold value, the unit says affected, and

- **State 3:** While the value of the escalation vector(s) is greater than its corresponding threshold value.

To study the domino accidental sequence, one can take as starting point, the failure of at least one unit as initiating event. Based on the assumption, there is at least one failed subsystem. Figure 2 presents the possible transitions states in the case of two subsystems/units.

### *3.3 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 for an entry point is greater than its corresponding threshold value $y_{0i}$, the system says failed. Then, the failure function that describes the state of the system may define as follows:

$$G(\vec{x}) = \vec{y}_0 - \vec{y} \tag{7}$$

Where $\vec{y}_0$ is the threshold criterion (defined for each system) and $\vec{y}$ is the output of target system. If it exists *i* for which $G_i(x, t) < 0$ , then the system says failed.

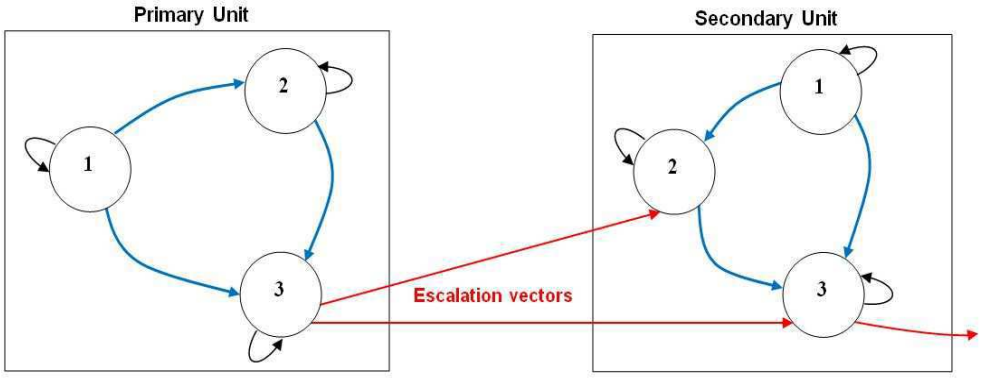


Fig. 2. Transition between states

After calculating the failure function, the failure probability $P_{f_i}$ for each escalation vector may be calculated by the following equation:

$$P_{f_i} = P[G_i(x,t) < 0] \tag{8}$$

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

$$P_{F_j} = P\left[\cup_{i=1}^{k}\{G_i(\vec{X}) < 0\}\right] \tag{9}$$

### *3.4 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 the whole system. Domino effect consists in interaction between a minimum of two zones. The damage radii and the impacted zones are presented in the figure 3. The damage level is increased in involved areas, but also on each impacted zone.

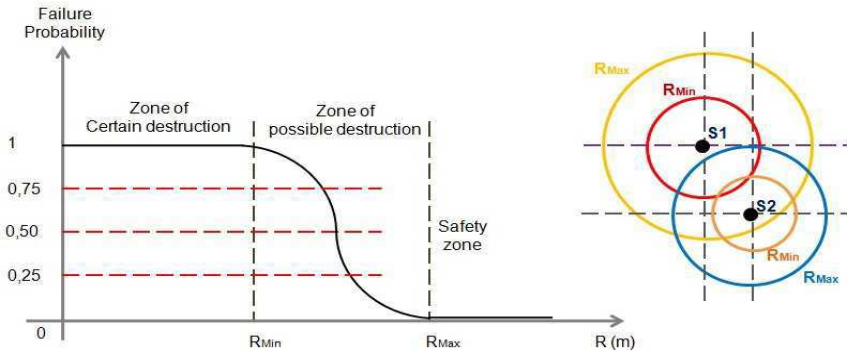


Fig.3. The affected zones

According to the figure 3, we can define three main affected zones i) zone of certain destruction; all process equipment located in this area are failed with failure probability $P_F = 1$, ii) zone of possible destruction; in this zone the failure probability is between $0 \leq P_F \leq 1$, and iii) safety zone; the failure probability of the process equipment $P_F = 0$.

The probability of each domino scenario (domino accidental sequence) may be calculated as follows:

$$P_{Do_i} = \prod_{j=1}^{n} P_{F_j} \tag{10}$$

where $n$ is the number of the failed sub-systems involving in the domino sequence, $P_{Do_i}$ is the joint probability that each unit from sequence $i$ fails.

## 4. The case-study

The above defined methodology was used in the case-study in order to assess domino effect in the case of storage area. Figure 4 shows the lay-out considered in this case study. The type of equipments/units and their inventory are shown in the table 3 bellow.

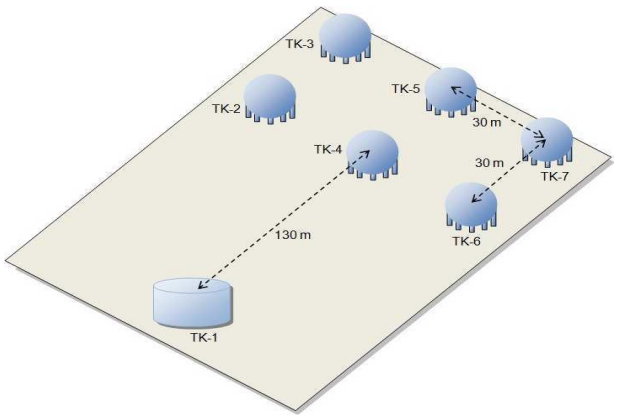


Fig.4. Lay-out used for the case study

Table 3. Equipment considered in the case-study

| Tank | Type | Substance | Content (t) | Failure frequency |
|---|---|---|---|---|
| TK1 | Pressurized tank | LPG | 150 | $9 \times 10^{-6}$ |
| TK2-7 | Atmospheric tank | Ethanol | 315 | $10^{-6}$ |

### *4.1 Effects on surrounding equipments*

We assume that a primary scenario has caused the rupture (catastrophic failure) of one tank. The latter can generate three escalation vectors; i) heat radiation, ii) overpressure wave and iii) fragments, these latter may affect the surrounding equipments.

Some simplifications are used in the present study, only the effects of heat radiation and overpressure wave has been considered. The influence parameters used in this case are tabulated in the table 4.

Table 4. The influence parameters used in the case of heat radiation and overpressure waves, R is spherical tank rayon.

| *Random parameters* | *Probabilistic distribution* |
|---|---|
| $E_{TNT}$: Explosion energy | $E_{TNT} \sim N(4.50, 0.15)$ |
| $m$: Mass involved in the explosion | $m \sim N(0.80, 0.04) \times m_t$ |
| $\mu$: Explosion efficiency | $\mu \sim N(0.65, 0.18)$ |
| $\tau$: Atmospheric transmissivity | $\tau \sim U(0.20, 0.80)$ |
| $F_s$: Fraction of the generated heat | $F_s \sim N(0.26, 0.08)$ |
| *D: Pool diameter* | $D \sim Log - N(\frac{ln(2R \times D_{max})}{2}, 0.26 \times ln\,(\frac{D_{max}}{2R}))$ |

In the case-study, only primary and secondary events were considered. The figure 5 shows the failure probability in function of the distance resulting from the explosion of the TK1 in case of overpressure effects. We can define three types of zone: i) zone of certain destruction, ii) zone of possible destruction, and iii) safety zone.

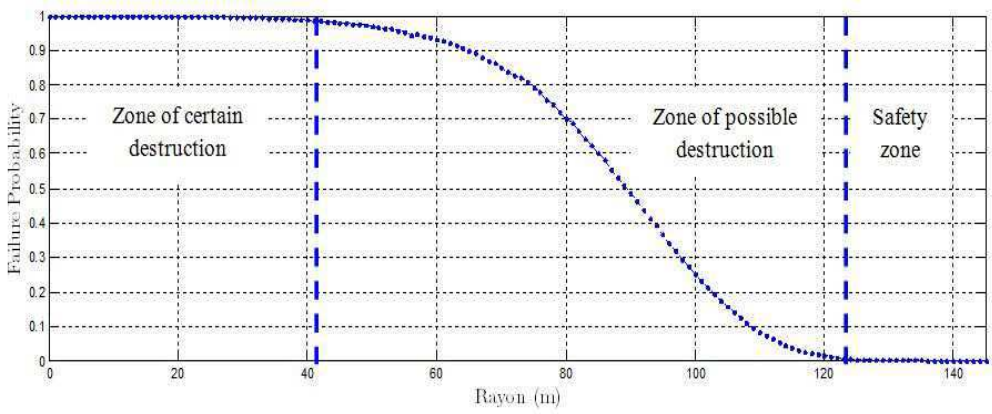


Fig. 5. Failure probability resulting from the rupture of the TK1 in the case of overpressure

We remark that the whole process equipment that are in the area limited by the radius of 132 $m$ have failed with failure probability $P_F = 9.4 \times 10^{-5}$ in the case of overpressure waves, and the radius of 420 $m$ with failure probability $P_F = 10^{-4}$ in the case of heat radiation.

The failure probability, $P_f$ due to the effects of the two escalation vectors (heat radiation and overpressure waves) are represented in the following table 5. The figure 6 presents the affected zones generated by the catastrophic failure (rupture) of the tanks in the case of heat radiation, $Z_1$ (zone of certain destruction) and $Z_2$ (zone of possible destruction) estimated for the failure probability $P_F = 0.9 \times 10^{-1}$ respectively.

Table 5. Probability $P_{f_j}$ due to the effects of heat radiation and overpressure

| Failed tank | Escalation Vector | Target tank | Failure probability |
|---|---|---|---|
| TK1 | Heat radiation | TK2-6 | $1.21 \times 10^{-1}$ |
| TK1 | Heat radiation | TK4 | $1.32 \times 10^{-1}$ |
| TK1 | Overpressure | TK2-6 | $7.51 \times 10^{-6}$ |
| TK1 | Overpressure | TK4 | $2.2 \times 10^{-4}$ |
| TK2 | Heat radiation | TK2-5-6 | $2.84 \times 10^{-1}$ |
| TK2 | Heat radiation | TK3-7 | $1.75 \times 10^{-1}$ |
| TK2 | Overpressure | TK2-5-6 | $9.46 \times 10^{-1}$ |
| TK2 | Overpressure | TK3-7 | $8.91 \times 10^{-1}$ |

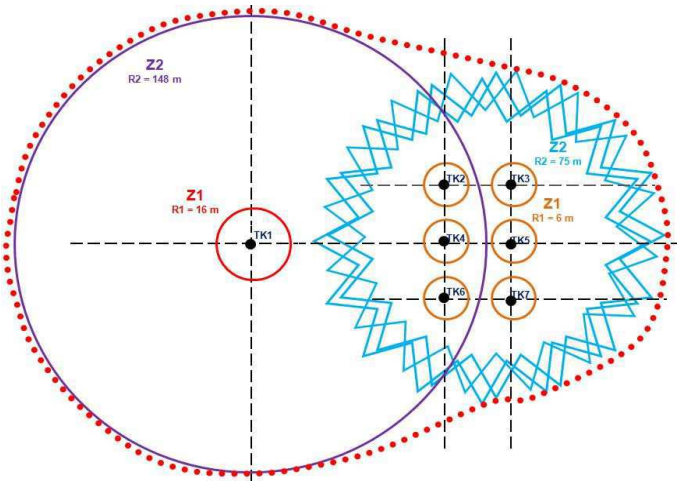


Fig.6: Affected zones Z1 and Z2 in case of heat radiation.

### 1.1. *Domino effect scenarios*

To estimate the domino effect sequences, we assume that the two events (heat radiation and overpressure waves) are independents. The probability of each domino sequence, $P_{DO_i}$ for each domino scenario is tabulated in the table 6.

Table 6. The probability for each considered domino scenario

| Scenarios | Domino effect sequence | Failure probability ($P_{Do_i}$) |
|---|---|---|
| 1 | TK1-TK4-TK5 | $1.17 \times 10^{-6}$ |
| 2 | TK4-TK6-TK7 | $1.08 \times 10^{-6}$ |
| 3 | TK4-TK6-TK7 | $8.75 \times 10^{-7}$ |
| 4 | TK5-TK4-TK1 | $2.02 \times 10^{-8}$ |

## 5. Conclusion

A quantitative method for the assessment of domino effects in industrial sites has been developed in this paper. It allows quantifying the effect of heat load and over pressuring waves in industrial plants and/or storage areas. Based on this method, we can evaluate the failure probability for each subsystem (unit), after the probability of domino scenario (domino sequence) may be evaluated for all the system. The three areas defined in this study (zone of certain destruction, zone of possible destruction, and safety zone) may be useful in the choice of safe distances between industrial equipments.

Domino effect caused by fragments is not studied in this paper. However, the projectiles generated by an explosion of a tank (unit) containing gas or highly pressurized liquids are threats to other surrounding equipment and can lead to successive explosions and a chain of accidents. Hence, domino effect caused by fragments must be considered to evaluate the total failure probability for each equipment resulting from the combination of these events (heat load, overpressure and fragments). Also, heat radiation and overpressure effects can affect not only the industrial equipments but also environment and people. So, a human vulnerability models to the heat radiation and overpressure effects should be developed to estimate the individual and societal risk.

The analysis above shows the importance of domino effect assessment in the framework of risk analysis. Hence, it shows that must much more importance be attached to the study of this phenomenon. Finally, domino effects need more scientific investigations, particularly in terms of quantitative assessment of risks and damage with probabilistic and deterministic modeling.

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