Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 45 (2012) 159 – 166

Procedia Engineering

www.elsevier.com/locate/procedia

2012 International Symposium on Safety Science and Technology

Explosions and structural fragments as industrial hazard: domino effect and risks

Ahmed MEBARKI[a,]*, Sandra JEREZ[a], Igor MATASIC[a], Gaëtan PRODHOMME[b], Mathieu REIMERINGER[b]

[a]*Université Paris-Est, Laboratoire Modélisation et Simulation Multi Echelle, MSME, UMR 8208* CNRS*, 5 Bd Descartes, 77454 Marne-La-Vallée, France*

[b]*INERIS, Institut National de l'Environnement Industriel et des Risques, Parc Technologique ALATA***,** *BP 2 - 60550 Verneuil-en-Halatte, France*

Abstract

This study deals with industrial accidents and domino effects that may occur in an industrial plant, the initial accident being supposed to take place in any of the tanks either under or at atmospheric pressure. This initial sequence might generate sets of structural fragments, fire balls, blast waves as well as critical losses of containment (liquid and gas) that threaten the surrounding facilities and may cause serious damages. The structural fragments, the blast wave and the fire ball can be described following database and feedback collected from past accidents. The vulnerability of the potential targeted tanks is investigated in order to assess the risk of propagation of the first sequence of industrial hazard. Cascading sequences of accidents, explosions and fires can take place, giving rise to the domino effect. This risk of domino effect occurrence is investigated herein. The interaction and the behavior of the targets affected or impacted by the first explosion effects are described by adequate simplified mechanical models: perforation and penetration of metal fragments when they impact surrounding tanks, as well as global failure such as overturning, buckling, excessive bending or shear effects, etc. Sensitivity analysis is performed thanks to Monte Carlo simulations: the probability of impact and risk of failure of target tanks are reported. A comparison between risks due to blast wave and fragments impacts is performed.

© 2012 The Authors. Published by Elsevier Ltd. Selection and/or peer-review under responsibility of the Beijing Institute of Technology. Open access under CC BY-NC-ND license.

Keywords: Industrial accidents, Explosions, Domino effect, Atmospheric tank, Tank under pressure, Failure risk.

1. Introduction

The hazardous substances that are produced and stored in industrial plants can, under severe conditions, generate explosions, fires and fragmentations of the tanks and the pipelines. Actually, internal or external conditions can trigger an initial sequence of a severe accident that may propagate and affect or impact the tanks, pipelines, power lines and facilities erected within the industrial plant. Catastrophic consequences may then affect the whole plant and its neighborhood, i.e. important structural damages as well as human losses or severe injuries.

Literature and past accidents reports show that industrial accidents may simultaneously give rise to blast waves, structural fragments generation and projection, fireballs producing thermal radiation or thermal flows as well as loss of confinement with ejection of potential flammable gases and liquids [1-4].

Modeling and analysis of the whole events and their specific effects (mechanical, thermal, chemical, etc) is still a complex scientific and multidisciplinary challenge [1; 5-13]:

---

* Corresponding author. Tel.: +33160957787; fax: +33160957799.
E-mail address: Ahmed.Mebarki@univ-paris-est.fr

1877-7058 © 2012 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2012.08.137

- *Triggering event*: The probability of occurrence as well as the thermodynamic and mechanical conditions for the first accident is assessed according to adequate modelling that may rely on past accidents and existing databases.
- *Subsequent effects and propagation*: generation and fragments ejection, blast wave and pressure front, fireballs and thermal flows, and confined products ejection (gases, liquids) as sub-events require mechanical modeling and adequate probabilistic description.
- *Effects on the surrounding facilities*: adequate behavior and response of the affected targets are required, such as penetration or perforation of the fragments as well as the damages suffered by the targeted facilities (tanks, pipelines, etc). Indirect effects can also take place such as fire ignitions for instance.
- *Successive sequences of accidents*: the sequences of sub-events taking place within the industrial plant are potential causes for domino effect initiation. Detailed analyses are then required.

The domino effect generates disastrous situation with an expected cost that is derived according to its socio-economic consequences weighted by its occurrence probability. Optimization of the global generalized cost is helpful in designing the required protective measures that might be decided by the stakeholders in order to mitigate the potential disaster, and protect adequately the most sensitive and highly strategic installations.

2. Domino effect and integrated probabilistic framework: theoretical considerations

2.1. General case: set of tanks and domino effect sequences

We consider the general case of an industrial plant containing several tanks under pressure or at atmospheric pressure, see Fig.1. A first accident or explosion can take place in any of these tanks, under a given set of internal or external causes, i.e.:

- *Internal causes*: corrosion, weak welding, cracking, over pressure or critical temperature of the stored gas or liquid, etc.
- *External causes*: malevolent acts, natural events such as strong quakes, tsunamis, explosions or impacts, fires and thermal effects, lightning, etc.

Each tank, denoted as a Source “S” of industrial hazard, may explode and generate mechanical, chemical or thermal threats to the other tanks and facilities within the plant. These potential sources of industrial hazard are denoted S(i) with i= 1 up to N_s, N_s being the number of tanks in the industrial plant. When an accident affects a given source S(i), it may generate one or various sub-events, i.e. :

- Sets of structural fragments that become projectiles when ejected from the tank source,
- A fire ball and thermal flows,
- A blast wave, and
- A loss of containment (gas and liquid losses).

The event E_1^g corresponding to any first accident has a probability of occurrence during any given reference period, T_{REF} (expected plant lifetime, for instance) defined as:

$$P\left(E_1^g\right) = P\left(E_1^g \Big|_{T_{REF}}\right) \tag{1}$$

The probability of occurrence of only one accident, once within the industrial plant, during the entire reference period, T_{REF}, can be defined as:

$$\begin{aligned} P\left(E_1^g \Big|_{T_{ref}}\right) = & \left[N_a.\left(\left(\lambda_a.T_{REF}\right).e^{-(\lambda_a.T_{REF})}\right).\left(1-\left(\lambda_a.T_{REF}\right).e^{-(\lambda_a.T_{REF})}\right)^{N_a-1}\right] + \\ & \left[N_p.\left(\left(\lambda_p.T_{REF}\right).e^{-(\lambda_p.T_{REF})}\right).\left(1-\left(\lambda_p.T_{REF}\right).e^{-(\lambda_p.T_{REF})}\right)^{N_p-1}\right] \end{aligned} \tag{2}$$

Where: λ_a, λ_p= average yearly accident ratios for the source tanks, respectively, at atmospheric pressure (total number of such tanks= N_a) or under pressure (total number of such tanks= N_p).

The propagation as industrial hazard threatening the other tanks and facilities has a probability of occurrence defined as:

$$P\left(E_1^{propa}\right) = P\left(E_1^{propa} \Big|_{E_1^g}\right).P\left(E_1^g\right) \tag{3}$$

The sub-events, i.e. structural projectiles, blast wave, thermal effects and containment loss, may cause damages to the targets erected in the vicinity of the sources. The probability of damages occurrence is defined as:

$$P\left(E_1^{\text{damage}}\right)=P\left(E_1^{\text{damage}}\Big|_{E_1^{\text{propa}}}\right)P\left(E_1^{\text{propa}}\Big|_{E_1^{g}}\right)P\left(E_1^{g}\right) \tag{4}$$

The targets may be seriously damaged and may give rise to a new sequence of accidents (explosions, fires, etc). For the general purpose, one could say that any sequence E_n^g, where n is the range of the accidents sequence (n≥1), can give rise to an additional sequence (n+1), event E_{n+1}^g, with a probability of occurrence defined as:

$$P\left(E_{n+1}^{g}\right)=P\left(E_{n+1}^{g}\Big|_{E_n^{\text{damage}}}\right)P\left(E_n^{\text{damage}}\Big|_{E_n^{\text{propa}}}\right)P\left(E_n^{\text{propa}}\Big|_{E_n^{g}}\right)P\left(E_n^{g}\right) \tag{5}$$

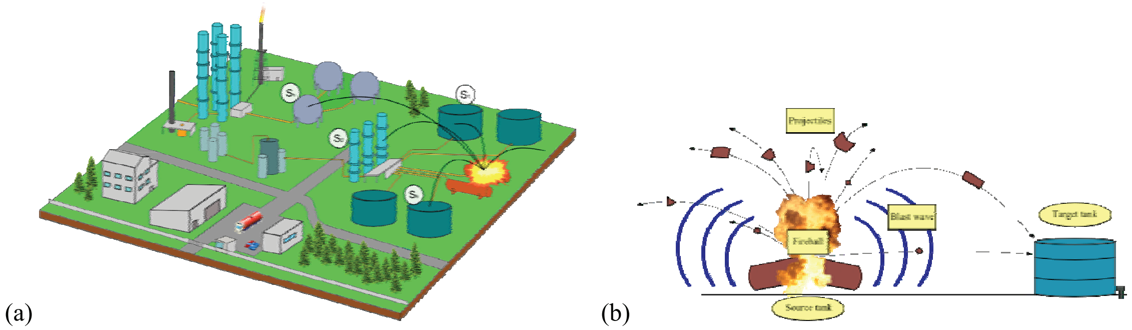

Fig. 1. Illustration of a generic industrial plant with (a) First accident sequence and its propagation (b) Detailed events.

2.2. Decision making and domino effect mitigation

The industrial accidents have in general several consequences of great importance, such as:

- Socio-economic and employees' jobs losses due to production interruption, reconstruction, repair or strengthening of the industrial plant,
- Environmental consequences in case of containment losses such as liquids or gases,
- Fires that threaten the whole plant as well as the surrounding buildings, facilities, installations, etc
- Threats to the health and physical integrity of the employees and inhabitants in case of toxic products release, etc.

In order to reduce or mitigate the disaster, one may consider either, see Fig.2:

- reduction of the hazards and threats by isolating the sources of possible accidents,
- reduction of the vulnerability of the potential targets by protective measures (better design, barriers and protections, erection of buildings, tanks and installations with large relative security distances),
- regular inspections and severe security measures, etc.
- protection against confinement losses such as containment and retention basins in case of petrol oil, for instance,
- use of automatic protective systems such as shutdown systems, alarms, fire protection, etc.

From a theoretical point of view, for any general configuration (industrial plant, surrounding buildings, facilities and other plants, strategic installations, operational headquarters, etc), the total expected cost of losses is, [14]:

$$C_{\text{losses}}^{g}=\sum_{k=1}^{n}P\left(E_k^{g}\right)C_k^{g} \quad \textit{where} \quad P\left(E_k^{g}\right)=P\left(E_k^{g}\Big|_{E_{k-1}^{\text{damage}}}\right)P\left(E_{k-1}^{\text{damage}}\Big|_{E_{k-1}^{\text{propa}}}\right)P\left(E_{k-1}^{\text{propa}}\Big|_{E_{k-1}^{g}}\right)P\left(E_{k-1}^{g}\right) \tag{6}$$

where : C_k^g = socio-economic losses as consequences of the sequence k of the domino effect, k=1 up to the range n of sequences under study (until the total plant is destroyed or reaches a given threshold of destruction, C_{losses}^g = mathematical expected value of the socio-economic consequences on the whole industrial plant and its concerned vicinity.

In order to mitigate the industrial disaster, the stockholders may decide to adopt several protective solutions in order to optimise the economic investments so that to reach the optimal global cost:

$$C_{\text{opt}}^g = \text{Min}\left\{ C_0^g + \Delta C_0^g + \sum_{k=1}^{n} \left(P\left(E_k^g\right) + \Delta P\left(E_k^g\right) \right) C_g \right\} \tag{7}$$

where: C_{opt}^g = optimal global cost of the entire zone (industrial plant and its affected surroundings), C_0^g = initial global cost before adopting any additional protective measures so that the initial risk of domino effect $P\left(E_k^g\right)$ is reduced by $\Delta P\left(E_k^g\right)$ as consequence of the protective measures.

In fact, this optimal global cost seems theoretically easy to be calculated. In fact, several aspects such as respect of human life, pollutions and aggressive products release, reactions of the public opinion and political decisions make this optimization not so easy to be reached in practice. However, this theoretical formulation may also be helpful in prospecting objective investments and accompanying measures (survey and early warning systems, automatic control and shutdowns, protective barriers, vicinity planning and organization) that result in risk reduction, disaster mitigation and satisfy resilience and quick recovery requirements.

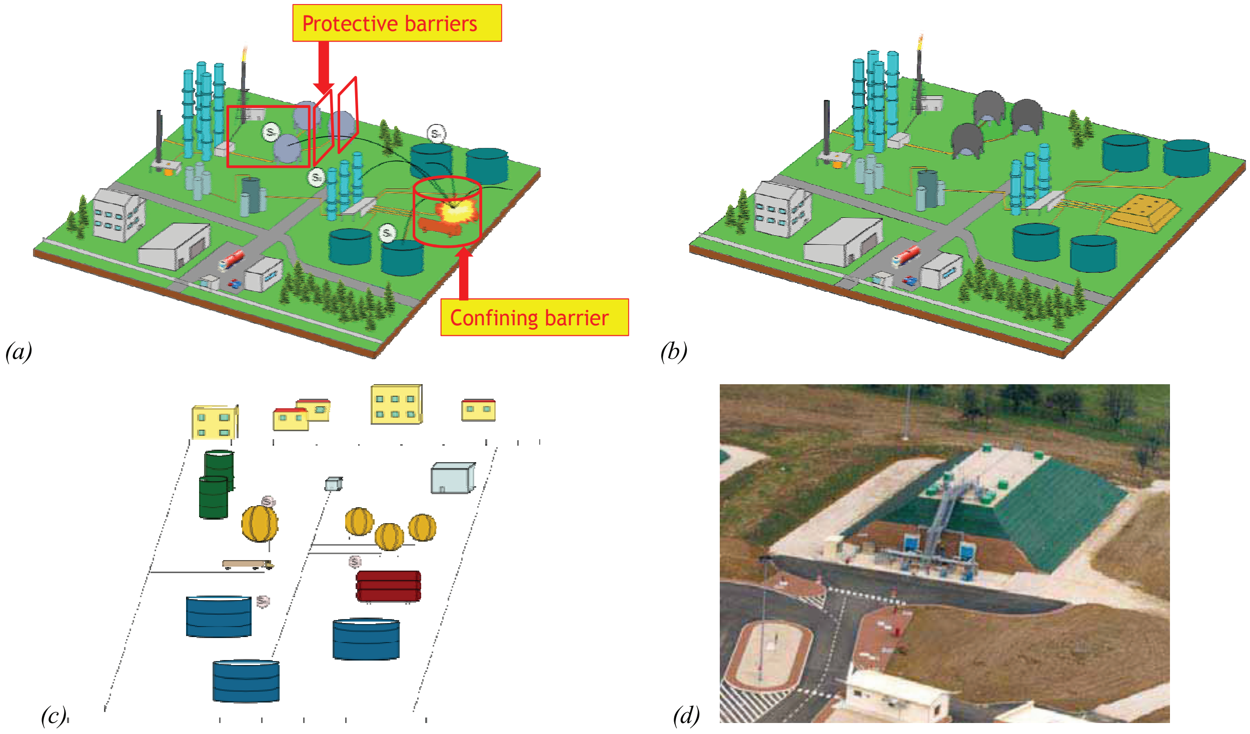

Fig. 2. Protective measures regarding potential sources or targets.

3. Applications and sensitivity analysis

3.1. Risk of failure

The present study considers the case of tanks with various filling levels. The present case is restricted to the analysis of the fragments impacts and the blast wave. For sake of simplicity, the thermal flows effects and the containment losses effects are not included in the present results.

Monte Carlo simulations are used in order to evaluate the probability of impacts as well as the probability of failure.

3.2. Structural fragments: Probability of impacts and risk of failure

The probability of failure is obtained by Monte Carlo simulations as, [8-12; 14]:

$$P_{rup} = \sum_{k=1}^{N_{sim}} \frac{1_{(\text{State of a target} \neq 0)}(k)}{N_{sim}} \tag{8}$$

With:

$$1_{(\text{State of a target} \neq 0)}(k) = \begin{bmatrix} 1 \quad \text{if a target is completely damaged} \\ 0 \quad \text{if not} \end{bmatrix} \tag{9}$$

And: N_{sim}= total number of simulations.

Table 1. Probabilistic description of the structural fragments [8-9]

Random variable	Probability density function	Probability density function formulas	Comments and Details
Number of fragments (n)	Discrete exponential distribution	$p_N(n) = e^{(-\lambda_0 - \lambda_1 n - \lambda_2 n^2)}$	λ_0, λ_1 and λ_2 are multipliers of Lagrange obtained from the accidental data
Relative frequency of any projectile form (f_p)	Uniform distribution by intervals	f_p	-
Projectile mass (m_p)	Uniform distribution	$m_p = V_p \times \rho$	Volume of fragments is a product of random variables and follows a uniform distribution.
Projectile departure velocity (v_p)	Uniform distribution	$v_p = \sqrt{\frac{2E_c}{m_p}}$ $E_c = \alpha E_{exp}$	Velocity of projectiles depends from the kinetic energy transmitted to projectiles. Kinetic energy is a fraction of the explosion energy which can be represented by the ratio α. This factor follows a uniform distribution.
Horizontal departure angle (□)	Uniform distribution by intervals	□	
Vertical departure angle (φ)	Uniform distribution	φ with arcsin (φ) following uniform distribution.	

Furthermore, a uniform random variable, H, is considered in order to express the filling level of a source tank. Its values range within the interval[0; H_{max}], where H_{max} is the maximal filling level of a tank.

The trajectory of the fragments and their impact on target tanks are evaluated according to existing developments [8-9].

3.3. Blast waves: Effects on target tanks and Risk of failure

After an explosion, a blast wave moves through the air and in contact with surrounding tanks it can produce mechanical effects on affected tanks, resulting in:

- Excessive bending,
- Tank overturning,
- Global buckling,
- Tank sliding on the ground surface, and
- Excessive shear and bending of the target anchors.

3.4. Results and Comments

For illustrative purposes, the source tank is cylindrical and pressurized, whereas the target tank is at atmospheric pressure, see Table 2. The source tank content is liquefied propane. Target tank is supposed without any liquefied content, full of evaporated gas-oxygen mixture. With this assumption, secondary effects due to liquid dynamic movement are intentionally neglected and, on the other side, a target tank is more prone to mechanical damage.

Table 2. Case study: source and target tanks definition

Parameter	Source tank	Target tank
Radius (R)	3.5 m	6 m
Length (L)	15 m	12 m
Capacity (V)	757 m^3	1350 m^3
Shell thickness (e)	0.007 m	0.005 m
Burst pressure (P_e)	800000 Pa	-
Ultimate stress (σ_u)	360 Gpa	360 Gpa
Ultimate strain (ε_u)	0.23	0.23

The target tank is located at a distance of 100 meters from the source tank. Considering the origin of coordinate system at the centre of source tank, the centre of the target tank is then located at (100m: horizontal distance, 0m, 6m: height). Table 3 provides the results obtained from the simulations, i.e.: projectiles impacting the target, distribution of projectiles and distribution of projectiles kinetic energy at the impact on the ground for each angular sector, see Table 3 and Fig. 3.

Table 3. Properties of the structural fragments ejected as projectiles impacting the target

Parameter	Value
Average speed at the impact	82.98 m/s
Average kinetic energy at the impact	14.463 MJ
Average mass of projectiles	8954 kg
Ratio of end cups	9.09 %
Ratio of elongated end cups	45.45 %
Ratio of plates	45.45 %
P_{imp} : Probability of the impact	**$5.5x10^{-3}$**

From the results of simulations for projectiles impact and overpressure wave impact on the atmospheric tank it is possible to compare levels of risk from each phenomena and for different levels of damage. It is found that overpressure waves can produce significant damage at the near field. On the other hand, risk of projectiles impact is much lower at the near field but projectiles can trigger the domino effect at much higher distance.

Fig. 4 shows that the probability of failure from the blast wave is 3 to 7 times greater than the probability of failure produced by projectiles. Also, in this model only massive projectiles are considered as the potential projectiles and small, light projectiles are intentionally neglected.

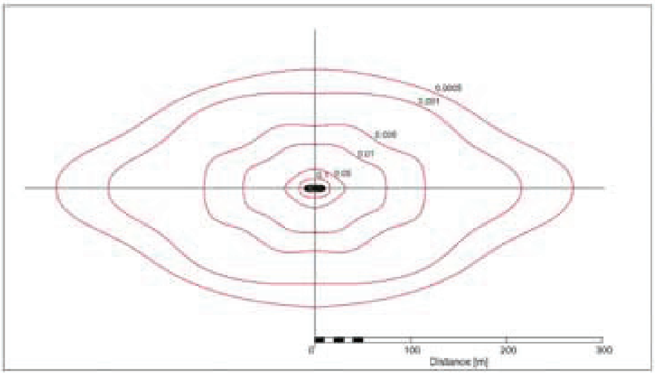

Fig. 3. Distribution of projectiles: iso-values of probability of impact.

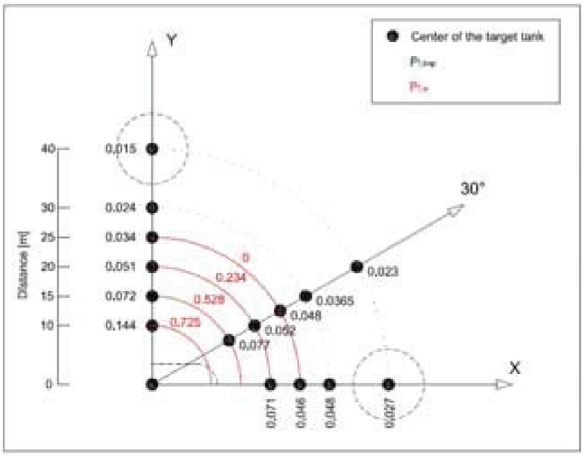

Fig. 4. Iso-values of probability of failure: Probability of tank failure from the projectiles and the overpressure wave impact.

4. Conclusions

The domino effect is a cascading sequence of accidents and explosions, disseminating from an initial source to the surrounding tanks in an industrial plant. Under these successive sequences, the industrial plant and the facilities, constructions and also human beings are severely threatened and may be suffer important and irreversible losses.

The study of this effect from the initial possible accident until the propagation within the plant requires multi-disciplinary approaches. The purpose of the present study if to provide a theoretical formulation that describes and evaluates the risk of occurrence of the triggering event, due to external or internal causes, the propagation effect as it may produce four sub-events, mainly: fragments ejected as projectiles, blast waves, fire balls as well as loss of confinement.

Probabilistic formulation is developed in order to describe the occurrence of the first event, as well as the probability of occurrence of the four sub-events. The interaction between the surrounding vessels and facilities and the mechanical as well as thermal effect of these sub-events may cause global or local damage as well as a possible fire ignition and explosion taking rise within the affected targets or their immediate vicinity such as pipelines and power lines, for instance. Mechanical, thermo-mechanical and also chemo-thermo-mechanical analyses are therefore required in order to quantify the resulting effect on the considered targets (tanks or power lines impacted, heated, blasted, etc). In the case of impact by structural fragments for instance, penetration and perforation as well as interaction projectile-impacted tank need the use of adequate material and structural behaviours, performed in general by numeric simulations.

This study provides the theoretical aspects that should be considered for a detailed analysis of the domino effect. Relying on these developments, numeric simulations can be performed and sensitivity analysis as well as critical scenarios can be studied.

For the case study considered in this paper, it is found that overpressure waves can produce significant damage at the near field. On the other hand, risk of projectiles impact is much lower at the near field but projectiles can trigger the domino effect at much higher distance. Actually, the probability of failure from the blast wave is 3 to 7 times greater than the probability of failure produced by projectiles. Also, in this model only massive projectiles are considered as the potential projectiles and small, light projectiles are intentionally neglected.

Relying on the expected numeric results, one may perform an optimisation of the generalised cost resulting from initial costs and expected socio-economic consequences. Adequate investments and protective options can then be objectively decided by the stakeholders in order to mitigate the potential disasters and aim a quick recovery.

Acknowledgements

This paper is a synthesis of research works developed in the framework of various research programs: VULCAIN and INTERNATECH, with financial support provided by French Agence Nationale de la Recherche (ANR: *PGCU 2007*, and *Flash Japon 2011*). The Chinese-French bilateral cooperation program PHC XU GUANGQI 2012 (Code Project: 27939XK) has also been helpful for the preparation and final redaction of the present paper.

References

[1] Abbasi, T. and Abbasi, S.A, 2007. The boiling liquid expanding vapour explosion (BLEVE): Mechanism, consequence assessment, management. *Journal of Hazardous Materials*, 141: 489-519.

[2] ARIA base of BARPI, France (www.aria.environnement.gouv.fr)

[3] Holden P.L., 1988. Assessment of missile hazards: Review of incident experience relevant to major hazard plant. Safety and reliability directorate, Health & Safety Directorate.

[4] Lees F.P., 2005. *Prevention in process industries*, Butterwort Heinemann,

[5] Antonioni G., Spadoni G. and Cozzani V. Application of domino effect quantitative risk assessment to an extended industrial area. *Journal of Loss Prevention in the Process Industries*, 22: 614-624.

[6] Cozzani V. Salzano E, 2004. The quantitative assessment of domino effects caused by overpressure- Part I: Probit models, *Journal of Hazardous Materials*, A107: 67–80.

[7] Marhavilas P.K., Koulouriotis D. and Gemeni V, 2011. Risk analysis and assessment methodologies in the work sites : On a review, classification and comparative study of the scientific literature of the period 2000-2009. *Journal of Loss Prevention in the Process Industries*, 24(5): 477-523.

[8] Mébarki A., Mercier F., Nguyen Q.B., Ami Saada R., 2009. Structural fragments and explosions in industrial facilities. Part I: Probabilistic description of the source terms, *Journal of Loss Prevention in the Process Industries*, 22: 408–416.

[9] Mébarki A., Mercier F., Nguyen Q.B., Ami Saada R. , 2009. Structural fragments and explosions in industrial facilities. Part II: Probabilistic description of the source terms, *Journal of Loss Prevention in the Process Industries*, 22: 408–416.

[10] Mébarki A., Mercier F., Nguyen Q.B., Ami Saada R., Meftah F. Reimeringer M, 2007. A probabilistic model for the vulnerability of metal plates under the impact of cylindrical projectiles. *Journal of Loss Prevention in the Process Industries*, 20: 128–134.

[11] Mébarki A., Mercier F., Nguyen Q.B., Ami Saada R., Meftah F., Reimeringer M, 2008. Reliability analysis of metallic targets under metallic rods impact: Towards a simplified probabilistic approach. *Journal of Loss Prevention in the Process Industries* 21: 518– 527.

[12] Mingguang Z. and Juncheng J, 2008. An improved probit method for assessment of domino effect to chemical process equipment caused by overpressure. *Journal of Hazardous Materials*, 158: 280 – 286.

[13] Talaslidis D.G., Manolis G.D., Paraskevopoulos E., Panagiotopoulos C., Pelekasis N. and Tsamopoulos J.A. , 2004. Risk analysis of industrial structures under extreme transient loads. *Soil Dynamics and Earthquake Engineering*, 24: 435-448.

[14] Mébarki A., Genatios C., Lafuente M., 2008. *Risques Naturels et Technologiques : Aléas, Vulnérabilité et Fiabilité des Constructions – vers une formulation probabiliste intégrée*, Presses Ponts et Chaussées, ISBN 978-2-85978-436-2, Paris.