# Domino effect analysis in industrial sites

Louise Sandoval, Agnès Vallee, Benjamin Le-Roux, Gaëtan Prod'Homme, Franck Prats

# Domino effect analysis in industrial sites

Louise Sandoval*, Agnès Vallée, Benjamin Le-Roux, Gaëtan Prod'Homme, Franck Prats

Institut National de l'Environnement Industriel et des Risques (INERIS), Direction des Risques Accidentels, B.P.2, Parc ALATA, 60550 Verneuil-en-Halatte
*louise.sandoval@ineris.fr]

## 1. Introduction

Among all industrial accidents, those involving domino effects, that means the complex escalation and propagation of an accident in chemical and process industries, are amongst the most damaging. This kind of accident can lead to consequences over the population and the environment around the installations involved. For example, catastrophic accidents can be mentioned as that in Feyzin (1966), in Mexico City (1984), in Tianjin (2015).
The good knowledge of cascading effects and their management is a real issue within an industrial site.
This article introduces an approach developed by INERIS to better understand domino effects and help writers to integrate domino effects in hazard studies or in specific domino effect studies.
This approach proposes the identification and assessment of domino scenarios. It follows work accomplished since 2002 about structural resistance due to accidental load.

## 2. Aim of the method

The aim of this method is to develop an approach based on the evaluation of dominos effects in industrial establishment beside regulatory studies such as security report in France. This approach is also based on different degrees of complexity for the structural vulnerability assessment. The current French practice on safety report (for SEVESO facilities) is only based on threshold approach; it can lead to conservative or dangerous assessment.

INERIS defines a domino accidental event as the result of a dangerous phenomenon occurring on a first equipment triggering a second one or more and leading to a secondary scenario; only if consequences are more severe than those of the primary event.

According to feedbacks available on the database ARIA (BARPI), explosions are the most frequent cause of domino effect (51 %) followed by fire (49 %). In 96 % of domino effect events, 62 % includes one domino sequence and 34 % concerns two domino sequences maximum.

This method draws on methods developed in Europe, such as:

- the method developed in Belgium by the Polytechnic Faculty of Mons (FPM), 1998;
- the RIVM approach (National Institute for Public Health and the Environment, Netherlands), 2003;
- the HSE approach (Health and Safety Executive, UK), 1998;
- the method suggested by UIC (Chemical Industry Association), in France, 2017.

## 3. Vulnerability approach

The vulnerability can be defined as the susceptibility degree of a system to collapse or degrade under certain types of effects. Several ways to evaluate the structural damage causes on target are proposed in this method (several degrees of complexity):

- The simplest way is to use careful damage threshold value for all facilities or to use damage threshold value for different equipment category or referring to experience feedback (level 1);
- Another way is to refer to abacus to characterize the damage more carefully (level 2);
- The most complex method is to use advanced modelling (level 3).

The choice of the degree is made by the user needs and the knowledge of phenomenon.

### 3.1 Threshold-based approach and thresholds based on experience feedback (level1)

Threshold approach is based on regulation thresholds, as in safety report or experience feedback. For the record, the French threshold values are provided in the ministerial decree of September the 29th, 2005.

- 8 kW/m² for heat radiation effects;
- 200 mbar for overpressure effects.

A modulation of these thresholds is possible depending on facilities' materials and structures used.
Note that other thresholds are proposed in the French regulation for flammable liquids and in pyrotechnic sector.

The use of threshold values to identify the possible domino targets is a common practice in the analysis of domino hazard. The damage threshold value for different equipment category can also be based on post accidental feedback; for example, destruction damage of pipe rack around 400-550 mbar (Green Book TNO 1989) or rupture of atmospheric storage tanks around 160-200 mbar (Ollen 2005, Cozzani & 2004).

The following table specifies the types of equipment for which various empirical thresholds defined on experience feedback (for information proposes only).
For a given equipment (atmospheric, horizontal, small or pressurized), which contains a flammable substance and under X bar pressure, potential leakage and dangerous phenomenon are deduced.

*Table 1: Dominos effects thresholds for one type of equipment and PhD (Cozzani V., Salzano E.)*

| Collapse blast loading | Equipment | | | |
|---|---|---|---|---|
| | Atmospheric | Horizontal | Small (a few m$^3$) | Pressurized |
| Small leakage | 70 mbar<br>Small pool fire | 140 mbar<br>Small pool fire<br>Small flash fire | 120 mbar<br>Small pool fire<br>Small flash fire | 300 mbar<br>Small jetfire |
| Medium leakage | 160 mbar<br>Pool fire<br>Flash fire<br>UVCE | 370 mbar<br>Pool fire<br>Flash fire<br>UVCE | 370 mbar<br>Small pool fire<br>Small flash fire | 380 mbar<br>Jetfire<br>Flash fire<br>UVCE |
| Global collapse | 200 mbar<br>Pool fire<br>Flash fire<br>UVCE | 450 mbar<br>Pool fire<br>Flash fire<br>UVCE | 590 mbar<br>Small pool fire<br>Small flash fire | 610 mbar<br>BLEVE<br>Flash fire<br>UVCE |

### 3.2 Abacus (level 2)

To characterize the damage more carefully, abacus can be used. It permits to characterize damage on industrial facilities without realizing refined models and keeping careful assessment.
Abacus are available for different industrial equipment (atmospheric storage equipment, pipeline, etc.), considering criteria (intensity level, application time) and the technology used. Usually, table are for heat radiation or abacus for overpressure effects.
For example, the vulnerability analysis is detailed of the case of an LPG storage under thermal effects. The thermal load applied is a full fire engulfment. Parameters are:

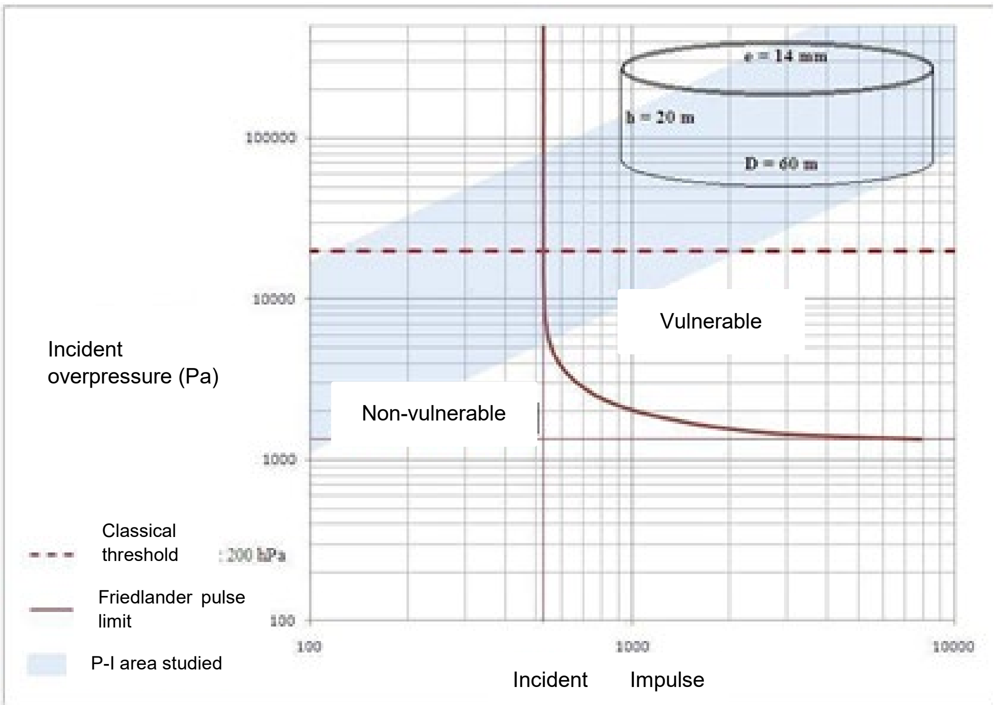
- total tank volume;
- storage filling rate;
- nominal diameter of the PRV (Pressure Relief Valve).

*Table 2: Time before BLEVE occurrence for 3 storages (15 m³, 30 m³ and 60 m³) caught fire (Casceff)*

| Volume ($m^3$) | Length (m) | Radius (m) | Filling rate (%) | Nominal diameter of pressure relieve valve (mm) | Elapsed time before BLEVE (seconds) |
|---|---|---|---|---|---|
| 15 | 4,6 | 1 | 20 | NO | 357 |
| 30 | 6 | 1,20 | | NO | 389 |
| 60 | 12 | 1,22 | | NO | 406 |
| 15 | 4,6 | 1 | | DN45 | 820 |
| 30 | 6 | 1,2 | | DN45 | 830 |
| 60 | 12 | 1,22 | | DN45 | 835 |
| 15 | 4,6 | 1 | 50 | N0 | 371 |
| 30 | 6 | 1,20 | | N0 | 405 |
| 60 | 12 | 1,22 | | N0 | 427 |
| 15 | 4.6 | 1 | | DN45 | No collapse |
| 30 | 6 | 1.20 | | DN45 | No collapse |
| 60 | 12 | 1.22 | | DN45 | 470 |
| 15 | 4.6 | 1 | 80 % | NO | 362 |
| 30 | 6 | 1.20 | | NO | 389 |
| 60 | 12 | 1.22 | | NO | 417 |
| 15 | 4.6 | 1 | | DN45 | No collapse |
| 30 | 6 | 1.20 | | DN45 | 391 |
| 60 | 12 | 1.22 | | DN45 | 417 |

P-I diagram is commonly used in overpressure resistance domain. This diagram couples overpressure intensity (area under the curve) to impulse. The following diagram gives, for example, the damage curve for an empty tank of 60,000 m³ depending on maximal overpressure and the impulsion associated to an explosion. So, the vertical asymptote corresponds to short impulse charges and the horizontal one corresponds to quasi-static loadings.

*Figure 1: Impulsion – Pressure diagram (PI) vulnerability of a 60,000 m³ empty tank (Duong D.H and al.)*



### 3.3 Refined models (level 3)

Modelling tools permit editor to forecast structure damage caused by heat radiation or overpressure effects. Tools are described in INERIS report "Référentiel sur la résistance des structures aux actions accidentelles (2007)". For example, modelling tools permit to better analyze the source term and can consider the environment of industrial plants.

## 4. Domino effect analysis developed by INERIS

This iterative methodology is composed by four main stages:

- Identification of equipment in the study perimeter (steps 0, 1, 2);
- Identification of domino effect sequences: using threshold values, abacus or modelling (Steps 3,4 5);
- Risk evaluation and assessment: determination of probability and severity rate, crossing grid probability / severity (Step 6);
- Risk reduction and refine the hypothesis: using the different levels to evaluate the structural damage causes on target or setting up measures to reduce risks (Step 7).

This methodology is based for the identification of domino scenarios and for the assessment of consequences and expected frequencies of the escalation events.

### 4.1 Step 0: Study perimeter identification and goal

The first step is the identification of the study perimeter and the goal to reach. The study area can be one unit, a part of an establishment or the industrial plant. Note that the study writer is free to make his own perimeter, according to his goal.
The writer can also define an acceptation grid (probability / severity) to positioned potential domino scenarios (step 7). An example is given here, based on the French approach. The red means that the risk is considered as non-acceptable, the green means that the risk is considered as acceptable and the yellow means that the risk can be acceptable if safety measures are considered.

*Figure 2: Example of acceptation grid*

| S \ P | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ |
|---|---|---|---|---|---|
| Disastrous | yellow | yellow | red | red | red |
| Catastrophic | yellow | yellow | yellow | red | red |
| Important | yellow | yellow | yellow | yellow | red |
| Serious | green | green | green | yellow | yellow |
| Low | green | green | green | yellow | yellow |

### 4.2 Step 1: Equipment identification

This step is the identification of equipment that may be damaged by effects (thermal, overpressure) generated by the primary accidental scenario in the area determined previously, in step 0.

### 4.3 Step 2: Identification of equipment that can cause damage

This step consists on the identification of equipment that may cause damage, inside (storage area, utilities, gas pipeline, etc.) and outside (transport infrastructure, other industrial sites, etc.) the defined area and that can have an impact on target equipment. This identification draws on activity risk inventory about the plant and the knowledge of the study area.

### 4.4 Step 3: Vulnerability approach

The research of potential domino effect sequences begins. The first step is based on threshold values. A careful global threshold, for each type of effect, is defined for all equipment identified in Steps 1 and 2. This threshold is determined by the prescriber.
Vulnerability approaches are described in paragraph 3.

### 4.5 Step 4: Intensity of the escalation vector for the primary scenarios

This characterization can be realized using qualitative approach or using models.

Qualitative approach: the intensity of the escalation vector can be characterized in the qualitative way, depending on all information known about industrial facilities that may cause damage and drawing on experience feedbacks.

Quantitative approach: models can be used to characterize the intensity of the escalation vector, in quantitative way. Input data required are:

- Source term of facilities that may cause damage;
- Type of effect (thermal or overpressure);
- Domino effect thresholds chosen by the writer.

For example, the following table can be the result of this step.

*Table 3: Example of intensity characterization for three equipment*

| Equipment that can cause damage | Dangerous phenomenon | Type of effect | Dominos effect distances according to thresholds (for example: 7 kW/m$^2$ and 180 mbar) |
|---|---|---|---|
| Hydrocarbon storage tank | Storage tank fire | Thermal | 80 m |
| | Collapse | Overpressure | 150 m |
| Natural gas piping | Jet fire | Thermal | 70 m |
| | Pool fire | | 25 m |

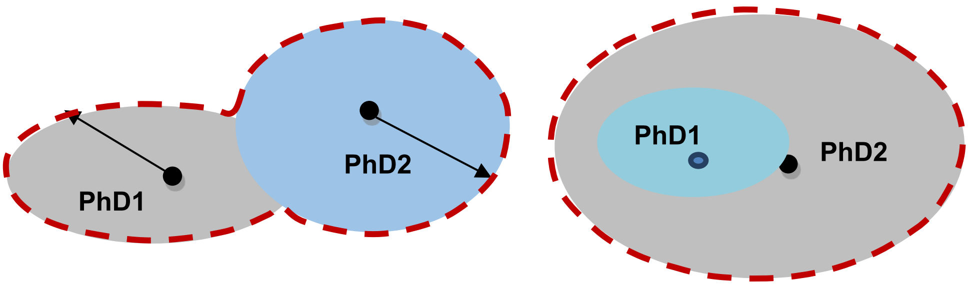
### 4.6 Step 5: Vulnerability level crossed by intensity of the escalation vector

Cross can be made using table (vulnerability level / Intensity of the escalation vector) to spotlight possible domino effect sequences. The retained sequences are analysed in the next step: severity rate and probability are evaluated.

### 4.7 Step 6: Severity rate and probability determination

Once the first domino effect analysis done, the aim of this step is to evaluate risks using probability and severity of the accident (for all sequences retained in the previous step). This assessment is made for each target unit. Severity is determined considering risk zone envelope of each dangerous phenomenon involved in domino effect sequence. Each phenomenon severity is aggregated as shown in the following figure:

*Figure 3: Example of severity aggregations (two dangerous phenomena). The red envelope represents the severity rate considered for the two dangerous phenomena.*




Note that an accident is usually considered as ‘‘domino event’’ only if its overall severity is higher or at least comparable to that of the primary accidental scenario. After this assessment, possible domino effect sequences are positioned in the acceptation grid defined by the writer (see Step 0 in paragraph 4.1).

### 4.8 Step 7: Check of risk acceptance

The assessment of consequences can be done, using the grid probability / severity. Risks are classified according to their estimated likelihood and potential severity and is based on risk control plan defined in step 0 by the writer.

### 4.9 Step 8: Searching for an acceptability

The following points can be done simultaneously or not, to make the domino effect scenario admissible.

- Fine-tune the primary accidental scenario occurrence which triggers the domino effect;
- Fine-tuning or reducing domino effect sequence probability;
- Make reliable prevention and protection measures for dealing with possible domino effects: specific protection measures to avoid domino effects intended;
- Fine-tune the vulnerability assessment: the degree of vulnerability chosen by the writer, as shown in paragraph "Vulnerability approach", can be modified;
- Fine-tune effects of the primary accidental scenario: reconsidering the source term and using another modelling tool;
- Fine-tuning or reducing severity: considering time between two phenomena or people protection.

## 5. Conclusions

The domino effect occurs in many major accidents, increasing their consequences and complexity. In France, domino effects are considered in safety reports, using the quantitative way. The method, introduced in this article, suggests a different and more complete approach.

New developments of this method can be imagined, for example in the context of emergency plan: allows the emergency responders to prioritize their mitigation actions according to the domino effect study.

### References


Abdolhamidzadeh B, Abbasi T, Rashtchian D, and al. 2010. A new method for assessing domino effect in chemical process industry. Journal of Hazardous Materials, 182(1): 416-426.

Casceff. 2017. Methodology for creating a model of an incident with cascading effects for future threat (D4.2).

Cozzani V Reniers G, 2013. Domino effects in the process industries: Modelling, prevention and managing. Elsevier.

Cozzani V, Gubinelli G. and Salzano E. 2006. Escalation thresholds in the assessment of domino accidental events. Journal of Hazardous Materials, A129, 1-21.

Cozzani V., Salzano E. 2004. Threshold values for domino effects caused by blast wave interaction with process equipment. Journal of Loss Prevention in the process industries. 437-447.

Delvosalle C, Fievez C, Benjelloun F. 1998. Development of a methodology for the identification of potential domino effects in "SEVESO" industries. Proceedings 9th International Symposium on Loss Prevention and Safety Promotion in the Process Industries.

Duong D.H, Hanus J.L, Bouazaoui L. et al. 2012. Response of a tank under blast loading – part II : experimental structural response and simplified analytical approach.

HSE, 1998. Development of methods to assess the significance of domino effects from major hazard sites.

INERIS, 2002. Méthode pour l'Identification et la Caractérisation des effets Dominos (MICADO), INERIS-DRA-2002-25472.

Khan, F. I., & Abbasi, S. A. 2001. Journal of Loss Prevention in the Process Industries, 14, 43.

RIVM, 2003. Instrument Domino-Effecten (IDE).

UIC, 2017. Guide sur les effets dominos.