

ABACUS TO DETERMINE THE PROBABILITY OF DEATH OR GLASS BREAKAGE TO THE OVERPRESSURE EFFECT BY TWO METHODS: TNT AND TNO MULTI-ENERGY

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Safety and environmental protection are among the most important concerns of companies worldwide. They develop complex software to model the consequences of damage in an accident at a petrochemical plant. In particular, the explosions. Generally, in order to achieve the objectives, we suggest an abacus very easy to use and simple as to determine the fatality probability (lethality likelihood) or material damage (glass breakage) by the overpressure effect by two methods: TNT and TNO Multi-Energy, and at the same time to determine the strengths and weaknesses of these two methods.

Keywords: fatality probability, TNT, TNO multi-energy, abacus, overpressure.

1. Introduction

Oil has been the main source of energy in the world for 40 years. This has very important implications for the country's economy. It is therefore extremely important to have several refineries around the world to make the most of crude oil. Even when precautions are taken to reduce the accident risks in chemical plants that happen from time to time According to the Labor Statistics Bureau in 2009, industrial accidents were the causes of non-productive time losses due to no fatal injuries for more than 1.2 million workers in the United States. Although, this represents 9 % decrease in accidents compared to 2008, there is still room for improvement. The industrial accidents death number recorded in 2009 is 4340. Based on the main causes of accidents, companies may take the necessary steps to reduce their happening probability in the future [1-3]. In addition, some domino effects may occur in these accidents types that could increase damage and affect other areas [4-6].

As a result, hygiene and industrial safety is a key factor in the hydrocarbon industry. Thus, estimating and evaluating the effects of such explosions in real scenarios involving diverse and complex environments will be possible [7, 8]. This allows protecting goods and people working on such sites that store, transport or handle flammable and hazardous materials. In order to achieve the objectives, an easy and simple abacus for use has been suggested in order to determine the fatality probability or glass breakage damage by the overpressure

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effect by two methods: TNT (trinitrotoluene) and TNO (Toegepast Natuurwetenschappelijk Onderzoek) Multi-Energy, and at the same time to determine the strengths and weaknesses between these two methods [9].

2. Methodology

The explosion effects are mainly characterized by a shock wave of high intensity but short duration that spreads in the environment and sweeps everything in its path. Thus, explosions, whatever their origin, are rare phenomena but with fast kinetics, and their anticipation is not always possible. Indeed, the consequences can be devastating and unpredictable as well on the man (eardrum crack, serious lesions for ears and lungs, immediate death, etc.) than on the constructions (broken windows, walls collapse, structures degradation, etc.) Therefore [10], prevention of such phenomena aims to prevent explosions or their effects through targeted measures so that human safety is ensured and the material damage is as limited as possible, so that it can evaluate the effects of such explosions in real scenarios involving diverse and complex environments. Generally, in order to determine the fatality probability or material damage of the overpressure effect, the TNT and TNO multi-energy methods were used. However, with the drawbacks recorded in the application of these methods, among others the uncertainty of the results and the difficulties of their use, an abacus has been proposed to determine the death probability or material damage of the overpressure and which gives the same results. This abacus was determined using the two methods mentioned below known in the literature, namely, Fig 1.

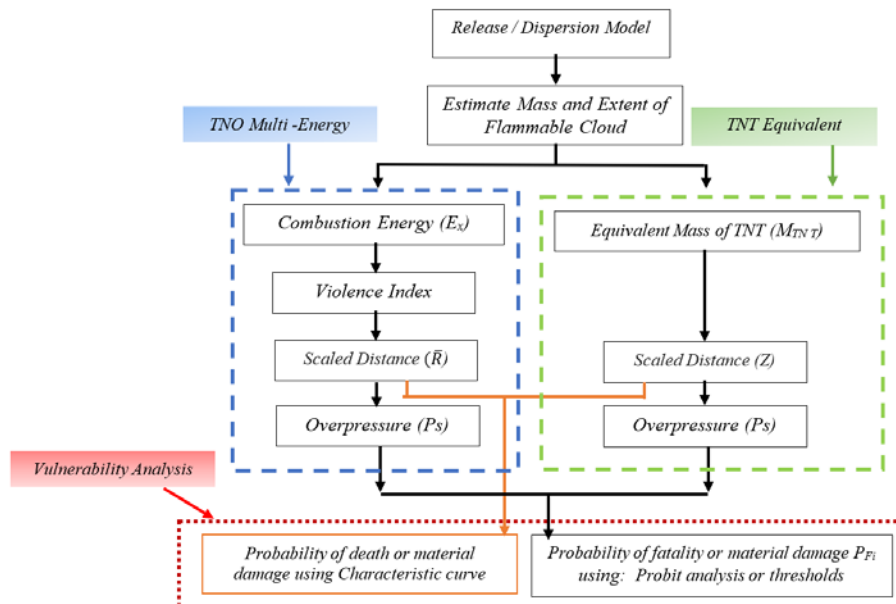


Fig. 1. Work methodology

A) The TNO multi-energy method

The Multi-Energy method has been proposed by the TNO [11-13] following the extensive test campaigns carried out in the 1970s and 1980s and the developments of theories of hemispheric gas deflagrations. The Multi-Energy method is based on the following hypotheses:

- The flame propagates at a constant speed to be taken as the maximum possible for the facility considered;
- The maximum flame propagation velocity is empirically determined based on cloud responsiveness, geometry and congestion rate.

The application of the Multi-Energy method is also based on two fundamental steps:

- The characterization of flame acceleration zones in the explosive cloud;
- The determination of the flame velocity in each zone, i.e.; to describe the explosion violence.

For this, it is necessary to take into account many parameters which have an influence on the speed of propagation of the flames, among which may be mentioned:

- The density of obstacles;
- The degree of containment;
- The shape and dimensions of the flammable cloud;
- The reactivity of the fuel;
- The energy and position of the ignition source.

The method is conducted in four steps to evaluate the level of pressure reached as a function of the level of containment or obstruction of the flammable mixture, namely:

a. Calculate the energy explosion

The Combustion energy is the chemical reaction that takes place when oxygen is combined with combustible material (ex, gas). The calculation of this energy is only valid in the case of a UVCE (Unconfined Vapour Cloud Explosion). The UVCE represents the ignition (in contact with a sufficient heat source) of a flammable vapor cloud whose part between the LFL (Lower Flammability Limit) and the UFL(Upper Flammability Limit) will be the seat of combustion.

The formation and dispersion of a flammable cloud (sufficiently volatile) can generate a UVCE whose stages are as follows:

- Release into the atmosphere of a volatile flammable gas or liquid, with or without aerosol emission;
- Evaporation of the liquid layer formed in part of a liquid discharge;
- Formation of a flammable cloud between air and gas;

- Dispersion of the air-gas cloud between the LFL and the UFL which ignites in the presence of an ignition source;
- Propagation of the flame front in the flammable cloud causing an air shock wave.

The combustion energy is given by the following formula (1):

$$E_x = M_G \times \Delta H_C \quad (1)$$

where E_x is combustion energy in fuel-air mixture (J), M_G is denotes the mass of the flammable gas that takes Part in the explosion (kg), and ΔH_C is heat of combustion of the flammable (J/kg).

b. Choice of severity degree (Violence index)

Regarding the use of the Multi-Energy method, determining the maximum overpressure is to choosing an "violence index" among the 10 proposed [14]. For the record, the correspondence between the indices between 1 and 10 and the maximum overpressure levels is recalled in Table 1 and Fig 2.

Table 1

Violence index and their maximum overpressure

Index of the method (-)	1	2	3	4	5	6	7	8	9	10
Maximum overpressure (bar)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10

c. Determining the Scaled distance

It is expressed by the formula (2).

$$\bar{R} = R \times \left(\frac{E_x}{P_0} \right)^{-\frac{1}{3}} \quad (2)$$

where \bar{R} is scaled distance for TNO Multi-Energy (-), P_0 is ambient pressure ($P_0 = 101000$ Pa) and R is distance from the center of the explosion (m).

d. Determining the scaled overpressure

It is expressed by the formula (3).

$$\bar{P} = \frac{P_s}{P_0} \quad (3)$$

where P_s is denotes the overpressure caused by the explosion (bar) and \bar{P} is scaled blast overpressure (-).

The quantification of the overpressure wave is then determined by the use of the abacus curves of the multi-energy method [15] shown in Fig. 2.

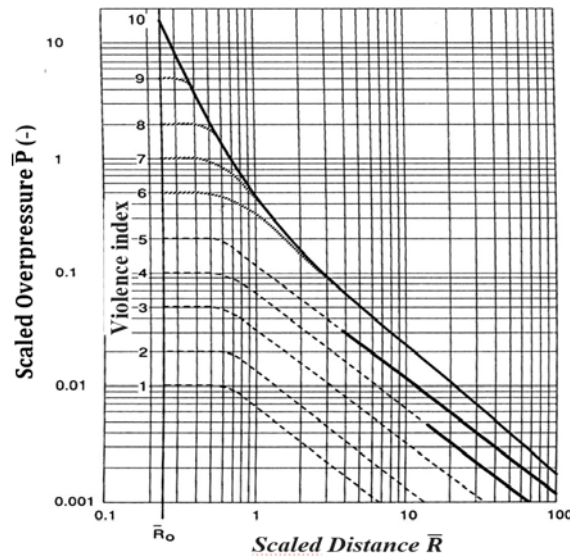


Fig .2. Overpressure as a function of the scaling distance [11, 16]

B) TNT equivalent method

The principle of the TNT equivalent model is to report the explosion energy to an equivalent mass of TNT and then make a link between the overpressure generated by the explosion and the distance at the explosion center. The literature, mainly of military origin, contains descriptions of many observations, mainly concerning the effects of detonation of TNT on individuals or facilities.

- 1st step: estimate the TNT mass (M_{TNT}) equation (5);
- 2nd step: Using the abacus, looking for the overpressure value as a function of the distance from the source of danger to a given point of impact Fig 3.

The method is based on the empirical diagram of Brasie & Simpson, Fig. 3 [17], and overpressure P_s (bar) is determined based on a scaled distance Z ($\text{m/kg}^{1/3}$), defined by equation (4):

$$Z = \frac{x}{M_{\text{TNT}}^{1/3}} \quad (4)$$

where x is distance from the center of the explosion (m) and M_{TNT} is equivalent TNT mass (kg) and calculated as follows:

$$M_{\text{TNT}} = \frac{f \times \Delta H_C \times M_G}{\Delta H_{\text{TNT}}} \quad (5)$$

where ΔH_{TNT} is the explosion energy of TNT equal 4.42 (MJ/kg) if you use the software EFFECTS and f is denotes the fraction of the energy released (-) as Shock wave (unitless).

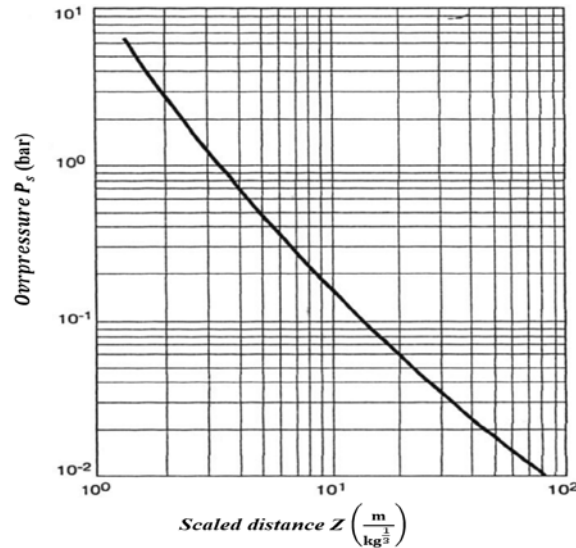


Fig. 3. Overpressure as a function of the scaling distance [17]

Instead of the diagram of Fig 3, one can also use the more recent analytical expression for the overpressure P_S (bar) shock wave according to equation (6):

$$P_S = \frac{808 \times \left(1 + \left(\frac{Z}{4.5} \right)^2 \right)}{\sqrt{1 + \left(\frac{Z}{0.048} \right)^2} \times \sqrt{1 + \left(\frac{Z}{0.32} \right)^2} \times \sqrt{1 + \left(\frac{Z}{1.35} \right)^2}} \quad (6)$$

3. Vulnerability analysis

A) Complex study (Variable probit)

The function that relates the magnitude of a consequence to the degree of harm it causes (i.e., dose-response relationship) is required to assess the consequences of an accident. The most frequently applied method is probit analysis, which relates the probit variable to the probability of achieving targets with harmful effect.

By definition, the probit variable (Y) is a measure of the percentage of a population that is subject to a given dose of an effect (V), which may experience a given injury degree. This variable obeys a normal distribution and is characterized by an average value of 5 and a standard deviation of 1. The relationship between the probit variable (Y) and the reaching probability (P_{Fi}) can be defined as follows (equation 7) [18, 19]:

$$P_{Fi} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp\left(-\frac{V^2}{2}\right) dV \quad (7)$$

If the population percentage that has experienced a given response is not plotted against the dose of the adverse effect, but rather as a function of its logarithm, equation (7) can be transformed to give the expression (8), which is often used to estimate the value of the variable probit (Y) [18, 20]:

$$Y = A + B \ln(V) \quad (8)$$

where: A and B are constants determined experimentally from accident information. V is a dose measure of the adverse effect, which may be a single parameter (for example, the explosion overpressure) or a combination of different parameters (for example, a combination of thermal relationship and time in the case of a fire).

According to [21], the probit equation for lethal effects or material damage takes the following forms depending on the effects:

$$\text{For toxic products: } Y = A + B \ln(C^n \times t)$$

where C is the concentration (ppm) and t is the exposure time (min).

$$\text{For thermal effects: } Y = A + B \ln(Q^{4/3} \times t)$$

where Q is the received stream (W/m^2) and t is the exposure time (s).

$$\text{For the overpressure: } Y = A + B \ln(P_s)$$

where P_s is the overpressure (Pa).

As shown in Table 2 which presents various probit equations for different types of exposure.

Table 2

The different models and their probit equations

Model	Probit functions	Reference
HSE (Health and Safety Executive) paper	$Y = -10.462 + 1.35 \ln(P_s)$	[22]
Eardrum Rupture (ER)	$Y = -12.60 + 1.524 \ln(P_s)$	[23]
Breakage of Windows Panes(BWP)	$Y = -16.58 + 2.530 \ln(P_s)$	[24]

Once the Y value is determined, the probit variable must be converted to the probability (percentage) of achieving in order to assess the actual consequences of the accident for the population (e.g., the number of people injured or dead). This can be done by referring to Fig 4.

Another expression that relates the probit variable to the probability of targets being reached by a given adverse effect is expressed by [19] in equation (9):

$$P_{Fi} = 50 \times \left(1 + \frac{Y-5}{|Y-5|} \times \operatorname{erf} \left(\frac{|Y-5|}{\sqrt{2}} \right) \right) \quad (9)$$

where “*erf*” is the error function.

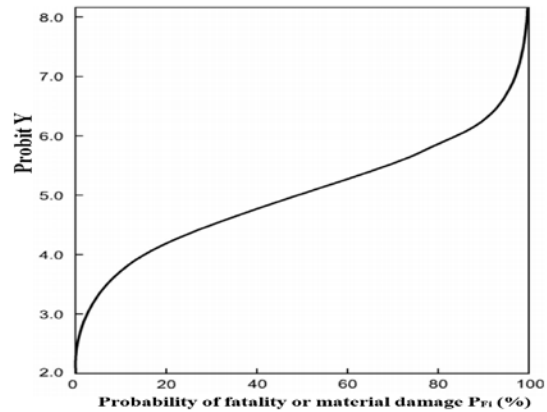


Fig .4. Relationship between the probit variable and the fatality probability or material damage [20].

Currently, probit equations are widely used to evaluate the consequences of major accidents on targets. However, the choice of the equation is decisive because, for the same dangerous effect, the prediction can vary considerably according to the chosen expression.

B) Simple study (Thresholds of overpressure effects)

The reference values [25] of the overpressure effects on humans and structures for classified installations are presented in Table 3 as follows.

Table 3

The overpressure thresholds and their effects

Peak overpressure (bar)	Effect on structures	Effect on the human body
0.07	Window glass shatters	Light injuries from fragments occur
0.1	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying glass and debris
0.3	Most buildings collapse	Injuries are universal, fatalities are widespread
0.7	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
1.4	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

C) Fatality Probability and material damage using an abacus

For each explosion, it is possible to obtain the overpressure relationship (P_S) - probit (Y_1) - probability of death or material damage (P_{Fi}) and scaled

distance (\bar{R} or Z) called here « abacus ». Fig. 5 shows, in graphical form, the characteristic curve established from the shock wave profiles on the overpressures – Scaled distance and scaled distance probability of death or material damage (drawn respectively from Figs. 2, 3 and 4, equation 9 and Table 2). The scaled distances to the explosion (\bar{R}_1 or Z) can also be included to display all the information in the same diagrams, presented in Figs. 6 and 7.

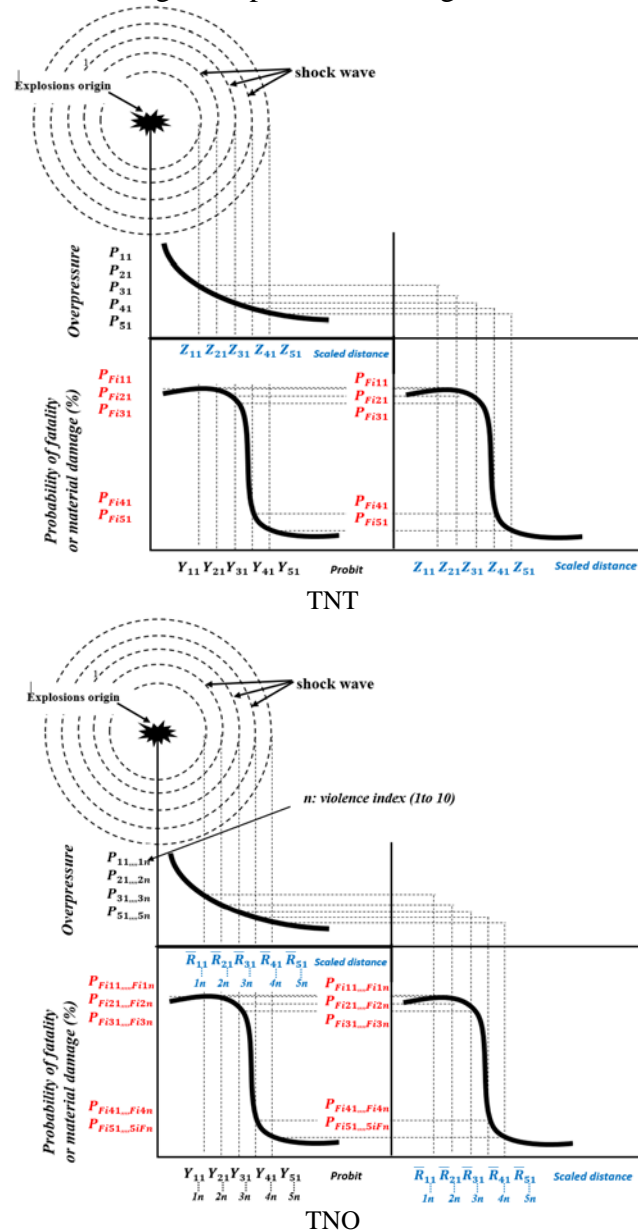


Fig.5. Abacus of an explosion obtained from the overpressure relationship - probit- death probability or material damage and scaled distance[16, 17, 20 ,26 ,27]

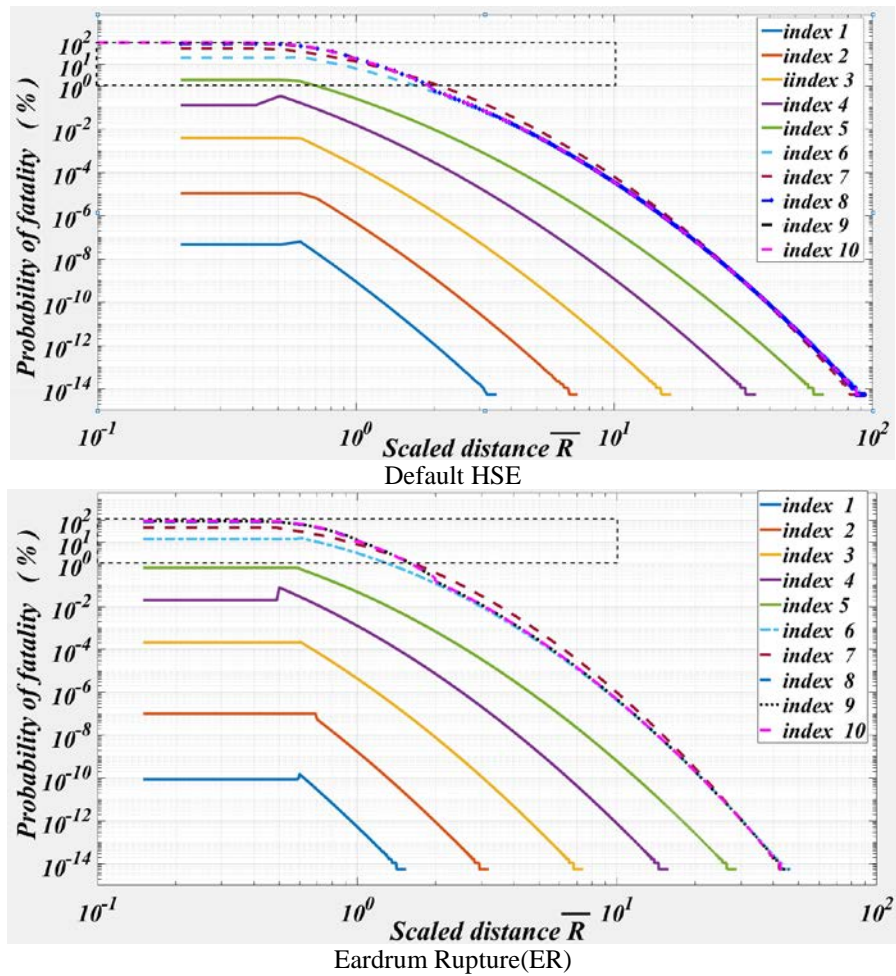


Fig. 6. General abacus of the fatality probability and material damage by the TNO method.

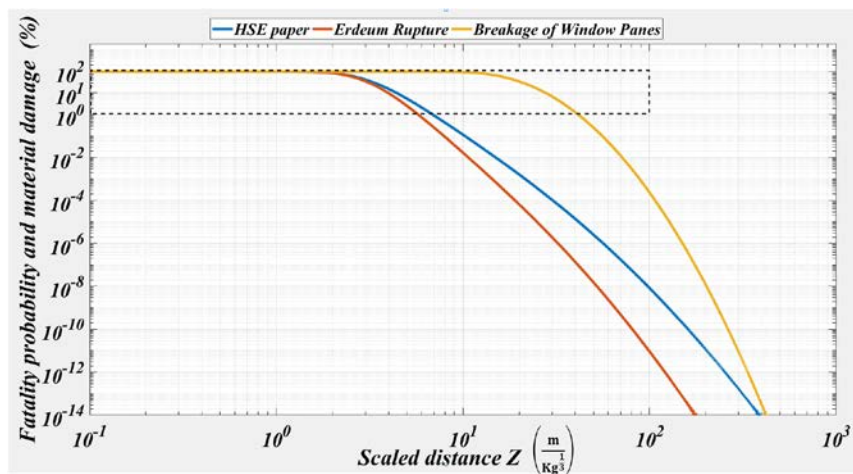


Fig. 7. General abacus of the fatality probability and material damage by the TNT method

4. Case study

In this work, we are interested in the hydrocarbon industrial complex, the latter is a town in the city of Laghouat in Algeria, where we find the largest natural gas field on the African continent where it is declared as a high-risk zone by the executive decree N° 05/476. This complex comprises several hydrocarbon processing modules with a Storage and Easy Transfer Center (CSTF). The latter is considered a critical source of danger, since it has a total storage capacity of 285000 m³ of condensate and 78000 m³ of LPG (Liquefied Petroleum Gas).

The LPG storage and transfer site holds the following facilities:

- 12 spheres with a measured capacity of 6500 m³ (7170 m³ Max) each bearing a total storage capacity of 78000 m³;
- 6 booster pumps P001 A / B / C / D / E / F: Flow rate 165 m³ / h at P = 15 to 18 bar each, of which 3 pumps have a second transfer function of LPG between the spheres;
- 3 pumps P002 A / B / C: Flow rate 350 m³ / h at P = 25 to 34 bar each, LPG shipping to the 24 " line with a flow rate of 350 m³ / h each;
- 5 Turbocharger units with 12 LPG refrigerants.
- This study uses one of 12 spheres as a study sample (Fig. 8) and (Table 4)

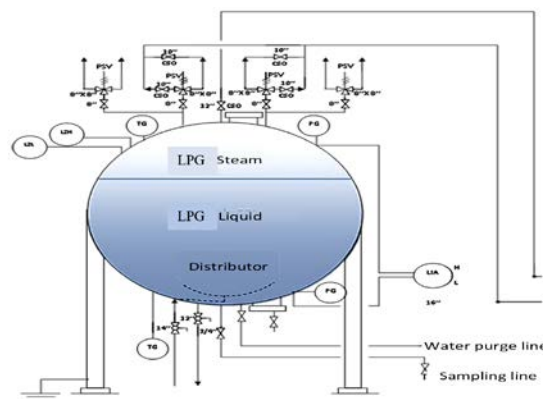


Fig. 8. LPG Sphere Design [28]

Table 4

Characteristics of LPG Spheres

Characteristics	Values
Substance	LPG
T Service (°C)	20
T Calculation (°C)	17 to 93.3
P Service (bar)	5.34
P Test (bar)	9.6
Total volume (m ³)	7170
Density (kg/m ³)	536

Firstly, the TNT equivalent mass must be calculated M_{TNT} (kg) from the equation (5).

$$M_{\text{TNT}} = \frac{f \times \Delta H_C \times M_G}{\Delta H_{\text{TNT}}} = \frac{0.1 \times 4.60122 \times 10^7 \left(\frac{\text{J}}{\text{Kg}} \right) \times 87203(\text{Kg})}{4.42 \times 10^6 \left(\frac{\text{J}}{\text{Kg}} \right)} = 90780(\text{Kg})$$

Since the fraction of energy released in the form of a shock wave is not known, it is arbitrarily assumed that $f = 0.1$ (values between 0.01 and 0.1).

The index 10 of the multi-energy method is an increasing situation. However, this index makes it possible to consider the phenomenon of bursting and propagation of shock waves. Therefore, the following distances are calculated from the explosion energy (equation 1) equal to:

$$E_X = M_G \times \Delta H_C = 4.60122 \times 10^7 \left(\frac{\text{J}}{\text{Kg}} \right) \times 87203(\text{Kg}) = 4.0124 \times 10^{12}(\text{J})$$

After calculating E_x and M_{TNT} , the scaled distance can be determined from equations (2 and 4). With the preceding hypotheses, the use of the charts (figures 2 and 3) makes it possible to determine the overpressure as a function of the distance and compared with the results obtained with the help of the software "EFFECTS", this software is an advanced software tool that allows you to model the behavior of toxic and/or flammable gases, liquefied gases and liquids [29] Fig 9.

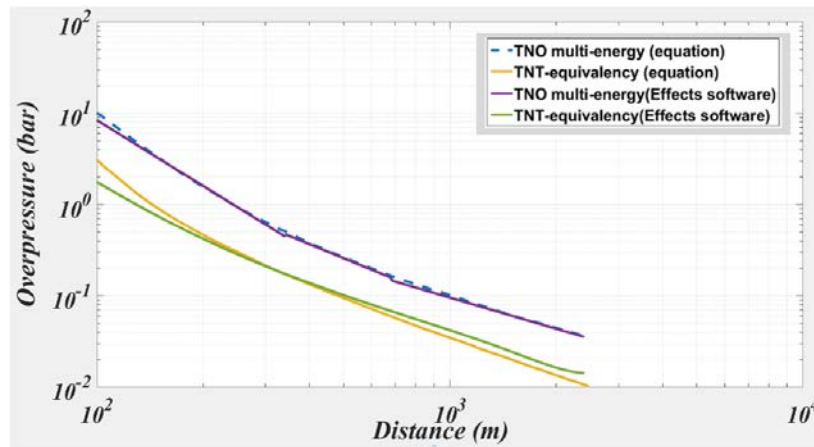


Fig. 9. The overpressure by two methods TNT and TNO

The values obtained by abuses of TNT and TNO [16,17] are in very close agreement with those obtained by EFFECTS software. Differences are observed only over in very small distances where the pressure increase is quite steep. Characteristic values of overpressure as a function of the distance for the TNO method are higher than those obtained by the Equivalent TNT method.

In general, one can observe that although the TNT method can quickly produce an answer in calculating the overpressure as a function of the distance, the values obtained by the TNO method are closer to the real conditions.

The zoomed parts selected by dashed squares in Figs. 6 and 7 show the probability of fatality (HSE, Eardrum rupture) and damage (window breakage) respectively. These are represented by the Scaled distance \bar{R} (for TNO) or Z (for TNT), see Fig. 10 and Tables 5 and 6. Thus, using this new methodology, simulation of explosions is simpler and faster.

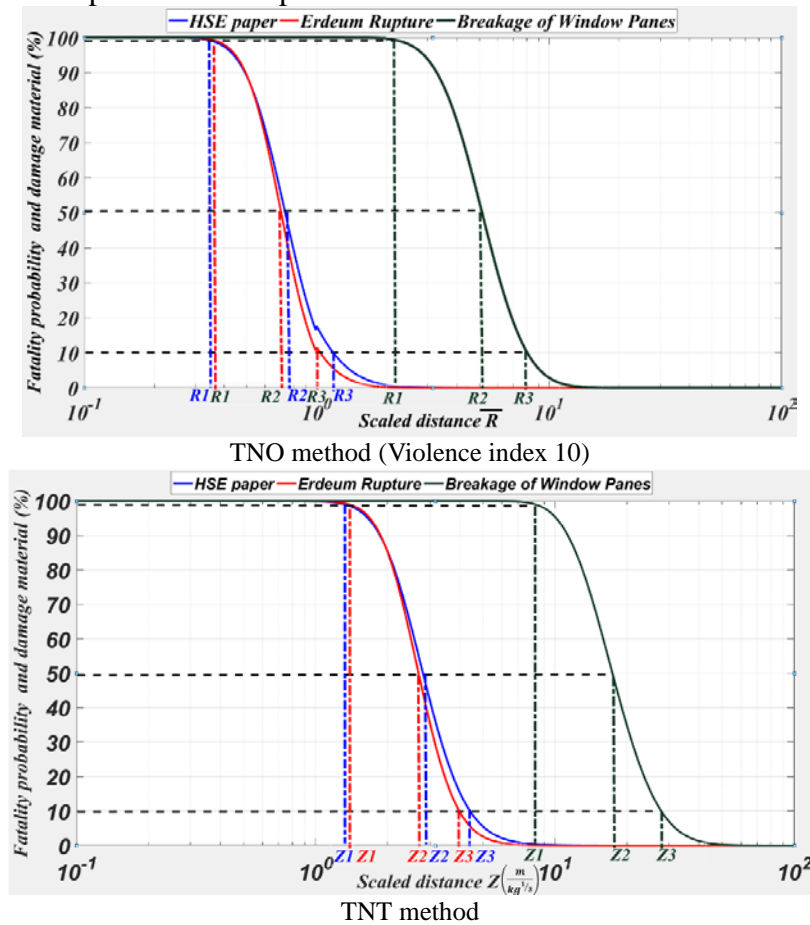


Fig. 10. Curves zoom probability of fatality or material damage by overpressure effect.

Table 5

The probability of death or material damage according to the TNT method

Probability of death or Damage (%)	TNT								
	10			50			99		
	ER	HSE	BWP	ER	HSE	BWP	ER	HSE	BWP
scaled distance Z ($\text{m}/\text{kg}^{1/3}$)	Z_1 3.96	Z_1 4.4	Z_1 27.8	Z_2 2.68	Z_2 2.8	Z_2 17.4	Z_3 1.37	Z_3 1.3	Z_3 8.3
Distance x (m)	177.9	197.74	1249.4	120.4	125.8	782	61.5	58.4	373

Table 6

The probability of death or material damage according to the TNO method

Probability of death or Damage (%)	TNO								
	10			50			99		
	ER	HSE	BWP	ER	HSE	BWP	ER	HSE	BWP
Scaled distance \bar{R} (-)	\bar{R}_1	\bar{R}_1	\bar{R}_1	\bar{R}_2	\bar{R}_2	\bar{R}_2	\bar{R}_3	\bar{R}_3	\bar{R}_3
	1	7	2.28	0.7	0.73	5.14	0.37	0.35	8.02
Distance R (m)	341	580	2736.5	238.8	249	1753.8	126.2	119.4	777.9

Fig. 11 and Tables 5 and 6 clearly show the different areas of lethality (Eardrum rupture or HSE paper) or material damage (Breakage of Window Panes) under the effect of the overpressure by two methods: TNT and TNO Multi-Energy.

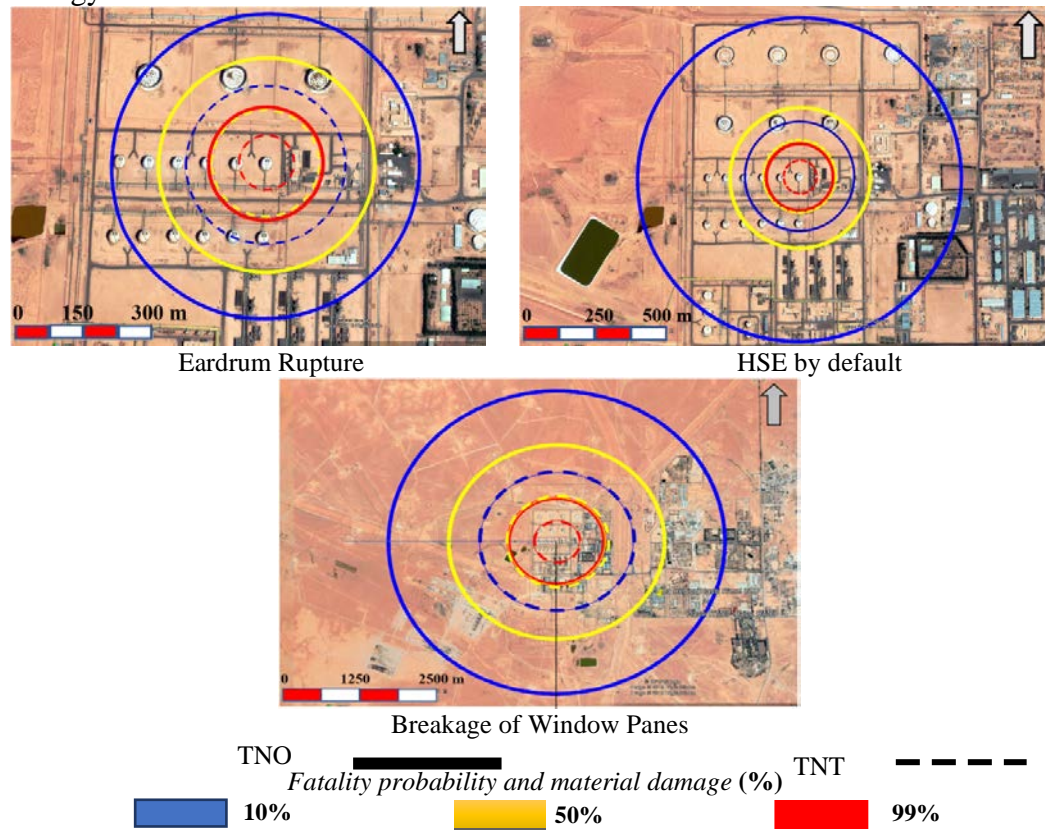


Fig. 11. Contours fatality probability and material damage by TNT and TNO method [28]

5. Discussion of results

The TNT method calculates the overpressure of an explosion without considering the configuration of the space where the explosion takes place. in

addition to that, an explosion in the middle of an area full of equipment, or in a closed space, will exhibit different power from an equivalent one in an open space

The parameter ' f ' in most cases is unknown and greatly influences the prediction. In addition, the method does not calculate the evolution over time of the explosion. The overpressure vs. distance curves obtained by the multi-energy method, as well as the one obtained by the Equivalent TNT method, are plotted. The following are noted:

- The values obtained by the Multi-Energy method are higher than those obtained by the Equivalent TNT method;
- The values produced by the multi-energy method are closer to the actual values observed as a function of the damage resulting from the explosion.

6. Conclusions

Consequences analysis is a powerful tool to reproduce the damage that occurred during a chemical plant accident. Although companies are developing complex software that requires enormous computing power, simple empirical models, such as TNT, TNO, can be used with a reasonable degree of accuracy, requiring much shorter computation times and less powerful equipment. The use of this developed abacus is very easy to handle and simple to determine the fatality probability or material damage of the overpressure effect and gives the same results as the two methods TNT and TNO multi-energy, even get to perform the consequences analysis of this type of accidents and predict or determine the safety zone of the oil industry.

The use of these simplified charts (model), allows an overview of the evolution and the relation of all the variables involved in the steam cloud explosions.

In conclusion, using this new methodology, simulation of explosions is done simpler and faster.

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