Consequence analysis of an explosion by simple models: Texas refinery gasoline explosion case

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Análisis de consecuencias de una explosión mediante modelos sencillos. Ejemplo de la explosión de la refinería de Texas

Anàlisi de conseqüències d'una explosió mitjançant models senzills. Exemple de l'explosió de la refineria de Texas

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RESUMEN

Los accidentes en las plantas petroquímicas y refinerías son bastantes destructivos, debido a la gran reactividad de los productos químicos que están presentes en las mismas. Un accidente que ocurrió en la refinería de la ciudad de Texas, el 23 de marzo de 2005, consistente en la explosión de una nube de vapor (ENV), que se produjo tras la fuga de gasolina y causó 15 muertes ha sido estudiado en términos de vulnerabilidad de las personas a la sobrepresión y la radiación térmica. Con este objetivo, se utilizaron varios modelos empíricos sencillos (TNT, TNO Multienergía y BST) para evaluar los efectos de la sobrepresión de la explosión. Además, para estudiar los efectos de la radiación térmica se utilizó un modelo que permitía calcular el daño causado por el calor irradiado por la explosión. Finalmente, se utilizó la metodología Probit para evaluar la vulnerabilidad de las personas. Aunque se observó diferencias en los resultados obtenidos por los modelos, todos ellos, los de sobrepresión y de radiación térmica, reprodujeron con bastante exactitud los daños reales causados por la explosión en la refinería. Se puede decir que los modelos TNO y BST son los que con mayor precisión predijeron los efectos de sobrepresión causados por la explosión. Por tanto, la utilización de modelos empíricos sencillos es factible para la evaluación de riesgos.

Palabras claves: Explosión de una nube de vapor (ENV); Análisis de consecuencias; Sobrepresión; Radiación térmica; Refinería

SUMMARY

Accidents in petrochemical plants and oil refineries are quite destructive, due to the high reactivity of chemicals involved in them. An accident that occurred in the Texas City refinery, on March 23rd 2005, consisting on a vapour cloud explosion (VCE) that followed a gasoline release and caused 15 deaths, has been studied in terms of people vulnerability to overpressure and thermal radiation. With this aim, simple models (TNT, TNO Multi-Energy, BST) have been used in order to evaluate the effects of the explosion. Moreover, a thermal radiation model was used to estimate the damage caused by the heat released as consequence of the explosion. Finally, the Probit methodology was used to evaluate the vulnerability of persons. Although differences between the data derived from each of them existed, they all reproduced actual damages with a reasonable accuracy. The results reached let us say that the TNO and BST models predict with a reasonable accuracy the effects of the explosion that occurred. Furthermore, the use of simplified empirical models can be used for risk assessment.

Keywords: Vapour Cloud Explosion (VCE); Consequence analysis; overpressure; thermal radiation; Refinery

RESUM

Els accidents en les plantes petroquímiques i refineries són bastant destructius, degut a la gran reactivitat dels productes químics que són presents en elles. Un accident que succeí a la refineria de la ciutat de Texas, el 23 de març de 2005, consistent en l'explosió d'un núvol de vapor (ENV), que es va produir en haver-hi una fuita de gasolina i què causà 15 morts, s'estudia pel que fa a vulnerabilitat de les persones a la sobrepressió i a la radiació tèrmica. Amb aquest objectiu, s'utilitzen varis models empírics senzills (TNT, TNO Multienergia i BST) per avaluar els efectes de la sobrepressió de l'explosió. A més, per estudiar els efectes de la radiació tèrmica s'empra un model que permet calcular el dany causat per la calor irradiada per l'explosió. Finalment, s'utilitza la metodologia Probit per avaluar la vulnerabilitat de les persones. Tot i que s'observen diferències en els resultats obtinguts amb els diferents models, tots ells, tant els de sobrepressió com els de radiació tèrmica, reprodueixen amb força exactitud els danys reals causats per l'explosió en la refineria. Es pot dir que els

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models TNO i BST són els que prediuen amb major precisió els efectes de sobrepressió causats per l'explosió. Per tant, la utilització de models empírics senzills és factible per a la avaluació de riscos.

Mots clau: Explosió d'un núvol de vapor (ENV); Anàlisi de conseqüències; Sobrepressió; Radiació tèrmica; Refineria

INTRODUCTION

Petroleum has been the main energy source of the world in the latest 40 years as it can be seen in Figure 1 (http://www.eia.doe.gov/emeu/consumptionbriefs/cbecs/cbecs_trends/figb8.gif). It has very important effects on the economy of the countries due to the high fluctuation of crude oil prices and the fact that only a few countries posses oil reservoirs. It makes it very important the presence of a great number of refineries all over the world in order to make the most of crude oil.

Every year several fatal accidents occur in chemical plants. Because of their peculiar characteristics (volatile compounds, flammability, etc.), many of these accidents occur in refineries which are especially dangerous. This is due to the fact that they are vapour cloud explosions (VCE) or boiling liquid expanding vapor explosions (BLEVES). In addition, some domino effects can occur in this kind of accidents that could increase the damages and affect other zones (Delvosalle et al., 2002).

Recently, one of these accidents occurred in Texas City, Texas (USA) on March 23, 2005. This is an interesting case of study not only for being recent but also for its consequences. In this accident 15 people died and important material damages occurred (BP fatal accident report).

Consequence analysis is used to estimate the magnitude of accident effects in human health, damages in facility/equipment, economical losses or environmental impacts associated with accidents involving hazardous materials (toxic, flammable, explosive, radioactive, etc.). Consequence analysis estimates releases to the environment, fire or explosions, and estimates the effects that a release might have on buildings, employees, or the public (Lobato et al., 2006).

Recently, Vapour Cloud Explosions (VCEs) can be analysed by means of different models. Computational Fluids Dynamics (CFD) modelling techniques have been considered for this purpose (Skalovonnos and Rigas, 2004; Tufano et al., 1998). These models require a big mathematical effort and powerful equipment to be handled (Puttock at al., 2000). Furthermore, CFD model requires a few simplified assumptions and some adjustable parameters to be applied, because of the lack of fundamental knowledge on turbulent flows in unsteady, compressible and reacting media (Popot et at., 1996; Tufano et al., 1998).

There are several simplified models such as the TNT-equivalent method, TNO multy-energy and the Baker-Strehlow-Tang model (BST) collected in the literature, that have been used to model the effect of VCEs (Lobato et al., 2006; Pierorazio et al., 2005; Rigas and Sklavounos, 2002; Shariff et al., 2006). Maybe, the best simulation of explosions could be the combined use of simplified models, as an initial approach, with CFD methods.

In a consequence study of a VCE, the overpressure of the explosion must be related with different damages caused to both building and humans. Damage criteria can be taken from tables that relate overpressure with the Probit equation (Finney, 1971; CCPS, 2000).

In this work, the consequence analysis of an accident that occurred in the Texas City refinery, on 2005, consisting of a VCE that followed to a gasoline release, has been evaluated using three different simplified models to estimate the overpressure of the explosion and the Probit equation to estimate the vulnerability of persons. Moreover, a simple thermal radiation model has been used to estimate, in conjunction with Probit equation, the vulnerability corresponding to the fire ball caused by the explosion.

2. THEORY

2.1. Evaluation of evaporated mass.

The evaluation of the quantity of evaporated mass is the most important parameter to be considered in this work. The complexity of the target liquid (gasoline) makes difficult its treatment, as it can be considered neither an overheated nor a boiling liquid.

The total leak amount, m_T (kg), can be calculated by multiplying the discharge rate, Q_D (kg/s), by the leak time, t_L(s), (Eq. (1)), both data are available in the fatal accident investigation report (BP fatal accident report).

$$m_T = Q_D \cdot t_L \quad (1)$$

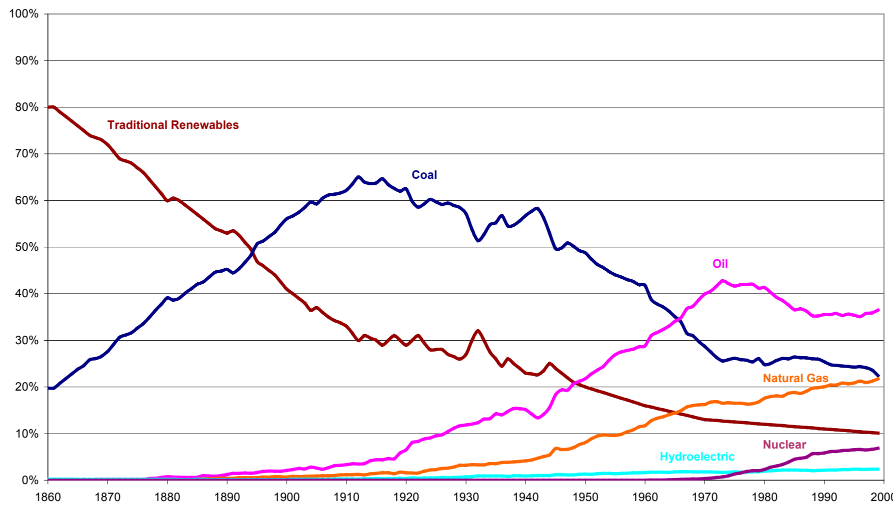


Figure 1. Evolution of energy sources demand in the last century.

This calculation provides the total mass present in the leak, a part of which suffers a flash distillation as a result of its pressure change. It has been considered that only the gasoline fractions with a distillation temperature lower than its storage temperature (374.25 K) can suffer this flash distillation. Using a typical ASTM distillation curve (Table 1), these fractions represent approximately, 17 % of the total mass. Consequently, the amount of gasoline, m_0 (kg), that will suffer this flash distillation can be calculated by using the following equation (Eq. (2)).

$$m_0 = 0.17 \cdot m_T \quad (2)$$

Using this data, an energy balance can be applied to calculate the mass of vapour cloud that produces the explosion (Eq. (3)):

$$m_v = m_0 \cdot \left[1 - \exp\left(\frac{C_p \cdot (T_0 - T_{eb})}{h_v}\right)\right] \quad (3)$$

where m_v (kg) is the initial mass that contributes to the explosion, C_p (kJ/kg·K) is the heat capacity of the target liquid, T_o and T_{eb} (K) represent respectively the initial and boiling temperatures of the liquid and h_v (kJ/kg) is the heat of evaporation of gasoline.

The initial boiling point of the target gasoline (303 K) is quite close to room temperature (300 K). For this reason, the amount of evaporated mass due to the liquid behaviour as a boiling liquid will be considered negligible.

Table 1. ASTM distillation curve for a standard gasoline.

Distillate Volume (%)	T (K)
Initial point	303.15
10	330.15
20	349.15
30	363.15
40	372.15
50	380.15
60	389.15
70	400.15
80	415.15
90	437.15
Final point	471.15

2.2. Evaluation of overpressure.

2.2.1. TNT Equivalency Explosion Model.

The TNT equivalency explosion model has been chosen because it is simple and tends to be better for estimating far-field damage. With this model, the overpressure developed at specified distances (points of interest) can be calculated. In order to apply the TNT model to the estimation of the effects of a VCE, the fraction of total energy of the explosion used in the shock wave must be calculated first. Once the corresponding value is estimated, it is converted into the equivalent mass of TNT, W_{TNT} (kg):

$$W_{TNT} = \frac{m_v \eta \Delta H_{c(gas)}}{\Delta H_{c(TNT)}} \quad (4)$$

where W_{TNT} is the equivalent mass of TNT (kg) that would produce the same effects as the explosion, η represents the explosion yield (dimensionless), it is generally accepted that, taking as a basis for calculation the total quantity of vapor in the cloud, the value of η is between 1% and 10 % for most explosions. W_{gas} is the total mass of flammable gas in the cloud, $\Delta H_{c(gas)}$ is the lower heat of combustion of the material (kJ/kg), and $\Delta H_{c(TNT)}$ is the heat of combustion of TNT (approximately 4680 kJ/kg).

Despite the limitations due to its simplified nature, the TNT model is still widely used to predict overpressures at a given distance from the center of an explosion (Rigas and Sklavounos, 2002). This model is based on an empirical law, established from trials done using explosives. This law establishes equivalent effects for explosions occurring at the same normalized distance, expressed as:

$$z = \frac{R_d}{(W_{TNT})^{1/3}} \quad (5)$$

where *z* is the normalized or scaled distance (m/kg$^{1/3}$), R_d is the real distance (m), and W_{TNT} is the equivalent mass of TNT (kg), calculated by equation 4.

For any given scaled distance, there is a corresponding value of overpressure, which is obtained from an empirical chart (see Figure 2) of scaled distance versus overpressure. This graph is based on the results of numerous experimental programs involving high explosives (CCPS, 2000; Bodhurtha, 1980; Lees, 1980). Once this overpressure is obtained, the probability of suffering different damages can be calculated from the data reported in Table 2. Data presented in bold in this table are the damage thresholds used in the present work to carry out the study of the effects caused by the explosion.

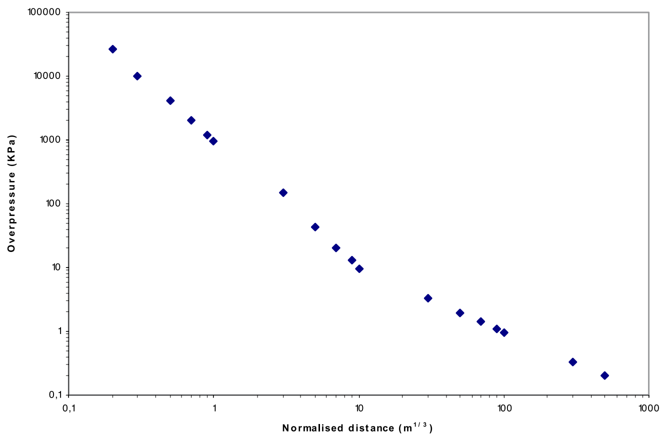


Figure 2. *Overpressure vs. normalised distance for its use in TNT model.*

Table 2. *Different damages caused by the overpressure (Bodhurtha, 1980; Santamaría y Braña, 1998; Lobato et al., 2006; Sariff et al., 2006). The data presented in bold represent the damage threshold selected in the present work.*

Overpressure (KPa)	Damage
0.204	Occasional breakage of large windows already under strain
0.275	Loud noise. Breakage of windows due to sound waves
0.681	Breakage of small panes of glass already under strain
2.04	20 % windows broken. Minor structural damage to houses
6.8	Partial demolition of houses, which become uninhabitable
13.6	Partial collapse of house roofs and walls
13.1-20.4	Destruction of cement walls of 20-30 cm width
16.2	**1% of eardrum breakage**
17	Destruction of 50 % of brickwork of houses. Distortion of steel frame building
20.4-27.7	Rupture of storage tanks
34-47.6	Almost total destruction of houses
47.7-54.4	Breakage of brick walls of 20-30 cm width
68.9	**Probable total destruction of buildings. Machines weighing 3500 kg displaced and highly damaged**
101	**1% death due to lung haemorrhage**
169.2	**90% death due to lung haemorrhage**

2.2.2 TNO Multi-Energy Model

This model is increasingly accepted as a more reasonable alternative to be used as a simple and practical method (Bodhurtha, 1980; Díaz Alonso et al., 2006). It is based on the premise that a vapour cloud explosion can occur only within that portion of a flammable vapour that is partially confined. Thus, the amount of energy released during a VCE is limited either by the volume of the partially-confined portion of the flammable vapour cloud (if the flammable vapour cloud is larger than the partially-confined region) or by the volume of the vapour cloud (if the vapour cloud is smaller than the volume of the portion of the partially-confined space). In both cases, the volume of the cloud within the partially-confined space can be converted into a hemisphere of equal volume. The model treats the hemispherical cloud as a homogeneous, stoichiometric mixture of flammable gas and air, with a combustion energy of 3.1 10^6 J/m^3 (the average heat of combustion of a stoichiometric mixture of hydrogen and air). TNO model has used a flux-corrected transport code to numerically simulate the explosion of a hemispherical, homogeneous, stoichiometric cloud, with constant flame speed. TNO presents the results of this modelling as a family of curves in Figure 3 (Mercx et al., 2000; Van der Berg, 1985). In this chart, ten curves that span the range of severities from mild deflagrations to detonations have been shown. Each curve is assigned an integer that indicates its severity. Thus, curve #1 means mild deflagration and #10 stands for detonation.

These curves correlate dimensionless overpressure (overpressure divided by atmospheric pressure) with combustion energy scaled distance, which is calculated as follows:

$$\overline{R} = R_d\,(P_0/E)^{1/3} \quad (6)$$

where $\overline{R}$ is the combustion energy scaled distance, dimensionless, R_d is the distance from the centre of the hemisphere, m, P_0 is the atmospheric pressure, J/m^3, and E is the total available energy, J.

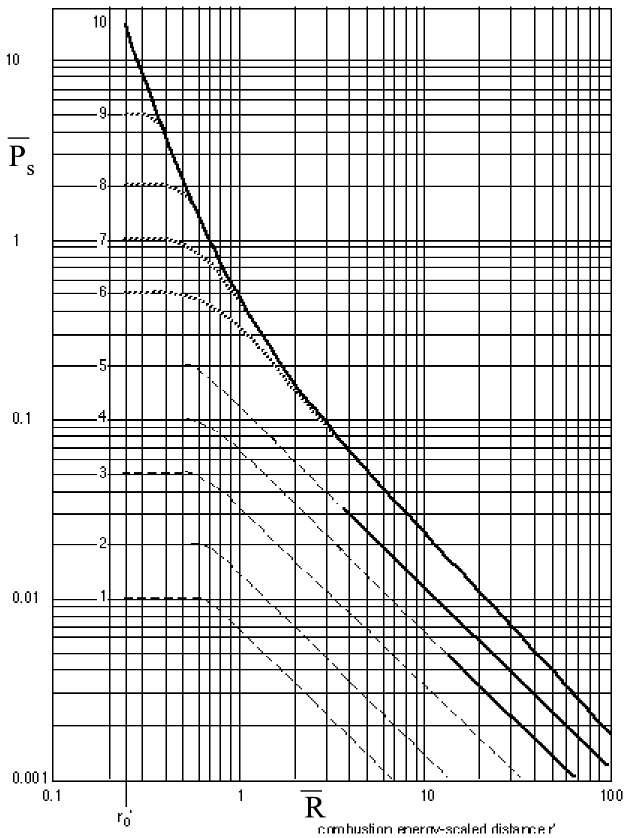


Figure 3. Normalised overpressure vs. normalised distance for its use in TNO Multi-Energy model.

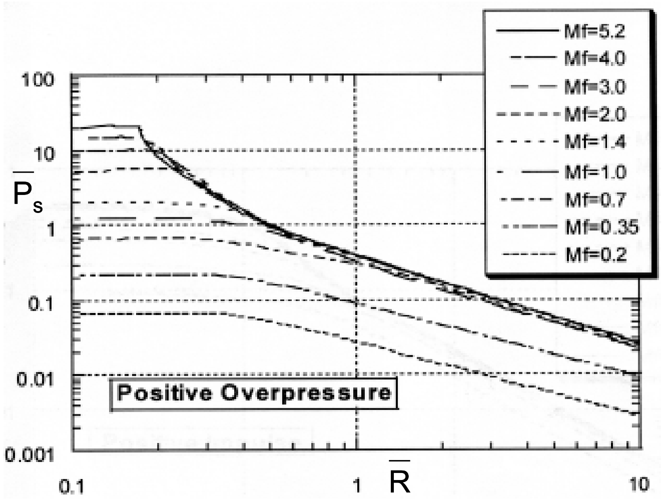


Figure 4. Normalised overpressure vs. normalised distance for its use in BST model.

With the equation 7 the peak side-on overpressure P_s (N/m^2), can be calculated

$$P_s = \overline{P}_s\ P_0 \quad (7)$$

where $\overline{P}_s$ is the dimensionless peak overpressure, which can be calculated, once is known $\overline{R}$, from Figure 3.

2.2.3. Baker-Strehlow-Tang Model (BST)

This model has some similarities with the TNO Multi-Energy Model. Each model uses a family of curves to correlate $\overline{P}_s$ with $\overline{R}$, and both models use equation 6 to calculate. The method used to construct the graphical relationship between dimensionless and combustion energy scaled distance, $\overline{R}$, is different to that used in the TNO model. The curves used in the BST model, shown in Figure 4, are based on numerical modelling of constant velocity flames and accelerating flames spreading through spherical vapour clouds [10]. With this method, the strength of the blast wave is proportional to the maximum flame speed achieved within the cloud. Thus, each curve in Figure 4 is marked with a flame velocity, which is presented in the form of a Mach number, M_f. In Table 3, the appropriate flame speed (Mach number) for the specific situation being modelled can be selected (Pierorazio et al., 2005; Baker et al., 1989).

Table 3. *Flame Speed in Mach Numbers (M_f) for ignition sources used in the Baker-Strehlow-Tang Model.*

Flame Expansion	Fuel Reactivity	Obstacle Density		
		Low	Medium	High
1 D	High	5.2	5.2	5.2
	Medium	1.03	1.77	2.27
	Low	0.294	1.03	2.27
2 D	High	0.59	1.03	1.77
	Medium	0.47	0.66	1.6
	Low	0.079	0.47	0.66
2.5 D	High	0.47	0.58	1.18
	Medium	0.29	0.55	1.0
	Low	0.053	0.35	0.50
3 D	High	0.36	0.153	0.588
	Medium	0.11	0.44	0.50
	Low	0.026	0.23	0.34

2.3. Thermal radiation caused by a fireball

Thermal radiation model caused by a fireball was used to estimate the damage caused by the explosion heat. In this work, the radiation flow on the affected surface has been calculated. Total evaporated mass, calculated somewhere else, is needed to apply this model. Once the total evaporated mass is estimated, the flow of radiation per surface area and time unit, I ($Jm^{-2}s^{-1}$) was calculated using equations 8 to 10 (Santamaría and Braña, 1998):

$$I = \frac{F_R (\Delta H_{c(gas)}) m_v}{\pi (D_{MAX})^2 t} \quad (8)$$

$$D_{max} = 6.48 m_v^{0.325} \quad (9)$$

$$t = 0.825 m_v^{0.26} \quad (10)$$

where F_R (dimensionless), is defined as the ratio between the energy emitted by radiation and the total energy released by the combustion. The F_R values are in the range 0.15 to 0.4, m_v (kg) is the initial mass that contributes to the fireball, t (s) is the duration of the fireball, D_{max} (m) is the maximum diameter of the ball.

To calculate the radiation flux over the affected surface I_R ($Jm^{-2}s^{-1}$) up to 100 m must be considered the geometric view factor, F_{vg} and the transmissivity τ, defined as the fraction of energy transmitted and calculated approximately as follows:

$$\tau = 2.02 (P_\omega X)^{-0.09} \quad (11)$$

where P_w (Pa), is the partial pressure of the water vapour and X (m) is the distance to the centre of the ball.

$$I_R = I \tau F_{vg} \quad (12)$$

$$F_{vg} = \frac{D_{max}^2}{4X^2} \quad (13)$$

2.3.1. Thermal radiation vulnerability study

Once the radiated energy caused by a fireball is calculated, an estimation of the vulnerability of persons can be calculated. In this work, Probit methodology has been used as a way of dealing with probabilities. The connection between Probit units (Y) and the percentage of affected population is given in Table 4 (Eisenberg and Lynch, 1975). Probit units are calculated as follows:

$$Y = K_1 + K_2 \ln V \quad (14)$$

K_1 and K_2 are empirical constants and take respectively the values of -14.9 and 2.56 in the case of a fireball (Eisenberg and Lynch, 1975; www.mtas.es/insht/ntp/ntp_291.htm). V measures the intensity of the damage-causative factor. In the case of fireballs, V represents the thermal radiation received, and it is calculated as follows:

$$V = t \frac{\sqrt[3]{I_R^4}}{10^4} \quad (15)$$

3. Fatal Accident Scenario

The Texas City Refinery is BP's largest and most complex oil refinery in the USA. It produces jet fuels, diesel fuels and chemical feed stocks. The refinery has a rated capacity of 460,000 barrels per day (bpd) and a production of up to 11 million gallons of gasoline per day (about 48.5 millions litters). The BP Texas refinery is located at Texas City (Texas), it has 486 hectares and supplies 30 per cent of all the BP production in the United States and 3 per cent of all the production in that country. The BP Texas refinery has 30 process units. Among these units, the isomerisation plant (ISOM) is located, where the refinery converts low octane blending feeds into a higher octane feed that is included in the unleaded regular gasoline pool. The fatal accident occurred in the unit mentioned above and at that time, approximately 800 additional staff were on site for turnaround work (BP fatal accident investigation report, 2007).

On Wednesday, March 23rd of 2005, at 13:20h, during the start-up of the Isomerisation Unit (ISOM), an explosion and fire occurred, killing fifteen and harmed over 170 people in the BP Products North America owned and operated by Texas City Refinery.

The temperature was 24.1°C, barometric pressure 101,140 Pa, humidity 35% and wind speed 1.5 m/s. The incident was an explosion in the west section of the complex, where the isomerisation plant (ISOM) was situated, and involved the F-20 unit (Figure 5). The flames reached 21 metres height and people found explosion fragments at 8 kilometres from the refinery. Figure 5 shows a scheme of the isomeration plant where the explosion occurred (BP fatal accident investigation report, 2007). The raffinate splitter is a single fractionating column, 164 ft tall (50 metres) with 70 distillation stages. It has an approximate volume of 3,700 barrels, and processes up to 45,000 BP of raffinate from the ARU. The blowdown system had to receive quench and dispose hot hydrocarbon vapours and minor associated liquids from the ISOM relief, vent, and pump-out systems during upsets or shutdowns. The blowdown system consisted on the relief pipe work headers, the F-20 unit and the Pump-Out Pump. Vapours dispersed from the top of the stack and liquids flew out of the drum through a gooseneck into the site's closed sewer system. F-20 is a vertical drum of 10-ft (3 metres) diameter with a 113-ft-high stack (34.5 metres).

Table 4. *Probit units and percentages.*

Probit	%	Probit	%	Probit	%	Probit	%	Probit	%
0	0	3.92	14	4.42	28	5.10	54	5.92	82
2.67	1	3.96	15	4.45	29	5.15	56	5.99	84
2.95	2	4.01	16	4.48	30	5.20	58	6.08	86
3.12	3	4.05	17	4.53	32	5.25	60	6.18	88
3.25	4	4.08	18	4.59	34	5.31	62	6.28	90
3.35	5	4.12	19	4.64	36	5.36	64	6.41	92
3.45	6	4.16	20	4.69	38	5.41	66	6.48	93
3.52	7	4.19	21	4.75	40	5.47	68	6.55	94
3.59	8	4.23	22	4.80	42	5.52	70	6.64	95
3.66	9	4.26	23	4.85	44	5.58	72	6.75	96
3.72	10	4.29	24	4.90	46	5.64	74	6.88	97
3.77	11	4.33	25	4.95	48	5.71	76	7.05	98
3.82	12	4.36	26	5.00	50	5.77	78	7.33	99
3.87	13	4.39	27	5.05	52	5.84	80	8.09	99.9

In the ISOM unit, trailers were used as temporary offices. Several trailers involved in the incident were located between two operating units, the ISOM and the Naphta Desulphurisation Unit (NDU). The closest trailer (J.E. Merit trailer) was located at 150 ft (45.7 metres) from the base of F-20 and it was there where most of the fatalities occurred at the time of the explosion. In these trailers, fourteen out of the fifteen fatalities took place (BP fatal accident investigation report, 2007).
The gasoline flowed from the F-20 for 6 minutes, which resulted in a pool fire and a vapour cloud explosion. The ignition source that leaded to the explosion and following fire was probably a starting-up vehicle engine. The failure to institute liquid rundown from the tower, and the failure to take effective emergency action, resulted in the loss of containment that preceded the explosion. This was indicative of the failure in following the established security policies and procedures.

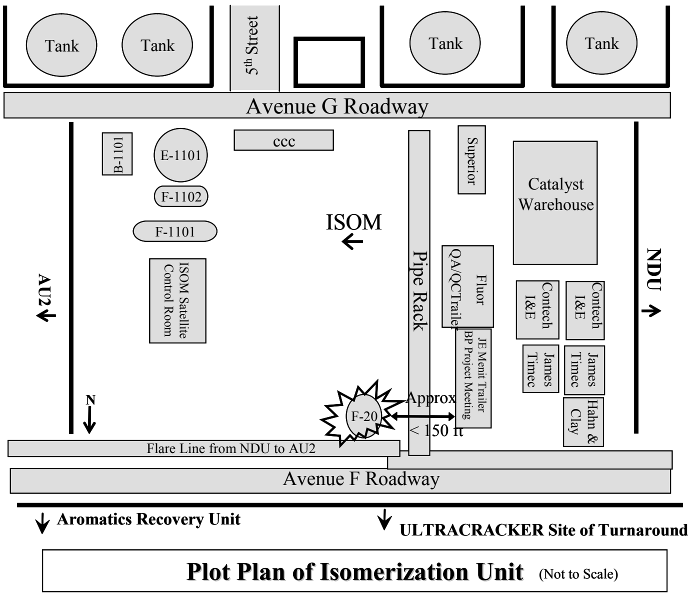


Figure 5. *Scheme of the Isomeration plant of the Refinery where the explosion occurred. Situation of different places. Not scale.*

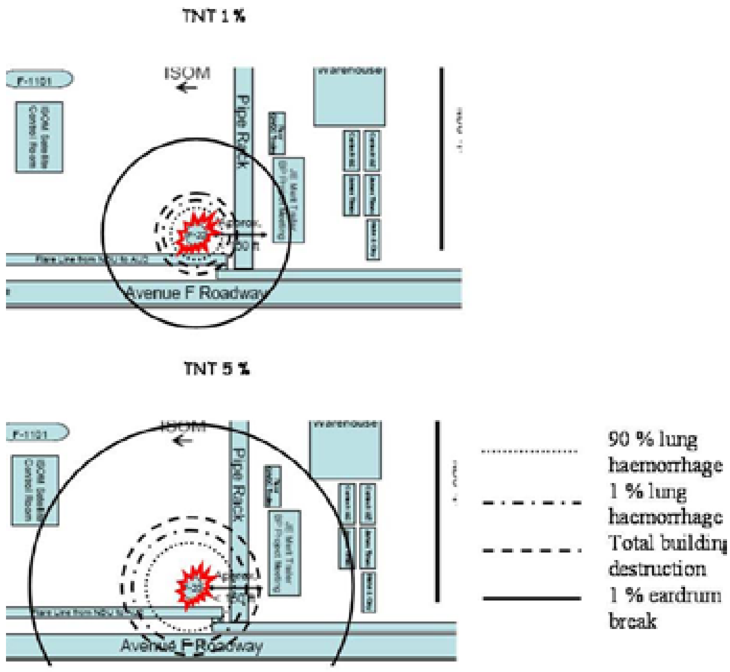
4. RESULTS AND DISCUSSION

4.1. Evaluation of evaporated mass.

As it has been previously described, the total mass in the leak can be calculated by multiplying the average discharge rate (220 kg/s) by the leak time (6 minutes). Using Eq. (1), the total leak mass equals 79,200 kg.
Next, the application of Eq. (2) gives a fraction of the total mass equal to 13,644 kg. Finally, applying Eq. (3) and using typical C_p and h_v values (C_p = 2,217 J·kg^{-1}K^{-1}, h_v = 3.5 · 10^5 J·kg^{-1}) the calculated evaporated mass is 4881.9 kg. This value will be used for both the calculation of the overpressure variation with distance and the effect of thermal radiation.
Taking into account ARAMIS project (Delvosalle et al., 2006) this amount of vapour cloud has a probability of 0.5 of immediate ignition. Once this ignition is produced, (if it is considered as a fully developed VCE) its consequences are irreversible injuries or death outside the site. Consequently, this result agrees with the real injuries in Texas fatal accident and with the rest of the results derived from the present work.

4.2. Effects of the explosion

Once it is known the amount of evaporated mass that explodes, simple models, as TNT, TNO and BST were used to estimate the damage caused by the overpressure of the explosion. Some standard damages caused by overpressure are shown in Table 2. These values let us set representative limits of damage over the map of the plant. Results obtained with these simple models were compared with those supplied by BP in a public report of the accident.
In the case of TNT, different explosion yields were taken from 1% to 10 %, getting results of overpressure versus distance. As it is shown in Figure 6, results obtained for explosion yields equal to 10% reproduce reasonably well what really happened in the accident, where the big majority of fatalities occurred in J.E. Merit Trailer, which was located at 45.7 m from the explosion and would suffer total demolition according to the model. TNO model was also used to calculate the overpressure at different distances. Results are shown in Figure 7 and predict more severe effects than the previous model, including 90 % lung haemorrhage in the people who were within the region where the trailer was located, apart from the total demolition of the trailer. Finally, BST model was used with the same purpose, considering a 3D flame expansion, high fuel reactivity and high obstacle density, leading to a value of M_w=0.588. Figure 8 shows the effect of the explosion using the BST model and that the calculated damages using the BST model were slightly more severe than those obtained with TNO. In any of the cases, and as commented above, this model also reproduces what happened in the accident. It is important to notice that, when talking about death, it is hard to simulate and get representative figures, due, mainly, to the domino effect that accompanies this sort of accidents. That is the reason why we talk in terms of building demolition and lung haemorrhage.
Predicted damages caused by overpressure vary with the applied model, increasing in the following order.
TNT<TNO<Baker-Strehlow



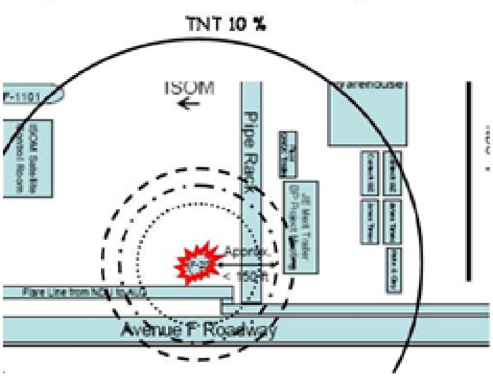


Figure 6. *Schematic representation of TNT model results for explosion yields from 1 to 10 % and for different overpressure damages.*

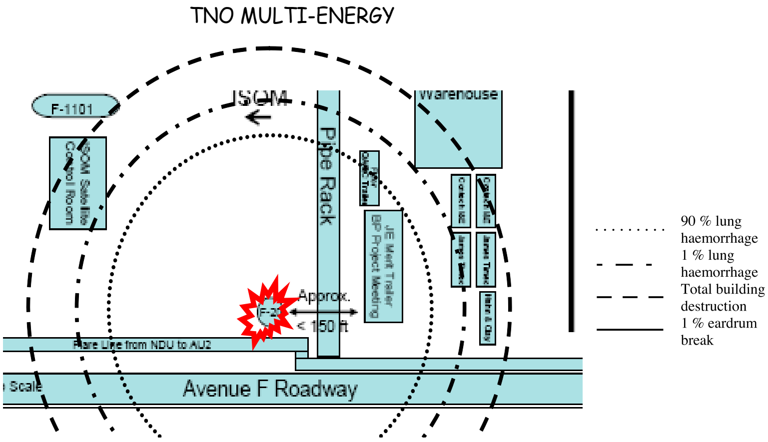


Figure 7. *Schematic representation of TNO Multi-Energy model results for different overpressure damages.*

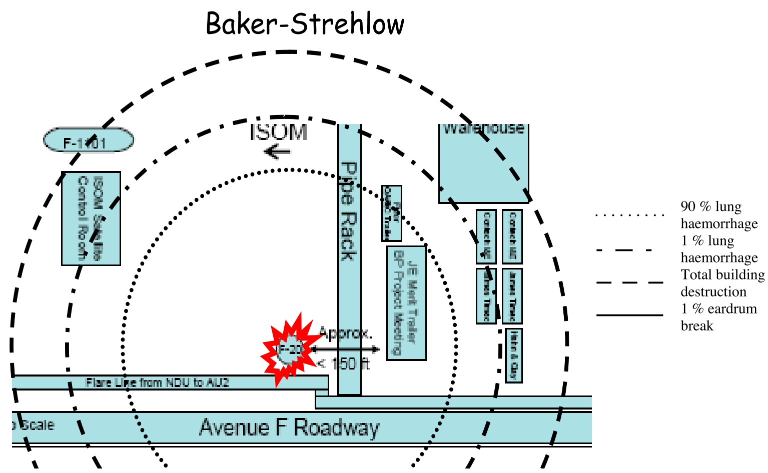


Figure 8. *Schematic representation of Baker-Strehlow-Tang model results for different overpressure damages.*

Figure 9 compares overpressure values versus distance obtained with the three different models used in this work, establishing critical distances and the associated damage. In this Figure, horizontal lines represent different overpressure threshold for certain damage, and the vertical line represents the nearest trailer position. When the curve predicted by a model is placed right to the intersection between the vertical and horizontal lines, it means that this damage would be produced at that distance taking into account that model. Therefore, death threshold and trailer position plotted in this figure show how TNO and BST models predict more than 90% of death at nearest trailer distance. Moreover, it is noticeable that at a distance up to 125 m there are a total building destructions using the TNO and BST models whereas with the TNT model these destructions occurs up to 50 m and using a yield reaction of 10 %.

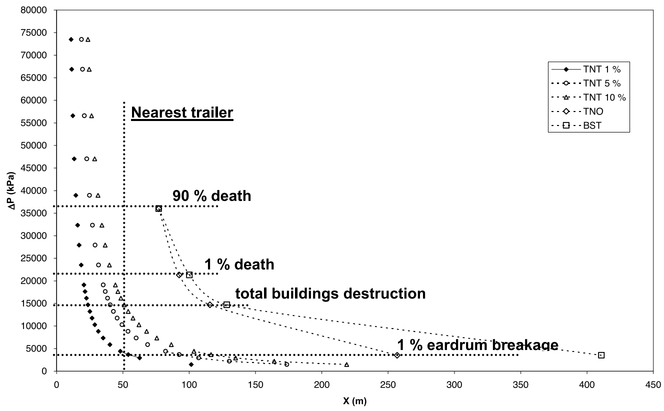


Figure 9. *Comparison of the results obtained with different models applied to standard damages.*

Despite the differences in the results got with the different models, they all are in a similar and reasonably coherent order of magnitude. It can be said that what really happened was an intermediate situation between the predicted by the models.

4.3 Effect of thermal radiation

The methodology explained in point 2.3. to calculate Probit units was applied from 5 to 150 metres. All the results are shown in Table 5. As it can be observed, at 45.7 metres (the distance of the nearest trailer) the probability is, theoretically, over 100 %. The 100 % death probability threshold is situated at, approximately, up to 90 metres. It slightly overestimates what really occurred, but it is definitely in a reasonable order of magnitude. It can be observed, that the 50 % of probability of death is reached at distances close to 120 metres what demonstrates that this types of accidents are very dangerous.

Table 5. *Probability of death by thermal radiation up to 150 m.*

X (m)	t (s)	F_{vg}	I_R (kW/m²)	V	Y	Death probability (%)
25	1.48	4.20	1953.4	183326	16.12	100
50	1.39	1.05	458.8	26568	11.18	100
75	1.34	0.47	196.6	8583.1	8.29	100
90	1.32	0.32	134.3	5164.1	6.99	98
100	1.31	0.26	107.8	3850.2	6.24	89
110	1.30	0.22	88.3	2952.1	5.64	75
115	1.29	0.20	80.5	2608.2	5.24	60
120	1.29	0.18	73.6	2316.5	4.93	48
125	1.28	0.17	67.6	2067.4	4.64	36
130	1.28	0.16	62.3	1853.4	4.36	26
140	1.27	0.13	53.3	1507.6	3.83	12
150	1.26	0.12	46.2	1243.9	3.34	5

5. CONCLUSIONS

Consequence analysis is a powerful tool to reproduce damages occurred in a chemical plant accident. Though companies develop complex software that requires huge computation capacity, simple empirical models, such as TNT, TNO or BST can be used with a reasonable degree of accuracy, needing much shorter computation times and not so powerful equipment to deal with calculations. A spreadsheet excel and the Figures are enough to make all the calculations.

Evaporated mass calculation is a critical data to deal with the rest of predictions. From empirical data, and making several simplifications, the value obtained was 4881.9 kg. Data obtained vary with the model applied, though all of them are within a reasonably narrow range. That suggests that the actual damages can be conceived as an intermediate situation between those predicted by the models. Damages calculated for overpressure increase in the following order:

TNT<TNO<BST

Damages predicted for thermal radiation were also within the actual range of fatalities. Although dealing with fatalities is always difficult, due to the domino effect that accompanies this kind of accidents, overpressure and thermal radiation obtained by the models used at the distance of the nearest trailer match the injuries occurred the day of the accident.

Finally, it can be said that these three simple models are useful to carry out the consequence analysis of this type of accidents and allow predicting or determining the safety zone of chemical industries.

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