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Study of Internal Pressure Impact on Sphere Tank Towards Vapour Cloud Explosion: Feyzin Incident

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***Abstract*— In the case of Liquefied Petroleum Gas (LPG) tank explosion(s), risk impact assessment on the storage facilities must be carried out. Since every LPG tank has its operating condition, it is essential to decide what the best operating conditions are for each tank. This effort is made to avert an accident from happening, as fires and explosions can be devastating in terms of lives lost and destruction to buildings and the environment. Boil-off and/or ignition of flammable gas can cause the pressure in the tank to increase. Therefore, a method called Planas-Cuchi is applied to determine the Peak Side-On Overpressure, P^o, of the LPG tank during the occurrence of explosion. Thermodynamic properties of saturated propane, C_3H_8, has been chosen as a reference and basis of calculation to determine the parameters involved, such as Explosion Energy, E, Equivalent Mass of TNT, W_{TNT}, and Scaled Overpressure, P_S. A cylindrical LPG tank in Feyzin Refinery, France is selected as a point of study in this research. At the end of this study, the most suitable operating pressure of the LPG tank will be determined, and the results are compared and validated using the TNT Equivalent (BREEZE software), Baker-Strehlow model and ARIA investigation report.**

***Keywords*— LPG; peak side-on overpressure; *planas-cuchi*; explosion; *feyzin*.**

I. Introduction

Today, the demand for LPG keeps rising, notably in the commercial and residential sectors of developing countries. This is in line with the increasing population growth and total demand for energy. LPG is often composed of propane, butane or some combination thereof, and they are stored in liquid form under pressure. However, they vaporize into gas form when the pressure is released. The broad application of LPG also raises the potential for fires and leaks in the LPG containers. These incidents may lead to a more severe accident as they are exposed to the risk of BLEVE or VCE occurrence.

It is learned that nearly all the cases reported in the literature refer to open environments while BLEVE or VCE occurrence in confined or congested areas are infrequent [1]. The *Feyzin* Refinery accident in France happened in a clearing (open space), and for this reason, it has been chosen as this research's point of the study. The open space situation also justifies the use of TNT Equivalent method instead of *Baker-Strehlow*. With regards to a VCE event, it is normally caused by pressure changes in the LPG sphere tank leakage. The effect of pressure changes that lead to fire and explosion will have severe consequences on the surrounding. Therefore, the impacts will be assessed through the manipulation of pressure changes in the LPG tank using mathematical models related to VCE such as TNT Equivalent and *Planas-Cuchi* [2].

II. Material and Method

A. Study area: LPG storage facility at Feyzin Refinery, France

On the morning of January 4th, 1966, a series of explosion went down at a standard LPG storage facility in *Feyzin* (Rhône), France. Due to a human error caused by an operator with the valves, there came to be a leak coming from T61-443 propane sphere that brought about an unfortunate BLEVE incident. According to the French Ministry of the Environment [3], the *Feyzin* refinery has a total capacity of 13,000 m^3 and is located 22.5 m from the highway called the A7 highway. The fireball created a destructive blast ***wave*** through Rhône valley, shattering windows up to a distance of 8 km. 45 minutes after the first BLEVE occurred at tank T61-443, a second BLEVE ensued at tank T61-442. The accident resulted in a death toll of 18 people, leaving 89 injured and vandalizing 6 fire trucks, 1475 shelters with its explosions. 12 storage vessels were also destroyed; 6 spheres, 2 cylinders, and 4 floating cap tanks, while tones of flammable materials were burned; 1012 t of propane, 2027 t of butane and 1500 t of LPG product. Based on Figure 1, the propane gas started to escape from the 2-inch bottom-venting pipe of sphere tank T61-443 for approximately 10 minutes when the operator failed to close the first valve. It is estimated that the initial mass flow rate of propane released into the atmosphere to be 11.5 kg/s [4].

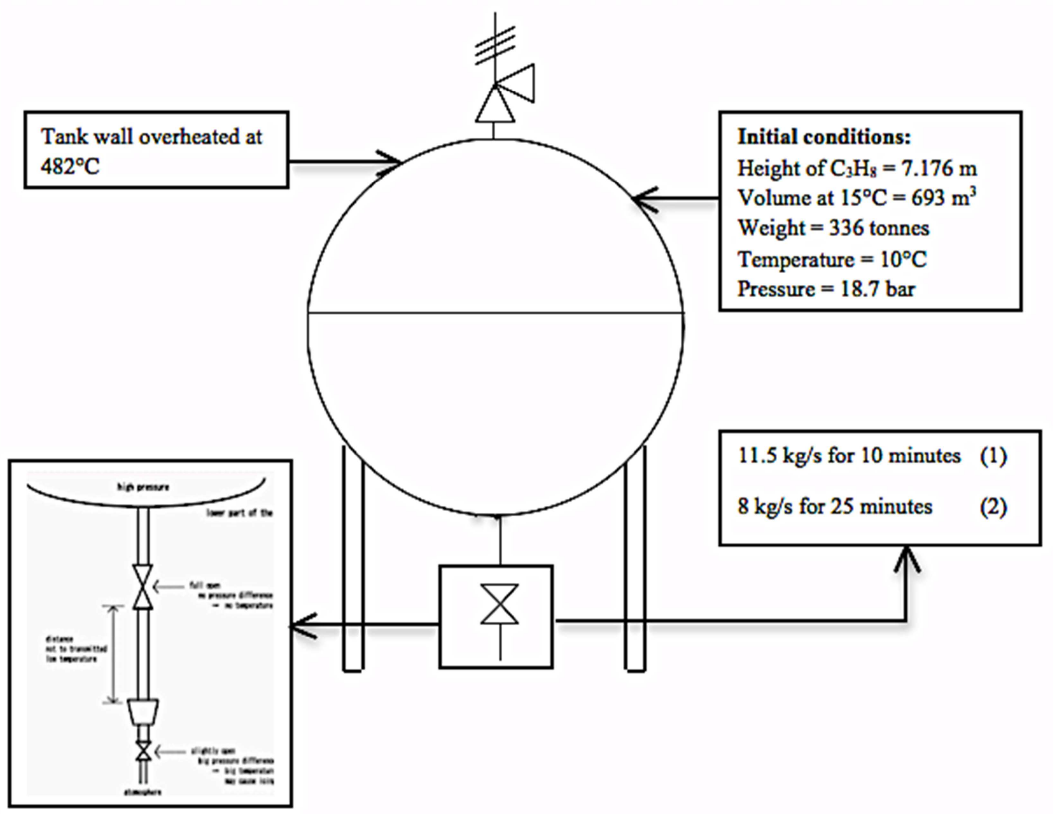

Fig. 1 Simplification of fire explosion occurrence at sphere tank T61-443

TABLE I
PHYSICAL AND CHEMICAL PROPERTIES OF PROPANE, C3H8

PHYSICAL PROPERTIES
➢ Appearance: colorless gas. (Cold vapor cloud may be white, but the lack of visible gas cloud does not indicate the absence of gas). A colorless liquid when pressurized.
➢ Vapour density: 1.87 kg/m^3 at 15°C and 1 atm
➢ Liquid density: 580 kg/m^3
CHEMICAL PROPERTIES
➢ Molecular weight: 44.09
➢ Melting point/freezing point: -189.7°C (-309.4°F)
➢ Boiling point: -42.11°C (-43.8°F)
➢ Flash point: -104°C (-155.2°F)
➢ Auto-ignition temperature: 450°C (842°F)

Table 1 provides the vital information on the chemical and physical properties of LPG (propane) that was stored in tank T61-443. The data are needed to determine the impacts of the incident.

Circumstances above lead to the calculated quantity of released propane at 6.9 tones (11.5 kg/s x 600 s). In the first 10 minutes from when the leakage started, no fire or explosion had occurred in the *Feyzin* refinery plant. Witnesses stated that the fire incident at tank T61-443 only happened 25 minutes after the dispersion of propane cloud around the plant. The cause of fire came from a car that had moved into the propane cloud, resulting in the ignition of the cloud, producing a flash fire that propagated back to tank T61-443 [3]. By considering Davenport et al. (1993) findings for the delayed ignition that occurred only 60 minutes after release time of propane gas at sphere T61-443 and the decrement of flow rate to 8kg/s after 10 minutes, the quantity of released propane for the next 25 minutes is calculated to be 12 tones (8 kg/s x 1500 s) [5]. This makes the total amount of liquid propane released to be 18.9 tones (6.9+12 tones). Although there was an uncontrolled release (leakage) from the valve opening to minimize the pressure changes, the gas released was not enough to relieve the pressure rise in the sphere [6].

B. Prediction methods

In this paper, selected models used in the analysis of VCE will be discussed. Thus, the result obtained from the accidents above will be carefully analyzed to estimate the suitability of these models.

1) TNT Equivalent and Baker-Strehlow Methods versus Planas-Cuchi+TNT Equivalent Coupling Method: Previously, the TNT and *Baker-Strehlow* (BS) methods are often used to predict VCE blast load impacts. TNT model has some issues to its use and is considered to be less accurate as it less attttention on the obstacles that may affect the pressure contours. *Baker-Strehlow* however, includes obstacle into its calculation, therefore, making it more accurate than TNT. Nevertheless, all 3 models do not make allowance for what happens to the flammable material (LPG) contained in the sphere tank given its thermodynamics aspect to which an inaccurate result is produced. The *Planas-Cuchi* and TNT Equivalent Coupling method considers from when the flammable material is within the operating conditions until just before it explodes and forms VCE. What happens inside the sphere is already justified by the experimental work done using the Peng-Robinson Equation of State simulation prepared in the MATLAB (Source: BiTP Vol. 30 Issue 2, 2013, pp. 31-39). This reduces the inaccuracies gap of the calculation result.

Taking the operating pressure as a criterion for analyzing the magnitude of consequences impact, a pressure of 10 bar to design pressure of sphere tank of 60 bar is constructed at an interval of 10 bar. The worst pressure consequences can be determined from these stages of the process. The safety valve was set to lift open at 20 bar (corresponding to propane temperature of 60°C) to prevent the internal pressure of tank from reaching its rupture pressure. Therefore, it is safe to assume that the pressure inside the vessel had remained at 20 bar while boiling off the liquid propane into vapor.

There is a sudden physical process related to the disintegration of the tank and rapid transition in the state of the LPG present in the tank that creates a wave of overpressure that propagates through the atmosphere, causing some serious damages from its immense energy. When the wall of the tank begins to fracture, it will cause a rapid pressure drop up to p_{atm}, at which the boiling temperature for liquefied gases is significantly lower than the ambient temperature [7]. This will release the liquid in which part of it will evaporate and rapidly create a boiling pool, or its vapor will burn if ignited. Then, propane will rapidly change its state from that of liquid to gas. This liquid-to-gas transition will result in a tremendous increase in volume taken up by the LPG in the tank, causing it to exceed the critical parameters; a change from liquid to 'overcritical liquid' state. This will inevitably result in an explosion of the 'overcritical liquid' contained in the tank [8].

TABLE II
THERMODYNAMIC PROPERTIES OF SATURATED PROPANE, C3H8 – PRESSURE TABLE

Pressure, bar	Temperature		Specific Volume, m^3/kg		Internal Energy, kJ/kg	
	℃	K	v_f	v_g	u_f	u_g
17.00	49.65	322.8	2.227	0.02606	228.3	472.7
18.00	52.30	325.45	2.253	0.02441	236.2	474.9
19.00	54.83	327.98	2.280	0.02292	243.8	476.9
20.00	57.27	330.42	2.308	0.02157	251.3	478.7
22.00	61.90	335.05	2.364	0.01921	265.8	481.7
24.00	66.21	339.36	2.424	0.01721	279.7	484.3
26.00	70.27	343.42	2.487	0.1549	293.1	486.2
28.00	74.10	347.25	2.555	0.01398	306.2	487.5
30.00	77.72	350.87	2.630	0.01263	319.2	488.1
35.00	86.01	359.16	2.862	0.009771	351.4	486.3

2) TNT Equivalent and Baker-Strehlow Methods versus Planas-Cuchi + TNT Equivalent Coupling Method: This coupling method is used to determine the Peak Side-On Overpressure, P^o, by considering the thermodynamic properties of propane (C_3H_8) at various pressure differences. To get the Explosion Energy, E value at the respective pressure difference, ΔP, the thermodynamic properties of propane. Table 2 below provides the thermodynamic properties of saturated propane by the view of the pressure found (bar). The details to *Planas Cuchi* + TNT Equivalent Coupling method used can be referred in [9], [10]. In this study, several pressures must be known to predict the impact coming from the fire and explosion. The pressures are:

- Maximum set pressure (MSP) = 1870 kPa
- Upstream pressure (MSP + atmospheric pressure) = 18.7 + 1 bar = 19.7 bar = 1970 kPa
- Burst pressure = 2210 kPa
- Test pressure = 28.05 bar = 2805 kPa
- Prediction impact from sphere wall T61-443 fire explosion

Table 3 and 4 are used as guidelines to estimate the consequences done to human and structure.

TABLE III
CONSEQUENCES OF OVERPRESSURE ON STRUCTURES AND PEOPLE [11]

Overpressure (kPa)	Effect on Structures	Effect on the Human Body
6.9(E_8)	Window glass shutters	Light injuries from fragments occur
13.8(E_{10})	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying grass or debris
20.7($E_{13, lower}$)	Residential structures collapse	Serious injuries are common, fatalities may occur
34.5($E_{14, lower}$)	Most buildings collapse	Injuries are universal; fatalities are widespread
69.0 (E_{15})	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
137.9(E_{16})	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

TABLE IV
CONSEQUENCES OF OVERPRESSURE ON BUILDING AND STRUCTURES [12]

Overpressure (kPa)	Damage
0.21(E_1)	The occasional breaking of large glass windows already under strain
0.69(E_2)	Breakage of small windows under strain
1.03(E_3)	Typical pressure for glass breakage
2.07(E_4)	"Safe distance" (probability 0.95 of no severe damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken
2.76(E_5)	Limited minor structural damage
3.4 – 6.9(E_6)	Large and small windows usually shatter; occasional damage to window frames
4.8(E_7)	Minor damage to house structures
6.9(E_8)	Partial demolition of houses, inhabitable, corrugated asbestos shatters; corrugated steel/aluminum panels, fastenings fail, followed by buckling; wood panels (standard housing), panels blow in
6.9 – 13.8(E_9)	Partial collapse of walls and roofs of houses, concrete or cinder block walls, not reinforced, shatter
13.8(E_{10})	50% destruction of brickwork of houses
13.8 – 20.7(E_{11})	Frameless, self-framing steel panel buildings demolished; rupture of oil storage tanks
17.2(E_{12})	The cladding of light industrial buildings ruptures
20.7 – 27.6(E_{13})	Wooden utility poles snap; tall hydraulic presses (40,000 lb) in buildings slightly damaged
34.5 – 48.2(E_{14})	Nearly destruction of houses
68.9(E_{15})	Probable destruction of buildings; heavy machine tools (7,000 lb), moved and badly damaged, very heavy machine tools (12,000 lb) survive

III. RESULTS AND DISCUSSION

In this analysis, the amount of propane involved was 336,000 kg with a total volume of 1,218 m^3. To compare the *Planas-Cuchi* and TNT Equivalent Coupling method with TNT Equivalent and *Baker-Strehlow* methods, the same radius of 50 m, 100 m, 150 m, 160 m, 300 m, 2.2 km, 4.2 km, 8 km, and 16 km [10] have been used as fixed variables in the comparison of peak overpressure between the 3 methods.

A. Prediction of burst pressure over sphere wall T61-443

The rupture pressure can be estimated from knowledge of the membrane stress in a spherical vessel.

$$\text{Rupture pressure, } P_R = \frac{4t\sigma_{TS}}{D} \quad (1)$$

Where,
Wall thickness, t = 45 mm = 0.045 m
The tensile strength of structural steel, $\sigma_{TS} = 620 \text{ MN/m}^2$

Based on Equation (1), the blast from sphere tank T61-443's wall will occur when the pressure inside the sphere is 79.71 bar, closing to 80 bar.

$$(P_R = \frac{4t\sigma_{TS}}{D} = \frac{4\ x\ 0.045\ x\ 620x10^6}{14} = 79.71 \text{ bar } \approx 80 \text{ bar}$$

To verify that the blast at sphere tank T61-443 had occurred at a pressure exceeding 79.71 bar, a detailed analysis is carried out by considering the sphere tank T61-443's internal pressure changes, ΔP, that is from the normal operation pressure of 18.7 bar to 20 until 80 bar. Table 5.1 till 5.9 show the comparison made between the Planas-Cuchi + TNT Equivalent Coupling model and ARIA report.

B. Comparison of prediction of peak overpressure from P = 20 bar to P =80 bar using Planas Cuchi + TNT Equivalent Coupling method with the ARIA report from Table V to XIII.

TABLE V
AT P = 2000 KPA (20 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	P^0 (kPa)	Diagnose	Diagnose
336 t of propane at T61-443	50	42.06	E14	Fatalities approach 100% (E_{15})
	100	15.70	E11	Injuries are universal; fatalities are widespread (E_{13})
	150	9.79	E9	Serious injuries, fatality may occur (E_{11})
	160	9.12	E9	Serious injuries, fatality may occur (E_{11})
	300	4.69	E7	Serious injuries, fatality may occur (E_{11})
	2,200	0.63	E2	Roofs damaged (E_4)
	4,200	0.33	E1	Walls moved (E_4)
	8,000	0.17	E1	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.09	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE VI

AT P = 3000 KPA (30 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	**P^0 (kPa)**	**Diagnose**	**Diagnose**
336 t of propane at T61-443	50	121.86	E15	Fatalities approach 100% (E_{15})
	100	33.98	E14	Injuries are universal; fatalities are widespread (E_{13})
	150	19.10	E11	Serious injuries, fatality may occur (E_{11})
	160	17.58	E11	Serious injuries, fatality may occur (E_{11})
	300	8.47	E9	Serious injuries, fatality may occur (E_{11})
	2,200	1.11	E3	Roofs damaged (E_4)
	4,200	0.58	E2	Walls moved (E_4)
	8,000	0.30	E1	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.15	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE VII

AT P = 4000 KPA (40 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	**P^0 (kPa)**	**Diagnose**	**Diagnose**
336 t of propane at T61-443	50	179.17	E15	Fatalities approach 100% (E_{15})
	100	45.35	E14	Injuries are universal; fatalities are widespread (E_{13})
	150	24.26	E13	Serious injuries, fatality may occur (E_{11})
	160	22.20	E13	Serious injuries, fatality may occur (E_{11})
	300	10.30	E9	Serious injuries, fatality may occur (E_{11})
	2,200	1.32	E3	Roofs damaged (E_4)
	4,200	0.69	E2	Walls moved (E_4)
	8,000	0.36	E1	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.18	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE VIII

AT P = 4248 KPA (42.48 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	**P^0 (kPa)**	**Diagnose**	**Diagnose**
336 t of propane at T61-443	50	195.96	E15	Fatalities approach 100% (E_{15})
	100	48.62	E14	Injuries are universal; fatalities are widespread (E_{13})
	150	25.68	E13	Serious injuries, fatality may occur (E_{11})
	160	23.45	E13	Serious injuries, fatality may occur (E_{11})
	300	10.74	E9	Serious injuries, fatality may occur (E_{11})
	2,200	1.37	E3	Roofs damaged (E_4)
	4,200	0.72	E2	Walls moved (E_4)
	8,000	0.38	E1	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.19	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE IX

AT P = 5000 KPA (50 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	P^0 (kPa)	Diagnose	Diagnose
336 t of propane at T61-443	50	236.31	E15	Fatalities approach 100% (E_{15})
	100	56.25	E14	Injuries are universal; fatalities are widespread (E_{13})
	150	28.96	E13	Serious injuries, fatality may occur (E_{11})
	160	26.36	E13	Serious injuries, fatality may occur (E_{11})
	300	11.84	E9	Serious injuries, fatality may occur (E_{11})
	2,200	1.49	E3	Roofs damaged (E_4)
	4,200	0.78	E2	Walls moved (E_4)
	8,000	0.41	E1	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.21	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE X

AT P = 6000 KPA (60 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	P^0 (kPa)	Diagnose	Diagnose
336 t of propane at T61-443	50	285.05	E15	Fatalities approach 100% (E_{15})
	100	65.38	E15	Injuries are universal; fatalities are widespread (E_{13})
	150	32.77	E14	Serious injuries, fatality may occur (E_{11})
	160	29.71	E13	Serious injuries, fatality may occur (E_{11})
	300	13.02	E9	Serious injuries, fatality may occur (E_{11})
	2,200	1.62	E4	Roofs damaged (E_4)
	4,200	0.85	E3	Walls moved (E_4)
	8,000	0.45	E2	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.22	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE XI

AT P = 7000 KPA (70 BAR)*

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	P^0 (kPa)	Diagnose	Diagnose
336 t of propane at T61-443	50	329.38	E15	Fatalities approach 100% (E_{15})
	100	73.63	E15	Injuries are universal; fatalities are widespread (E_{13})
	150	36.13	E14	Serious injuries, fatality may occur (E_{11})
	160	32.66	E14	Serious injuries, fatality may occur (E_{11})
	300	14.02	E11	Serious injuries, fatality may occur (E_{11})
	2,200	1.73	E4	Roofs damaged (E_4)
	4,200	0.90	E3	Walls moved (E_4)
	8,000	0.47	E2	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.24	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE XII

AT P = 7500 KPA (75 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	**P^0 (kPa)**	**Diagnose**	**Diagnose**
336 t of propane at T61-443	50	350.04	E15	Fatalities approach 100% (E_{15})
	100	77.47	E15	Injuries are universal; fatalities are widespread (E_{13})
	150	37.68	E14	Serious injuries, fatality may occur (E_{11})
	160	34.02	E14	Serious injuries, fatality may occur (E_{11})
	300	14.47	E11	Serious injuries, fatality may occur (E_{11})
	2,200	1.77	E4	Roofs damaged (E_4)
	4,200	0.93	E3	Walls moved (E_4)
	8,000	0.49	E2	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.24	E1	Blast from the explosion was felt, doors opened (E_1)

TABLE XIII

AT P = 8000 KPA (80 BAR)

Incident Case	Radius	Planas-Cuchi + TNT Equivalent Coupling method		ARIA Report for Ministry of Environment French (witness' observation)
	r (m)	**P^0 (kPa)**	**Diagnose**	**Diagnose**
336 t of propane at T61-443	50	369.77	E15	Fatalities approach 100% (E_{15})
	100	81.13	E15	Injuries are universal; fatalities are widespread (E_{13})
	150	39.15	E14	Serious injuries, fatality may occur (E_{11})
	160	35.30	E14	Serious injuries, fatality may occur (E_{11})
	300	14.88	E11	Serious injuries, fatality may occur (E_{11})
	2,200	1.82	E4	Roofs damaged (E_4)
	4,200	0.95	E3	Walls moved (E_4)
	8,000	0.50	E2	Blast from the explosion was felt, doors opened (E_2)
	16,000	0.25	E1	Blast from the explosion was felt, doors opened (E_1)

Note: Some row and columns are highlighted/shaded means that it complies to the ARIA report.

Some row and columns are highlighted or shaded, which means that they are complying with the ARIA report. Based on the results obtained from Table 5.1 to 5.9, it indicates that the damages sustained in the event of T61-443 sphere tank exploding shows the expression level of damage on buildings and structures that surround the area of the explosion. The witnesses' in *Feyzin* refinery when the internal pressure inside T61-443 rises to 70-80 bar when the distance of a receptor that absorbs the explosion energy is between 300 m to 16 km. The results are closer to the real damage that had occurred at the site between 50-160 m could make an explosion of T61-443 occur when the internal pressure of the tank is at 30 bar. This indicates that the probability for rupture of T61-443 wall surface before reaching the wall's burst pressure of 80 bar, maybe a legitimate hypothesis. To measure the extent to which the accuracy of the model results in *Planas-Cuchi* + TNT Equivalent, comparisons on the measurement of the level of damage done are conducted on the other two models, namely, *Baker-Strehlow* and TNT Equivalent [13].

In Table 6, the comparison is being made at P = 70 bar because it is the point of pressure change that starts to comply most with the ARIA report. Then, the overpressure at different radii is calculated using the 3 methods above and is compared to one another whilst using the French Ministry of Environment report as guideline in determining the accuracy of each model. Table 6 shows the *Planas-Cuchi* + TNT Equivalent Coupling method to have the most accurate or most similar diagnose as the ones done in ARIA Report. On the other hand, TNT Equivalent method alone shows little accuracy in for the near-range distances but soon begins to conform to that of ARIA report. Meanwhile, *Baker-Strehlow* shows quite different values from the witness' observation. Between 50 – 160 m, the overpressure value generated from the explosion at tank T61-443 has dropped quite drastically for the Coupling method and TNT Equivalent method, particularly in the latter while *Baker-Strehlow* model shows consistency. The overpressure effects had gone south of Rhône valley, causing damage to ceilings and room at 2.2 km away. At a distance of 4.2 km, it was observed that some walls were moved and damaged while inflicting minor structure damage and breaking windows at 8 km away. In addition, some villagers at Vienne, which was located at 16 km upstream from the refinery, had claimed that they felt the blast from the explosion. Although the damaging impact did on building structures was interpreted through the means of calculating the overpressure from the Coupling and *Baker-Strehlow* models, this was found to have deviated from the actual structural building analyzed in the report compared to the TNT Equivalent model impact analysis results at 4.2 km, 8 km, and 16 km. At 2.2 km, *Planas-Cuchi* + TNT Equivalent model gave a truer value to the said report.

TABLE XIV

AT P = 8000 KPA (80 BAR)

Incident Case	**Radius**	***Planas-Cuchi*+TNT Equivalent method**	**TNT Equivalent method**	***Baker-Strehlow* method**	**ARIA Report for Ministry of Environment French (witness' observation)**
	r (m)	**P^0 (kPa)**	**P^0 (kPa)**	**P^0 (kPa)**	**Diagnose**
336 t of propane at T61-443	50	329.38 (E_{15})	1219.18 (E_{15})	4.36 (E_6)	Fatalities approach 100% (E_{15})
	100	73.63 (E_{15})	255.52 (E_{15})	4.36 (E_6)	Injuries are universal, fatalities are widespread (E_{13})
	150	36.13 (E_{14})	100.25 (E_{15})	4.36 (E_6)	Serious injuries, fatality may occur (E_{11})
	160	32.66 (E_{14})	86.79 (E_{15})	4.36 (E_6)	Serious injuries, fatality may occur (E_{11})
	300	14.02 (E_{11})	24.73 (E_{13})	2.94 (E_5)	Serious injuries, fatality may occur (E_{11})
	2,200	1.73 (E_4)	4.22 (E_7)	0.42 (E_1)	Roofs damaged (E_4)
	4,200	0.90 (E_3)	2.18 (E_4)	0.22 (E_1)	Walls moved (E_4)
	8,000	0.47 (E_2)	1.146 (E_3)	0.13 (E_1)	Blast from explosion was felt, doors opened (E_2)
	16,000	0.24 (E_1)	0.284 (E_1)	0.10 (E_1)	Blast from explosion was felt, doors opened (E_1)

IV. CONCLUSION

Current studies have shown that chemical process industries involving propane storages are risky and bear a high potential for the occurrence of incidents such as VCE and BLEVEs. All 3 models demonstrate that there is a decrease in overpressure value as the distance from the source of explosion becomes greater. This is practically understood as the energy of explosion reduces by time and distance during energy dissipation and dispersion. Nevertheless, both TNT Equivalent and *Baker-Strehlow* models show a great deviation in the value of overpressure produced as compared to that of *Planas-Cuchi* and TNT Equivalent Coupling model. This is particularly seen at distance 50 m, 300 m, 2200 m, 8000 m, and 16000 m, in which the Coupling model displays higher precision in the results produced when compared with what witness(es) had observed and analysed in the French Ministry of Environment report. Thus, for future fire explosion analysis that concerns the condition of pressure changes in a vessel, the *Planas-Cuchi* and TNT Equivalent Coupling model would be most recommended.

NOMENCLATURE

t	wall thickness	m
r	radius	m
σ_{TS}	tensile strength of structural steel	MN/m^2
P_R	rupture pressure	bar
σ_{TS}	peak side-on overpressure	kPa
E	explosion energy	MJ
W_{TNT}	equivalent mass of TNT	kg
P_S	scaled overpressure	kPa
P_{atm}	atmospheric pressure	kPa
P^o	peak side-on overpressure	kPa
LPG	liquefied petroleum gas	

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