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# Study of Vapour Cloud Explosion Impact from Pressure Changes in the Liquefied Petroleum Gas Sphere Tank Storage Leakage

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**Abstract.** This research was carried out to determine the risk impact of Liquefied Petroleum Gas (LPG) storage facilities, especially in the event of LPG tank explosion. In order to prevent the LPG tank explosion from occurring, it is important to decide the most suitable operating condition for the LPG tank itself, as the explosion of LPG tank could affect and cause extensive damage to the surrounding. The explosion of LPG tank usually occurs due to the rise of pressure in the tank. Thus, in this research, a method called Planas-Cuchi was applied to determine the Peak Side-On Overpressure ( $P^0$ ) of the LPG tank during the occurrence of explosion. Thermodynamic properties of saturated propane, ( $C_3H_8$ ) have been chosen as a reference and basis of calculation to determine the parameters such as Explosion Energy (E), Equivalent Mass of TNT ( $W_{TNT}$ ), and Scaled Overpressure ( $P_s$ ). A cylindrical LPG tank in Feyzin Refinery, France was selected as a case study in this research and at the end of this research, the most suitable operating pressure of the LPG tank was determined.

## 1. Introduction

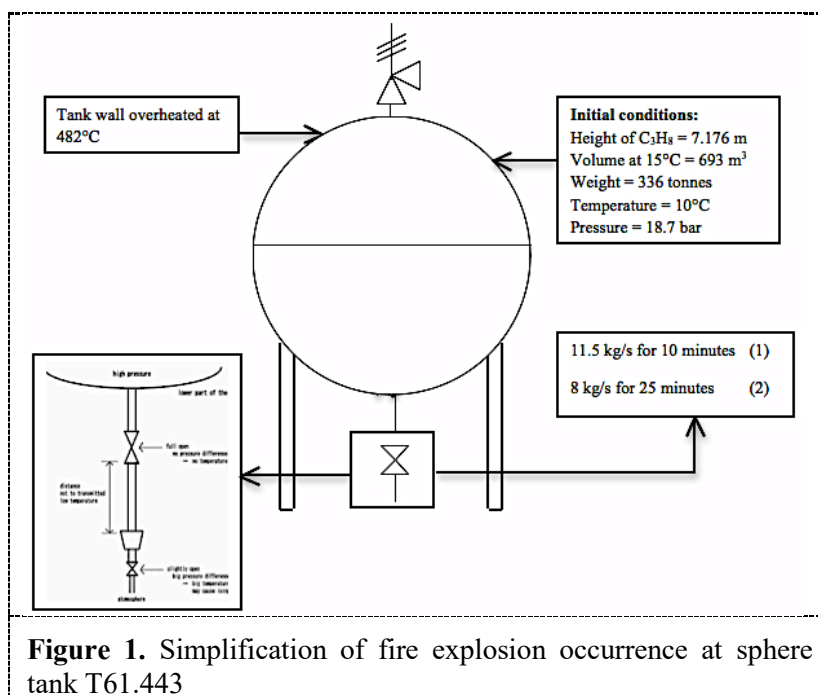
LPG comprises flammable combination of hydrocarbon gases such as propane ( $C_3H_8$ ) and is used to power many of the equipment we have today. However, LPG can be extremely dangerous if mistake occurs. Some of the accidents happening at these petrochemical plants can be studied through historical record. For instance, the Flixborough (Nypro UK) Explosion in 1974 resulted in 30 tonnes of cyclohexane leakage from a vertical crack of one of the onsite reactors, causing the death of 28 workers and injured 36 more. Another major LPG accident was the PEMEX LPG Terminal tragedy in Mexico City in 1984, which claimed over 500 lives and some 4,000 people injured. It was caused by a rupture at an 8-inch pipe that was connecting a sphere and a series of cylinders and the operators' inability to identify the source of the pressure drop, causing the LPG to leak continuously. The first BLEVE (Boiling Liquid Expanding Vapour Explosion) occurred 15 minutes after the initial release and a series of BLEVEs ensued. The explosions were so catastrophic that they caused severe damage to the immediate surroundings with window/glass thrown away up to 4km from the source. There are also nearly similar incidents such as BP Texas City Refinery Explosion in 2005 and one that is in close proximity to Malaysia, Shell's Pulau Bukom (Singapore) Plant Fire Breakout in 2011. These incidents were usually caused by vapour cloud explosion (VCE) coming from pressure changes in the LPG sphere tank leakage. To ensure these incidents are not repeated, assessments will be made using models related to VCE.



## 2. Method of Analysis

### 2.1 Study Area: LPG Storage Facility at Feyzin Refinery, France

On the morning of January 4<sup>th</sup>, 1966, a series of explosion went down at a typical LPG storage facility in Feyzin (Rhône), France. Due to a human error caused by an operator handling the valves, there came to be a leak coming from T61-443 propane sphere that brought about a disastrous BLEVE incident. According to the French Ministry of the Environment (1), the Feyzin refinery has a total capacity of 13,000 m<sup>3</sup> and is located 22.5 m from the a highway called the A7 highway. The fireball created a destructive blast wave through Rhône valley, shattering windows up to a distance of 8 km. Forty-five minutes after the first BLEVE occurred at tank T61-443, a second BLEVE ensued at tank T61-442. The explosion resulted in a death toll of 18 people, 89 injured and damaging 6 fire trucks, and 1475 shelters with its explosions. Twelve storage vessels were also destroyed; 6 spheres, 2 cylinders and 4 floating cap tanks while tonnes of flammable materials were burned; 1012 t of propane, 2027 t of butane and 1500 t of LPG products (2). 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. During that time, Török et al. (2011) estimated that the initial mass flow rate of propane released into the atmosphere was 11.5 kg/s.



Circumstances above lead to the released propane at estimated 6.9 tonnes (11.5kg/s x 600s). In the first 10 minutes after 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 the ignition of the cloud, producing a flash fire that propagated back to tank T61-443 (1). Based on Davenport et al. (3) findings, the delayed ignition occurred only 60 minutes after release time of propane gas at sphere T61-443 and the drop of flow rate to 8kg/s after 10 minutes and the quantity of released propane for the next 25 minutes was estimated at 12 tonnes (8kg/s x 1500s). This makes the total amount of liquid propane released was 18.9 tonnes (6.9+12 tonnes). Although there was an uncontrolled release (leakage) from the valve opening to minimize the pressure changes, the gas released was insufficient to relieve the pressure rise in the sphere. Table 1 provides 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 from the incident.

**Table 1. Physical and Chemical Properties of Propane, C<sub>3</sub>H<sub>8</sub>**

<b>PHYSICAL PROPERTIES</b>	
<ul style="list-style-type: none"> <li>• Appearance: Colourless gas. (Cold vapour cloud may be white but the lack of visible gas cloud does not indicate the absence of gas). A colourless liquid when pressurized.</li> <li>• Vapour density: 1.87 kg/m<sup>3</sup> at 15°C and 1 atm</li> <li>• Liquid density: 580 kg/m<sup>3</sup></li> </ul>	
<b>CHEMICAL PROPERTIES</b>	
<ul style="list-style-type: none"> <li>• Molecular weight: 44.09</li> <li>• Melting point/freezing point: -189.7°C (-309.4°F)</li> <li>• Boiling point: -42.11°C (-43.8°F)</li> <li>• Flash point: -104°C (-155.2°F)</li> <li>• Auto-ignition temperature: 450°C (842°F)</li> </ul>	

## 2.2 Prediction Methods

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

### 2.2.1 TNT Equivalent and Baker-Strehlow Methods versus Planas-Cuchi + TNT Equivalent Coupling Method

Previously, the TNT and Baker-Strehlow (BS) methods were often used to predict VCE blast load impacts. TNT model is considered to be less accurate as it does not take into account the obstacles that may affect the pressure contours. On the other hand, Baker-Strehlow includes obstacle into its calculation, making it more accurate than TNT. Nevertheless, all 3 models do not take into account for what happens to the flammable material (LPG) contained in the sphere tank with respect to its thermodynamics aspect, thus an inaccurate result is produced. The Planas-Cuchi and TNT Equivalent Coupling method considers the moment 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 using 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 bars to design pressure of sphere tank of 60 bar was constructed at an interval of 10 bar. The worst pressure consequences can be determined from these stages of processes. 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 whilst boiling off the liquid propane into vapour. There was a sudden physical process related to the disintegration of tank and rapid transition in the state of the LPG present in the tank that created a wave of overpressure that propagated through the atmosphere, causing some serious damages from its immense energy. When the wall of the tank begun to fracture, a rapid pressure drop occurred down to  $p_{atm}$ , at which the boiling temperature for liquefied gases is significantly lower than the ambient temperature. The liquid was released in which part of it evaporated and rapidly created a boiling pool, or its vapour burnt when 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.

### 2.2.2 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<sub>3</sub>H<sub>8</sub>) at various pressure differences. To get the Explosion

Energy,  $E$  value at the respective pressure difference,  $\Delta P$ , the thermodynamic properties of propane was identified. Table 2 below provides the thermodynamic properties of saturated propane by view of the pressure (bar).

**Table 2.** Thermodynamic properties of saturated propane ( $C_3H_8$ ) – pressure table

Pressure, bar	Temperature		Specific Volume, $m^3/kg$		Internal Energy, $kJ/kg$	
	$^{\circ}C$	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

The steps in the Planas-Cuchi methodology below show the sequence on how to determine the Peak Side-On Overpressure. As a VCE occurs at an LPG storage facility, the vapour fraction with respect to total mass involved in the incident is to be calculated using Equation (1).

$$x = \frac{m_T P_{v_{L0}} - V_T P + m_T u_{L0} - U}{[(u_{L0} - u_{V0}) - (v_{V0} - v_{L0})P]m_T} \quad (1)$$

Once the value of  $U$  is obtained, it is then substituted into Equation (2) to calculate the overall variation of the internal energy of the tank's content,  $-\Delta U$ .

$$-\Delta U = (u_{L0} - u_{V0})m_T x - m_T u_{L0} + U \quad (2)$$

This methodology considers the real expansion work done by taking into account the real gas behaviour and adiabatic irreversible expansion from when the whole content of the tank changes from the state of explosion until it reaches its final state. Therefore, this work must be equivalent to the change in internal energy of the tank's content [refer to Equation (3)].

$$E = -P\Delta V = \Delta U \quad (3)$$

In order to get the TNT equivalent mass,  $W_{TNT}$  from the explosion energy,  $E$ , Equation (4) may be utilized.

$$W_{TNT} = \frac{\beta E}{\Delta H_{TNT}} = 1.068 \times 10^{-7} E \quad (4)$$

Once the TNT equivalent mass is calculated, the scaled distance,  $Z_e$  can be known using Equation (5).

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

Scaled Pressure,  $P_s$  can be calculated using Equation (6).

$$P_s(\text{kPa}) = \frac{1616 \left[ 1 + \left( \frac{Z_e}{4.5} \right)^2 \right]}{\sqrt{1 + \left( \frac{Z_e}{0.048} \right)^2} \sqrt{1 + \left( \frac{Z_e}{0.32} \right)^2} \sqrt{1 + \left( \frac{Z_e}{1.35} \right)^2}} \quad (6)$$

where,  $P^0$  is calculated by using an Equation (7) and (8).

$$P_s = \frac{P^0}{P_a} \quad (7)$$

$$P^0(\text{kPa}) = P_a \cdot \frac{1616 \left[ 1 + \left( \frac{Z_e}{4.5} \right)^2 \right]}{\sqrt{1 + \left( \frac{Z_e}{0.048} \right)^2} \sqrt{1 + \left( \frac{Z_e}{0.32} \right)^2} \sqrt{1 + \left( \frac{Z_e}{1.35} \right)^2}} \quad (8)$$

whereby,  $P^0$  is the overpressure, and  $P_a$  is the atmospheric pressure.

### 2.3 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.

Tensile strength of structural steel  $\sigma_{TS} = 620 \text{ MN/m}^2$ ,

$$\text{Rupture pressure, } P_R = \frac{4t\sigma_{TS}}{D} \quad (9)$$

### 2.4 Prediction of Impact from Sphere Wall T61-443 Fire Explosion

Table 3 and 4 are referred to estimate the consequences of overpressure on human and structures.

**Table 3.** Consequences of Overpressure on Human and Structures (4)

Overpressure (kPa)	Effect on Structures	Effect on the Human Body
6.9	Window glass shutters	Light injuries from fragments occur
13.8	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying grass or debris
20.7	Residential structures collapse	Serious injuries are common, fatalities may occur

34.5	Most buildings collapse	Injuries are universal, fatalities are widespread
69.0	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
137.9	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

**Table 4.** Consequences of Overpressure on Building and Structures (4)

Overpressure (kPa)	Damage
0.21(E <sub>1</sub> )	Occasional breaking of large glass windows already under strain
0.69(E <sub>2</sub> )	Breakage of small windows under strain
1.03(E <sub>3</sub> )	Typical pressure for glass breakage
2.07(E <sub>4</sub> )	“Safe distance” (probability 0.95 of no serious damage below this value); projectile limit; some damage to house ceilings; 10% window glass broken
2.76(E <sub>5</sub> )	Limited minor structural damage
3.4 – 6.9(E <sub>6</sub> )	Large and small windows usually shatter; occasional damage to window frames
4.8(E <sub>7</sub> )	Minor damage to house structures
6.9(E <sub>8</sub> )	Partial demolition of houses, inhabitable, corrugated asbestos shatters; corrugated steel/aluminium panels, fastenings fail, followed by buckling; wood panels (standard housing), panels blow in
6.9 – 13.8(E <sub>9</sub> )	Partial collapse of walls and roofs of houses, concrete or cinder block walls, not reinforced, shatter
13.8(E <sub>10</sub> )	50% destruction of brickwork of houses
13.8 – 20.7(E <sub>11</sub> )	Frameless, self-framing steel panel buildings demolished; rupture of oil storage tanks
17.2(E <sub>12</sub> )	Cladding of light industrial buildings ruptures
20.7 – 27.6(E <sub>13</sub> )	Wooden utility poles snap; tall hydraulic presses (40,000 lb) in buildings slightly damaged
34.5 – 48.2(E <sub>14</sub> )	Nearly complete destruction of houses
68.9(E <sub>15</sub> )	Probable total destruction of buildings; heavy machine tools (7,000 lb), moved and badly damaged, very heavy machine tools (12,000 lb) survive

### 3. Results and Discussion

In this analysis, the amount of propane involved was 336,000 kg with a total volume of 1,218 m<sup>3</sup>. 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 have been used as fixed variable in the comparison of peak overpressure between the 3 methods.



**Table 5:** Comparison prediction of peak overpressure between Planas-Cuchi and TNT Equivalent Coupling, TNT equivalent and Baker-Strehlow methods.

Incident Case	Radius	Planas-Cuchi + TNT equivalent method	TNT equivalent method	Baker-Strehlow method	ARIA Report for Ministry of Environment French (witness' observation)
336 t of propane at T61-443	r (m)	P <sup>0</sup> (kPa)	P <sup>0</sup> (kPa)	P <sup>0</sup> (kPa)	Diagnose
	50	91.78 (E <sub>15</sub> )	1219.18 (E <sub>15</sub> )	4.36 (E <sub>6</sub> )	Fatalities approach 100% (E <sub>15</sub> )
	100	27.63 (E <sub>13</sub> )	255.52 (E <sub>15</sub> )	4.36 (E <sub>6</sub> )	Injuries are universal, fatalities are widespread (E <sub>13</sub> )
	150	16.05 (E <sub>11</sub> )	100.25 (E <sub>15</sub> )	4.36 (E <sub>6</sub> )	Serious injuries, fatality may occur (E <sub>11</sub> )
	160	14.83 (E <sub>11</sub> )	86.79 (E <sub>15</sub> )	4.36 (E <sub>6</sub> )	Serious injuries, fatality may occur (E <sub>11</sub> )
	300	7.31 (E <sub>9</sub> )	24.73 (E <sub>13</sub> )	2.94 (E <sub>5</sub> )	Serious injuries, fatality may occur (E <sub>11</sub> )
	2,200	0.96 (E <sub>3</sub> )	4.22 (E <sub>7</sub> )	0.42 (E <sub>1</sub> )	Roofs damaged (E <sub>4</sub> )
	4,200	0.50 (E <sub>2</sub> )	2.18 (E <sub>4</sub> )	0.22 (E <sub>1</sub> )	Walls moved (E <sub>4</sub> )
	8,000	0.26 (E <sub>1</sub> )	1.146 (E <sub>3</sub> )	0.13 (E <sub>1</sub> )	Blast from explosion was felt, doors opened (E <sub>2</sub> )
	16,000	0.13 (E <sub>1</sub> )	0.284 (E <sub>1</sub> )	0.10 (E <sub>1</sub> )	Blast from explosion was felt, doors opened (E <sub>1</sub> )

Based on Equation [9], the blast from sphere tank's wall will occur when the pressure inside the sphere is close or over 80 bar ( $P_R = \frac{4t\sigma_{TS}}{D} = \frac{4 \times 0.045 \times 620 \times 10^6}{14} = 79.71 \text{ bar} \approx 80 \text{ bar}$ ). Taking  $\Delta P = 800 \text{ kPa}$  to be constant at each radius, Table 5 shows the comparison between the 3 models. The overpressures at different radii were calculated using the 3 methods above and were compared to one another whilst using the French Ministry of Environment report as guideline in determining the accuracy of each model. Table 4 shows the Planas-Cuchi + TNT Equivalent Coupling method was the most accurate or most similar diagnose as the ones done in ARIA Report. On the other hand, TNT equivalent method alone shows some accuracy in for the near-range distances but soon begins to differ from ARIA's 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 had 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 damage impact done on building structures was interpreted through the means of calculating the overpressure from the Coupling and Baker-Strehlow models, this was found to have obviously 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 more correct value to the said report.



#### 4. 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 was a decrease in overpressure value as the distance from the source of explosion became 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 - 2200 m in which the Coupling model displays higher precision in the results produced when compared with what witness(es) had observed and analyzed in the French Ministry of Environment report. Table 5 proves the accuracy of the Planas-Cuchi and TNT Equivalent Coupling method's result on the overall distance; from 50 m to 16 km. Although the TNT Equivalent method shows more precise impact properties in accordance to the ARIA report from 4.2 km to 16 km, the result deviation from the Planas-Cuchi and TNT Equivalent Coupling method is not obvious for the distances said. 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.

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