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Assessment of an explosive LPG release accident: A case study

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Abstract

In the present paper, an accident occurred during a liquefied petroleum gas (LPG) tank filling activity has been taken into consideration. During the transfer of LPG from the source road tank car to the receiving fixed storage vessel, an accidental release of LPG gave rise to different final consequences ranging from a pool fire, to a fireball and to the catastrophic rupture of the tank with successive explosion of its contents. The sequence of events has been investigated by using some of the consequence calculation models most commonly adopted in risk analysis and accident investigation. On one hand, this allows to better understand the link between the various events of the accident. On the other hand, a comparison between the results of the calculations and the damages actually observed after the accident, allows to check the accuracy of the prediction models and to critically assess their validity. In particular, it was shown that the largest uncertainty is associated with the calculation of the energy involved in the physical expansion of the fluid (both liquid and vapor) after the catastrophic rupture of the tank.

Keywords: LPG; Explosion; Accident investigation; Consequences calculation; Model validation

1. Introduction

Incident investigation is nowadays widely recognized as an important part of a comprehensive and efficient process safety management. A detailed and systematic analysis of an accidental event, either a major one or a near-miss, allows to identify not only its immediate (primary) cause, but also the whole set of so-called root causes whose combination led to the failure of the system and to the occurrence of the corresponding harmful consequences (major accident), or to an unplanned temporary hazardous condition (near miss). Through reporting the results of the analysis, and through communicating and disseminating the report to other facilities/companies/organizations, the adoption of appropriate changes to similar existing installations or the introduction of preventive measures in the design of new systems will avoid the recurrence of similar events or, at least, reduce their frequency of occurrence. Different techniques have been developed in recent years and they are widely available in the literature [1].

At the same time, incident investigation is a very important and useful activity also from a different point of view. In fact, all of the models and methods used for quantifying the consequences of dangerous phenomena (explosions, fires, toxic chemicals dispersion and so on) belong to one of the following groups: analytical models, numerical simulations, and empirical or semi-empirical models. In the first two cases experimental data to check the applicability and the accuracy of the models predictions are successively required. Only in the case of empirical models, their development is directly based on some experimental data and, even in this case, their applicability will be limited to a more or less narrow range of variability of the investigated parameters, depending on the extent of the experimental campaign. However, for obvious reasons, the availability of data from large-scale experiments is very scarce, most of the data deriving from small-scale experiments under controlled conditions.

Based on these considerations, the application of consequence calculation models in the analytical investigation of real accidents can be very important for at least two reasons. On one hand it provides an analytical tool for identifying the various steps in the sequence of events making up the accident and their relative links. On the other hand, the damages detected after the accident (physical damages to property or the environment or sometimes, unfortunately, even injuries or fatalities) can serve, once connected with the corresponding causing event (explosion, fire, etc.), as a sort of "experimental data" to check the

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Nomenclature

A	pool surface area
c_p	specific heat
D	tank diameter
$D_{\max}$	maximum diameter of the fireball
D_{pool}	pool diameter
E	emitted radiation flux
$E_{\text{p,s}}$	received radiation flux
F	geometrical view factor
h	heat transfer coefficient
H	fireball's height
H_{pool}	pool fire height
ΔH_{c}	heat of combustion per unit mass
ΔH^*	modified heat of vaporization
I	radiative heat flux
L	tank length
m	combustion rate
m_{b}	pool fire mass-burning rate
m_{f}	initial mass of flammable
q_{ev}	heat flux due to liquid evaporation inside the tank
$q_{\text{pv–l}}$	radiative heat flux between tank wall in contact with the vapor and the liquid
q_{rel}	heat flux due to release rate
Q	volumetric release rate
R	radiation fraction
t_{c}	duration of combustion
T	temperature
U	overall heat transfer coefficient
V	volume
x	distance from accident location
$\dot{y}$	vertical rate of liquid level decrease

Greek letters

α_{p}	tank shell absorptance (absorptivity)
ε_{p}	tank shell emissivity
ρ	density
ρ_{a}	air density
ρ_{p}	tank shell density
σ	Stefan-Boltzmann constant
τ	air transmissivity

Subscripts

a	ambient
b	boiling
l	liquid
p	point source model
pl	tank wall in contact with liquid
pv	tank wall in contact with vapor
s	solid flame model
v	vapor

reliability of the results of the adopted calculation models. These models are widely used mainly in design, layout and emergency planning activities, and, accordingly, in many cases a number of conservative assumptions are appropriately adopted, so that when applied to real situations the possibility of some discrepancies with the actual values can arise. Under this respect, it would be very useful to collect from past accidents and share among all the actors involved in process safety and emergency planning, as much information as possible.

In the present paper, an accident occurred in Italy during an liquefied petroleum gas (LPG) tank filling activity has been taken into consideration. Thanks to the report from different eyewitnesses, both the immediate cause of the accident and the sequence of events have been identified. The root causes contributing to the occurrence of the failure are still under investigation and will not be dealt with here. Conversely, the observed physical damages produced by the various events have been used to check the accuracy of the results obtained with some of the most commonly used consequence calculation models.

2. Description of the accident

The accident here described occurred at an unloading facility, during the transfer of LPG from a road tank car to a fixed storage vessel. The transfer happened via a pipeline composed both of a short hard metal section connected with the tank of origin and of a flexible hose until the receiving tank. The source tank was cylindrical horizontal ($L = 3.6$ m, $D = 2$ m) with a total capacity of about 13 m^3, and it was around 65% full, corresponding to about 4200 kg of LPG, at the arrival at the facility. The receiving vessel was a buried vertical cylindrical tank with a total capacity of about 3 m^3. The facility was located close to an industrial installation and it was partially confined on all sides and also provided with a shed above the unloading platform. Two warehouses were at a distance of 20 and 30 m from the unloading tank during transfer.

In the present case, thanks to the availability of various witnesses, the identification of the sequence of events has been rather straightforward, and the efforts were mainly focused on the comparison between the actual consequences and those predicted by means of the most commonly adopted calculation models.

2.1. The sequence of the accident

The initiating event of the sequence was the accidental release of liquid LPG, from the backside of the tank truck, where all the pumping equipments were located. The exact location of the release was not identified, however following the accident reconstruction it was agreed that it must have occurred from the pipeline very close to the source tank connection.

The release generated a liquid pool in the vicinity of the truck, and the fast partial evaporation (flash) of the release stream as well as the successive continuous evaporation from the pool, produced a vapor cloud denser than air which stratified on the ground and whose dispersion was partially hindered by the configuration of the surrounding area. Based on eyewitnesses, 5 min after the beginning of the release, the vapor cloud got ignited (presumably by a car/truck traveling along the nearby road) and the generated flash-fire traveled back to the truck, ignit-

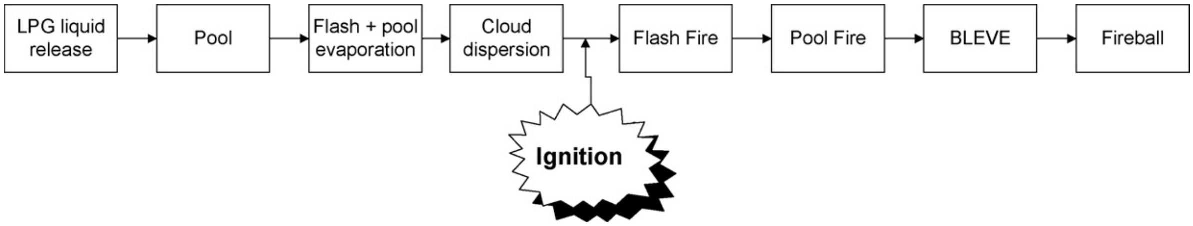

Fig. 1. The sequence of the events.

ing the liquid on the ground and generating a pool fire, also, with high flames. Consequently, the unloading tank, still containing LPG, was almost fully engulfed in the pool fire, until, after about 25 min from the ignition of the pool, it ruptured catastrophically giving rise to an explosion boiling liquid expanding vapor explosion (BLEVE), with the production of projectiles, of a shock wave and, upon ignition of the released liquid, of a fireball. The whole sequence of events, based on the their timing, is represented in Fig. 1.

2.2. The consequences of the accident

Assessing the injuries, the damages and the other physical consequences of the chain of all the occurred events is a fundamental step for a reliable and accurate investigation of an accident. With reference to the thermal radiation, no one was injured up to a distance of about 100 m from the fireball. Based on the witnesses, the maximum height of the fireball was about 20–25 m from the ground, i.e. almost double the height of the warehouses.

As far as the physical damages are concerned, apart from the road tanker which was completely destroyed by the explosion, the structures which suffered some damages by the blast wave were the two warehouses. They both consisted of a concrete structure, with concrete panels, 30 cm thick and with an exposed surface area larger than 30 m^2. On top of the buildings, glass windows with metal frames were present. The glass windows of both the warehouses were destroyed by the explosion; the concrete panels of the building closer to the explosion (20 m) were substantially damaged, but they were not shattered, while those of the second warehouse (30 m) suffered only minor damages. Based on data reported in the literature [2,3], it can be argued that the maximum pressures acting on the above panels were in the range 50–60 mbar and about 30 mbar, respectively.

3. Analysis of the accident

In the present analysis, the last event (i.e. the fireball) will be analyzed first and then the modeling procedure will go backwards up until the initial release, trying to identify all the main parameters of each step of the chain.

3.1. The fireball

The catastrophic release of a substantial amount of flammable liquid will give rise, upon ignition, to a particular fire which goes under the name of fireball, and the major consequences of such a phenomenon are due to thermal radiation. Basically, similarly with other fire phenomena, two approaches for the calculation of its consequences are available in the literature: the point source model and the solid flame model [4,5].

In the first case, it is assumed that a fraction (R) of the total heat of combustion is emitted evenly in all directions as radiation from a single point at the center of the flame. The corresponding radiation flux, E_p (W/m^2), at a distance x_p (m) from the flame center can be calculated as

$$E_{\mathrm{p}} = \frac{Rm\Delta H_{\mathrm{c}}\tau}{4\pi x_{\mathrm{p}}^2} \tag{1}$$

where m is the combustion rate (kg/s), ΔH_c the heat of combustion per unit mass (J/kg) and τ is the air transmissivity (dimensionless).

Alternatively, according to the solid flame model, the received radiation flux E_s, at a distance x_s from the fire surface, which in this case is approximated by a sphere, is given by

$$E_{\mathrm{s}} = E\tau F \tag{2}$$

where F is the geometrical view factor between the emitting and receiving surfaces, and E is the emitted radiation power per unit surface area of the fire (W/m^2)

$$E = \frac{Rm_{\mathrm{f}}\Delta H_{\mathrm{c}}}{\pi D_{\max}^2 t_{\mathrm{c}}} \tag{3}$$

where m_f is the initial mass of flammable (kg), D_{max} is the maximum diameter of the fireball (m) and t_c the duration of combustion (s).

The application of Eqs. (1) and (3), requires the knowledge of geometrical and other specific parameters of the fire (size, height, duration, etc.). Different models for their calculation are available in the literature [5], but most of them have the same form, the differences being only in the values of the numerical constants.

In particular, the maximum diameter and the duration of the fireball can be estimated by means of the following equations:

$$D_{\max} = \alpha m_{\mathrm{f}}^{\beta} \tag{4}$$

$$t_{\mathrm{c}} = \gamma m_{\mathrm{f}}^{\delta} \tag{5}$$

The numerical values of the constants in Eqs. (4) and (5) relative to four different models widely used by risk analysts in consequences calculations are reported in Table 1.

A further important parameter of the fireball is represented by the height of the center of the sphere from the ground, H (m). This is not always explicitly taken into consideration by the

Table 1a
Characteristic fireball's parameters according to different models: (a) $H = 20$ m and (b) $H = 25$ m

Model	α	β	γ	δ	m_f	t_c	E	E_p	t_{pain}	E_s	t_{pain}
(a) $H = 20$ m											
Fay–Lewis [10]	6.36	0.333	2.57	0.167	250.15	6.46	125.12	2.42		5.56	
Moorhouse [8]	5.33	0.327	0.923	0.303	475.18	5.97	257.10	4.97	16	11.42	4
Roberts [7]	5.8	0.333	0.45	0.333	329.92	3.10	343.64	6.64	8	15.27	3
TNO [9]	6.48	0.325	0.852	0.26	270.56	3.65	239.32	4.62	15	10.63	6
(b) $H = 25$ m											
Fay–Lewis [10]	6.36	0.333	2.57	0.167	488.91	7.23	139.93	4.16		6.22	
Moorhouse [8]	5.33	0.327	0.923	0.303	940.20	7.35	264.76	7.86	8	11.76	4
Roberts [7]	5.8	0.333	0.45	0.333	644.82	3.88	343.87	10.22	5	15.28	3
TNO [9]	6.48	0.325	0.852	0.26	537.58	4.37	254.57	7.56	8	11.31	4

Other parameters: $R = 0.35$; $x_p = 121$ m; $x_s = 82$ m; $F = 0.06$; $\tau_r = 0.71$; $\tau_s = 0.74$.

models, and it is experimentally determined that $H \geq D_{max}/2$. However, because of conservative reasons, it is often assumed that the fireball "touches" the ground, so that $H = D_{max}/2$.

In the case under investigation, the height of the fireball has been reported by witnesses as being about 20–25 m, so that, adopting the above relationship between height and diameter, the mass of the flammable can be estimated by using Eq. (4). In Table 1, the initial mass of the flammable in the cloud (m_f) and the duration of the combustion (t_c) are reported for the two extreme values of the fireball's height, respectively. In all cases a mass of less than 1000 kg is calculated, with most of the calculations ranging between about 250 and 600 kg. It is worth noting that even if the mass of flammable markedly varies with the fireball's height (it almost doubles at 25 m), the combustion time is less affected by H.

The surface emissive power (E), calculated by using Eq. (3), is also reported in Table 1. Experimental values for E from typical hydrocarbon (propane and butane) fireballs range between 320 and 370 kW/m^2 [6], so that it can be seen that the results obtained with the Roberts' model [7] fall well within this range, while those from the Moorhouse [8] and TNO [9] models are somewhat smaller than the lower experimental limit. Differently, the Fay–Lewis model [10], which was developed from small-scale experiments (gas bubbles less than 200 cm^3), markedly underestimates the surface emissive power. Under this respect, it is worth reminding that some scale effect has already been reported in the literature, with the surface emissive power increasing with the fireball's diameter [11].

After evaluating the atmospheric transmissivity between either the center, or the surface of the fireball, and a target at a distance of 100 m from its vertical axis [4], the received thermal radiation flux has been calculated both with the point source (E_p) and the solid flame (E_s) models. In the latter case the view factor between the emitting surface and the receiving target was also calculated. It can be seen that the point source model always provides radiation fluxes which are, on an average, half the corresponding value of the solid flame model. This is due to the relatively short distance between fireball and target. Correspondingly, the time required to achieve the pain threshold, at a given radiation level [12], is larger (almost double) for the point source model. With the exception of one case for the Moorhouse model, in all other cases, the time for reaching the pain threshold is always greater than the duration time of the fireball, which is consistent with the fact that no injuries due to radiation are reported after the accident.

To summarize, we can say that, among the four models here adopted, the Roberts' model seems to provide the more realistic values of the fireball parameters, and that almost all of them, agree in suggesting an average amount of about 500 kg of propane in the flammable cloud at the moment of the ignition.

3.2. The BLEVE

The sudden and catastrophic loss of containment of a superheated and pressurized liquid will give rise to a shock wave (in some cases two distinct shock waves), due to the immediate explosive expansion of the vapor contents (in equilibrium with the liquid inside the tank), and to the fast evaporation (flash) of the liquid phase. Typically, this happens when a vessel containing a liquefied gas is exposed to an external fire (or some other heat source) for a time period sufficient to heat up the metal shell of the tank to a temperature above which it is no longer able to withstand the internal pressure.

This physical phenomenon is known under the name of BLEVE, and its main consequences are the generation of a shock pressure wave and the launching of fragments of the metal vessel. In order to estimate the consequences of such an event, namely the overpressure profile as a function of the distance from the exploding vessel, different models are available, and in all cases the system's conditions at the moment of the burst (temperature and pressure) are required. However, since the vessel under investigation was exposed to an external fire, these conditions are not known in advance, depending on the heat received, the exposure time and so on. Consequently, an analysis of the heating up phase has been carried out, taking into account that the vessel was fully engulfed in a pool fire of propane (average heat flux of about 200–250 kW/m^2 [13]) for about 25 min, and that a leak was present which, at least partially, relieved the pressure increase (the tank was not provided with a pressure relief valve).

Generally, the rapidity of the tank rupture depends on various parameters such as the initial conditions, the input heat flux, the possible presence of a pressure relief valve, the thickness

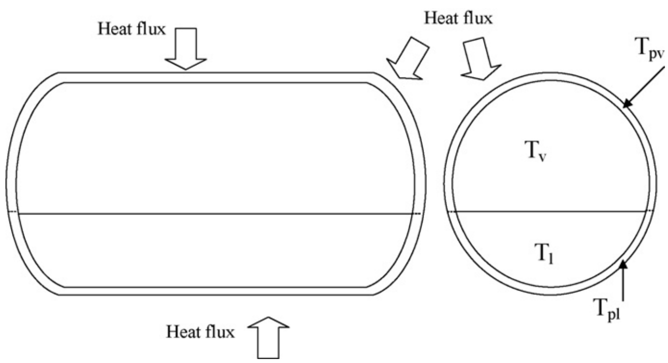

Fig. 2. Tank system representation for energy balance and temperatures calculation.

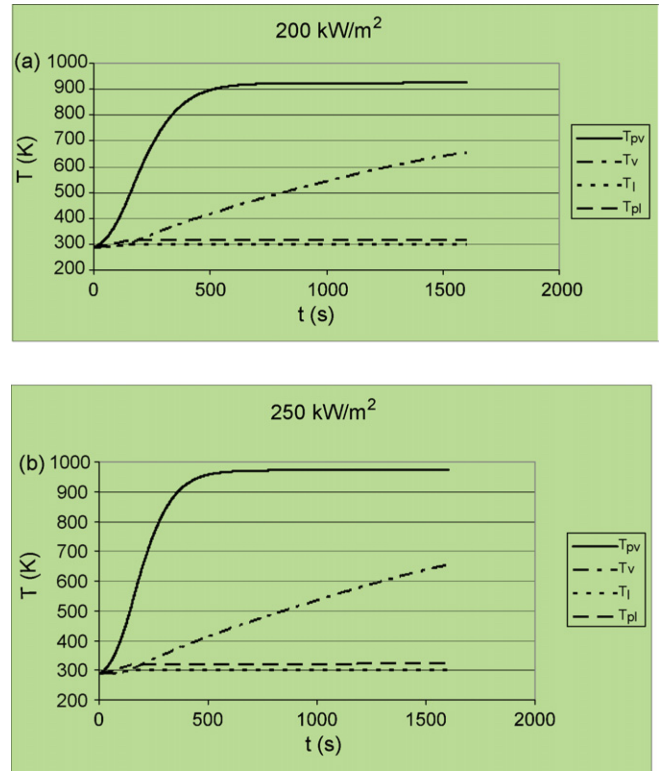

Fig. 3. Temperature histories for the different tank areas as a function of time: (a) input heat flux of 200 kW/m^2 and (b) input heat flux of 250 kW/m^2.

of the shell and, very important, the liquid level in the tank. In fact, due to the low heat transfer coefficient between the shell and the vapor inside the vessel, the area of the shell in contact with the vapor reaches very high temperatures (much higher than the area in contact with the liquid) so that the mechanical strength of the vessel is very much affected by this parameter. In order to estimate the initial liquid contents in the vessel, some preliminary runs were carried out under different release conditions, and it was concluded that an average release rate of about 1.75 kg/s can be assumed, so that, with reference to a mass of about 500–600 kg at the moment of the rupture, around 3100–3200 kg of propane were present at the beginning of the pool fire, corresponding with a fill level of about 49%. The initial temperature (ambient temperature) and pressure (vapor pressure at T_a) were, 288 K and 7.5 bar, respectively.

For the analysis, the vessel volume has been divided into four parts, as shown in Fig. 2: the liquid and the vapor phases in the tank, the shell in contact with the liquid and that in contact with the vapor. For each of these volumes, a homogeneous thermal distribution has been assumed and the corresponding average temperature is calculated from an energy balance for the volume. By taking into account all the heat inflows and outflows and after properly evaluating the corresponding heat transfer coefficients, the following energy balance equations are derived for the four volumes of Fig. 2:

$$\rho_p V_{pv} c_{pp} \frac{dT_{pv}}{dt} = \alpha_p I A_{pv} - h_{a,pv} A_{pv}(T_{pv} - T_a) - \varepsilon_p \sigma A_{pv}(T_{pv}^4 - T_a^4) - U_{pv} A_{pv}(T_{pv} - T_v) - q_{pv\text{–}l} - h_{pv,pl} A_{pvpl}(T_{pv} - T_{pl}) \quad (6)$$

$$\rho_v V_v c_{pv} \frac{dT_v}{dt} = U_{pv} A_{pv}(T_{pv} - T_v) + q_{ev} \quad (7)$$

$$\rho_l V_l c_{pl} \frac{dT_l}{dt} = U_{pl} A_{pl,l}(T_{pl} - T_l) + q_{pv\to l} - q_{ev} - q_{rel} \quad (8)$$

$$\rho_p V_{pl} c_{pp} \frac{dT_{pl}}{dt} = \alpha_p I A_{pl} - h_{a,pl} A_{pl}(T_{pl} - T_a) - \varepsilon_p \sigma A_{pl}(T_{pl}^4 - T_a^4) - U_{pl} A_{pl}(T_{pl} - T_l) - h_{pv,pl} A_{pvpl}(T_{pl} - T_{pv}) \quad (9)$$

The meaning of the parameters in Eqs. (6)–(9) are explained in Nomenclature.

In Fig. 3a and b, the temperature histories for the different tank areas are shown as a function of time, for an input heat flux of 200 and 250 kW/m^2, respectively. In particular, in order to better represent the real situation, the liquid and the vapor were not assumed to be in thermal equilibrium, but the distinct heat transfer rates between these phases and the tank wall, under boiling and ordinary gas–solid convection regimes, respectively, have also been considered. This explains the difference in the profiles for T_v and T_l. It is interesting noting that, despite the strong heat input from the external fire, the liquid's temperature does not increase very much with respect to the ambient one; this is also confirmed by experimental measurements reported in the literature [14] under similar conditions.

It can be seen that, with the exception of T_{pv}, the time profiles for all other temperatures do not vary with the heat input. Instead, the temperature of the tank wall in contact with the vapor reaches a higher final value after a steeper increase, for a larger heat flux (see Fig. 4 for a direct comparison). After 25 min from the beginning of the pool fire T_{pv} reaches a value of 650 and 700 °C for the two heat inputs of 200 and 250 kW/m^2, respectively, the temperature of 600 °C being attained after 420 and 330 s. The results of these numerical simulations are in agreement with some experimental data reported in the literature. Moodie et al. [14] carried out some tests with a cylindrical tank 4.88-m long, 1.7-m diameter with shell thickness of 11.85 mm. The tanks were fully engulfed in kerosene pool fires for which a

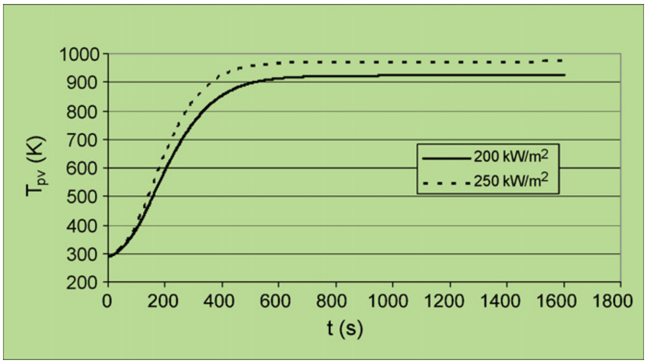

Fig. 4. Temperature of the tank wall in contact with the vapor. Direct comparison for heat inputs of 200 and 250 kW/m^2.

heat flux of about 90–100 kW/m^2 can be assumed, and different fill levels were adopted during the experimentation. At fill levels of 36 and 58%, the fires lasted 21 and 26 min, and the maximum temperature of the wall in contact with the vapor was 657 and 610 °C, respectively. These results are in agreement with the present simulations, also taking into account that in the experimentation by Moodie et al. the heat flux was much lower and the shell thickness much larger than in our case. At a fill level of 72%, the fire lasted 31 min and the shell temperature was "only" 572 °C, thus confirming that the larger the liquid contents, the slower the temperature increase.

A metal's mechanical properties markedly depend on the working temperature, and it is known that at the temperatures reached by a tank exposed to an external fire (600–700 °C) steel's tensile strength can reduce down to 15–20% that at ambient conditions [15]. So if we assume a tensile strength of 60–65 kg/mm^2 at ambient temperature, it can become about 9–13 kg/mm^2 under "fire conditions", which is comparable or even lower than the load due to the internal pressure, calculated as 13.5 kg/mm^2. Even if these calculations do not allow to predict the moment of the rupture, however they largely account for the tank failure.

After the catastrophic rupture, the vapor contents of the tank will immediately expand, giving rise to a shock wave, originating at the vessel surface and traveling through the surrounding air. At the same time the liquid phase will quickly vaporize, producing a second shock wave. Each of the two explosions can be characterized by an energy contents and, since the two waves can be very close to each other, in many cases their energies are summed up. However, this can lead to large overestimation of the peak pressure. The energy associated with the expansion of a gas can be calculated by different equations. In Table 2 the energies associated with the expansion of 12 m^3 of vapor propane and 1 m^3 of liquid propane, i.e. the phase distribution in the tank at the moment of the rupture according to the calculations from the previous step, are reported. The calculations for the vapor phase have been performed by using four different models among those most commonly reported in the literature. With reference to the liquid phase, and assuming a specific explosion energy [5] of 34.5 kJ/kg for liquid propane at 300 K (see Fig. 3a and b), the total energy associated to the expansion of 500 kg of liquid propane is 34,500 kJ (the specific energy has to be multiplied by 2 according to the method by Baker et al. [18]). The equivalent mass of TNT and the overpressure at 30 m from the center of the explosion, calculated with the TNT equivalency model [4,19], are also reported in Table 2. Despite the uncertainties in the exact quantification of the blast overpressure based on the damages actually observed after the accident, the calculated values seem to be more or less largely overestimated, with the Brode and the Brown equations providing unrealistic results.

More refined models attempting to calculate the blast parameters for actual vapor explosions, rather than for solids detonations (as for the TNT equivalency method), are available in the literatures [4,5]. Prugh [20] tries to estimate the peak pressure at the surface of the expanding gas at the moment of the burst, while Baker et al. [18] make use of data from small-scale physical explosion experiments. In Table 3, the peak overpressures obtained from the above models, along with those estimated from the reported accident damages, are shown. As a first consideration, it can be seen that both Prugh and Baker et al. models (2nd and 3rd columns in Table 3) highly overestimate the peak pressure, with the Prugh's method providing lower values. However it must be reminded that, in order to take into account ground reflections of the shock wave, the Baker et al. method makes use of an explosion energy which is the double that calculated with the Brode equation. Apparently, this leads to a large overestimation of the calculated pressure profile. The Prugh and the Baker et al. models use the explosion energy calculated by the Brown's and the Brode's equations, respectively. Since the Crowl's equation provided lower values for the explosion energy (Table 2),

Table 2
Explosion energy for propane expansion

Phase	Model	Energy (kJ)	TNT equivalency	
			Mass (kg)	Overpressure at 30 m (kPa)
Vapor	Brode [16]	95,920	20.45	13
Vapor	Brown [5]	88,425	18.85	12.6
Vapor	Isentropic expansion [5]	29,600	6.3	7.87
Vapor	Crowl [17]	25,552	5.45	7.4
Liquid	[5]	34,500	7.36	8.4

Table 3
Calculated and estimated peak overpressures (kPa) for vessel explosion

Distance (m)	Model					
	Prugh (vapor)	Baker (vapor)	Crowl/Prugh (vapor)	Baker (liquid BLEVE)	Planas et al.	Actual (estimated)
20	18.3	28	11	16.9	8.9	5–6
30	11.1	15.5	6.9	9.8	5.4	3

an attempt has been made to use the result from this equation in the two methods above. The "best" result has been obtained by combining the Crowl's equation with the Prugh's method. However, despite the low overpressures calculated, they are still about twice those estimated from the observed damages (Table 3).

As a second consideration, it is found that the overpressure associated with the liquid expansion is of the same order of magnitude of that generated by the vapor. As a consequence, in this case, the summation of the two energies would increase the overestimation.

Third, it is generally recognized in the literature [5] that, depending on the type and characteristics of the vessel, a fraction of the fluid's total internal energy, ranging between about 20 and 50%, can be dissipated in vessel deformation, fragments and liquid acceleration and other energy losses. If we take half the energy calculated by the Crowl's equation, overpressures of about 8 and 5 kPa are calculated at 20 and 30 m from the explosion, respectively, which are not very far from the accident estimates.

Finally, in a more recent paper [21], a new approach has been suggested, attempting to more realistically describe the whole BLEVE phenomenon as an irreversible process. The details of the model can be found in the original paper. Here it is only stressed that the model suggests a non-isentropic expansion, and this will influence the way the vapor fraction after rupture is calculated (flash fraction). By adopting this methodology, the resulting TNT equivalent mass, accounting for both vapor and liquid, is about 2.5 kg, and the corresponding overpressures at 20 and 30 m from the explosion center are 8.9 and 5.4 kPa, respectively, i.e. in reasonable agreement with the ones deduced from the accident reconstruction.

In conclusion we can say that, despite the difficulties generally found in correlating the damages actually reported after an accident with exact values of the blast overpressure, the most commonly used prediction methods, still very useful as prevention and planning tools, seem to be too conservative with respect to the detected damages. Conversely, at least for the present case, the non-isentropic approach has proved to be less conservative but probably more realistic.

3.3. The pool fire

Based on the above results, we finally have to assess the size and duration of the pool fire from which all the final consequences derive. A conservative equation for calculating the liquid consumption from the pool, assuming the whole heat produced from the fire is used to vaporize the liquid from the pool [22], provides:

$$\dot{y} = 1.27 \times 10^{-6} \frac{\Delta H_c}{\Delta H^*} \tag{10}$$

where $\dot{y}$ is the vertical rate of liquid level decrease (m/s), ΔH_c (kJ/kg) the heat of combustion and ΔH^* (kJ/kg) the modified heat of vaporization, i.e.:

$$\Delta H^* = \Delta H_v + \int_{T_a}^{T_b} c_p \mathrm{d}T \tag{11}$$

In Eq. (11) ΔH_v is the heat of vaporization at the normal boiling point T_b, and T_a is the ambient temperature.

Under the hypothesis of steady state conditions, the released liquid flow rate Q (m^3/s) equals the amount of liquid leaving the pool $\dot{y}A$ (m^3/s), where A is the total surface area of the pool, so that the diameter of the unconfined pool D_{pool} can be calculated as:

$$D_{pool} = 2\sqrt{\frac{Q}{\pi \dot{y}}} \tag{12}$$

By adopting the previously estimated release rate of 1.75 kg/s, a maximum diameter of about 4.6 m is calculated. Furthermore, based on the weather report of the day of the accident and on the configuration of the surroundings of the location, no wind conditions can be adopted so that a vertical cylindrical fire can be considered and the corresponding height H_{pool} (m) can be calculated from [23]:

$$\frac{H_{pool}}{D_{pool}} = 42\left(\frac{m_b}{\rho_a \sqrt{g D_{pool}}}\right)^{0.61} \tag{13}$$

where m_b is the mass-burning rate (kg/sm^2), ρ_a the air density (kg/m^3) and g the acceleration of gravity (9.81 m/s^2). This model implicitly assumes that the mass-burning rate is equal to the release rate. The resulting flame height of about 15 m, agrees with the collected witnesses of "high flames" and the engulfing effect on the road tank car.

4. Conclusions

Most of the available models for the calculation of the consequences of hazardous phenomena such as fires and explosions are either based on theoretical considerations or derived from small-scale experiments. In both cases they often lack a sound full-scale experimental validation. Furthermore, being mainly used in a priori activities (design, layout and emergency planning), they are often affected by the assumption of a number of conservative hypotheses. As a consequence, discrepancies with actual observations can be found when they are applied to real accidental situations.

In the present paper, an accident occurred during the transfer of LPG from a road tank car to a fixed storage vessel has been investigated. The physical damages observed on the accident site and the report from different eyewitnesses have been compared with the results obtained with some of the most commonly used consequences calculation models, and their accuracy has been checked.

The so-called effect models, relate the consequences (damages to property, to the environment, or to people) of harmful phenomena (fires, explosions) to some representative physical parameters (heat radiation flux, overpressure, etc.). Despite most of these models are still affected by large uncertainties, some conclusions have been reached.

In the case of the fireball it was shown that, with the exception of one model, based on very small-scale experiments, all of the others provide quite similar results within a relatively narrow range of variability. The calculated result is also in good agreement with a dynamic simulation of the accidental release, which accounts for both the amount of flammable in the burning cloud (and hence for the size of the fireball) and the origin of the rupture of the tank (temperature increase of the tank shell).

Conversely, the largest uncertainty was found to be associated with the calculation of the physical explosion (BLEVE) after the catastrophic rupture of the tank.

In particular, it was shown that, unless a large and uncertain reduction factor is introduced, when the energies involved in the physical expansion of the vapor and the liquid, separately, are calculated with the usual models, a large overestimation of the resulting peak pressure is obtained. An even larger overestimation would be obtained if the two energy values, for the liquid and the vapor, were taken into account together (simultaneous action). A value of the shock wave overpressure much more consistent with the observed damages is obtained by applying a more recent model attempting to represent a more realistic non-ideal expansion of the fluids.

In conclusion, the reported results highlight again, if necessary, the need for the availability of more experimental data, which would allow to better validate the models proposed in the literature to represent so complex physical phenomena. In this view, even the publication and dissemination, whenever possible, of information from past accidents would be of great help.

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