The Bologna LPG BLEVE

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1 Introduction

At 1:44 pm of the 6th of August 2018, in the Bologna highway, in Borgo Panigale, a road tanker carrying LPG crashed onto an heavy good vehicle loaded with some tons of waste flammable liquid, that was still for a previous queue. The impact caused the release of all the waste flammable liquid, which immediately ignited forming a pool fire. The flames immediately enveloped the front portion of the LPG tank. In the following minutes, the heat of the fire progressively weakened the shell of the tank and, at the same time, the increased the LPG pressure. Under the simultaneous action of fire and of the internal pressure, the tank collapsed abruptly, releasing the full inventory of LPG. The released LPG immediately flashed and expanded. This phenomenon, known as Boiling Liquid Expanding Vapor Explosion or BLEVE [1], produced a shockwave that caused the collapse of the bridge deck that supported the road section and the overpressure damages observed in the surrounding buildings. Immediately LPG vapors ignited, producing a fireball whose thermal radiation caused both the burn injuries suffered by exposed people and the ignition of secondary fires along the road. The accident investigation of the author, based on available evidences, including the footages available in open sources, enable to reconstruct all the phases of the event. In the following we will expose the findings related to the pool fire that engulfed the LPG truck, the modeling of thermal transient in the tank that led to BLEVE performed with the tool AFFTAC - Analysis of Fire Effects on Tank Cars, developed by RSI-AAR Tank Car Safety and Research Project and analysis of the overpressure effects in the near field and in the far-field. It will be shown that AFFTAC model output are very consistent with the actual dynamics of the event. Blast analysis will enable to establish the magnitude of the explosion and its TNT equivalency, Concerning near field overpressure effects, it was found out that are very similar to that documented in the 1998 Horstwalde BAM tests [2]. The work will show that the Bologna BLEVE is an LPG transportation accident whose development was rather typical and that provides a solid benchmark for modeling approaches that had been proposed in the technical literature, making it a valuable – real world-lesson on the forensic investigation and consequence modeling of BLEVE accidents.

2 The accident

The accident event involved three heavy vehicles, which on August 6, 2018 at about 13:44 were passing through the Bologna freeway link, in the locality of Borgo Panigale. Two of these vehicles were used to transport hazardous substances. In both cases the hazardous substances were flammable, however in one case it was liquefied gas under pressure (LPG) and in the other case it was a load of flammable liquids,

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in IBC containers. The other vehicle was a car carrier. The car carrier was still due to a queue and the lorry with the IBCs of flammable liquids was slowly approaching the queue, braking and already at a very low speed. The LPG tanker crashed onto the IBCs carrier, apparently without any braking. The IBC carrier slipped forwarded and crashed onto the car carrier, while being compressed by the momentum of the rear collision. As a matter of fact, after the impact, all the flammable liquid in the IBCs was released on the road surface. The flammable liquid on the roadway was promptly ignited, giving rise to a major pool fire. The exact ignition mechanism could not be identified, but two credible ignition sources are the hot surfaces of the engines/exhaust system of the involved vehicles or mechanical sparks from metal elements from the vehicles that upon collision were grinding on the road pavement or each other. The fire engulfed the LPG tanker, leading to collapse of the tank and subsequent BLEVE. Figure 1 show the vehicles and the road in the immediate aftermath of the BLEVE.

Figure 1: The vehicles and the road in the immediate aftermath of the BLEVE.

3 Building up conditions for BLEVE: physical evidences and AFFTAC modeling

The IBCs carrier was loaded with around 10 Intermediate Bulk Containers of 1 cubic meter capacity, holding flammable liquid wastes. Given the fact that the liquid was promptly ignited upon release, it may be inferred that their *flash point* was lower than their actual temperature.

As shown by Figure 2, the anterior section of the LPG tank was engulfed in a pool fire that lasted around 7 minutes and 20 seconds. This duration is consistent with burning time that may be estimated from the IBCs volume, given the flammable hydrocarbon pool fire mass loss rate available in the technical literature [3]. In fact, a mass of flammable hydrocarbon liquids corresponding to around 10000 kg of material have around 400 GJ of thermal energy, based on an average heat of combustion value. A similar amount of flammable liquid will form a circular puddles with equivalent diameters between 40 m and 55 m, depending on the effective depth of the liquid layer (which depend on roughness of the asphalt pavement). Considering, for example, a puddle of 1200 square meters of extension, if the Heat Release Rate per Unit Area was 500 kW/m^2 the entire amount of liquid would be consumed in 11 minutes, while if the Heat Release Rate per Unit Area was equal to 1000 kW/m^2 the fire would consume all fuel in 5 and a half minutes. In the present case, the active phase of the pool fire lasted about 7 minutes , so the average thermal power was 950 MW and, considering a pool of extension equal to 1200 m^2 , the average Heat Release Rate per Unit Area was effectively close to 800 kW/m2. These data indicate that the pool fire was undoubtedly a fire of major proportions, which affected the vehicles involved and, in particular, the front part of the fuel tank, with a very severe thermal impact. These converging estimates define the characteristics of this phase of the event and further confirm that the pool fire was fueled by the flammable liquid transported in the semi-trailer loaded with IBCs. On the contrary, the release of LPG from a breach in the tank shell would have produced a vigorous two-phase outflow that would have initially formed a plume of white steam and then, following ignition, gave rise to a jet fire characterized by a dart of flame. which would have produced effects totally different from those observed. Based on calculations using the ALOHA-EPA model, propane released from a 5-cm-diameter hole would fuel a jet fire characterized by a flame dart of about 30 meters in length and would consume the entire contents of the tanker in about 10 minutes. A flame dart of this size would produce a localized and recognizable thermal effect and, most importantly, would be clearly visible in the video recording of the event, which show a pool fire instead. Further, an eventual release of LPG from the tanker would have contributed to decrease the pressure and especially the fraction of liquid phase present. This would have delayed or even prevented the collapse conditions from being reached and would have decreased the magnitude of the explosion. The LPG tank was not equipped with neither a pressure safety valve nor a thermal insulation or a fireproofing, but these protective measures are not required by the Italian law or by the ADR agreement. Therefore, during fire exposure no venting of the LPG tank took place and pressure steadily built up inside the tank, upon heating of the load. Figure 3 show a schematization of the flame engulfment of the tank, that is around 60% of the surface of the tank itself. The area covered in red was steadily engulfed in flame, therefore it may be assumed that was exposed to heat fluxes between 75 kW/m^2 and 150 kW/m^2.

Figure 2: The pool fire that engulfed the anterior section of the LPG tank.

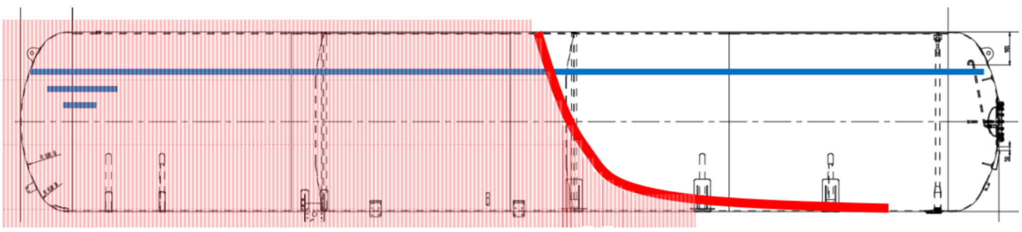

Figure 3: Schematization of the engulfed surface of the tank.

In order to analyze in more detail the effect of exposure of the tank to the external fire and the and the achievement of collapse conditions, this phase has been modelled using the AFFTAC - Analysis of Fire Effects on Tank Cars software tool, developed within the RSI-AAR project. Tank Car Safety and Research Project. The AFFTAC calculation code is a tool developed for modeling the heat exchange in transient regime taking into account both the heat exchange between the pool fire and the tank shell, and of the internal heat exchange between the tank walls, the liquid phase and the tank, the liquid phase and the vapor phase. Based on the temperature of the liquid phase the calculation code AFFTAC calculates both the volume occupied by this phase and the pressure inside the tank. The transient heat transfer calculation also returns the temperature of the tank shell both in the portion in contact with the liquid phase, and in the portion directly in contact with the vapor phase, which is the most critical area because after short time fire exposure will reach temperatures at which the yield stress of shell's steel is greatly reduced.

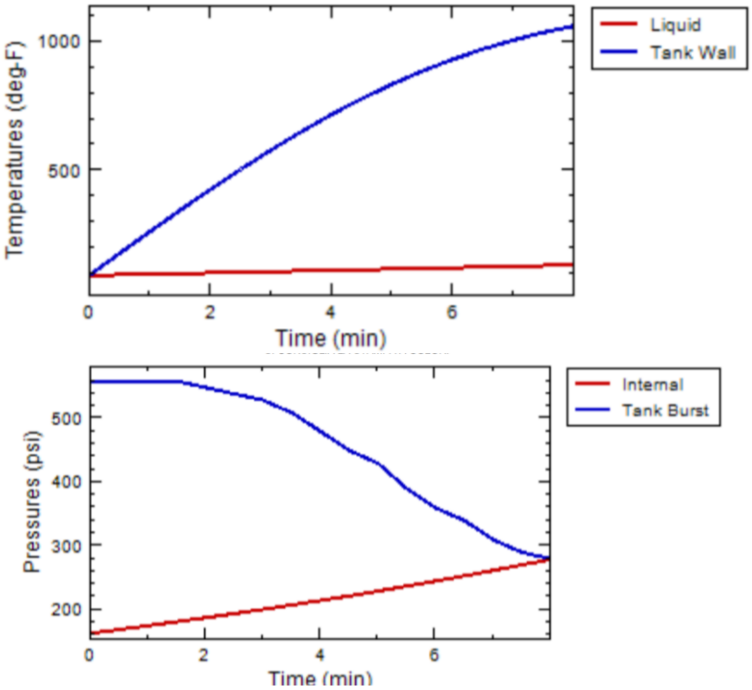

Figure 4: AFFTAC modeling results.

The AFFTAC calculation code then determines, based on the temperature of the most thermally stressed area of the metal plating, the reduction in yield strength or ultimate tensile strength and therefore the effective collapse pressure. When the pressure of the fluid contained in the vessel reaches the collapse pressure, failure is considered to occur. Among the input parameters of the AFFTAC calculation code were the characteristics geometric characteristics of the tank and its filling conditions. The calculation was run for 23 tons of propane in a 55 cubic meter cylindrical tank (liquid phase fraction equal to 80%.), typical values for similar LPG road tanker. The initial liquid phase temperature was set equal to 35°C, which is an average value determined by means of a transient heat transfer calculation that models the heating effect of the solar radiation during the tanker voyage, under summer condition, as well as natural convection to surrounding air, in the warm days of August in Northern Italy. With respect to heat transfer conditions, the external fire exposure condition was modeled using a flame temperature of 800°C, which is a value representative of the turbulent diffusive flame conditions typical of pool fires, such as the one we are concerned with. The extension of the surface of the reservoir directly affected by the flames was set equal to 60% of the total area of the tank. The graph of Figure 4 shows the AFFTAC results, with the time evolution of the liquid and tank wall temperature in the area corresponding to the vapor space. In about 7 minutes the tank wall reaches a temperature close to 1100°F, or 600°C. The temperature of the liquid reaches exceed 53°C, which is the upper limit temperature of propane. The AFFTAC code indicate that the internal pressure exceeds the collapse pressure at 8 minutes. This condition occurs when the when the fluid pressure reaches 280 psi, or 19.3 bar. Indeed, the failure time predicted by the AFFTAC code with a very small set of reasonable parameters is consistent with the actual timeframe of the accident (8 minutes predicted time to failure, against 7 minutes and around 20 seconds of actual time toi failure).

4 Blast analysis

Upon failure of the shell, the compressed vapor phase expanded and the superheated liquid phase flashed explosively, giving rise to the well known mechanism of Boiling Liquid Expanding Vapor Explosion [1]. Subsequently, the propane vapor ignited, giving rise to the fireball. Figure 5 depicts a frame extracted by an bystander footage of the event, showing the cloud of propane vapors that are expanding in the surrounding environment and almost simultaneously igniting.

Figure 5: Frame from a footage of the event, showing the propane vapors expanding and partially already involved in combustion.

In order to estimate the magnitude of the BLEVE explosion, the calculation method proposed by Planas Cuchi [4] was applied. This method is particularly appropriate for application to the analysis of accidental events, since it is based on a thermodynamic transformation that captures the irreversible and non-isoentropic character of the process and is carried out using actual gas properties inferred from the corresponding tables of propane saturated vapor and saturated liquid. Applying therefore the Planas Cuchi calculation method for a range of liquid propane pressures between 18 bar and 24 bar, at the end of BLEVE there is the vaporization of an amount of propane amount of propane between 56% and 66% of the liquid phase initially present and the energy released by BLEVE is between 545 MJ and 635 MJ. It is customary to express the energy released by an explosion also in terms of equivalent mass of TNT, using the equivalence factor equal to 4.69 MJ/kg. The estimated range for the blast energy corresponds to a range of kilograms of TNT equivalent between 116 kg and 135 kg. See Figure 6 for the results of the calculation, parametrized as a function of the initial pressure of the propane. According to AFFTAC modeling failure took place at around 19.3 barg, which means that explosion energy should have been 590 MJ, equivalent to 120 kg of TNT. See Figure 7 for some details of the structural effects in the epicenter of the explosion, which included the localized shattering of concrete elements and the displacement of heavy concrete New Jersey barriers. Such near field effects are very similar to that documented in the 1998 Horstwalde BAM tests, which included the projection of concrete slabs that were around the perimeter of the tank and the fracturing of the foundation slab below it. According to very well established overpressure effects tables, such effects indicate a local overpressure greater than 1 barg. With regard to the overpressure in the epicenter zone, it rapidly relaxes from the initial value within the superheated phases (between 18 and 24 bar) to that of the environment, while the expansion of the biphasic fluid compresses the surrounding air and generates a shock wave that then propagates in the surrounding urban environment. The intensity of the shock wave can be determined by applying the well knwon equation from gasdynamics and the thermodynamics of ideal gases:

$$\frac{P_0}{P_{atm}} = (\bar{P}_{so} + 1)\left[1 - \bar{P}_{so}\frac{(\gamma_{gc} - 1)\left(a_{atm}/a_{gc}\right)}{\sqrt{2\gamma_{atm}(2\gamma_{atm} + (\gamma_{atm} + 1))\bar{P}_{so}}}\right]^{\left(-2\gamma_{gc}/\gamma_{gc}-1\right)}$$

According to AFFTAC modeling failure took place at around 19.3 barg. With this input, the above equation gives an overpressure around 1,4 barg, which indeed is consistent with the structural damage in the epicenter of the BLEVE.

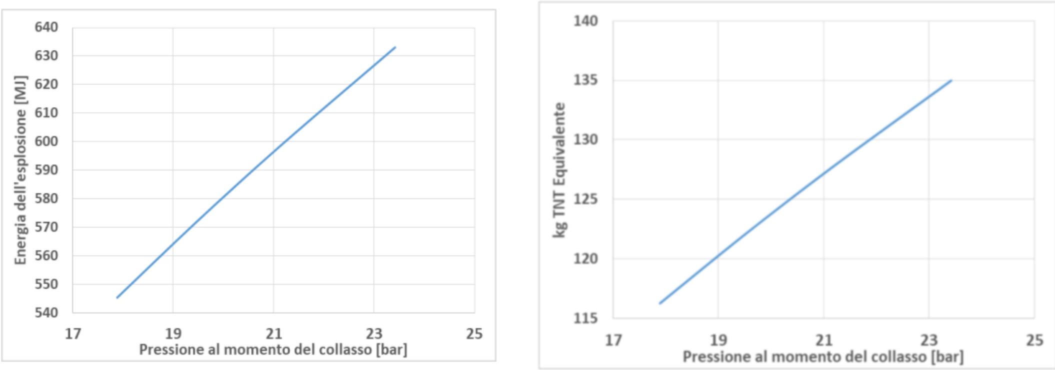

Figure 6: Results of the Planas Cuchi modeling of explosion energy, as a function of initial pressure

Figure 7: Structural effects in the epicenter of the explosion

6 Concluding remarks

The Bologna BLEVE is an LPG transportation accident whose development was rather typical and that is well tackled by modeling approaches that had been proposed in the technical literature, making it a valuable – real world-lesson for the forensic investigation and consequence modeling of BLEVE accidents.

References

[1] Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards, 2nd Edition, AIChE – CCPS, Wiley 2010

[2] BAM – Study of the failure limits of a railway tank car filled with liquefied petroleum gas subjected to an open poolfire test. Final Report, 1999

[3] NFPA 921 – 2017 Guide for Fire and Explosion Investigations.

[4] E. Planas-Cuchi, J.M. Salla, J. Casal, Calculating overpressure from BLEVE explosions, Journal of Loss Prevention in the Process Industries, Volume 17, Issue 6, 2004, Pages 431-436