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Essential Points in the Emergency Management in Transport Accidents which Can Lead to a BLEVE-Fireball

Behrouz Hemmatian, Joaquim Casal, Eulàlia Planas*

Centre for Technological Risk Studies (CERTEC). Universitat Politècnica de Catalunya·EEBE. Eduard Maristany 10. 08019-Barcelona (Catalonia, Spain)
eulalia.planas@upc.edu

Huge amounts of hazardous materials are transported by rail and road, being from time to time involved in traffic accidents. In these cases, flammable materials such as, for example, LPG, can originate a severe accident if a loss of containment takes place: a BLEVE explosion usually followed by a fireball. This type of accident, which often follows the domino effect sequence of fire→explosion, has caused the death of many people, including firefighters and spectators, the mechanical and thermal effects reaching significant distances.
A historical survey has been performed on 167 accidents obtained from diverse databases. The results thus obtained have been used, together with the adequate mathematical models, to analyze the time to failure that can be expected and to estimate the lethality reach of the diverse effects –overpressure, ejected fragments, thermal radiation. Finally, a set of considerations concerning the safety and emergency measures that should be adopted in these accidents are commented.

1. Introduction

Approximately 40% of major accidents occur during transportation. In fixed plants usually people involved know what to do in such a case and emergency plans are ready to be applied. Nevertheless, if the accident occurs during transportation, especially in road or rail modes, often other people can be affected. A typical case is that of a road tanker transporting a hazardous material which has undergone a traffic accident. Often a number of spectators remain relatively near the tanker, especially if there is a fire. These spectators take a “safety distance” based on the fire radiation. But an explosion –possibly a BLEVE– can occur at any moment (D’Aulisa et al., 2014; Hemmatian et al, 2015). And if the explosion is followed by a fireball, this distance will not be enough at all. Such accidents can be very severe (Busini et al., 2011) and a few principles should be clear for the emergency management in order to decrease or avoid the consequences on people. Here, the results obtained from a historical analysis and from the application of BLEVE and fireball mathematical models are used to define several simple measures which should be taken in these accidents, with an especial emphasis on the transportation of LNG and LPG.

2. Analysis of past accidents

2.1 Historical survey

A historical analysis has been performed (Hemmatian, 2016) on a set of 167 BLEVE accidents occurred after 1st January 1961, the largest sample of BLEVE accidents studied until now. The Major Hazard Incident Data Service database (MHIDAS, 2007) was used to obtain most of the data. Other sources were: Analysis, Research and Information on Accidents (ARIA, 2012); Major Accidents Reporting System (MARS, 2012); Failure and Accidents Technical information System (FACTS, 2010). The lacking information in some accidents was searched from other sources such as the U. S. Chemical Safety Board (CSB, 2012), US. National Transport Safety Board (NTSB, 2013) or the National Fire Protection Association (NFPA, 2012).

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Table 1 shows the substances involved in the 167 accidents analyzed. 247 substances were identified, as in some of the accidents more than one substance were simultaneously involved. LPG was by large the most frequent material (66% of BLEVEs), followed by vinyl chloride (6%) and oil (6%).

Table 1: Substances involved in BLEVEs (% calculated for 167 accidents)

Substance	Number of accidents	Percentage
LPG	111	66
Vinyl chloride	10	6
Oil	10	6
Gasoline/Petrol/Diesel/Kerosene	8	5
Ethylene oxide	7	4
Carbon dioxide	6	4
Water	5	3
LNG	5	3
Other chemical substances	85	52
Total	247	149

Transport implied almost half of the BLEVEs (Table 2; some accidents had different origins). When analyzing “all” accidents (Haastrup et al., 1990; Vílchez et al., 1995), approximate values of 40% for transport are found; for the case of BLEVE this percentage increases up to 47%. Among BLEVEs that occurred in transportation, 57% involved rail tankers, 37% occurred with road tankers, 6% in ships and 1% in pipelines.

Table 2: General origin of BLEVEs (% calculated for 167 accidents)

General origin	No. of accidents	Overall percentage
Transport	78	46.7
Storage area	39	23.4
Transfer	22	13.2
Process plant	19	11.4
Other activities	15	9.0
Total	173	103.7

2.2 Transport accidents which can lead to a BLEVE

When a road or rail tanker transporting a flammable liquid (as, for example, LNG or LPG) undergoes a traffic accident or a derailment, the following accidental sequence can occur: damage of thermal insulation → loss of containment → ignition → flames impingement on the vessel → pressure increase → SRV opening → more flames impingement → BLEVE of the vessel.

This sequence can take a variable time, depending on the specific circumstances. If the flames impinge on a non-insulated vessel wall, the explosion can occur after one minute, after one hour or, even, can never occur.

If there is a certain delay, two things will happen: a) as the fire is something “attractive” for many people, probably a certain number of spectators will come to look at the accident, and b) the firefighters will come and will try to control the emergency. The spectators will adopt a “safety distance” (for example, of the order of 100 m) according to their experience and knowledge (in most cases, quite limited) of which are the hazards that a large fire can imply. However, even though this distance could be enough for a relatively large pool fire, it is completely insufficient if a BLEVE followed by a fireball takes place. And this is the reason why in such accidents spectators can be wounded or even killed. Furthermore, many firefighters have also died, due to the uncertainty concerning the time to failure; even though in industrialized countries firefighters are more and more aware of the convenience of evacuating in the situations which can lead to a BLEVE, still accidents occur in which the explosion happens while they are trying to extinguish the fire, with the associated severe consequences. In such situations, the measures taken during the emergency are essential to reduce the consequences of the event; two representative cases have been described in the literature (Planas et al., 2004 and 2015).

2.3 Amount of hazardous material involved

For safe transportation of hazardous materials by rail and road, several regulations exist in different countries. The UN Recommendations on the Transport of Dangerous Goods (2011) is the basis for many national and international regulations. Here, the common classes of rail and road tankers used for transportation of LPG and LNG have been taken from the US Department of Transportation. The report from Molag and Kruithof (2006) has also been considered for defining the various scenarios. The tankers and their specific parameters considered in this study are summarized in Table 3:

Table 3: Capacities of different rail and road tankers

	Rail tankers		Road tankers	
	Volume (m^3)	Filling degree (%) at loading temp. and Prupt (kPa)*	Volume (m^3)	Filling degree (%) at loading temp. and Prupt (kPa)*
Propane	127.1; 121.1; 110; 94.1; 63	90% → 1137 kPa 86% → 1500 kPa 81% → 2000 kPa	64; 45.4; 34.1; 24.6; 13.2; 10.6; 2.8	86% → 1500 kPa 81% → 2000 kPa
Butane	127.1; 121.1; 110; 94.1; 63	90% → 1137 kPa 86% → 1500 kPa 81% → 2000 kPa	64; 45.4; 34.1; 24.6; 13.2; 10.6; 2.8	85% → 700 kPa 76% → 1500 kPa
Methane	111	91% → 206.8 kPa 87% → 482.6 kPa 85% →689.5 kPa	56	94% → 103.4 kPa 93% → 137.9 kPa 91% → 206.8 kPa 90% → 275.8 kPa 89% → 344.7 kPa 87% → 482.6 kPa 85% → 689.5 kPa

*Loading temperature: 289 K for propane and butane and 113 K for methane.

Different volumes of rail and road tankers are used in the transportation of LPG. Rail tankers range between 63 m^3 and 127.1 m^3, and road tankers range between 2.8 m^3 and 64 m^3 (Leffler, 2014). In the case of LNG, the capacities of 111 m^3 and 56 m^3 have been considered for rail and road tankers, respectively. The maximum filling degree is in fact determined by the existing regulations (which are not the same for all countries) and by the properties of the transported material. In the EU, this is regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR); the maximum allowed filling degree in the worst conditions (i.e., at the conditions at which the safety relief valve will open) is 95%. Thus, this assumption condition will be assumed for the diverse calculations here.

3. Effects and consequences from BLEVE-fireball

3.1 Overpressure

To find the corresponding consequences on people, the Probit function can be used. For direct overpressure effects (as usually transportation accidents will occur in non-congested zones) the lethality due to pulmonary hemorrhage can be estimated as a function of ΔP (overpressure, $N \cdot m^{-2}$) by using Eq. (1) (Casal, 2008):

$$Y = -77.1 + 6.91 \cdot \ln \Delta P \tag{1}$$

At short distances ΔP varies with the direction (Birk et al., 2007), but it is not necessary to take this into account.

For 1% of lethality, a threshold value of 103 kPa is obtained. The corresponding distances for propane, butane and methane (assimilated to natural gas) have been calculated for different vessel pressures and volumes. The reach for lethality due to ΔP direct effects is quite reduced (< 15 m for road tankers and < 20 m for rail tankers), as could have been expected: the value required for lethality is rather high and ΔP decreases quickly with the distance. If other criteria are applied (0.35 bar/15% lethality, 0.5 bar/50% lethality) the reach increases.

3.2 Ejected fragments

As for the ejected fragments, diverse vessel breaking patterns are found (Gubinelli and Cozzani, 2009; Tugnoli et al., 2014). Among them, the one dividing the vessel in one bottom and the rest is the most frequent one (60% of cases). The prediction of the range of ejected fragments is rather difficult. However, a few authors have proposed expressions to calculate in an approximate way the maximum distance which can be reached by the fragment originated from cylindrical vessels (those used in transportation). Baum (1988) proposed the following expressions, where *m* is the mass of substance contained in the vessel (kg) and l is the range (m):

For tanks < 5m^3 vol.: $l = 90 \cdot m^{0.33}$; for tanks > 5 m^3 vol.: $l = 465 \cdot m^{0.1}$ (2)

The resulting distances for different values of vessel volume have been calculated (Figure 1). Very large distances can be covered by the fragments (much larger than those found for overpressure). This is due to the special way usually found in cylindrical tanks fragmentation, which gives rise to relatively aerodynamic fragments which travel in a way similar to that of a rocket or a missile; thus, ranges larger than one kilometer can be reached. Instead, for the case of spherical vessels, shorter distances are reached (the maximum distance registered for a large fragment of these vessels is 600 m).

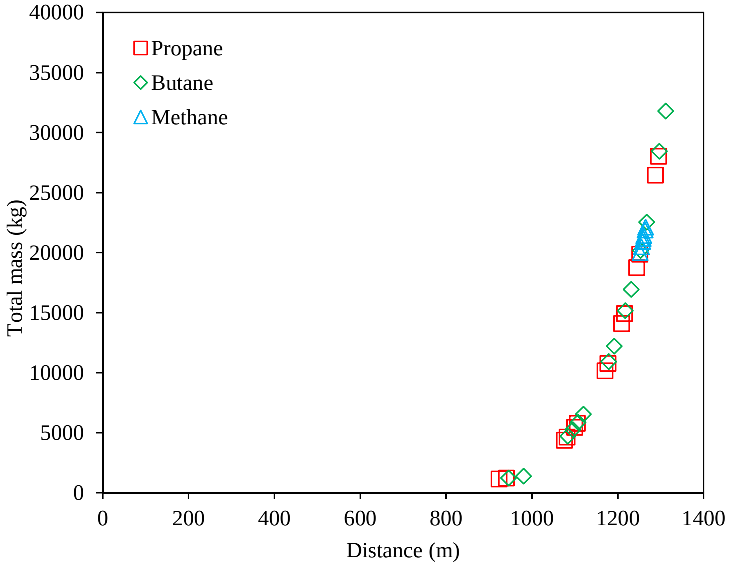

Figure 1: Distances reached by the ejected fragments (road tankers).

Another aspect which should be considered is the direction followed by the fragments. Whereas for a spherical vessel this cannot be predicted due to the irregular shape of fragments, for cylindrical tanks (those found in road and rail transportation) often the fragments are ejected following the vessel longitudinal axis. Although this is completely true in some cases (see, for ex., the Tivissa accident, Planas et al., 2015), there is some scattering; Holden and Reeves (1985) suggested that in 62.5% of cases the fragments were ejected in the main axis direction, with a scattering covering an angle of 45º. Nevertheless, depending on the vessel failure mode, they can also be ejected in other directions

3.3 Fireball thermal radiation

BLEVE will be almost always followed by a fireball if the contained substance is flammable. In this situation, predicting the effects of fire and its thermal radiation is crucial from the point of view of emergency management. Thus, the threshold values for thermal radiation were calculated for 1% lethality (with and without protection; protection is considered when, as in the case of firefighters, special resistant dresses are used), and 1% first and second degree burns, as well as the corresponding distances. In all cases, large distances are required to avoid consequences on people, much higher than those corresponding to the overpressure wave.

3.4 Lethality distances

The values obtained from the data exposed in the previous sections allowed the calculation of the distances corresponding to the lethality threshold (1% lethality) for both blast and thermal radiation, as well as for first and second degree burns. As blast damage reach is much shorter in all cases than thermal effects, only thermal effects and fragments distances were taken into account here to consider the order of magnitude that evacuation distances should cover.

The values obtained for the maximum distances corresponding to thermal radiation thresholds have been summarized in Table 4. Approximate distances of 500 m (LPG) and 400 m (LNG) have been obtained for the typical tanks used in road transport, and 670 m (LPG) and 520 m (LNG) have been obtained in the case of rail transportation. These values, together with those obtained for the ejection of fragments (Table 5), give an idea of the order of magnitude of the evacuation distances that should be considered in these types of accidents.

Table 4: Maximum distances for thermal radiation consequences (m)

	Propane		Butane		Methane	
	Rail	Road	Rail	Road	Rail	Road
1% lethality (protected)	370	270	370	265	280	205
1% lethality (unprotected)	430	310	425	305	325	240
1% second degree burns (unprotected)	440	320	440	315	335	245
1% first degree burns (unprotected)	670	490	665	480	515	380

Table 5: Maximum distances for ejected fragments reach (m)

Propane		Butane		Methane	
Rail	Road	Rail	Road	Rail	Road
1390	1295	1410	1310	1350	1265

4. Time to failure

Once a pressurized vessel is subjected to the action of flames, its temperature and pressure will increase; this can lead to its collapse or it can stand, depending on the circumstances. Even if the vessel cannot stand, its failure can occur in a relatively short time or after a long time. In the San Juanico accident (México, 1984) the first BLEVEs occurred 69 s after (supposedly) one or more jet fires impinged on the vessels; however, in the Zarzalico accident (Planas et al., 2015), the tank stood during 70 min a very strong fire.

The following circumstances can have a significant influence: i) Existence of a safety valve, which will keep a certain pressure value; it can not guarantee that the vessel will not explode, but could imply a certain delay in the explosion (Molag and Kruithof, 2006); however, it could also imply an additional heat input from the jet fire. ii) Existence of passive fire protection, which can delay the failure of the equipment one hour or more, or even avoid it (Paltrinieri et al, 2009; Birk, 2014). However, if a traffic accident or a derailment has occurred, the protective layer can be damaged and it will not protect anymore the vessel wall from the fire. The impingement of a high momentum jet fire can also erode it. iii) The mass contained in the vessel: the higher the filling degree, the smaller the probability that the flames impinge on the unprotected wall. iv) If the flames impinge on the vessel wall above or below the liquid level. Above the liquid level the wall is not protected –cooled– by the liquid and its heating can originate the failure, even if a safety valve avoids the pressure to exceed a certain value.

To show how the time to failure of a pressurized vessel subjected to the action of a fire can vary, information on a few representative accidents (Hemmatian et al., 2015) occurred during transportation has been included in Table 6. It is clear from these data that the time to failure can range from a couple of minutes or even less to up more than one hour or, simply, can never happen.

Table 6: Time to failure for different cases (transportation)

Date	Place	Sequence	Material	Time to failure
1980	USA	Fire→BLEVE	Petrol road tanker	3 min
1970	USA	Fire→BLEVEs	LPG rail tankers	First car in 5 min, 6 cars in 40 min
1987	Australia	Fire→BLEVE	LPG rail tanker	15 min
2002	Spain	Fire→BLEVE	LNG road tanker	20 min
1972	USA	Fire→BLEVE	Propylene road tanker	25 min
1973	USA	Fire→BLEVE	LPG rail tanker	30 min
1970	France	Fire→BLEVE	Propane rail tanker	40 min
1970	USA	Fire→BLEVE	Ethylene oxide rail tanker	45 min
2011	Spain	Fire→BLEVE	LNG road tanker	70 min
1976	USA	Fire→BLEVE	Isobutane rail tank	1.5 h

5. Conclusions

In road or rail transportation of dangerous materials, especially flammable liquids or liquefied flammable gases, if there is a situation (fire affecting a tank) which can potentially lead to a BLEVE, the following potential mechanical and thermal effects should be considered: overpressure, ejection of fragments and thermal radiation. While the effects of overpressure wave cover a relatively short distance, those associated to ejected fragments can reach long distances and the thermal radiation –if a fireball occurs– can cover an important area. The following points should be taken into account and applied in the management of the emergency in order to avoid or reduce the consequences on people:

- If fire is affecting the tank, the explosion –probably followed by a fireball– can occur at any moment, from the first minute up to several hours after the beginning of the emergency.
- Even if the tank is thermally insulated, an impact or jet erosion can have damaged the insulation and the situation should not be considered safe.
- The fact that a safety relief valve is activated does not imply a safe situation, a BLEVE can still occur.
- Although in cylindrical tanks fragments are prone to be ejected approximately along the tank main axis, depending on the failure mode they can follow other directions.
- As the explosion can occur at any moment from the beginning of the accident, immediate evacuation of people to a safe distance must be applied.
- People should be evacuated to a distance of at least 700 m and preferably –if possible– to 1200 or 1400 m.
- Unless there is the need of rescuing someone from the trucks or wagons that suffered the accident, the firefighters should withdraw to the same distances too.

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