LIQUEFIED NATURAL GAS ROAD TANKER EXPLOSION

Juan Manuel Bonilla Martinez
Chemical Engineer
Fire Officer at Murcia Fire Service & Rescue

KEYWORDS: Explosion, liquefied natural gas, road tanker, virtual-pipeline, BLEVE[1], fire-fighting, thermal radiation, blast overpressure, fragment projection

ABSTRACT

On the 20th of October 2011 there was a traffic accident in Murcia (Spain) involving a Liquid Natural Gas tanker which resulted in the cargo exploding. This the second explosion of this type recorded in the World, following that which occurred in Tivissa (Spain) in 2002. The initial accident occurred when the tanker collided with another lorry which was stationary on the hard shoulder. A fire started immediately igniting plastic and rubber materials and the fuel tank and which finally engulfed the cargo tank. The cargo tank was of a single wall construction with polyurethane insulation and aluminium cladding. The inlet and outlet pipes for both liquid and gas were fitted with valves flush with the tank wall but there were other connections from the tank leading to the exterior. One of these connections was broken as a result of the accident and this allowed the tank contents to leak and feed the fire. The fire was burning for 71 minutes at which time the tank exploded and collapsed. The fireball that resulted was 124 metres high with a radius of 82 metres. Further damage was caused by thermal radiation, a pressure wave (broken windows) and debris being thrown over a distance of 200 metres. The only fatality was the driver of the tanker.

I. INTRODUCTION

This supporting paper reports an LNG (liquefied natural gas) road tanker accident in Murcia (province of Spain). On the 20th of October 2011 there was a traffic accident involving a Liquid Natural Gas tanker which resulted in the cargo exploding. This the second explosion of this type recorded in the World, following that which occurred in Tivissa (Spain) in 2002. The initial accident occurred when the tanker collided with another lorry which was stationary on the hard shoulder. A fire started immediately igniting plastic and rubber materials and the fuel tank and which finally engulfed the cargo tank. The cargo tank was of a single wall construction with polyurethane insulation and aluminium cladding. The inlet and outlet pipes for both liquid and gas were fitted with valves flush with the tank wall but there were other connections from the tank leading to the exterior. One of these connections was broken as a result of the accident and this allowed the tank contents to leak and feed the fire. The fire was burning for 71 minutes at which time the tank exploded and collapsed. The fireball that resulted was ~100 metres high with a radius of ~75 metres. Further damage was caused by thermal radiation, a pressure wave (broken windows) and debris being thrown over a distance of 200 metres. The only fatality was the driver of the tanker.

II. OBJECTIVES OF THE PAPER

This study was conducted to assess and compare the data measured on the ground respect the theoretical risk analysis calculations in order to learn some lessons and provide safety recommendations on LNG virtual pipeline. It looks what are possible causes and set some conclusions intended to preventing similar accidents in the future.

III. DEVELOPMENT

The tanker was carrying 46 m^3 (so equivalent mass of 21,589 Kg) of LNG at -161.3ºC and ~1.1 bar. Until now only a single accident of this type has been recorded worldwide. This accident is the second one, and curiously both have been occurred in Spain. These accidents have some similarities but the time to

[1] Boiling Liquid Expanding Vapor Explosion

explosion after the initial ignition are far different (20 minutes vs 71 minutes). The tanker construction was essentially the same.

The accident occurred on the A-91 motorway, near the regional border between Murcia and Granada. Around it, close to the road tanker existed a petrol station with restaurant and an isolated country house. The crash was produced between the road tanker and a lorry carrying precast concrete panels, that had stopped because of mechanical failure. After the crash, the road tanker charged with LNG was suddenly ignited and the fire began to grow. The road tanker driver was trapped and engulfed by flames. Nothing could be done to save his life due to voracious -out of control- fire.

There are mainly two different configuration of LNG road tankers operating around the world:

- Single walled LNG tankers with external insulation are occasionally used in some European and Asian countries. In this type of container, the fire can impinge directly on the tank surface and a BLEVE is possible. It should be considered as a consequence of the accident, that insulation may break off.

- Double walled tankers, vacuum-insulated between the annular concentric thickness. These tankers are mainly used in the US, and are also in some European countries. The double walled road tankers have an improved fire resistance. The flames cannot directly impinge on the inner tank which contains the cargo. Nevertheless, the tank can BLEVE although there are more time to act and take decisions (emergency response).

The Spanish road tanker was single walled. The tanker exploded and broke up into three main fragments and several secondary fragments. A very strong thermal radiation was evidenced in the ground, and broken glasses were reported. The firefighters stated that a fireball was expanded over them.

Table 1. Mechanical design characteristics of the road tanker

Feature	Description/Units
Overall length	14 metres
Overall width	2.6 metres
Internal diameter	2.34 metres
Total height	3.8 metres
Total volume	56,500 L
Test pressure	9.1 bar
Design pressure	7 bar
Design temperature	+50 / –196ºC
Inner shellside material	Stainless steel 304LN
Inner shellside thickness	4 mm cylindrical shell / 6 mm tank ends
Baffle plates	7 units 3mm thick
Insulation material	130 mm injected rigid polyurethane foam
Outer shellside material	2-mm aluminium / polyester tank end-cap
Pressure relief devices (PRD)	3 valves. Maximum allowable pressure 7 bar and 9.1 bar

The probable causes of the leakage seems to be located on the central loading cabinet where all the fittings and valves are placed. An accidental breakage of piping took place and the cargo began to leak. It should be noted that there are at least four pipes from the tank leading to the exterior. Then, a two phase jet fire is fed from the cargo after initial diesel combustion.

The fire behaviour of a LNG road tanker engulfed by a jet fire is controlled by mechanical design and thus by its thermal resistances. The first barrier or obstacle that flames reach is aluminium cladding. The high thermal conductivity will heat it very fast and a high deformation is expected. For this reason, this layer will be disintegrated and become detached quickly. The next stage is rigid polyurethane foam, intended for use as thermal insulation but not offer a satisfying fire performance. Rigid polyurethane foams will, when ignited, burn rapidly and produce intense heat, dense smoke and gases which are irritating, flammable and/or toxic, and should be considered combustible. Thus, the steel layer make contact with flames. The stainless steel thermal conductivity is good, as experience majority of metals, and therefore allow heat to travel through them quite quickly.

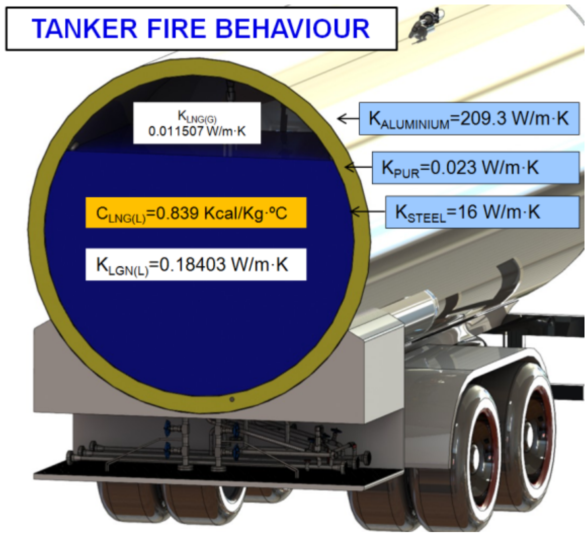

Figure 1. Thermal resistances to fire-induced explosion in a LNG road tanker

Now, the flame can follow two paths:

1) Fire impingement in gas phase. A gas acts as insulator, the heat cannot progress and in this manner the temperature of the steel wall temperature would be increased widely, producing thermal degradation of metallic material and different mechanical failure modes can befall.

2) Fire Impingement in liquid phase. In this case the LNG has a high specific heat and a lot of heat must be delivered to increase one degree of temperature per unit mass. Take into account that liquid water specific heat is approximately 1 Kcal/KgºC, which is higher than any other common substance, and LNG is about 0.841 Kcal/KgºC. The initial volume of liquid natural gas is 46.000 litres at -161ºC. A big inertia play against and the heating process will be sluggish. Consequently the wall temperature of steel in contact con liquid natural gas is going to be similar that LNG wetted surface.

The wall temperature distribution in each case has been estimated, as shown in the following figure:

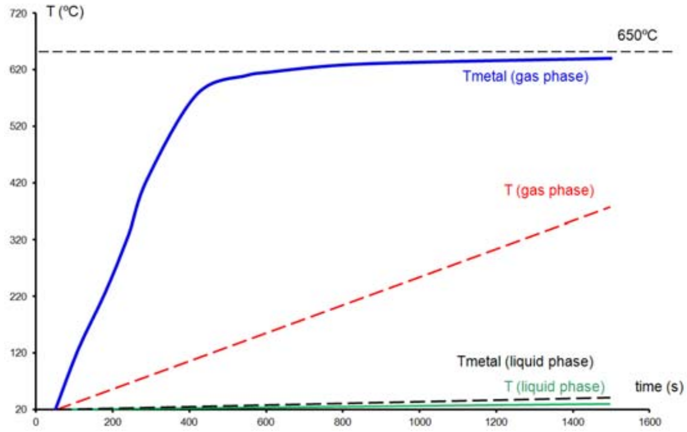

Figure 2. Temperature distribution. Fire induced road tanker. Heat input=250 kW/m^2

IV. RESULTS

Next are detailed the real explosion effects compared with some theoretical estimations.

Thermal radiation

First of all, fireball diameter (D) and BLEVE duration (t) should be calculated. Both values are needed to determine surface emissive power (SEP-E_p). Bibliographical references show that many authors have developed certain correlations that fit real data measured in explosions. These equations take the following form:

$D=a \cdot M^b$ Fireball diameter (m)

$t=c \cdot M^d$ Explosion duration (s)

where a,b,c y d are constants and M is fuel mass (Kg).

Actually, comparative analysis indicate that best fit can be obtained with Gayle's coefficients:

a	b	c	d
6.14	0.325	0.410	0.340

This will transform the equations into:

$$D=6.14 \cdot M^{0.325}$$

$$t=0.41 \cdot M^{0.340}$$

The calculations are shown in the following table for the different hypothesis considered:

Hypothesis	D (m)	t (s)
All cargo exploded M=21.589 Kg	157,32	12,2
Half cargo exploded M=10.795 Kg	125,6	9,6

It should be remarked that the estimation of the mass contribution to the fireball is very complex to estimate. Anyway, results obtained under this criteria can be considered conservative, and therefore on the safety side. Now, the thermal radiation will be calculated using the solid body model.

$$I=\tau \cdot F \cdot E_p$$

This equation indicate that radiation intensity depends on atmospheric transmissivity (τ), view factor (F) and fuel surface emissive power (E_p). First of all we determine the view factor:

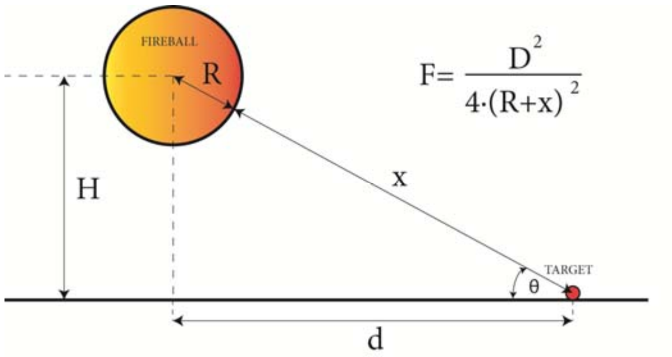

Figure 3. Determination of view factor

To determine view factor, we need to know "x", value that can be obtained applying Pythagora's theorem to the triangle of figure 3:

$$(x+R)^2=H^2+d^2$$
$$(x+R)=\sqrt{(H^2+d^2)}$$
$$x=\sqrt{(H^2+d^2)}-R$$

To solve the last equation, we need to know the value of H (fireball height) and the target distance. We fix target distance into 150 metres, exclusion zone used by firefighters. Respect to H, the experts use the following formula:

$$H=0.75 \cdot D$$

Hypothesis	D (m)	H(m)
All cargo exploded M=21.589 Kg	157,32	118,0
Half cargo exploded M=10.795 Kg	125,6	94,2

We calculate "x" value:

Hypothesis	x (m)
All cargo exploded M=21.589 Kg	112,2
Half cargo exploded M=10.795 Kg	114,3

And finally view factor:

Hypothesis	F
All cargo exploded M=21.589 Kg	0.16
Half cargo exploded M=10.795 Kg	0.12

Now proceed with surface emissive power calculation.

$$E_p=(\eta\cdot M\cdot H_c)/(\pi\cdot D^2\cdot t)$$

where η is the % of energy transmitted as thermal radiation, M is the fuel mass (Kg), H_c is heat of combustion (KJ/Kg), D is fireball diameter (m) and t is fireball duration (s).

M value is known, ***D*** and ***t*** also, and heat of combustion of LNG is 50.200 KJ/Kg (Basic Properties of LNG-GIIGNL's Technical Study Group-The International Group of LNG Importers). The most important inaccuracy in the $\boldsymbol{E_p}$ calculation induced by $\boldsymbol{E_p}$ is clearly $\boldsymbol{\eta}$, because its determination is complex and imprecise. Some authors consider a value range between 0.13 and 0.35, while others consider range of 0.24 to 0.4. Any case 0.4 is the maximum value.

Roberts proposed this equation to calculate η:

$$\eta=0.27\cdot P_0^{0.32} \qquad \text{(η maximum value limited to 0.4)}$$

where P_0 is the relative pressure of pressure vessel just before explosion (Pa). Considering that superheat limit locus of LNG is reached, the equivalent pressure would be 13.43 atm, or in other units, 1.36 MPa. This, we would have homogeneous nucleation condition and could be considered a BLEVE. We get:

$$\eta=0.27\cdot 1.36^{0.32}=0.29$$

This value represents that only 29% of energy is transformed in thermal radiation, what is conservative. Now the calculation of E_p is immediate:

$$E_p=(0.29\cdot M\cdot 50.200)/(3.14\cdot D^2\cdot t)$$

Hypothesis	E_p (kW/m^2)
All cargo exploded M=21.589 Kg	331.49
Half cargo exploded M=10.795 Kg	330.46

Finally we should calculate atmospheric transmissivity to get the radiation intensity value.

$$\tau=2.02\ (P_w\cdot x)^{-0.09}$$

where Pw is partial steam water pressure at atmospheric conditions (Pa). The day of the accident, a Spanish Government Meteorological Station (AEMET: 7211B - Puerto Lumbreras) measured a relative humidity of 65% and average temperature of 18.5ºC. The formal definition of relative humidity is:

$$H_R=(\text{Water Steam partial pressure /Water Pressure})\cdot 100$$

The water pressure at 18.5ºC is 2137,3 Pa (NIST Chemical Database). If we substitute in the former equation, obtain:

$$P_w=1389,2\ Pa$$

And atmospheric transmissivity is:

Hypothesis	τ
All cargo exploded M=21.589 Kg	0.688
Half cargo exploded M=10.795 Kg	0.687

The radiation intensity for a distance of 150 metres is:

Hypothesis	I (kW/m^2)
All cargo exploded M=21.589 Kg	36.5
Half cargo exploded M=10.795 Kg	27.2

For a vertical and horizontal surface we can also get the radiation intensity (from figure 3):

$$\text{sen } \theta = H/(R+x)$$
$$\cos \theta = d/(R+x)$$
$$I_H = I \cdot \text{sen } \theta$$
$$I_V = I \cdot \cos \theta$$

From this equations the vertical and horizontal intensities can be calculated:

Hypothesis	I (kW/m^2)	sen θ	cos θ	I_H (kW/m^2)	I_V (kW/m^2)
All cargo exploded M=21.589 Kg	36.5	0.61	0.785	22.2	28.6
Half cargo exploded M=10.795 Kg	27.2	0.53	0.84	14.4	22.8

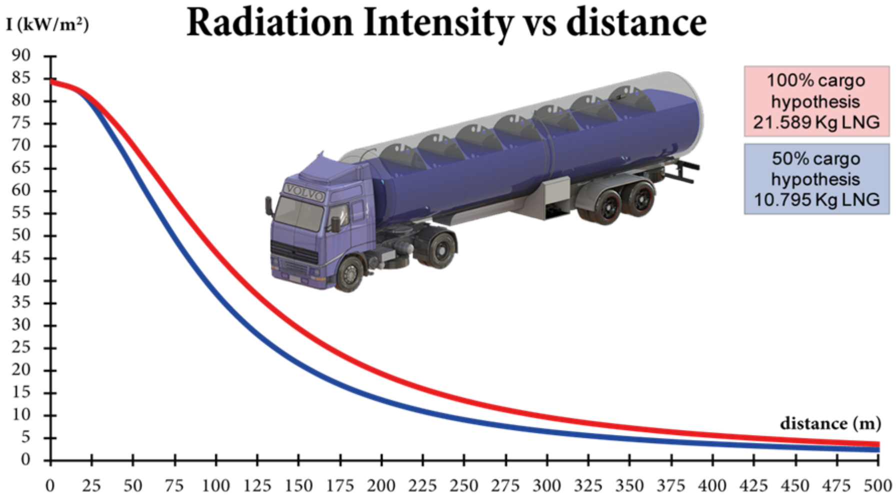

Figure 4. Radiation intensity vs distance for full and half cargo hypothesis

Figure 5. Some radiation evidences (traffic signals and burnt car)

Blast wave overpressure

The overpressure calculation will be based on TNT equivalent method. This method implies a certain inaccuracy due to the lower energy release velocity in a BLEVE explosion and higher vessel volume respect to equivalent powder mass. Nevertheless is a very extended method to calculate overpressure in BLEVE scenarios. The former inaccuracy is corrected with the scaled distance:

$$dr=d/(\beta\cdot W_{TNT})^{1/3}$$

where d (m) is the target distance and W_{TNT} is equivalent mass of TNT (Kg). TNT equivalent mass is determined by the following equation:

$$W_{TNT}=(0.021\cdot P\cdot V^{*})\cdot(1-(P_A/P)^{(\gamma-1/\gamma)})/(\gamma-1)$$

where V^{*} is vapor volume contained in the vessel plus vapor volume generated by the explosion (m^3), γ is ratio of specific heats, P is the pressure in the vessel just before the explosion (bar) and P_A is the atmospheric pressure (bar).

Meanwhile V^{*} can be calculated by:

$$V^{*}=V+V_1\cdot f\cdot(\rho_L/\rho_V)$$

V is vapor volume in the vessel just before the explosion (m^3), V_1 is the liquid volume just before the explosion (m^3), f is the fraction of liquids that vaporizes under depressurization, and ρ_L ρ_V are liquid an vapr density respectively.

f value is estimated by:

$$f=1-e^{(-2.63(Cp/Hv)\cdot(Tc-Tb)\cdot(1-((Tc-To)/(Tc-Tb))\hat{}0.38))}$$

where Tc is the critical temperature (K), Tb is the boiling point at atmospheric pressure (K), To is the temperature at the moment of the explosion (K) and Hv is the enthalpy of vaporization (KJ/Kg).

Parameter	Value	Units	Reference
γ	1,30	-	Encyclopedia Air Liquide (methane value)
P	13,60	bar	Document BLEVE- CEPREVEN
P_A	1,01325	bar	-
V	23,0	m^3	Half cargo hypothesis (10.795 Kg)
V_1	33,0	m^3	Half cargo hypothesis (10.795 Kg)
ρ_L	346,69	Kg/m^3	NIST Chemistry Database (methane value)
ρ_V	20,75	Kg/m^3	NIST Chemistry Database (methane value)
To	155,380	K	NIST Chemistry Database (methane value)
Tb	111,667	K	NIST Chemistry Database (methane value)
Tc	190,564	K	NIST Chemistry Database (methane value)
H_V	510,00	KJ/Kg	Encyclopedia Air Liquide (methane value)

Substituting we obtain the following:

Parameter	Value	Units
f	0,130	-
V^*	94,77	m^3
W_{TNT}	40,67	Kg

Now we calculate the scaled distance by:

$$dr=d/(\beta\cdot W_{TNT})^{1/3}$$

To determine the scaled distance we only need to know β, that is assumed to be 0.4 (40% of the energy contributes to blast wave)

Parameter	Value	Units
dr	59,19	$m/Kg^{1/3}$

Finally the overpressure is estimated with graphical support (Reference: Van den Berg and Lannoy, 1993).

Parameter	Value	Units
Overpressure	~0,025	bar

However, the petrol station glasses were broken, so a real overpressure ~0.04-0.05 bar was reached (the distance of these glasses were approximately of 160 metres).

Figure 6. Blast overpressure effects

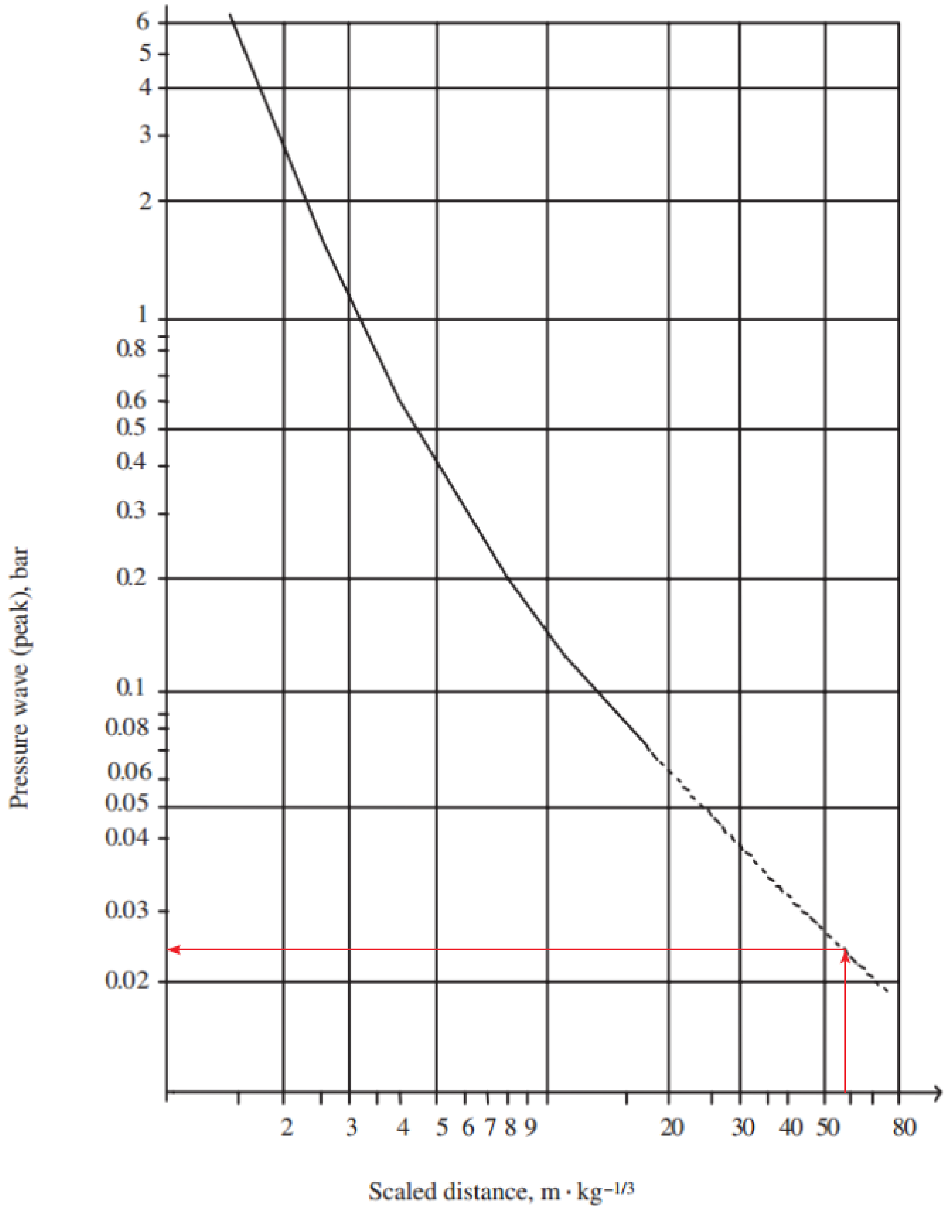

Figure 7. Overpressure vs scaled distance

Projection of fragments

The tanker was broke up in three main pieces:

- One rear end cap.
- Central section of the tank with the end cap attached.
- A piece of central section of the tank.

Other secondary fragments were projected in different directions and angles. All the baffles were detached from the tanker, as can be observed in the following figures.

Figure 8. Two main pieces of the tanker after explosion

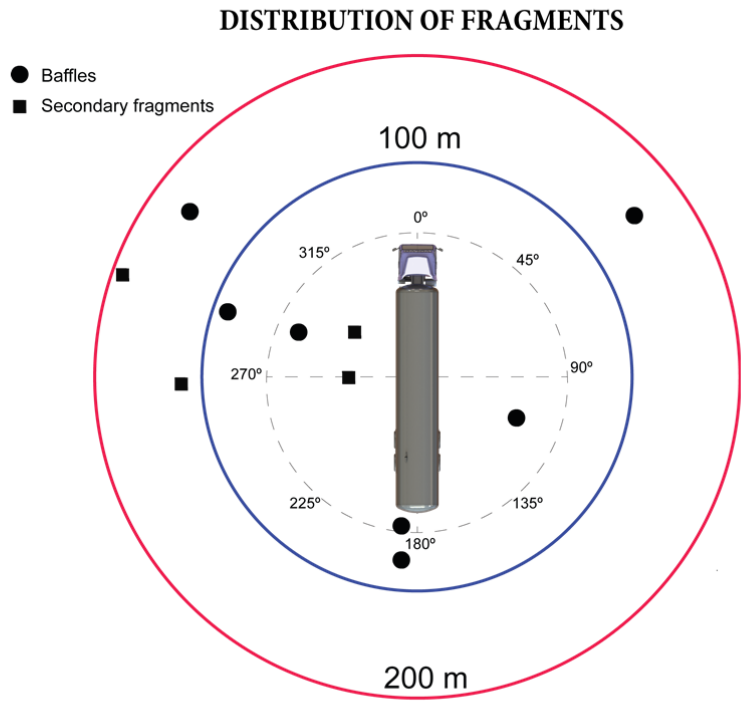

Figure 9. Distribution of fragments

V. CONCLUSIONS.

Regarding this accident, the following conclusion must be remarked.

1) LNG transport in single wall construction road tankers with polyurethane insulation and aluminium cladding is not safe and can BLEVE, as has been demonstrated in Tivissa and Zarzalico accidents (time to BLEVE of 20 min and 71 min respectively).

2) The effects of the explosion were very severe but citizens were evacuated with enough time to save lives.

3) LNG in road tankers can BLEVE if overheated.

4) The vacuum-insulated double wall tankers delay the time to BLEVE and is safer than single wall construction.

5) Legal regulations on virtual pipeline should be revised in order to increase safety in road tankers.

6) 300 metres can be set as hot zone for firefighters and 600 metres to guarantee citizens safety.

7) Cryogenic transport of flammable liquids is a very complex duty for firefighters, since water refrigeration produces cargo heating and BLEVE phenomena occurs in milliseconds. When the firefighters arrive, they don't know the accumulated thermal fatigue of steel and the internal pressure of the vessel.

8) The results of actual risk assessment calculations for BLEVE scenarios fits relatively well with the ground data measured in this accident.