Analysis of fire and explosion hazards during surface transport of liquefied petroleum gas: A case study

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The present paper presents an analysis and simulation of an accident involving a LPG truck tanker in Kannur, Kerala, India. The tanker hit a divider, overturned and cracked leading to leakage of LPG which caught fire, created BLEVE situation in the LPG tank, and subsequent fire and blast. The accident resulted in fatalities and injuries to the residents of the area, burnt tree orchards, houses, shops, vehicles, etc. The accident scenario was modelled and simulated using PHAST code. The results from the models and simulations of the fireball radiation and explosion overpressure showed remarkable agreement with the actual reported loss from the site. The model predictions of overpressure near the accident site up to a distance of about 70m seemed to be more realistic than that of simulations. The effect of jet fire scenario seemed to be inconsequential in comparison to that of the fireball scenario.

Keywords: LPG accident, explosion, overpressure, hazards, thermal radiation.

Introduction

Rising expectations for a better life and improved lifestyle have spurred the demand of quality fuels. The population growth and increasing industrialization have necessitated the rise in demand for such a fuel like liquefied petroleum gas (LPG). The LPG is transported from the refineries/gas separation units to the points of usage/bottling through various modes such as ships, rail tanks, tank trucks (TT), and pipelines.

LPG leakage/sudden release from a pressurized TT lead to vapor cloud formation and explosion resulting in subsequent fire and explosion in the presence of an ignition source. The present paper deals with a case study of a recent accident and subsequent events following the overturn and leakage of LPG from a bulk TT. The accident has been analyzed using available models and methods, and PHAST simulation code.

Case Study

An accident took place in Kannur, Kerala (India) on 27th August, 2012 at 11:30 p.m. wherein a LPG bulk TT owned by Indian Oil Corporation and loaded with about 17820 kg of LPG tried to overtake a vehicle at the Chala bypass near Bhagavathy temple. The truck hit the road divider and the driver lost control over the TT which overturned on the road. The TT was made of steel plates; 0.01m thick and had no insulation. The TT drain pipe got cracked and the vapour leaked slowly at the ground level and a white LPG vapor cloud appeared in a short duration. After about 20 min, the LPG vapor caught fire from the naked flame nearby, the source not identified, and the TT itself got engulfed in the fire creating a BLEVE like situation. An explosion took place followed by a fire and intermittent explosions. Two more explosions took place thereafter at a regular interval of about 3 min each (Kumar, 2013).

According to the eyewitnesses, the second blast was of short duration with the resulting flame rising up to 15 m high. The last blast broke TT into many fragments which flew like missiles to about 18-20 m height and upto about 400 m away laterally from the accident site into green field. The blast noise was heard even at a distance of 25 km from the site.

At the time of the accident, the night sky was almost clear with about 85% humidity and the ambient temperature was about 28-32 ^{0}C. The fire and the blast affected an area of about 200 m radius leaving 20 persons dead, 7 persons with serious injuries and 17 persons with radiation burns. Some eyewitnesses claimed that a huge fireball and bright light were seen after the explosion (Kumar, 2013). The accident took place in the congested area along the road, affecting coconut groves, vegetation, human and cattle/birds, vehicles, shops and houses. Seven shops and 35 houses were burnt. Three houses within a distance of 15 m from the site were completely destroyed. The outside walls and windows of all the houses within a periphery of 200 m were shattered due to shock waves generated after the explosion. 70 vehicles were also reported to be damaged, some of them completely. Fig. 1 shows some photographs of the axle section of the TT, the remains of the TT after the event, a house and a shot completely gutted due to fire and a burnt vehicle. Fig. 2 shows a plan view of the blast site and the affected area, showing the affected buildings (houses and shops) and the geographical features.

Specifications of the LPG tank (Anon.)

In India, all the LPG TTs are manufactured of stainless steel (SS) as per Bureau of Indian Standards IS: 2825 code with a minimum corrosion allowance of 0.5 mm. It had 3 internal baffles (each baffle having a radius of 3 m). The SS plates used in the fabrication were of varying thickness: walls of 4 mm and the ends of 6 mm, and the design pressure of 15.5 bar. The tank had a water capacity of about 38.3 m^3 (85% filled with liquid and the rest 15% filled with vapour) and painted with two coats of white enamel paint. The LPG temperature was slightly below -40 ^{o}C and the pressure below 1 bar. Two safety valves (each of 50 mm diameter), one at the top and second at the bottom of the tank on the unloading pipes, were installed. The tank also had a 457 mm diameter manhole; 51 mm diameter liquid inlet/outlet; 48 mm diameter vapor line connection; 48 mm drain; 48 mm diameter connection pressure gauge; 25 mm rotogauge and 6.25 mm fixed level gauge.

Results of model equations and PHAST simulation

The LPG TT explosion generates a large amount of thermal radiation, overpressure resulting in shock waves and missile fragments of the tank. Considering the initial mass of LPG contained in the tank, the fireball is considered to have had 16000 kg of LPG at the ambient pressure with a vapor fraction of 0.25. These values were taken as input parameters to the PHAST code along with the following empirical equations (CCPS, 1994; Casal et al., 2001), which were used to calculate the maximum diameter, time duration and the height of the fireball.

$$D_m = 6.48M^{0.325} \qquad (1)$$

$$t_m = 0.852M^{0.26} \qquad (2)$$

$$H = 0.75D_m \qquad (3)$$

Where, D_m is the maximum diameter of the fireball (m), t_m the maximum time of formation of the fireball (s), M the mass of LPG (kg) and H the height of the fireball (m).

The simulations of PHAST were made with the following assumptions: The LPG was considered to be pure propane at 1 bar pressure and saturated liquid. The total flammable mass was taken as 16000 kg. The leakage of LPG occurred from the rupture of the tank drain pipeline. The TNT equivalency method was used to calculate the effect of explosion with an efficiency of 10 % (Crowl and Louvar, 2002). The leakage and explosion are assumed to have taken place at the ground level with the outdoor release and a partial degree of confinement was to simulate the actual ground situation, reflecting the presence of obstacles, such as trees, walls, houses, vehicles, shops, etc., land depressions along the highway and the canal nearby. The partial confinement increases the overpressure generation and accelerates the flame front. The simulations for radiating heat were performed by considering a fireball scenario (catastrophic rupture) and jet fire scenario (drain line rupture). The atmospheric stability was considered to be the worst (i.e. night time F class stability with a wind speed of 1.5 m/s). The API method was used for the jet fire calculations.

The calculated values of the fireball parameters and the simulated values from the PHAST code are given in Table 1.

Estimation of thermal effects

The thermal radiation is calculated by surface emitted heat flux from fireball with the radiation fraction. Roberts (1981) suggested a radiation fraction of 0.25-0.4 of the heat of combustion of fuel:

$$E = \frac{F_r M \Delta H_c}{\pi D_m^2 t_m} \qquad (4)$$

Where E is the surface heat flux (kW/m^2), M is the flammable mass (kg), ΔH_c is the heat of combustion (kJ/mol), and F_r is the heat radiated fraction. During the formation of the fireball, the incident thermal radiation on the target can be estimated using the atmospheric transmissivity. Since the thermal radiation is scattered and is absorbed by the atmosphere, the effects of radiation are reduced as (TNO, 2005):

$$\tau = 2.02(P_w l)^{-0.09} \qquad (5)$$

$$l = (H_b^2 + x^2)^{0.5} - (0.5D_m) \qquad (6)$$

$$Q_r = \tau E F_{21} \qquad (7)$$

Where, l is the path length from the flame surface to the target, and x is the distance of target from events.

The calculations for jet fires were made by assuming that the LPG was released from a hole formed in the pipe beneath the TT. Four hole sizes, namely 0.01 m, 0.02 m, 0.03 m and 0.05 m, were used, as per (EGIG, 2001). The results are shown in Table 2. It is seen that the affected distance and the area depend on the hole size and the thermal radiation flux, whereas the flame length is a function of the hole diameter only. It may be seen that the radiation flux decreases with an increase in the distance. Thus, the larger the affected area and the distance from the site, the lower has been the effect of the radiation heat flux. The affected distance and the area, as also the flame length increase with an increase in the hole size. Thus, the maximum affected distance at the radiation level of 5 kW/m^2 is about 111 m for the hole size of 0.05 m as against a distance of 27.75 m for a hole size of 0.01m. The flame length is also 75.2 m for a hole size of 0.05 m as against the flame length of 12.85 m for the hole size of 0.01m.Larger the flame length, the larger will be the area affected with a larger heat flux.

Fig. 3 shows the simulated radiation heat flux in the downwind distance because of jet fire and the fireballs, and also the blast overpressure due to deflagration. An exposure of 30 s for the radiation of 15 kW/m^2 is sufficient to cause 3rd degree burns. For fatalities, generally a radiation level flux of 5-10 kW/m^2 is used. It has been reported that 12 people died because of severe burns in an area within 100 m radius around the accident site. Six persons received extensive burns (70-100% total body surface area burns) at a distance of about 150-200 m from the site. It is seen that the jet fire radiation of 20 kW/m^2 affects an area of about 40 m radius around the accident site. However, the fireball radiation level of 20 kW/m^2 affects upto an area of about 200 m radius.

Estimation of overpressure effects

The overpressure of LPG explosion is calculated by TNT equivalency method which is based on the equivalent mass of tri-nitrotoluene, m_{TNT} . It can be estimated by using the following equation (Crowl and Louvar, 2002):

$$m_{TNT} = \frac{\eta m \Delta H_c}{\Delta H_{TNT}} \tag{8}$$

Where, m_{TNT} is the equivalent mass of TNT (kg), η the explosion efficiency, m the mass of LPG (kg), ΔH_c the energy of explosion/ combustion of LPG (kJ/kg), ΔH_{TNT} the energy of explosion of TNT (kJ/kg). Using the equivalent mass of TNT, a scaled distance, z_e (m/kg$^{1/3}$) is estimated which relates the target distance, r, from the ground-zero point of the explosion as (CCPS, 1994; Crowl and Louvar, 2002):

$$z_e = \frac{r}{(m_{TNT})^{1/3}} \tag{9}$$

The overpressure can be calculated from the empirical equation (CCPS, 1994; Crowl and Louvar, 2002):

$$\frac{p_0}{p_a} = \frac{1616\left[1+\left(\frac{z_e}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{z_e}{0.048}\right)^2}\sqrt{1+\left(\frac{z_e}{0.32}\right)^2}\sqrt{1+\left(\frac{z_e}{1.35}\right)^2}} \tag{10}$$

Where, p_0 is the peak side-on overpressure because of explosion (bar), and p_a the ambient pressure.

The effect of overpressure on people and property can be estimated by using the probit correlations (Eisenberg, 1975; Lees, 1994) and the TNT equivalency method and the overpressure magnitude (Clancey, 1972; Glasstone and Dolan, 1977).

The overpressure calculations using TNT equivalency method and the PHAST simulations are given in Table 3. The PHAST simulations give a constant overpressure of 1 bar up to a distance of about 70 m. However, the TNT equivalency method shows very high overpressures near the blast site: more than 4.5 bar overpressure up to a distance of 50 m, and about 0.69 bar at a distance of about 120 m. These calculations show that the blast creates such a high overpressure (0.69 bar) as to kill almost all persons in the radius of 120 m from the blast site, unless they take shelter and refuse in concretized structures/ obstacle (Glasstone and Dolan, 1977).

A blast overpressure of 3.74 - 4.42 bar may result in 99% fatalities (Glasstone and Dolan, 1972). The blast overpressure alone (excluding the effect of wind in its wake) will be sufficient to result in 99% fatalities up to about 25 m radius from the blast site. A thermal dose of 2000 Thermal Dose Units (TDU)$\left[\left(\text{kW/m}^2\right)^{4/3}.\text{s}\right]$ for hydrocarbon industry is taken as LD_{50} for heat radiation (Rew, 1996). The probit relations given by Eisenberg predict a slightly lower percent fatality at this TDU. At 20 kW/m^2 radiation flux, an exposure time of about 37 s will produce the TDU of 2000$\left[\left(\text{kW/m}^2\right)^{4/3}.\text{s}\right]$.

The radiation heat flux and the overpressure/peak pressure generated due to blast have synergistic effect on the damage caused to the people and the property in the area around the blast site. Clancey (1972) and Glasstone and Dolan (1972) have given the damage potential of overpressure for common structures and human lives. The calculations and the simulations are found to correlate very well with the reported fatalities and damage to properties in an area up to 200 m from the site.

The BLEVE resulted in the LPG tank broken into several fragments which flew over with high speed. The cabin of the truck was completely destroyed and broke into small fragments. The back part of tank with a length of about 2 m struck a house and damaged it partially. The axle section of the tank and the mechanical frame of the tank were completely distorted. Some part of the LPG tank exhibited the effects of fire. Smaller fragments such as thin plate and the baffles were found strewn around the site. The 1/3rd part of the tank was found some 500 m away from the site of the accident and blown up to a height of 15-18 m above the ground.

Conclusion

The model based calculations and PHAST simulations of the actual accident scenario of a LPG tank truck very well correlate the accident damage data reported from the site. The overpressure calculations from the PHAST does not seem to be valid over a distance of about 70m from the blast site and predicts a constant overpressure of 1 bar. The TNT equivalency method gives very realistic results of blast overpressure nearer the blast site in comparison to the results obtained from the PHAST simulations.

The jet fire scenario shows very little impact as compared to that of the fireball radiation and BLEVE generated blast overpressure. The results show an area of about 200 m radius badly affected which corresponds to actual loss of life and property verified from the ground data.

References

1. Anon: http://www.oisd.nic.in/oisd-std-159
2. Casal, J., 2001, Evaluation of the effects and consequences of major accidents in industrial plant. 8: 147-193.
3. CCPS, Centre for Chemical Process Safety, 1994, Guidelines for evaluating the characteristics of vapor cloud explosions, flash fires and BLEVEs, AIChE, New York.
4. Clancey, V. J., 1972, Diagnostic features of explosion damage. 6th International meeting of forensic Sciences, Edinburgh.
5. Crowl, D. A, Louvar, J. F., 2002, Chemical Process Safety: Fundamentals with Applications. Prentice Hall International Series in the Chemical Engineering Sciences, 2nd Ed. New Jersey 07458: 263-269.
6. EGIG, 2000, Gas incident data, 5th Report of the European gas pipeline incident data group.
7. Eisenberg, N. A., 1975. Vulnerability model. A simulation system for assessing damage resulting from marine spills. Final report SA/A-O 15 245 (US DoT, US coast guard).
8. Glasstone, S., Dolan, P. J., 1972, The effects of nuclear weapons. Department of Defense Washington DC, 3rd Ed. Final report, ADA087568.
9. https://law.resource.org/pub/in/bis/S08/is.2825.1969.pdf (Indian Standard Code, 2825)
10. Kumar, P., 2013, Fire disaster following LPG tanker explosion at Chala in Kannur (Kerala, India): August 27, 2012, Burns, 39: pp 1479-1487.
11. Less, F. P., 1994, Loss prevention in the process industries. Butterworth-Heinemann.
12. Rew, P. J., 1996, LD50 Equivalent for the Effect of Thermal Radiation on Humans, Health and Safety Executive Contract Research Report.
13. Robert, A., 1981, Thermal radiation hazards from release of LPG pressurized storage, Fire Safety J, 40: 197-212.
14. TNO, 2005, Methods for the calculation of the physical effects due to the releases of hazardous materials (Green Book), The Hague: Dutch Ministry of Housing, Physical Planning and Environment.

Table 1. Fireball parameters from the LPG TT accident.

Parameter	Calculated value	Simulated value
Maximum Diameter (m)	150.63	149.44
Maximum Time duration (s)	10.6	9.92
Height of fire in BLEVE (m)	112.97	112.08

Table 2. Jet fire after LPG leakage from LPG TT.

Hole Diameter (m)	Thermal radiation (kW/m^2)	Affected distance (m)	Affected Area (m^2)	Flame length (m)
0.01	5	27.75	2419.85	12.85
	7	25.91	1054.36	
	12.5	19.39	590.44	
	25	12.41	483.97	
	37.5	10.13	322.65	
0.02	5	44.61	6252.06	20.62
	7	37.70	4465.76	
	12.5	39.90	2500.83	
	25	28.21	1250.41	
	37.5	23.04	833.61	
0.03	5	94.63	14067.14	31.69
	7	79.97	10047.96	
	12.5	59.85	5626.86	
	25	42.32	2813.43	
	37.5	34.55	1875.62	
0.05	5	110.77	16783.53	75.21
	10	85.21	13456.36	
	12.5	78.61	11682.41	
	25	54.29	7266.57	
	37.5	37.83	3810.34	

Table 3. Calculated the overpressure generated by TNT model.

Distance (m)	Overpressure (bar)	
	Calculated	Simulated
9.79	128.50	1.00
15.00	60.69	1.00
19.58	36.02	1.00
29.58	14.96	1.00
39.17	7.90	1.00
48.96	4.70	1.00
58.75	3.08	1.00
68.54	2.16	1.00
78.33	1.61	0.97
88.13	1.24	0.78
97.92	1.00	0.65
107.71	0.82	0.55
117.50	0.70	0.47
127.29	0.60	0.41
137.08	0.52	0.36
146.87	0.47	0.33
156.66	0.42	0.29
166.46	0.38	0.26
176.25	0.35	0.24
186.04	0.32	0.22
200.00	0.28	0.20
250.00	0.21	0.14

Figures

(a) (b) (c) (d) (e)

Figure 1. Photographs showing (a) the burning axel section of the TT (b) the remains of the TT after the event (c) a completely destroyed house and (d) a shop, (e) a completely burnt three wheeler auto.

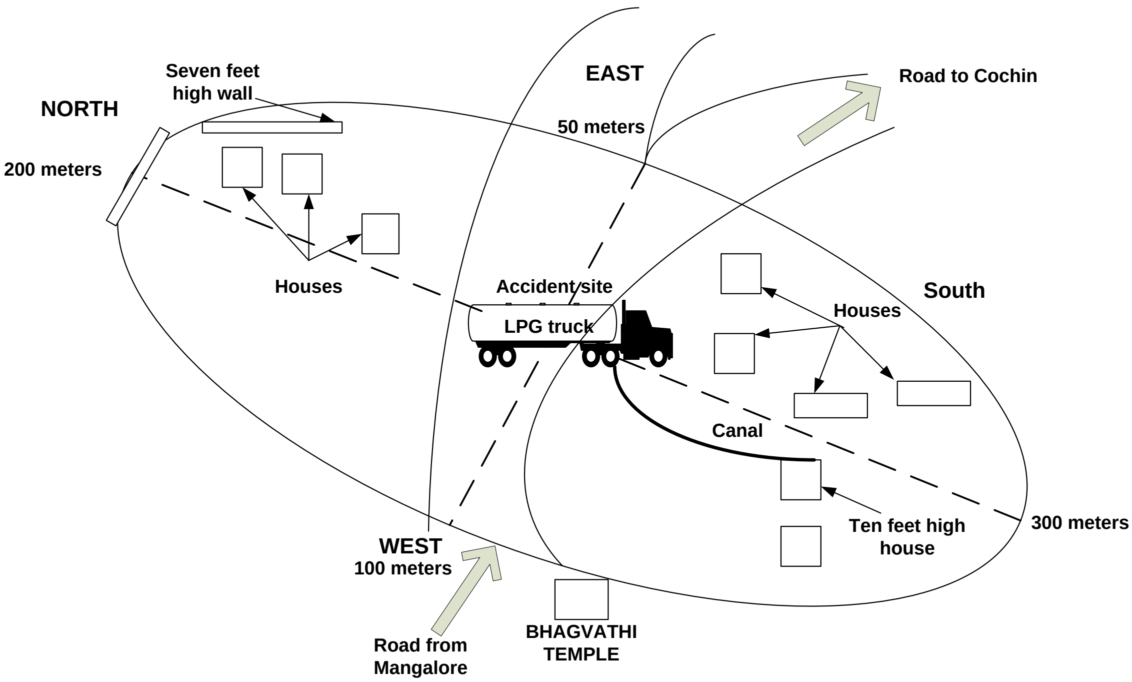

Figure 2. A Arial view of the blast site in (Kannur, LPG accident) and the affected area.

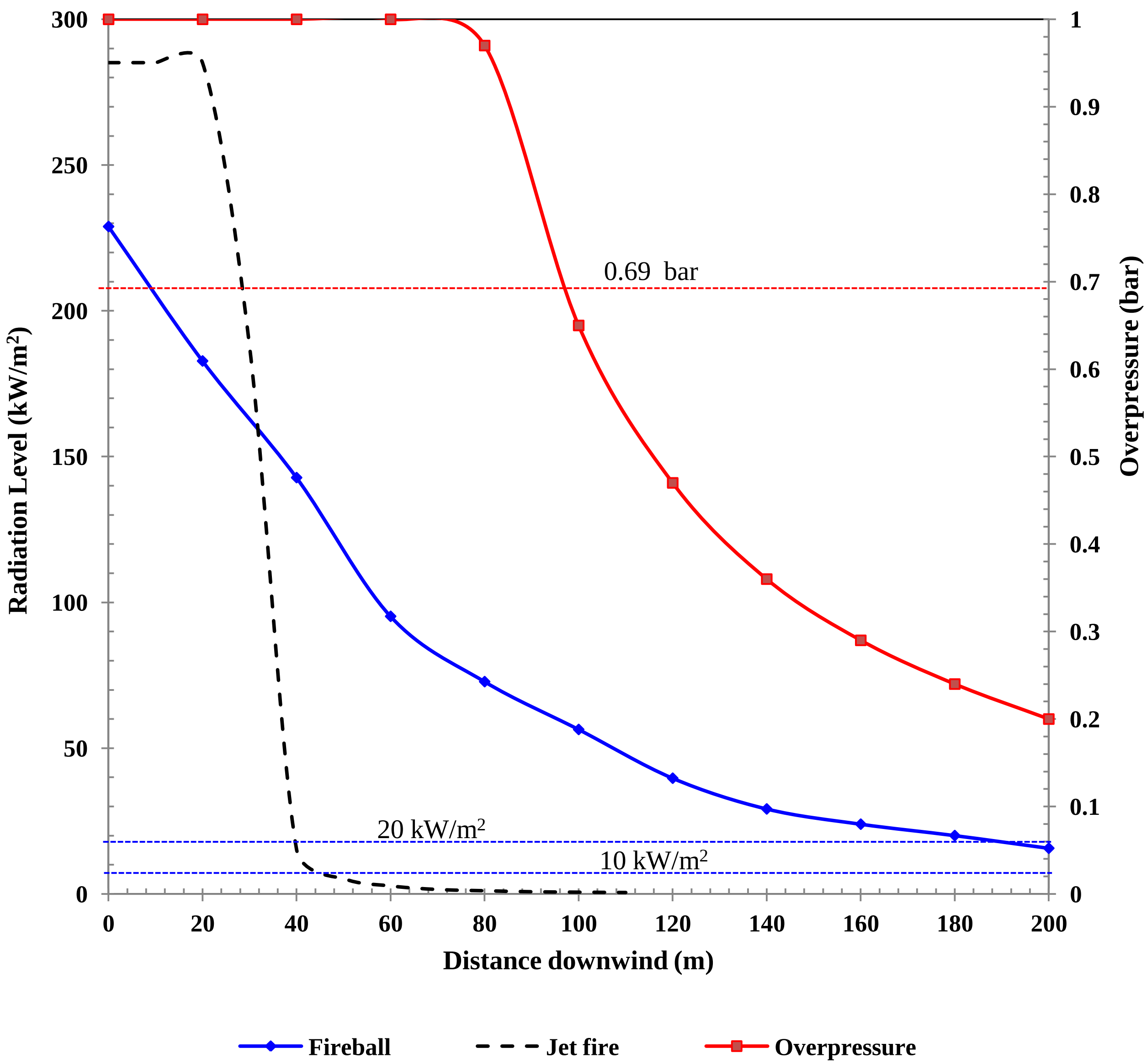

Figure 3. Consequences of jet fire and fireball from the simulation of PHAST in LPG accident of road tanker radiation intensity with the damage distance.