Quantified Risk Assessment

Understanding the Hazards of LPG Filling Stations

By Srinivasan Chandrasekaran and Kiran A

The oil and gas industry plays a vital role in the economic growth of many countries, including India. Petrochemical by-products are used in various forms, from household items to complex industrial applications.

Rapid growth of industrialization and the push for high production of oil and gas increases the risks inherent in these operations. In India, no standard procedures are followed when calculating the failure probability of different scenarios. However, to minimize the consequences of such incidents within acceptable risk levels, strict codes of conduct and preventive policies are enforced by various authorities [e.g., Oil Industry Safety Directorate (OISD)]. Because incidents (or near-hits) are inevitable, it is a common practice to conduct a risk assessment for such scenarios to ensure safe working practices inside the plant.

IN BRIEF
- Many incidents involving liquid petroleum gas (LPG) releases indicate that LPG filling stations are hazardous. The presented work is a preliminary study that aims to improve safety in LPG plants.
- This article examines the consequences and risks involved for different failure cases that are likely to occur. LPG filling stations at two different locations were used as case studies in quantitative risk assessment.
- Some major consequences are addressed, including dispersion, jet fire, fireball and boiling liquid expanding vapor explosion.
- Based on the results, safety measures are recommended.

The authors endeavored to develop incident modeling and conduct risk assessment focused on LPG plants. Common hazards posed by an LPG filling station include dispersion, jet fire, fireball and boiling liquid expanding vapor explosion (BLEVE). Risks associated with such hazards are also classified but no quantitative studies have been reported (Lisbona, Januswezki, Balmforth, et al., 2011). The current study aims to present a better idea of hazards, risks and consequences involving LPG filling stations.

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A Look at the Theory

As noted, consequences that arise from an LPG release include dispersion, jet fire, fireball and BLEVE. These consequences generally cause thermal radiation from fires and overpressure effects from explosion; it is these effects that cause damage. Table 1 gives the effect of thermal radiation for various thermal loads, and Table 2 presents overpressure effects.

Dispersion

Dispersion is the accidental discharge of flammable or toxic materials as pressurized liquid, gas or vapor (Johnson & Cornwell, 2007). The release of pressurized liquid discharge poses an even greater hazard. In the present study, dispersion effect is an important factor in calculating the lower flammability limit (LFL) of LPG release. LFL represents the range in which fuel will not ignite. The LFL for LPG with 60% butane and 40% propane was computed as 16,999 ppm.

Figure 1 depicts the release of material. The directions x, y, z correspond to the downwind, crosswind and vertical directions, respectively. According to Webber, Jones, Tickle, et al. (1992), the concentration at a point is given by Equation 1:

$$c(x,y,\zeta) = c_0(x)e^{\left\{-\left|\frac{\zeta}{R_z}\right|^n\right\}}e^{\left\{-\left|\frac{y}{R_y}\right|^m\right\}}$$

where R_z and R_y are the crosswind and vertical dispersion coefficients and ζ is the distance from the plume center.

Concentration of LPG at different locations is calculated using this equation and hazard distances are then computed.

Jet Fire

Jet fire is an intense, highly directional fire resulting from the ignition of a vapor or two-phase release with significant momentum (Gomez-Mares, Zarate & Casal, 2008). A jet fire is the result of combustion and ignition of a flammable fluid being released from a pipe or an orifice. Jet fires cause thermal radiation, which transmits heat energy and can damage nearby properties and potentially kill plant workers. The flame coordinates and dimensions of jet fire were calculated using Chamberlain's (1987) model. Figure 2 presents jet fire release coordinates. Emission from the surface, sides and ends are considered in calculating the surface emissive power (in W/m²), which is given by Equation 2:

$$W = \frac{F_s m H_{comb}}{A}$$

where F_s is the fraction of heat radiated from the surface flame, H_{comb} is the heat of combustion of fuel mixture in J/kg and A is the total surface area of the flame in m².

Fireball

Fireballs are caused by ignition of turbulent vapor or two-phase fuel in air with a short duration (Figure 3, p. 46; Satyanarayana, Borah & Rao, 1991). Fireballs are instantaneous in nature and generally occur due to catastrophic failure of pressurized vessels. Fireballs produce a large amount of thermal radiation, which will transmit heat energy to the surroundings. The fireball diameter is calculated using Equation 3:

$$D = 6.48M^{0.325}$$

where D is the diameter of the fireball (in meters).

Surface emissive power is given by Equation 4:

$$E_f = \frac{f_s M_f \Delta H_c}{4\pi r_f^2 t_f}$$

where, E_f is the surface emissive power from the fireball (in W/m²), f_s is the fraction of total available heat energy radiated by the flame, ΔH_c is the net available heat for radiation (in J/kg) and is equal to ΔH_{comb}, which is the heat of combustion of fuel and P_{sat} is the vessel burst pressure (in N/m²).

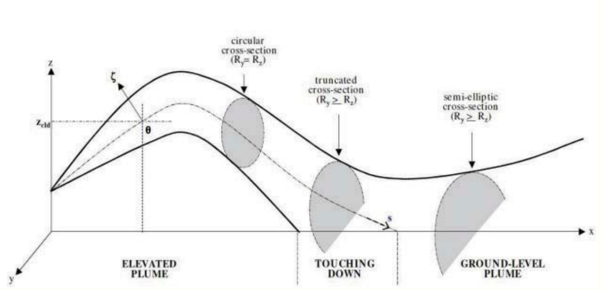
Table 1
Effects of Thermal Radiation

Incident thermal radiation intensity kW/m²	Types of damage
37.5	Sufficient to cause damage to process equipment
12.5	Minimum energy required for piloted ignition of wood, melting of plastic tubing, etc.
4.5	First-degree burn
1.6	Will cause no discomfort to long exposure
0.7	Equivalent to solar radiation

Table 2
Effect of Overpressure Due to Explosion

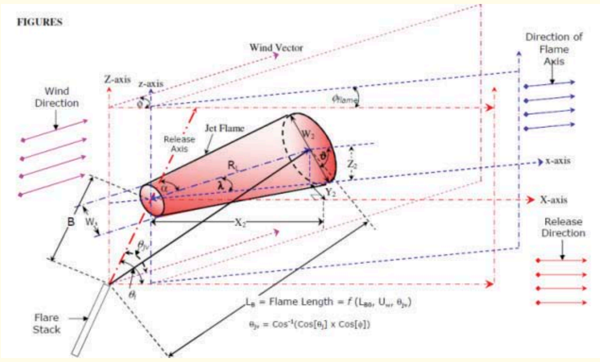
Blast overpressure (bar)	Damage type	Casualty probability
0.30	Major damage to structures (assumed fatal to the people inside structure)	0.25
0.17	Eardrum rupture	0.10
0.10	Repairable damage	0.10
0.03	Glass breakage	0.00
0.01	Crack of windows	0.00

Figure 1
Release of Material



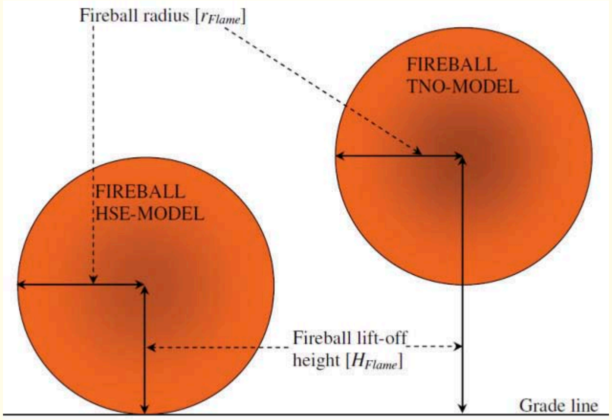
Note. *From "A Unified Model for Jet, Heavy and Passive Dispersion Including Droplet Rainout and Re-evaporation," by H.W.M. Wiltox and A. Holt, 1999, In* International Conference and Workshop on Modelling the Consequences of Accidental Releases of Hazardous Materials, *pp. 315-344.*

Figure 2
Jet Fire



Note. *From "Development in Design Methods for Predicting Thermal Radiation From Flares," by G.A. Chamberlain, 1987,* Chemical Engineering Research and Design, 65, *pp. 299-309.*

Figure 3
Fireball



Note. *From DNV Phast Risk v6.7 user manual,* by Det Norske Veritas, 2005.

BLEVE

BLEVE is due to the sudden loss of containments above its normal boiling point at the time of vessel failure (Abbassi & Abbasi, 2007). It will cause cracks to develop, which may be due to fire engulfment of a vessel that contains liquid under pressure. Due to fire outside the vessel, liquid inside will get vaporized. This will subsequently activate the safety valve, which will increase the vapor content inside the pressure vessel. The vessel's walls will expand in nonuniform ways because the vapor's heat capacity is less than that of the liquid. This will cause loss of strength and sudden release of containment. The sudden release will produce shock waves that will damage the plant and likely cause fatalities. Explosion energy (*E*) is calculated using Equation 5 (Brode, 1959):

$$E = \frac{(P_1 - P_0)V_1}{\gamma_1 - 1}$$

where P_1 is the absolute pressure during failing in Pascal, P_0 is the absolute pressure of atmosphere in Pascal, γ_1 is the specific heat ratio at failure state and V_1 is the volume occupied by stored gas m³.

Distance due to blast wave is determined using an empirical relationship as given in Equation 6 (Baker, Kuselsz, Richer, et al., 1977):

$$R = r\left[\frac{P_0}{E}\right]^{1/3}$$

where r is the distance from the explosion source in meters.

Risk

Risk is defined as the probability of occurrence of events and its consequences (ISO, 2002). It can be expressed in terms of individual risk and societal risk. Individual risk is the frequency at which a person may be expected to sustain a given level of harm from realization of a hazard. It is the ratio of number of fatalities and the number of people at risk.

Societal risk can be defined as the relationship between frequency and number of people suffering from realization of the hazard. Societal risks are generally expressed as FN curve (frequency of occurrence of events versus number of fatalities).

For different weather conditions, the individual risk is calculated using Equation 7 (Wiltox, 2001):

$$IR_{x,y|w} = F_{edy}\int_{\theta_1}^{\theta_2}\left[P_{\theta|w}P_{d|\theta_w}\right]d\theta$$

where, F_{edf} is the failure of occurring in time period, θ is the direction of release, θ_1 is the lower value of θ that impacts the calculation point, θ_2 is the upper value of θ that impacts the calculation point, $P_{\theta|w}$ is the probability of the release occurring in that direction of given weather, $P_{d|\theta w}$ is the probability of death given the release direction and weather.

The societal consequence is calculated using Equation 8 (Wiltox, 2001):

$$N_{edf|o} = \iint n_{x,y}P_{d,x,y|o}\,dxdy$$

where $N_{edf|o}$ is the number of people killed for the given accidental consequence, weather condition, wind direction and the type of incident (flammable, toxic or explosion), $n_{x,y}$ is the number of people considered in the grid cell and $P_{d,x,y|o}$ is the probability of death from the event.

Study Methodology

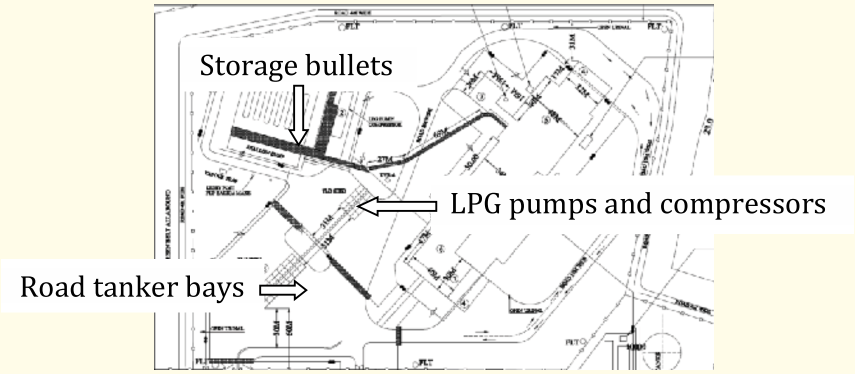
Two LPG filling stations at different locations are featured in this study. No actual incident or near-hit took place in these plants; the scenarios were created for the study. Detailed risk analyses were performed using DNV Phast Risk software. Figure 4 shows layouts of both plants and denote important areas considered. Table 3 (p. 48) provides relevant failure cases and their respective consequences, which were assumed for the study.

Input data required for the analysis are chemical properties of LPG, different release scenarios, in-situ storage conditions and weather data. For the analysis, an average value of the weather conditions for the year 2013 was used (Indian Meteorological Department). At these sites, LPG is stored in pressurized vessels at 5 to 7 kg/cm². For the cited input conditions, hazard distances for these failure scenarios are determined from the numerical analysis per IS 15656:2006.

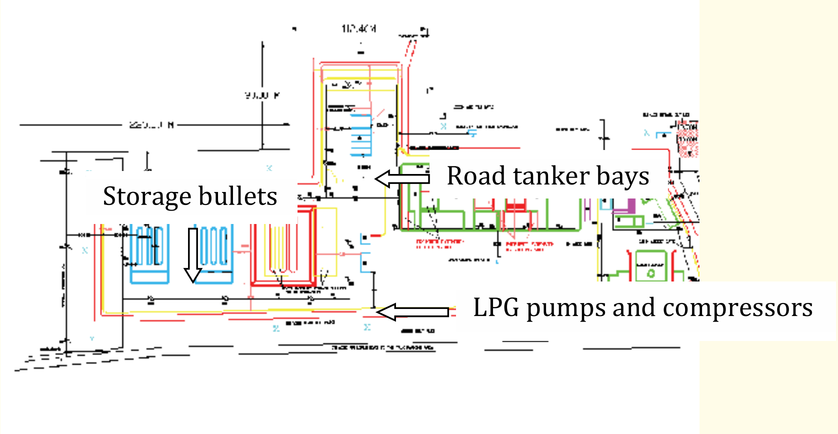
Risk is calculated for these consequences in terms of individual and societal risk. The probability of failure of the different scenarios is taken from an International Association of Oil and Gas Producers' handbook, and is used to calculate risk. The calculated risks are then compared to IS 15656:2006 to check whether these are within permissible limits. Safety measures are recommended for cases that are not within the permissible limits, then risk is recalculated with these updated safety measures.

Figure 4

Layout of Plant A



Layout of Plant B



Study Results & Discussion

Dispersion

Table 4 (p. 48) presents the maximum hazard distances for different failure cases for the considered year. As shown, the maximum LFL hazard distance of 157 m (plant A) and 101 m (plant B) is due to the catastrophic failure of the storage bullet. Furthermore, an increase in the mass demands a significant increase in the hazard distance. Figure 5 (p. 49) depicts the cloud concentration for different weather concentrations for the catastrophic failure of storage bullets at Plant A.

Thermal Radiation Due to Jet Fire

As noted, jet fire increases thermal radiation. For higher intensity thermal loads, plant and equipment damage increase. Thus, a site must calculate the hazard distances to keep critical equipment away from the hazard source. The hazard distances due to the thermal radiation from jet fire for intensity of 37.5 kW/m^2 thermal load were calculated for various scenarios (Table 5, p. 49). Figure 6 shows the jet fire envelope for the full bore failure of a pipeline from the storage bullet to the LPG pump station for Plant B for a 12.5 kW/m^2 thermal load.

Thermal Radiation Due to Fireball

Fireballs are generally short-lived and, therefore, do not cause a thermal load as high as 37.5 kW/m^2. Due to the catastrophic failure of a storage bullet, it is found that intensity of 12.5 kW/m^2 thermal load produced a hazard distance of 371 m (plant A) and 375 m (plant B). Table 6 (p. 50) provides the hazard distance from the fireball based on different failure scenarios. Figure 7 (p. 50) shows the damage envelope due to the catastrophic failure of a storage bullet at Plant A.

Overpressure Effects Due to BLEVE

BLEVE generates shock waves. Generally when an explosion occurs, shock waves cause more damage than thermal radiation. An intensity of 0.3 bar shock waves is sufficient enough to damage the plant (OISD, 2002). Due to the catastrophic failure of the storage bullet as hypothesized in this study, hazard distance was computed as 129 m for both plants. This distance is due to overpressure from BLEVE (Table 7, p. 50). Figure 8 (p. 50) shows the overpressure region for 0.01 bar shock wave due to catastrophic failure of a road tanker at both plants.

Risk

For different consequences, individual and societal risks are calculated for various failure scenarios. (Table 8, p. 51). The risk was 1.1E-4, and 3.3E-5 per average year for catastrophic failure of storage bullets in plants A and B, respectively. Similarly, for the road tanker failure, risk was 1.2E-5 and 9.1E-6 per average year for Plant A and B, respectively. For road tanker unloading arm failure, individual risk is found to be 3.6E-5 and 2.7E-5 per average year for plant A and B, respectively. These failure scenarios are seen as higher-risk events in comparison to the other failure scenarios of both plants.

Risk was then compared with Indian standards as shown in the as low as reasonably practicable (ALARP) triangle (Figure 9, p. 51). As this figure illustrates, he acceptable risk for existing hazardous industries is 1E-6 per average year and the intolerable risk is 1E-4 per average year.

The calculated risk was compared with the acceptable risk criteria and it was found that as with catastrophic failures of storage bullets and road tankers it is not within the acceptable limit. For plant A, the risk of catastrophic failure of storage

Table 3

Failure Cases & Consequences

No.	Failure case	Consequences
1	Full bore failure of LPG outlet line of bullets	Dispersion, jet fire
2	20% CSA failure of LPG outlet line of bullets	Dispersion, jet fire
3	LPG pump discharge line full bore failure	Dispersion, jet fire
4	Road tanker failure	Dispersion, fireball, BLEVE
5	LPG pump mechanical seal failure	Dispersion, jet fire
6	LPG pump outlet line gasket failure	Dispersion, jet fire
7	Road tanker unloading arm failure	Dispersion, jet fire
8	Catastrophic failure of a single bullet	Dispersion, fireball, BLEVE
9	LPG unloading vapor compressor outlet line full bore failure	Dispersion, jet fire

View additional figures related to FN curve data generated during this study at www.asse.org/psextra.

bullets was unacceptable; for plant B it was in the ALARP region.

Therefore, to reduce the risk and consequences, mounded storage bullets are recommended rather than unmounded storage bullets. In road tanker bays, it is best to avoid a concentration of personnel. Furthermore, the tanker's battery should be disconnected and proper grounding should be provided while loading and unloading.

Assuming strict implementation of these safety measures, risk was recalculated (Table 9, p. 51). The risk in terms of FN curve for catastrophic failure of storage bullets was not within the acceptable limits. To view figures related to FN curves data, visit **www.asse.org/psextra**.

Table 4

Dispersion Distance

No.	Failure case	LFL hazard distance for plant A (m)	LFL hazard distance for plant B (m)
1	Full bore failure of LPG outlet line of bullets	67	67
2	20% CSA failure of LPG outlet line of bullets	24	24
3	LPG pump discharge line full bore failure	40	40
4	Road tanker failure	139	71
5	LPG pump mechanical seal failure	28	29
6	LPG pump outlet line gasket failure	33	33
7	Road tanker unloading arm failure	21	23
8	Catastrophic failure of a single bullet	157	101

Conclusion

This article presents consequence analysis and risk assessment of LPG filling stations located at two different plants. Based on the hypothetical event scenarios assumed for the both plants, it was found that the risks involved for the catastrophic failure are not within the acceptable risk level of 1E-6 per average year. However, by changing to mounded bullets, the risk is 6.1E-8 per average year for both the plants.

For road tanker failure, the risk was found to be in the ALARP region, but it can be reduced by ensuring proper awareness among drivers and implementing proper safety measures, such as disconnecting the battery and proper grounding. After such measures, the risk was reduced to 5.2E-7 per average year for plant A and 3 E-7 per average year for plant B, bringing both sites within the permissible limit. This preliminary work provides insight on the risks created by the different failure scenarios and can be helpful in planning a plant expansion or designing a new installation. **PS**

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Figure 5

Cloud Concentration, Plant A

Cloud concentration due to catastrophic failure of storage bullet for different weather conditions along distance downwind at plant A.

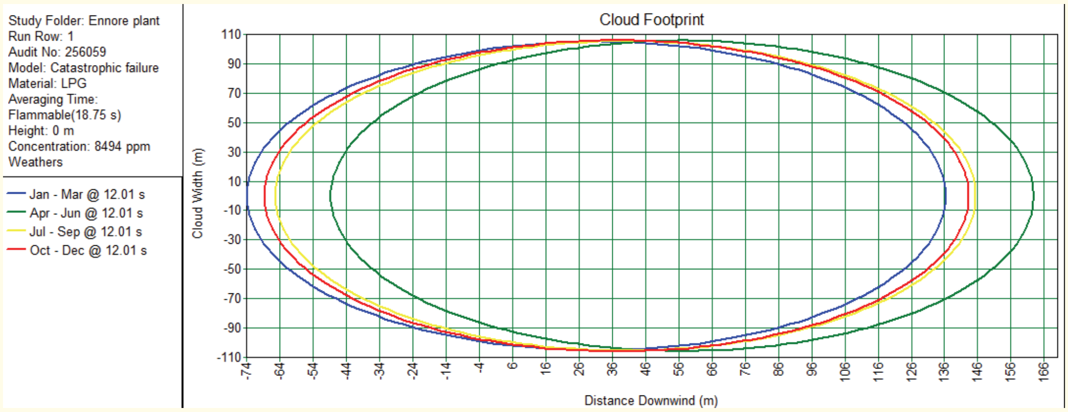


Table 5

Hazard Distance Due to Jet Fire

No.	Failure case	Hazard distance for intensity load 37.5 kW/m² (plant A)	Hazard distance for intensity load 37.5 kW/m² (plant B)
1	Full bore failure of LPG outlet line of bullets	54	50
2	20% CSA failure of LPG outlet line of bullets	28	25
3	LPG pump discharge line full bore failure	36	39
4	LPG pump mechanical seal failure	29	30
5	LPG pump outlet line gasket failure	32	35
6	Road tanker unloading arm failure	24	26

Figure 6

Jet Fire Envelope, Plant B

Jet fire envelope due to full bore failure of pipeline at plant B location.

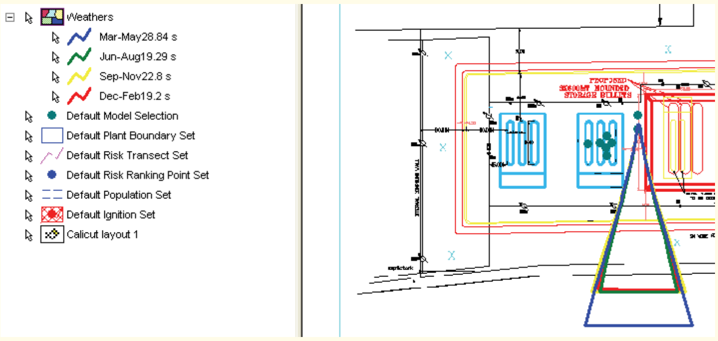
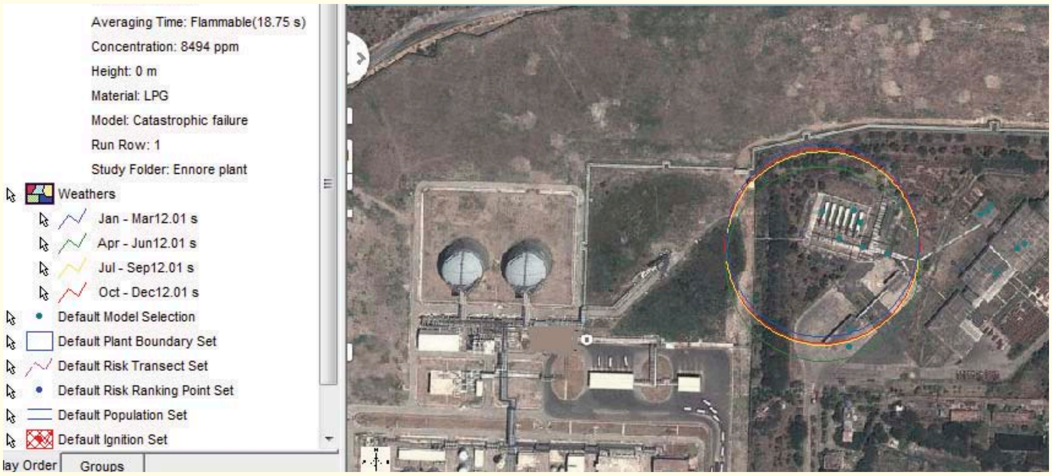


Table 6
Hazard Distance Due to Fireball

No.	Failure case	Hazard distance (m) for intensity load 12.5 kW/m² (plant A)	Hazard distance (m) for intensity load 12.5 kW/m² (plant B)
1	Road tanker failure	187	189
2	Catastrophic failure of a single bullet (capacity: 150 MT)	371	375

Figure 7
Damage Envelope, Plant A

The damage envelope for fireball due to catastrophic failure of storage bullet at plant A.



Averaging Time: Flammable(18.75 s)
Concentration: 8494 ppm
Height: 0 m
Material: LPG
Model: Catastrophic failure
Run Row: 1
Study Folder: Ennore plant

Fireballs are instantaneous in nature and generally occur due to catastrophic failure of pressurized vessels. Fireballs produce a large amount of thermal radiation, which will transmit heat energy to the surroundings.

Table 7
Hazard Distance Due to Overpressure From BLEVE

No.	Failure case	Hazard distance (m) for intensity load of 0.3 bar (plant A)	Hazard distance (m) for intensity load of 0.3 bar (plant B)
1	Road tanker failure	58	58
2	Catastrophic failure of a single bullet (Capacity: 150 MT)	129	129

Boiling liquid expanding vapor explosion (BLEVE) is due to the sudden loss of containments. The sudden release will produce shock waves that will damage the plant and likely cause fatalities.

Figure 8
Damage Envelopes

The damage envelope due to BLEVE for catastrophic failure of a road tanker at plant A (left) and plant B (right).

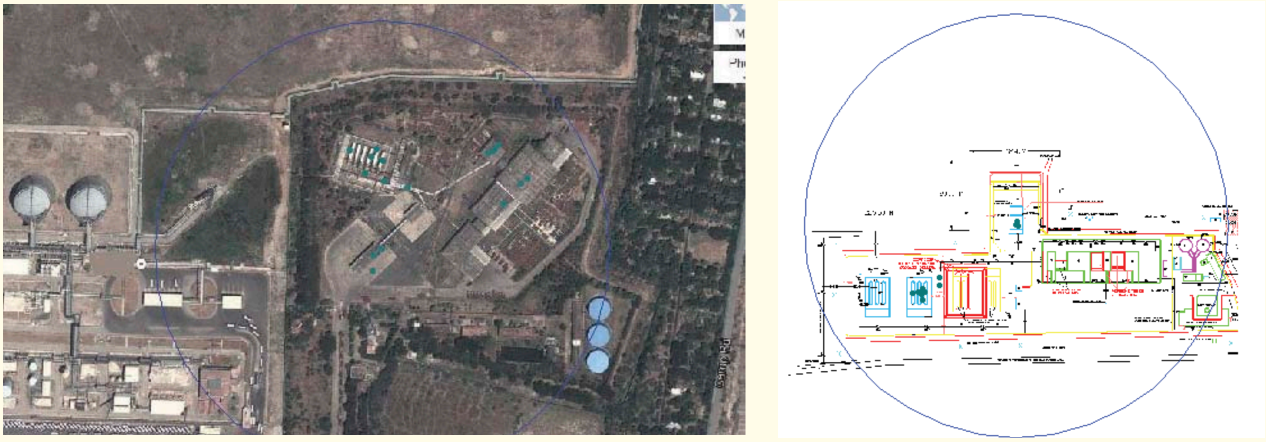


Table 8

Individual & Societal Risk for Different Failure Cases

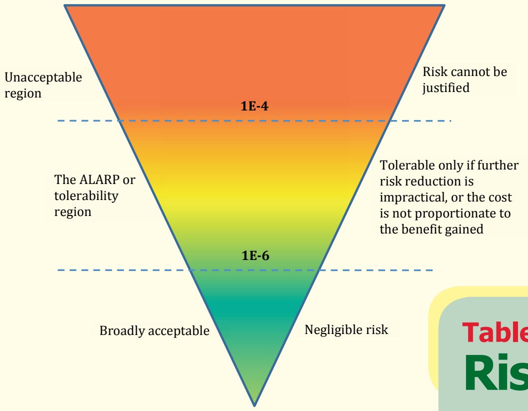
		Plant A		Plant B	
No.	**Failure case**	**Individual risk (per average year)**	**Societal risk (per average year)**	**Individual risk (per average year)**	**Societal risk (per average year)**
1	Full bore failure of LPG outlet line of bullets	2.5E-008	1.7E-008	2.4E-008	2.2E-008
2	20% CSA failure of LPG outlet line of bullets	8.5E-009	5.6E-009	8.2E-009	5.8E-009
3	Catastrophic failure of storage bullets	1.1E-004	7.4E-005	4.4E-005	3.3E-005
4	Road tanker failure	1.2E-005	8.7E-006	9.1E-006	8.5E-006
5	LPG pump discharge line full bore failure	2.4E-008	1.8E-008	5.4E-007	4.9E-007
6	LPG pump outlet line gasket failure	2.5E-008	1.9E-008	4.1E-007	3.7E-007
7	Road tanker unloading arm failure	3.6E-005	2.2E-005	2.7E-005	2.2E-005
8	Vapor compressor line failure	9.1E-008	5.5E-008	9.5E-008	7E-008

Note. *Values in red are not within the acceptable limit.*

Individual risk is the frequency at which a person may be expected to sustain a given level of harm from realization of a hazard. It is the ratio of number of fatalities and the number of people at risk. *Societal risk* can be defined as the relationship between frequency and number of people suffering from realization of the hazard.

Figure 9

ALARP Triangle



Consequences that arise from an LPG release include dispersion, jet fire, fireball and BLEVE. These consequences generally cause thermal radiation from fires and overpressure effects from explosion; it is these effects that cause damage.

The calculated risk was compared with the acceptable risk criteria and it was found that as with catastrophic failures of storage bullets and road tankers it is not within the acceptable limit.

Table 9

Risk After Recommendations

	Plant A		Plant B	
Failure case	**Individual risk (per average year)**	**Societal risk (per average year)**	**Individual risk (per average year)**	**Societal risk (per average year)**
Catastrophic failure of storage bullets	6.1E-8	6.3E-8	6.1E-8	6.3E-8
Road tanker failure	5.2E-7	3E-7	3.7E-7	3E-7
Road tanker unloading arm failure	9E-7	5.4E-7	5.3E-7	4.1E-7