11 HAZARD TO LIFE

11.1 Background

11.1.1 This section of the EIA presents the analysis and findings of the Hazard to Life Assessment undertaken for the Project.

11.1.2 In accordance with Section 3.4.9 of the EIA Study Brief (ESB-323/2019), a hazard to life assessment should be conducted to evaluate the risks associated with Potentially Hazardous Installation (Sha Tin Water Treatment Works) and the LPG storage installation at Worldwide Gardens during both construction and operation phases of the Project.

Sha Tin Water Treatment Works

11.1.3 The Sha Tin Water Treatment Works (Sha Tin WTW) is designated as a Potentially Hazardous Installation (PHI) owing to its use and storage of chlorine in 1 tonne drums. A Consultation Zone (CZ), centred at the chlorine store, of 1000m radius but excluding the areas located at over 150m above sea level is established around the Sha Tin WTW. Consultation Zones are established around PHIs to control developments in the vicinity and prevent population accumulating to the point where societal risks may become unacceptable. Any new development within the CZ of a PHI that may lead to an increase in population requires a hazard assessment to be conducted to ensure that the societal risks remain acceptable.

11.1.4 According to the latest information provided by the Water Supplies Department (WSD), it is understood that the upgrading works of the disinfection facilities in Sha Tin WTW will be completed in Year 2022, and all chlorine drums in Sha Tin WTW would be removed by Q4 2022 after the on-site chlorine generation (OSCG) plant is put into operation.

11.1.5 Based on the tentative construction programme of this Project, the construction works will be commenced in Year 2025, at which time the upgrading works of the Sha Tin WTW would already been completed. As such, risk impact due to storage of liquid chlorine in Sha Tin WTW would not be expected during the construction and operation phases of this Project, and thus no hazard to life assessment for the Sha Tin WTW is required.

LPG Storage Installation

11.1.6 The LPG Storage Installation (LPG Compound) in the Worldwide Gardens comprises of two 2.4 tonnes (water capacity of 4.3 kL each) underground storage vessels, which supplies LPG to the local residents of the Worldwide Gardens. Part of the LRT Road at Sha Tin side and the works areas near the junction of Lion Rock Tunnel Road and Hung Mui Kuk Road are located in close vicinity to the LPG Compound. Hence, a Quantitative Risk Assessment (QRA) was carried out to evaluate the potential hazard to life during both construction and operation phases of the Project. **Plate 11.1** shows the location of the LPG Compound.

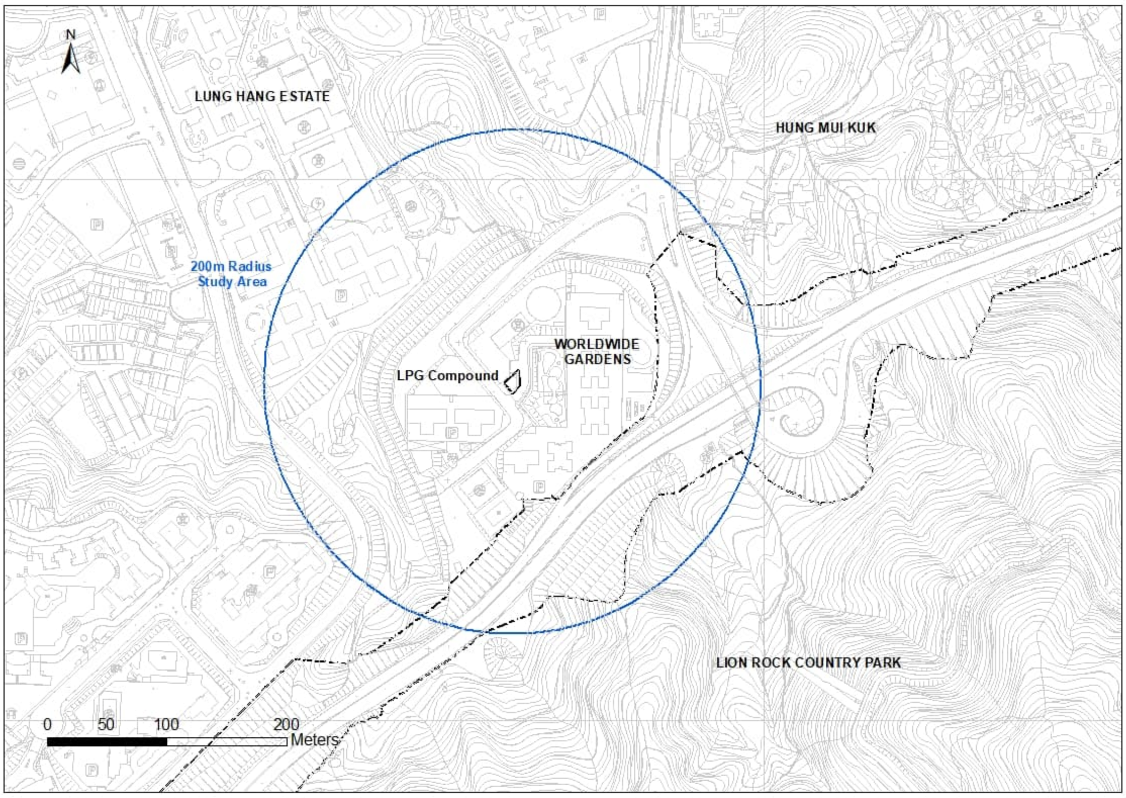


Plate 11.1 Location of the LPG Compound

11.2 Hazard to Life Assessment Objectives and Risk Criteria

Objectives

11.2.1 The Hazard to Life Assessment requirements for the LPG storage installations as detailed in Appendix G of the EIA Study Brief are shown below:

(a) Identify hazardous scenarios associated with the on-site transport, storage and use of gas as defined in the Gas Safety Ordinance (Cap. 51) at the LPG Storage Installation and then determine a set of relevant scenarios to be included in a Quantitative Risk Assessment (QRA);

(b) Execute a QRA of the set of hazardous scenarios determined in (a), expressing population risks in both individual and societal terms;

(c) Compare individual and societal risks with the criteria for evaluating hazard to life as stipulated in Annex 4 of the TM; and

(d) Identify and assess practicable and cost-effective risk mitigation measures.

EIAO TM Risk Criteria

11.2.2 Annex 4 of the EIAO-TM specifies the Individual and Societal Risk Guidelines. The Hong Kong Risk Guidelines (HKRG) per the EIAO-TM Annex 4 states that the individual risk is the predicted increase in the chance of fatality per year to an individual due to a potential hazard. The individual risk guidelines require that the maximum level of individual risk should not exceed 1 in 100,000 per year i.e. 1×10^{-5} per year. Societal risk expresses the risks to the whole population. It is expressed in terms of lines plotting the cumulative frequency (F) of N or more deaths in the population from incidents at the installation. Two F-N risk lines are used in the HKRG that demark "Acceptable" or "Unacceptable" societal risks. To avoid major disasters, there is a vertical cut-off line at the 1000 fatality level extending down to a frequency of 1 in a billion years. The intermediate region indicates the acceptability of societal risk is borderline and should be reduced to a level which is "as low as reasonably practicable" (ALARP). It seeks to ensure that all practicable and cost-effective measures that can reduce risk are considered. The HKRG is presented graphically in **Plate 11.2**.

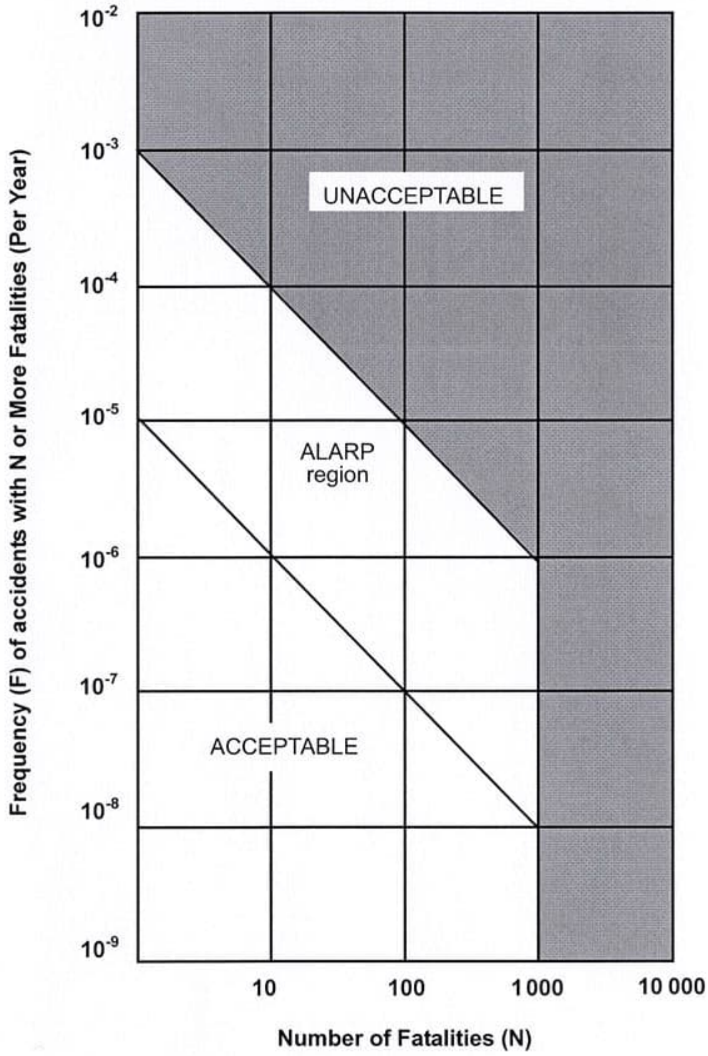


Plate 11.2 Societal Risk Guidelines

11.3 Study Approach

11.3.1 This assessment consists of the following six main tasks:

(a) **Data / Information Collection and Update**: collect relevant data / information that is essential for the hazard assessment;

(b) **Hazard Identification**: identify credible set of hazardous scenarios associated with the operation of the LPG Compound;

(c) **Frequency Estimation**: estimate the frequencies of each hazardous event leading to fatalities based on the collected data and operation data for LPG Compound with the support of justifications from reviewing historical accident data and previous hazard assessments;

(d) **Consequence Analysis**: analyze the consequences of the identified hazardous scenarios;

(e) **Risk Assessment and Evaluation**: evaluate the risks associated with the identified hazardous scenarios. The evaluated risks will be compared with HKRG to determine their acceptability. Where necessary, risk mitigation measures will be identified and assessed to comply with the "as low as reasonably practicable" (ALARP) principle used in the HKRG; and

(f) **Identification of Mitigation Measures**: review the recommended risk mitigation measures from previous studies. Practicable and cost-effective risk mitigation measures will be identified and assessed as necessary. The risk outcomes of the mitigated case will then be reassessed to determine the level of risk reduction.

11.3.2 The hazard assessment covers three scenarios:

- Year 2033 without Project (Base case) – The risk imposed by the LPG Compound to the planned population in 2033, in the absence of the Project.
- Year 2033 with Project (Construction phase) – The risk imposed by the LPG Compound to the planned population in 2033. This also accounts for the presence of the construction workers operating in close vicinity of the LPG Compound and any potential impacts associated with the construction activities.
- Year 2041 (Operation phase) – The risk imposed by the LPG Compound to the planned population in 2041 upon completion of the Project.

11.4 Site Description

<u>Study Area</u>

11.4.1 The LPG Compound is located at the southern direction of the commercial complex of the Worldwide Gardens, which is currently occupied by the Anfield School. The study area of 200m radius from the LPG compound was adopted in the study, as shown in **Plate 11.1**.

11.4.2 Based on information from survey maps and observations during the course of site visit in May 2020, the LPG Compound is surrounded by Lung Pak Road, the Anfield School and residential buildings. There is a 2m high cut slope located on the north-west boundary of the LPG Compound.

<u>Description of the LPG Compound</u>

LPG Storage

11.4.3 DSG Energy Limited (DSG) is the operator of the LPG Compound which supplies LPG to the local residents of Worldwide Gardens. According to the information provided by DSG, the LPG Compound consists of two 2.4 tonnes (water capacity of 4.3 kL each) underground storage vessels, which are filled to a maximum permissible level (85% of the maximum capacity) and equipped with two vaporizers onsite. Furthermore, the two storage vessels were manufactured in 1998 and 2011 and were neither stress relieved nor radiographed.

LPG Delivery and Transfer

11.4.4 LPG is delivered to the LPG Compound by road tankers. The maximum capacity of the road tanker is about 9 tonnes. Based on the information provided by DSG, there are approximately 40 annual LPG deliveries and about 2 tonnes of LPG is being transferred to the LPG Compound per delivery. The average resident time of the LPG road tanker at the LPG Compound is around 45 minutes, which includes the preparation time for facilitating the unloading operation.

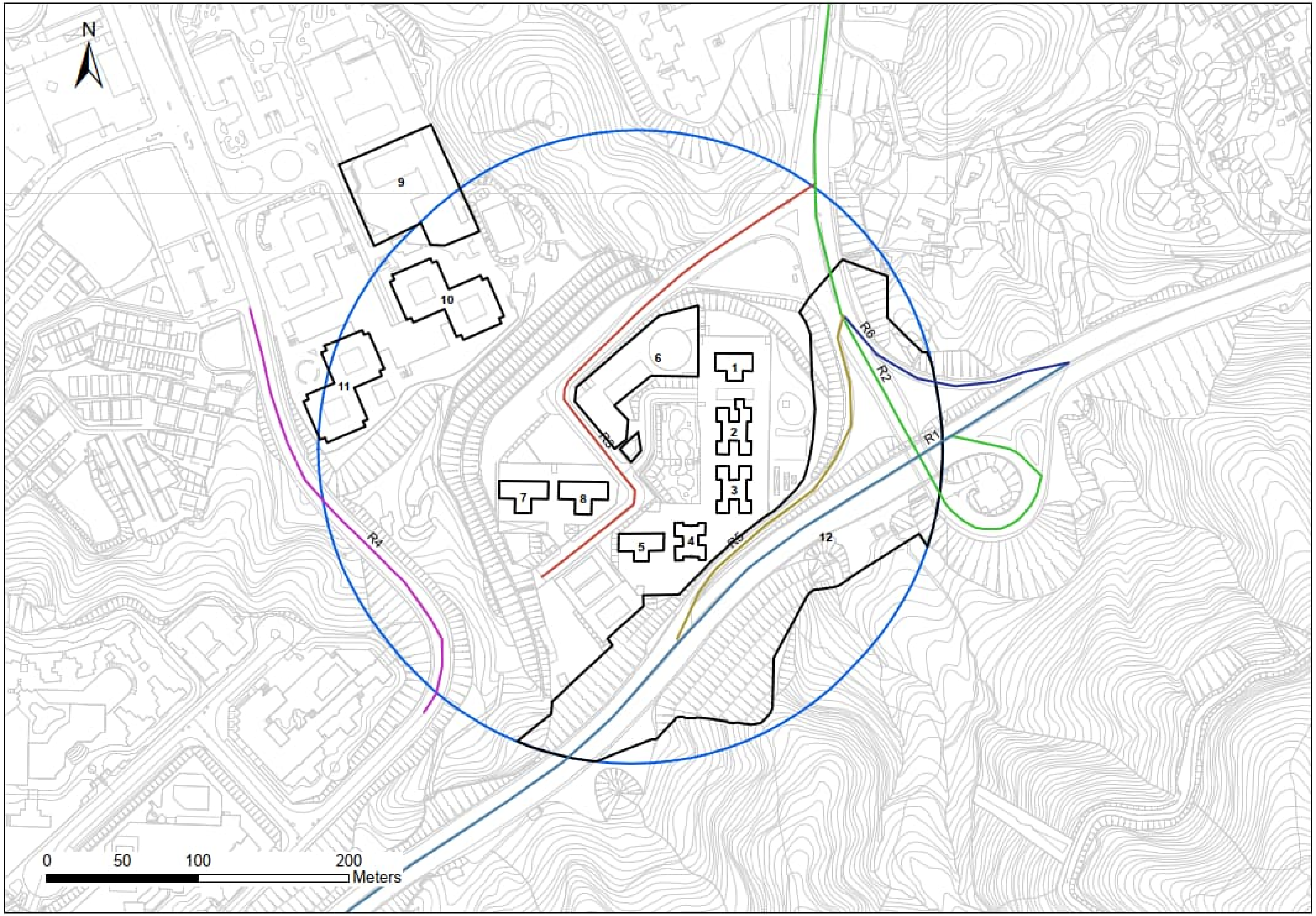
11.4.5 Owing to the site constraint, dedicated road tanker parking area is unavailable within the LPG Compound and the LPG road tankers have to be parked at the predefined area on the roadside next to the entrance of the LPG Compound during unloading operation. This practice was adopted since its operation in the 1970s. As advised by DSG, precautionary measures specified for the concerned LPG Compound are provided to minimize the potential risks due to this unloading arrangement.

Population

11.4.6 Societal risk is a measure of the consequence magnitude and the frequency of the hazardous events. To establish the impact of any release (expressed as the number of people likely to be affected), it is necessary to have a good knowledge of the future population levels around the LPG Compound. This includes residential population, institutional / commercial population and transport population. However, the road tanker operators at the LPG Compound are considered to be voluntary takers of risk and thus, excluded from the assessment.

11.4.7 The location of population groups and roads covered in the assessment is presented in **Plate 11.3**, while photos of the surrounding population, as taken on 26th January 2021, are provided in **Appendix 11.1**. Additionally, details on the estimated population for each population group are provided in **Appendix 11.2**.

Plate 11.3 Location of Population Groups in relation to LPG Compound



Proposed Road Works for the Project

11.4.8 Based on the tentative construction programme of the Project, construction activities on the portion of LRT Road and Hung Mui Kuk Road that fall within the 200 m radius from the LPG Compound will be undertaken between Q4 of 2028 to Q2 of 2033. These include:

- Site clearance
- Slope formation works
- Noise barrier & pipe pile wall/ L-shape retaining wall installation
- Roadworks, drainage, utilities, water mains
- Landscape works for slope

11.4.9 The number of construction workers is estimated according to the Consultant's experience/ analysis based on projects of similar nature. It is assumed that there will be 186 construction workers involved in the nearby construction activities. This estimate represents the maximum number of nearby construction workers envisaged during the peak construction period. The actual number of construction workers engaged in the road widening works along the portion of Lion Rock Tunnel Road and Hung Mui Kuk Road located within 200m radius study area is expected to be smaller. Nonetheless, this estimate is applied as a conservative approach.

Land and Building Population

11.4.10 Hong Kong conducts a population census once every ten years and a by-census in the middle of the intercensal period. The Census data on the number of floors and units of the residential developments, together with the Territory Population and Employment Data Matrix (TPEDM) data on average household size, were used to estimate the existing population of these developments.

11.4.11 The TPEDM population projections for different Planning Data Zones (PDZ) were obtained from the Planning Department (PlanD) to forecast the population for the assessment years.

11.4.12 The 2016-based TPEDM data showed a negative growth of average domestic household size in the PDZ 209 from 2016 to 2041. To be conservative, the residential population in the future assessment years are assumed to remain the same as those in Year 2016.

11.4.13 The population in each area are listed in **Table 11.1** and details on the estimated population for each population group at different time modes and provided in **Appendix 11.2**. It is estimated with the following assumptions:

(a) According to 2016-based TPEDM data, a negative growth rate of -0.27% is observed for the average domestic household size in Sha Tin District (i.e. PDZ 209) from 2016 to 2041, which decreases from 3.26 to 3.05. To be conservative, the average domestic household size in the future assessment years are assumed to remain the same as those in Year 2016 (i.e. 3.26).

(b) For Pok Oi Hospital Chan Kai Memorial College, the number of students was estimated based on the maximum capacity per classroom (i.e. max. capacity of 45 students for 26 classrooms)[1], while the number of staff recorded as of year 2020 is 56[2].

[1] Education Bureau, https://applications.edb.gov.hk/schoolsearch/permittedaccommodation.aspx?langno=1&scrn=190764000133 [Accessed on 23rd March 2021]

[2] School website, http://www.pohck.edu.hk/webpage1920/SubCoordinator2019-2020.pdf [Accessed on 23rd March 2021]

(c) For Anfield School, the number of students was estimated based on the maximum capacity per classroom (i.e. max. capacity of 25 students for 12 classrooms and max. capacity of 15 for 1 classrooms)[3], while the number of staff is estimated as 47[4].

(d) School populations was estimated based on the maximum student intake per class. Furthermore, it is anticipated that majority of students attending Anfield School and Pok Oi Hospital Chan Kai Memorial College reside within Sha Tin District. According to 2016-based TPEDM data, a negative growth rate for residential population is generally observed for PDZ 209 and the surrounding populations (i.e. PDZ 205, 206, 208, 210, 211, 384 and 385). As such, the changes in school populations is expected to be minimal.

Occupancies of different population groups at different time modes are summarised in **Table 11.5**. In general,

(e) The weekday and weekend night-time population are assumed to be 100% of the maximum residential population.

(f) The weekday and weekend daytime population are assumed to be 50% and 70% of the residential population, respectively.

(g) The weekday daytime population is assumed to be 100% of the maximum school population.

(h) An average of 5% outdoor populations is considered for both residential and school population group.

(i) For the proposed Project works area, the weekday and weekend daytime population are assumed to be 100% and 50%, respectively and 100% outdoor population is considered.

Table 11.1 Land and Building Population Data

ID	Description	Population		
		Year 2033 – Base Case [Note 1, 2]	Year 2033 – Construction Phase	Year 2041 – Operation Phase
1	Pine Court, Worldwide Gardens	98	98	98
2	Hibiscus Court, Worldwide Gardens	261	261	261
3	Lily Court, Worldwide Gardens	261	261	261
4	Laurel Court, Worldwide Gardens	274	274	274
5	Bauhinia Court, Worldwide Gardens	137	137	137
6	Anfield School	362	362	362
7	Begonia Court, Worldwide Gardens	150	150	150
8	Cypress Court, Worldwide Gardens	150	150	150
9	Pok Oi Hospital Chan Kai Memorial College	1226	1226	1226
10	Sheung Sum House, Lung Hang Estate			
10a	Low Block	1109	1109	1109
10b	High Block	1275	1275	1275
11	Wai Sum House, Lung Hang Estate			
11a	Low Block	1109	1109	1109
11b	High Block	1275	1275	1275
12	Proposed Project Works Area [Note 3]	0	186	0

Note 1: Populations for residential were estimated based on domestic household size in 2016-based TPEDM.
Note 2: School population for Pok Oi Hospital Chan Kai Memorial College and Anfield School was estimated based on the school information from the Education Bureau and school website.

[3] Education Bureau, https://applications.edb.gov.hk/schoolsearch/permittedaccommodation.aspx?langno=1&scrn=587567000123 [Accessed on 23rd March 2021]
[4] School website, http://www.anfield.edu.hk/taiwai/aboutus.php?id=6 [Accessed on 23rd March 2021]

Note 3: It was assumed that there will be a maximum of 186 construction workers in the nearby construction activities during the construction phase.

Road Population

11.4.14 The traffic population considered in this assessment included the population travelling in motor vehicles on Lion Rock Tunnel Road, Hung Mui Kuk Road, Chung Pak Road & Lung Pak Street, Fu Kin Street and slip roads (i.e. LRT Road to Hung Mui Kuk Road and Hung Mui Kuk Road to LRT Road). Speed limit on Lion Rock Tunnel Road was assumed to be 80km/hr and 50km/hr was considered for the remaining roads/ streets. The traffic population is predicted based on the following equation:

$$Traffic\ Population = \frac{Person\ per\ vehicle \times Vehicle\ per\ hour \times Road\ Length}{Speed}$$

11.4.15 Based on the latest Annual Traffic Census (ATC) [2], the occupancies for each vehicle type and vehicle mix were taken as the average at the core station no. 5024 (Lion Rock Tunnel) which are considered representative of the road traffic in the study area.

11.4.16 The traffic population was assumed to be 100% outdoor. The estimated road population in Year 2033 and Year 2041 are presented in **Table 11.2** and **Table 11.3**, respectively and the detailed calculations are provided in **Appendix 11.2**.

Table 11.2 Estimated Road Population (Year 2033)

Population ID	Description	Maximum Population [Note 1]	
		Daytime	Night-time
R1	Lion Rock Tunnel Road	895	431
R2	Hung Mui Kuk Road	711	341
R3	Chung Pak Road & Lung Pak Street	10	8
R4	Fu Kin Street	11	9
R5	Slip road (Lion Rock Tunnel Road to Hung Mui Kuk Road)	20	15
R6	Slip road (Hung Mui Kuk Road to Lion Rock Tunnel Road)	8	8

Note 1: Road population was estimated based on Traffic Impact Assessment forecasted for Year 2034. This was conservatively applied for the assessed scenarios (i.e. Year 2033 – Base Case and Year 2033 – Construction Phase).

Table 11.3 Estimated Road Population (Year 2041)

Population ID	Description	Maximum Population [Note 1]	
		Daytime	Night-time
R1	Lion Rock Tunnel Road	901	432
R2	Hung Mui Kuk Road	711	341
R3	Chung Pak Road & Lung Pak Street	10	8
R4	Fu Kin Street	11	9
R5	Slip road (Lion Rock Tunnel Road to Hung Mui Kuk Road)	20	15
R6	Slip road (Hung Mui Kuk Road to Lion Rock Tunnel Road)	8	8

Note 1: Road population was estimated based on Traffic Impact Assessment forecasted for Year 2041 and this was applied for Year 2041 – Operation Phase.

Time Modes and Occupancies of Population Groups

11.4.17 Four representative time modes were identified to address the variations in levels of activities that could lead to a release and the variation in population in the study area with time. **Table 11.4** shows the time periods used in the study. Furthermore, the assumptions of the occupancy rate for these specified time modes including the indoor ratio considered for various population groups are summarized in **Table 11.5**.

Table 11.4 Definitions of Time Modes

Time Period	Definition	Proportion of Time
Weekday Day	Mon-Fri, 7am-7pm	35.71%
Weekday Night	Mon-Fri, 7pm – 7am	35.71%
Weekend Day	Sat-Sun, 7am-7pm	14.29%
Weekend Night	Sat-Sun, 7pm – 7am	14.29%

Table 11.5 Occupancies of Population Groups at Different Time Modes

Population Group	Percentage of Occupancy at Different Time Modes				Indoor Ratio
	Weekday (Day)	Weekday (Night)	Weekend (Day)	Weekend (Night)	
Residential	50%	100%	70%	100%	95%
School	100%	0%	0%	0%	95%
Proposed Project Works Area	100%	0%	50%	0%	0%
Lion Rock Tunnel Road/ Hung Mui Kuk Road	100%	50%	100%	50%	0%
Chung Pak Road & Lung Pak Street/ Fu Kin Street/ Slip road (Lion Rock Tunnel Road to Hung Mui Kuk Road)	100%	80%	100%	80%	0%
Slip road (Hung Mui Kuk Road to Lion Rock Tunnel Road)	100%	100%	100%	100%	0%

11.5 Meteorology

11.5.1 Meteorological data is required for consequence modelling and risk calculation. Consequence modelling (dispersion modelling) requires wind speed and stability class to determine the degree of turbulent mixing potential whereas risk calculation requires wind-rose frequencies for each combination of wind speed and stability class.

11.5.2 Meteorological data was obtained from Sha Tin Weather Station (2019) where wind speed, stability class, weather class and wind direction are available. This data represents the weather conditions for the whole year in 2019 and has already taken into account of seasonal variations and is therefore considered applicable for the assessment. **Table 11.6** shows the wind speed-stability frequencies.

Table 11.6 Stability Category-Wind Speed Frequencies at Sha Tin Station

Daytime							
Wind Speed (m/s)	A	B	C	D	E	F	Total (%)
0.0-1.9	10.41	6.96	0.00	9.47	0.00	11.99	38.83
2.0-3.9	7.69	18.85	8.33	9.84	4.38	0.73	49.82
4.0-5.9	0.00	4.75	3.38	2.31	0.11	0.00	10.55

Daytime							
Wind Speed (m/s)	**A**	**B**	**C**	**D**	**E**	**F**	**Total (%)**
6.0-7.9	0.00	0.00	0.21	0.57	0.00	0.00	0.78
Over 8.0	0.00	0.00	0.02	0.00	0.00	0.00	0.02
All (%)	18.10	30.56	11.94	22.19	4.49	12.72	100.00

Night-time							
Wind Speed (m/s)	**A**	**B**	**C**	**D**	**E**	**F**	**Total (%)**
0.0-1.9	0.00	0.00	0.00	2.24	0.00	63.72	65.96
2.0-3.9	0.00	0.00	0.00	8.84	17.21	3.26	29.31
4.0-5.9	0.00	0.00	0.00	4.25	0.34	0.00	4.59
6.0-7.9	0.00	0.00	0.00	0.14	0.00	0.00	0.14
Over 8.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
All (%)	0.00	0.00	0.00	15.47	17.55	66.98	100.00

11.5.3 According to **Table 11.6**, 6 combinations (2B, 1D, 3D, 6D, 2E and 1F) and 5 combinations (1D, 4D, 6D, 2E and 1F) of wind speed and stability class were chosen for daytime and night-time meteorological conditions, respectively. These combinations are considered adequate to reflect the full range of observed variations in these quantities. It is not necessary and efficient to consider every combination observed. The principle is to group these combinations into representative weather classes that together cover all conditions observed.

11.5.4 Once the weather classes have been selected, frequencies for each wind direction for each weather class can then be determined. The frequency distributions for the daytime and night-time meteorological conditions are summarized in **Table 11.7**.

Table 11.7 Weather Class-Wind Direction Frequencies at Sha Tin Station

Daytime							
Direction	**2B**	**1D**	**3D**	**6D**	**2E**	**1F**	**Total (%)**
0 – 30	5.21	1.05	2.52	0.00	1.78	1.21	11.77
30 – 60	13.45	1.05	4.47	0.05	1.28	1.07	21.37
60 – 90	5.66	1.31	3.14	0.12	1.05	1.69	12.97
90 – 120	6.70	1.02	4.11	0.00	1.59	1.31	14.73
120 – 150	5.23	0.40	2.81	0.02	0.86	0.38	9.70
150 – 180	1.12	0.14	0.67	0.00	0.17	0.21	2.31
180 – 210	1.26	0.24	0.78	0.00	0.31	0.52	3.11
210 – 240	7.42	0.29	6.51	1.50	0.78	0.43	16.93
240 – 270	2.54	0.24	1.66	0.19	0.38	0.21	5.22
270 – 300	0.26	0.10	0.07	0.00	0.00	0.10	0.53
300 – 330	0.02	0.05	0.00	0.00	0.00	0.24	0.31
330 – 360	0.45	0.19	0.07	0.00	0.05	0.29	1.05
All (%)	49.32	6.08	26.81	1.88	8.25	7.66	100.00

Night-time						
Direction	**1D**	**4D**	**6D**	**2E**	**1F**	**Total (%)**
0 – 30	0.50	1.09	0.00	5.04	6.22	12.85

Night-time						
Direction	**1D**	**4D**	**6D**	**2E**	**1F**	**Total (%)**
30 – 60	0.30	1.86	0.02	5.59	6.10	13.87
60 – 90	0.17	1.99	0.02	5.14	8.86	16.18
90 – 120	0.15	1.34	0.00	5.84	6.12	13.45
120 – 150	0.10	0.82	0.00	3.06	4.80	8.78
150 – 180	0.00	0.30	0.05	0.84	3.80	4.99
180 – 210	0.02	0.12	0.00	0.92	3.31	4.37
210 – 240	0.00	4.90	0.22	5.34	2.29	12.75
240 – 270	0.05	2.16	0.02	2.34	1.64	6.21
270 – 300	0.05	0.00	0.00	0.15	1.69	1.89
300 – 330	0.07	0.00	0.00	0.02	1.37	1.46
330 – 360	0.17	0.00	0.00	0.32	2.71	3.20
All (%)	1.58	14.58	0.33	34.60	48.91	100.00

11.6 Hazard Identification Analysis

Introduction

11.6.1 A hazard is described as the property of a material or activity with the potential to do harm. A release of flammable gas such as LPG has the potential to cause fire or explosion if ignited. Without ignition, the gas vapour will disperse harmlessly. Under normal conditions, the LPG at the existing LPG Compound will be stored and handled under contained and controlled manners. For LPG to pose a hazard to the people in the surrounding area, a release must occur as a result of a failure of that containment or as a result of faulty transfer procedures.

11.6.2 This section of the report summarizes all possible failure cases and associated failure rates that could lead to a release of LPG. The failure rates adopted throughout this report are quoted in the paper on "Quantitative Risk Assessment Methodology for LPG Installations (Reeves, Minah and Chow, 1997)" [4]. Furthermore, reference for certain frequencies are drawn from approved EIA Reports [5][6] and QRA studies [7][8] where necessary and appropriate. In addition, possible initiating events are identified.

Behaviour of LPG Releases

11.6.3 LPG is a mixture of butane and propane. The gas is twice as heavy as air. For a release of LPG, the nature of the combustion will depend on the timing of ignition and the size of the release.

11.6.4 A release of several tonnes of LPG, if ignited immediately, will produce a fireball. Initially, the gas concentration in the mixture will be above the Upper Flammability Limit (UFL). As burning occurs around the edges of the release, this will entrain more air into the mixture and more combustion will take place. The process accelerates until the mixture rising above the ground as a ball of fire. A fireball may also result from a boiling liquid expanding vapour explosion (BLEVE). This results from the bursting of a vessel (owing to a high internal pressure and a weakening of the vessel material, as a result of a fire for example). The vessel contents rapidly vaporize and are ignited.

11.6.5 If not ignited immediately, the gas will disperse and dilute. If ignition occurs when the gas concentration is between the lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL), a flame front will propagate to produce a flash fire.

11.6.6 For small releases, immediate ignition will produce a long vigorous jet flame from the point of release. As for large releases, delayed ignition will generally produce a flash fire.

11.6.7 For all sizes of release, the LPG will disperse harmlessly if there is no source of ignition.

Hazard Analysis

Spontaneous Failures

Failure of Storage Vessel

11.6.8 Failure of a vessel can be resulted from (i) a cold catastrophic failure leading to instantaneous release of the full inventory and (ii) a partial failure leading to continuous release of the full inventory via a 25mm hole. The causes of failure are summarized as follows:

(a) Spontaneous failure due to corrosion, fatigue, etc.

(b) Overfilling

(c) Earthquake

Failure of Road Tanker

11.6.9 The causes of a road tanker failure are similar to those of a storage vessel. Furthermore, road tankers are vulnerable to collision with other road vehicles during delivery.

Guillotine Failure of Liquid Filling Line to Storage Vessel

11.6.10 Failure of the liquid line is possible as a result of corrosion or fatigue, vehicle impact and external events. Only guillotine failure of the LPG pipework is considered in this study as partial failure of pipework is deemed as an insignificant contributor towards the overall risk levels. The failure would result in LPG leaking from the full bore of the pipe. Moreover, part of the pipework is installed aboveground. Failure of the aboveground portion of the liquid filling line can result from vehicle impact while failure of the underground portion of the liquid filling line can result from earthquake.

Guillotine Failure of Liquid Supply Line to Vaporizers

11.6.11 The liquid supply line connects the underground storage vessel and vaporizers. Failure of the liquid line is possible as a result of corrosion or fatigue, vehicle impact and external events. Only guillotine failure of the LPG pipework is considered in this study as partial failure of pipework is an insignificant contributor to the overall risk levels. The failure would result in LPG leaking from the full bore of the pipe. Since the pipework is protected by fencing, vehicle impact is not considered credible. However, failure of the liquid line can result from earthquakes.

Failure of Vaporizers

11.6.12 Two units of vaporizers are installed at the LPG Compound. Each vaporizer can convert LPG to gaseous fuel at the maximum capacity of 0.15 tonnes / hour. Apart from spontaneous failure and loading failure, failure of the vaporizers can result from earthquakes and aircraft crashes.

Guillotine Failure of Liquid Line from Tanker Pipe to Loading Hose

11.6.13 The cause of failure of this line is similar to that of the liquid filling line to the storage vessel, namely mainly corrosion or fatigue. Moreover, the failure can be due to vehicle impact and other external events.

Failure of Flexible Hose

11.6.14 The loading hose could fail due to the following causes:

(a) Fatigue

(b) Hose misconnection

(c) Hose disconnection during loading or unloading process

(d) Operator / driver error

Loading / Unloading Failures

11.6.15 When LPG releases occur as a direct result of the road tanker unloading operation, the failure events can be regarded as loading failures. The failure events that were considered in the study include:

(a) Hose misconnection and disconnection error

(b) Tanker drive away error

(c) Road tanker collision

(d) Vehicle impact with road tanker during unloading

(e) Storage vessel overfilling

(f) Over-pressurization of pipework.

Hose Misconnection and Disconnection Error

11.6.16 A significant release of LPG during its transfer from road tanker to storage vessel could occur as a result of the failure of the transfer hoses and coupling, human error, or vehicle impact.

Tanker Drive away Error

11.6.17 This error could result from: (i) repositioning of the road tanker during delivery; and/or (ii) the driver driving the road tanker away before the delivery is completed. Since the LPG road tankers are to be parked uphill during the unloading operation, wheel-stoppers will be applied as an additional precautionary measure to prevent the road tankers from rolling backwards in case the conventional parking brake malfunctions.

Road Tanker Collision

11.6.18 Road tanker collision refers to an event in which an LPG road tanker strikes the facilities of the LPG Compound and causes damages to these facilities. There is no dedicated road tanker parking area and unloading area within the LPG Compound due to the site constraint and the LPG road tanker parked outside the LPG Compound during the LPG unloading operation. However, speed control and well-adopted training system are safety measures commonly adopted to avoid serious collision incidents. The probability of minor impact of the road tanker with sufficient energy to cause damage of its vessel (either rupture or leakage) mounted on the tanker is considered to be insignificant. The LPG facilities such as LPG storage vessels, vaporizers and pipework would not be affected by this event since they are installed within the LPG Compound.

Vehicle Impact with Road Tanker during Unloading

11.6.19 Dedicated road tanker parking area and unloading area is unavailable within the LPG Compound and the LPG road tankers park on the public road outside the LPG Compound. Safety precaution measures including safety cones and warning signs will be provided to warn other road users during unloading operation. Although the driver / assistant will monitor the road condition and signal will be provided on the road during the LPG unloading operation, there is a possibility that a vehicle collides with the road tanker during unloading operation leading to LPG release.

Storage Vessel Overfilling

11.6.20 Failure of the LPG storage vessel could occur as a result of overfilling of LPG from the road tanker to the vessel.

Over-pressurization of Pipework

11.6.21 Over-pressurization could be caused by continuing unloading operation when a storage vessel is overfilled or the isolation valves at the receiving storage vessel are closed.

External Events

11.6.22 A LPG release event could occur as a result of external events and the consequences could be catastrophic. The related external events are listed as follows:

(a) Earthquake

(b) Aircraft crash

(c) Landslide

(d) Severe environmental event such as typhoon or tsunami and subsequent outcomes such as falling trees

(e) Subsidence

(f) Lightning

(g) High wind loading

Earthquake

11.6.23 According to Reeves et al. (1997) [4], an earthquake of Modified Mercalli Intensity (MMI) VIII could provide enough intensity to result in damage to the storage vessel or pipework. Therefore, earthquake was considered in this study.

Aircraft Crash

11.6.24 Aircrafts crashing into the LPG Compound due to take-off and landing as well as arrival/ departure flight paths were accounted for in this study. The method given in HSE (1997) [10] for the calculation of aircraft crash frequency was adopted.

Landslide

11.6.25 The LPG Compound is not situated near any natural terrain, there is a 2m high cut slope located on the north-west boundary of the LPG Compound. The cut slope has been protected with 100% shotcrete that landslide is not anticipated. Therefore, this external event was not further considered in this study.

Severe environmental event

11.6.26 According to BDEIA [5], loss of LPG content owing to severe environmental events such as typhoon or tsunami (i.e. a tidal wave following an earthquake) was considered to be insignificant as the installation of LPG vessels is situated underground and away from the seashore. The Super Typhoon Mangkhut is one of the strongest storms attacking Hong Kong in recent years. It struck the Pearl River Estuary on 16 September 2018 and resulted in severe disasters in Hong Kong. Heavy rain, storm surge and high waves caused serious flooding in many coastal and low-lying areas and there were more than 60,000 reports of fallen trees, the highest number on record [9]. There is a tree sitting on the northern boundary of the LPG Compound, separated by a 2m boundary fence. Further, the LPG vessels are located underground and the vaporizers are sheltered inside a concrete structure, the probability of fallen trees damaging the LPG facilities in the LPG Compound was considered to be minimal.

Subsidence

11.6.27 Subsidence is usually slow in movement and such movement can be observed and remedial action can be taken in time. Therefore, the probabilities of severe environmental events and subsidence are very small or negligible and such external events were not further considered in this study.

Lightning and High wind loading

11.6.28 The LPG Compound is surrounded by tall buildings that shield the LPG Compound from damage by high winds. Also, lightning is more likely to strike the tall structures. Frequency of high winds damaging the LPG Compound and lightning strike on the LPG Compound was assumed to be less than the credible frequency of 1×10^{-9} per year. A LPG release due to high wind and lightning was therefore not further assessed in this study.

Safety Features

11.6.29 Safety features installed in the facilities of the LPG Compound can act in different combination to mitigate LPG releases. The safety features considered in this study are listed as follows:

(a) Non-return valve

(b) Excess flow valve

(c) Emergency shutdown system

(d) Breakaway coupling

(e) Manual isolation system

(f) Double-check filler valve

(g) Relief valve

Non-return Valve

11.6.30 Non-return valve on the liquid filling line can isolate release immediately. If it functions properly, there will be no significant consequence.

Excess Flow Valve

11.6.31 Excess flow valve installed at the road tanker and the storage vessel is expected to mitigate a release from guillotine failure of the pipework or the flexible filling hose.

Emergency Shutdown System

11.6.32 An Emergency Shutdown (ESD) system is installed on both the road tankers and the storage vessels. For a release from a road tanker, the emergency isolation system and engine emergency stop system can be activated to isolate the release due to equipment failure and human error. For a release from the vessels, the emergency isolation system can be triggered to prevent a release on the filling line or downstream of the hose connection.

Breakaway Coupling

11.6.33 There is a possibility of road tankers being driven away whilst the hose is still connected, thereby causing damage to the facilities of the LPG Compound and resulting in the release of LPG. The breakaway coupling is installed to prevent undue spillage of LPG owing to the movement of road tankers.

Manual Isolation System

11.6.34 A manual valve is installed for the operators / drivers to shut off the delivery connection manually in case of failure.

Double-check Filler Valve

11.6.35 Double-check filler valve is provided at the hose connection point on the liquid filling line to prevent release to be fed back from the vessel. The design of this valve is essentially 2 non-return valves in series.

Relief Valve

11.6.36 Relief valve is employed to ensure that the vessel is not subjected to an excessive internal pressure that may cause a failure as a result of overfilling. It also offers protection against excessive pressure build-up within the vessel in case of fire.

Human Error

11.6.37 When a failure of equipment or loading process occurs, it is possible for the operator to rectify the problem before a hazard event occurs. Human error is regarded as a failure case if the operator fails to rectify the problem.

Fire Protection / Fighting System

Chartek Coating

11.6.38 Chartek coating is a safety feature of all road tankers. The coating has been reported to provide protection for at least 30 minutes in the case of a jet fire. The coating could prevent a hot spot from developing in a jet fire attack on the road tanker, which can cause thermal weakening of the road tanker wall leading to BLEVE.

Water Spray System

11.6.39 There is no water spray system installed at the LPG Compound. No provision for fire services installation for controlling road tanker fires or lowering the temperature of fires to avoid BLEVE was applied.

Fire Service

11.6.40 The fire services will be available within a few minutes in case of a fire. The extinction of fire by fire fighters prevents BLEVE from occurring.

Escalation

11.6.41 BLEVE of a LPG road tanker can happen if the road tanker is impinged by jet fire from the aboveground LPG facilities listed below:

(a) Cold partial failure of road tanker

(b) Guillotine failure of liquid filling line to vessel

(c) Guillotine failure of liquid supply line to vaporizer

(d) Flexible hose during loading to storage vessel

(e) Liquid line from tanker to loading hose

(f) Vaporizer failure

Summary

11.6.42 The possible hazard events for the day-to-day operation of the LPG Compound have been identified and reviewed in previous section. Only those possible failure cases considered to have the potential to cause off-site fatality are summarized in **Table 11.8**.

Table 11.8 Identified Failure Case of the LPG Compound

Failure Types	Failure Cases
Spontaneous Failure of Pressurized LPG Equipment	• Storage Vessel Failure • Road Tanker Failure • Pipework Failure • Hose Failure • Vaporizer Failure
External Event	• Earthquake MMI VIII • Aircraft Crash
Delivery Failure	• Hose Misconnection Error • Hose Disconnection Error • Tanker Drive-away Error • Road Tanker Collision during Unloading • Vehicle Impact with Road Tanker during Unloading • Storage Vessel Overfilling • Over-pressurization of pipework
Safety System Failure	• Pressure Relief Valve Failure • Non-return Valve Failure • Excess Flow Valve Failure • Emergency Shutdown System Failure • Double-check Filler Valve Failure • Breakaway Coupling Failure • Human Error • Manual Isolation Valve Failure
Fire Fighting System Failure	• Fire Services Failure • Chartek Coating Failure

11.7 Hazard Occurrence

Introduction

11.7.1 Subsequent to the Hazard Identification and Analysis, the next step is to estimate the likelihoods of various LPG release scenarios. There are combinations of hazard initiating events, as identified in previous section, which would lead to a LPG release.

11.7.2 Fault Tree Analysis (FTA) permits the hazardous incident (“Significant Failure Events”) frequency to be estimated from a logical model of the failure mechanisms of a system. The model is based on the combinations of failures of more basic components, safety systems and human errors.

11.7.3 FTA is the use of a combination of simple logic gates, “AND” and “OR” gates, to synthesize a failure model of the hazardous installation. The “Significant Failure Events” frequency is calculated from failure data of more simple events.

11.7.4 A basic assumption in FTA is that all failures in a system are binary in nature, a component or operator either performs successfully or fails completely. In addition, the system is assumed to be functioning if all sub-components are operating properly.

11.7.5 The stepwise procedure for undertaking FTA is presented below:

(a) Hazard identification and selection of the “Significant Failure Events”

(b) Construction of fault tree

(c) Quantitative evaluation of the fault tree

Frequency Estimation

Spontaneous Failure of Pressurized LPG Equipment

Storage Vessel Failure

11.7.6 A release of LPG could occur as a result of catastrophic failure or partial failure of the storage vessel and such a failure would lead to either a loss of entire contents of the vessel or a continuous release of LPG to atmosphere.

11.7.7 Generic failure rates of 1.8×10^{-7} per vessel year [4] and 5.0×10^{-6} per vessel year [4] were adopted for cold catastrophic failure and cold partial failure, respectively.

11.7.8 The service life of both storage vessels will exceed 20 years by 2018 and 2031 respectively. Considering the assessment year for base case is 2033, a corrosion modification factor of 2 is applied to account for the age of vessels [4] for all hazard scenarios.

Road Tanker Failure

11.7.9 As discussed in Section **11.6.9**, the definitions of catastrophic and partial failures are similar to those of the storage vessel. It is generally considered that catastrophic failure rate for LPG road tankers could be higher than for a fixed storage vessel because of a) stresses experienced by the road tanker due to vibration during transportation; and b) cyclic loading associated with filling/unloading the road tanker.

11.7.10 Failure rates of 2.0×10^{-6} per tanker year [4] and 5.0×10^{-6} per tanker year [4] were adopted for catastrophic tanker failure and partial failure of road tanker, respectively.

Pipework Failure

11.7.11 According to the study conducted by Reeves et al. (1997) [4], it was assumed that releases from pipework partial failure were insignificant contributors to the overall risk levels. Therefore, only guillotine failure of LPG pipework was considered in this study. A generic guillotine failure of the pipework was taken to be 1.0×10^{-6} per meter per year.

Vaporizer Failure

11.7.12 The effect of partial failure of the vaporizer is ignored. A generic guillotine failure rate of the vaporizer coil was taken to be 1.0×10^{-6} per meter per year [4].

Hose Failure

11.7.13 The effect of partial failure of the hose was ignored. A generic guillotine failure rate of flexible hose was taken to be 1.8×10^{-7} per transfer [4] or 9.0×10^{-8} per hour [4].

External Events

Earthquake MMI VIII

11.7.14 The probability of 1.0×10^{-5} per year was adopted for the occurrence of an MMI VIII earthquake. The failure rate of pipework and partial failure of underground vessel owing to earthquakes was assumed to be 0.01 [5], whereas the probability of failure for road tanker was considered to be zero.

Aircraft Crash

11.7.15 The distance between the nearest arrival flight path for the Hong Kong International Airport (HKIA) and the LPG Compound is approximately 2.1km. The distance between the LPG Compound and HKIA is about 26km, which exceeds the criteria of 5 miles (8 km) for the consideration of airfield accident. At such distances, the LPG Compound does not come into the flight paths of the critical takeoff and landing phases, and therefore only the background crash rate and airway crash rate were accounted for. The frequency of aircraft crash was estimated using the methodology of the HSE (1997) [10]. The model took into account specific factors such as the target area of the LPG Compound and the distance between the LPG Compound and the runway threshold. The aircraft crash frequency per year was calculated as:

Frequency (per year) = Background Crash Rate + Airway Crash Rate

Frequency (per year) = $(A \times B_i) + (A \times N_i \times R_i \times afac/ alt)$

Where

A = Area of the LPG Compound (8.3×10^{-5} km^2)

N = Number of aircraft movements per year

Bi = Background crash rate for aircraft (2×10^{-6} per year per km^2 [10])

Ri = Aircraft in-flight reliability (4.7×10^{-11} per year per km per aircraft movement [10])

afac = Area factor obtained from Table 9 of UK HSE report [10]

Alt = Mean altitude of aircraft (5 km)

11.7.16 The area factor (afac) is defined as the probability of a crash at a given location relative to the airway. With reference to Table 9 of UK HSE report [10], afac of 0.37 was adopted based on the corresponding x1 of 0.42, as estimated from the below equation:

x1 = x/ alt

Where

x = Minimum horizontal distance from the nearest flight path to the LPG Compound (2.1km)

Alt = Mean altitude of aircraft (5 km)

11.7.17 According to the statistic of Civil International Air Transport Movements of Aircraft, 419,795 movements were recorded in 2019. Thus, the aircraft crash frequency was estimated as 2.87×10^{-10} per year.

Loading / Unloading Failures

Hose Misconnection Error

11.7.18 A significant release of LPG during its transfer from the road tanker to the storage vessel could occur as a result of failure of the transfer hoses and coupling, human error, or vehicle impact. The likelihood of such an event was taken as 3×10^{-5} per operation [4].

Hose Disconnection Error

11.7.19 A failure rate of 2.0×10^{-6} per operation [4] was adopted for this failure case.

Tanker Drive-away Error

11.7.20 Tanker drive-away error refers to an event in which the tanker moves away with the hose still connected. It could result from the tanker driver inadvertent driving the vehicle away before delivery is completed. It was considered that drive-away is unlikely. Even if such error do occur, it is highly likely that the failure can be immediately rectified since the delivery process would not go unattended. A failure rate of 4.0×10^{-6} per operation [4] was adopted.

Tanker Collision during Unloading

11.7.21 A release of LPG cloud occurs as a result of an incident involving an LPG tanker and LPG equipment during delivery. The failure rate of tanker impact during unloading was assumed to be 1.5×10^{-4} per delivery [4].

Vehicle Impact with Road Tanker during Unloading

11.7.22 A rate of 1×10^{-8} per operation [4] was adopted for the case that a vehicle impact into road tanker during unloading.

Overfilling of Storage Vessel

11.7.23 The practice on-site in unloading LPG to the storage vessel is that the vessel will only be filled to 85% of its maximum capacity. It was considered that the probability of the driver overfilling a storage vessel is low. A rate of 2.0×10^{-2} per operation [4] was adopted for this failure case.

Over-pressurization of Pipework

11.7.24 This event has been taken into account by pipework and hose failure data in Sections **11.7.11** and **11.7.13**. Hence, it was not considered separately in the assessment.

Safety System Failure

11.7.25 If the safety system operates as designed then releases would not present an off-site hazard. There is, however, potential for failure of the safety system. The typical safety systems involve pressure relief valve, non-return valve, excess flow valve, emergency shutdown system, breakaway coupling and double-check filler valve.

Pressure Relief Valve Failure

11.7.26 The pressure relief valve avoids the LPG pipework or underground storage vessels from getting overpressure. A generic failure of 1×10^{-4} [4] for the pressure relief valve per demand was adopted.

Pump Overpressure Protection System

11.7.27 Such system is installed on LPG road tankers to control the maximum outlet pressure of the pump. In addition to the internal pump overpressure by-pass, the pump or adjacent pipework is fitted with a separate by-pass valve that set at a lower differential pressure to automatically carry any excess liquid back to the road tanker vessel when the delivery valve is closed.

11.7.28 A generic failure of pump overpressure protection system of 1×10^{-4} per demand [4] was adopted.

Non-return Valve Failure

11.7.29 The non-return valve is intended to prevent back flow of LPG. A generic failure rate of 0.013 per demand [4] was adopted.

Excess Flow Valve Failure

11.7.30 The excess flow valve installed at the road tanker and the storage vessel is expected to be functional when guillotine failure of pipework or flexible hose occurs. A generic failure rate of 0.13 per demand [4] was adopted for the line to vaporizer.

Emergency Shutdown System Failure

11.7.31 A generic failure rate of 1.0×10^{-4} per demand [4] was assumed.

Breakaway Coupling Failure

11.7.32 A generic failure rate of 0.013 per demand [4] was adopted for the road tanker.

Double-check Filler Valve Failure

11.7.33 A double-check filler valve prevents the LPG release to be fed back from the storage vessel. The design has two non-return valves in series. A generic failure rate of 2.6×10^{-3} per demand [4] for common mode failure was adopted.

Manual Isolation Valve

11.7.34 Manual valve is installed for operators / drivers' intervention in case of failure.

11.7.35 A generic failure rate of 0.5 per demand [4] was adopted.

Human error

11.7.36 A probability of 1.5×10^{-3} per demand was assumed to account for the human error in which the operators fail to rectify the problem before any hazard event occurs.

Fire Fighting System Failure

Water Spray System Failure

11.7.37 Water Spray System is not installed on site.

Failure of Fire Services

11.7.38 It was assumed that the Fire Services would always be available, and therefore zero probability was applied for the failure of "fire services arrive late". A generic failure rate of 0.5 per demand [4] was assumed for the fire services to be ineffective against a fire attack.

Chartek Coating Failure

11.7.39 A generic failure rate of 0.1 per demand [4] was applied for Chartek coating fails to prevent a hot spot from developing on the road tanker in a jet fire attack owing to poor maintenance.

11.7.40 A summary of the identified failure cases and their associated failure rates adopted are presented in **Table 11.9**.

Table 11.9 Summary of Identified Failure Cases and Their Associated Failure Rates

Failure Cases	Failure Rates	Reference Source
Spontaneous Failure of Pressurized LPG Equipment		
Catastrophic Failure of Storage Vessel	1.8×10^{-7} per vessel year	Reference [4]
Partial Failure of Storage Vessel	5.0×10^{-6} per vessel year	Reference [4]
Catastrophic Failure of Road Tanker	2.0×10^{-6} per tanker year	Reference [4]
Partial Failure of Road Tanker	5.0×10^{-6} per tanker year	Reference [4]
Guillotine Failure of Pipework	1.0×10^{-6} per meter per year	Reference [4]
Vaporizer Failure	1.0×10^{-6} per meter per year	Reference [4]
Hose Failure	1.8×10^{-7} per transfer or 9.0×10^{-8} per hour	Reference [4]
External Event		
Earthquake MMI VIII	1.0×10^{-5} per year	Reference [4]
Aircraft Crash	2.87×10^{-10} per year	Refer to **Section 11.7.15** to **11.7.17**
LPG Loading Failure		
Hose Misconnection Failure	3.0×10^{-5} per operation	Reference [4]
Hose Disconnection Failure	2.0×10^{-6} per operation	Reference [4]
Tanker Drive-away Error	4.0×10^{-6} per operation	Reference [4]

Failure Cases	**Failure Rates**	**Reference Source**
Road Tanker Collision	1.5×10^{-4} per operation	Reference [4]
Vehicle Impact into Tanker During Unloading	1.0×10^{-8} per operation	Reference [4]
Storage Vessel Overfilling	2.0×10^{-2} per operation	Reference [4]
Safety Features Failure		
Pressure Relief Valve Failure	1.0×10^{-4} per demand	Reference [4] based on ESD system
Failure of Pump Over-pressurization Protection	1.0×10^{-4} per demand	Based on pressure relief valve
Non-return Valve Failure	0.013 per demand	Reference [4]
Excess Flow Valve Failure	1.00 per demand for liquid filling line and flexible hose 0.13 per demand for line to vaporizer	Reference [4]
Manual Isolation Valve Failure	0.5 per demand	Reference [4]
Emergency Shutdown System Failure	1.0×10^{-4} per demand	Reference [4]
Breakaway Coupling Failure	0.013 per demand for tanker	Reference [4] Conservative estimate, based on breakaway coupling for road tanker
Double-check Filler Valve Failure	2.6×10^{-3} per demand	Reference [4]
Operator fails to rectify problem	1.5×10^{-3} per demand	Reference [3]
Fire Protection / Fighting System Failure		
Water Spray System Failure	1.00 per demand	There is no water spray system
Failure of Fire Services	0.5 per demand	Reference [4]
Chartek Coating Failure	0.1	Reference [4]
Failure Probability		
Catastrophic failure of vessel provided over-pressurization	0.01	Reference [3]
Partial failure of vessel provided over-pressurization	0.1	Reference [3]; 10 times of catastrophic failure
Probability of catastrophic / guillotine failure due to aircraft crash [Note 1]	1	Assume 100% failure leading to rupture / guillotine failure
Probability of partial failure due to aircraft crash [Note 1]	0	Assume 100% failure leading to rupture / guillotine failure
Probability of equipment failure due to earthquake	0.01	Reference [5]
Probability of catastrophic / partial failure in earthquake	0.5 / 0.5	It is more likely that an earthquake leads to failure of pipeline connection rather than vessel failure while washed sand provides buffering effect to prevent vessel from damages. Pipeline failure has already been accounted in other hazardous events. Therefore, the 50:50

Failure Cases	Failure Rates	Reference Source
		split is conservatively adopted in vessel failure events.

Note 1: The probability of road tanker rupture and road tanker partial failure due to aircraft crash are considered as 1 and 0 respectively, which assumes only catastrophic failure of road tanker will be resulted in the event of aircraft crash. The probability for storage vessel failure due to aircraft crash will be significantly less as compared to other equipment since storage vessels are located underground. Hence, 0.01 and 0.09 are adopted for catastrophic and partial failure of storage vessels respectively.

Escalation

11.7.41 Escalation refers to the situation in which a relatively insignificant accident causes an event with much more significance to occur. This was addressed in this assessment with the event tree analysis in **Appendix 11.3**.

Frequency of Occurrence

Fault Tree Analysis

11.7.42 Fault tree analysis was used to provide models for the calculation of failure rates or the probabilities of the hazardous scenarios described in **Table 11.10**. Sets of fault tree diagrams are attached in **Appendix 11.4**.

Event Tree Analysis

11.7.43 The event trees evaluate the hazard event outcomes for the LPG events assessed in this study and they are shown in **Appendix 11.3**.

11.7.44 Potential hazardous event outcomes following an LPG release include BLEVE, fireball, jet fire, vapour cloud explosion (VCE) and flash fire.

11.7.45 In this study, it was considered that there are no significant areas of confinement / congestion to generate the turbulence required for a vapour cloud explosion upon ignition of a flammable gas cloud. Therefore, the probability of occurrence of a VCE was assigned a value of 0 for all LPG release events.

11.7.46 The frequencies of the hazardous outcomes assessed in this study are summarized in **Table 11.10**.

Table 11.10 Event Outcome Frequencies of Significant LPG Releases

Ref	Event Description	Hole Size (mm)	Outcome Event [Note 1]	Event Frequency per year	Outcome Probability	Probability of Failure to isolate	Total Outcome Frequency /year
F1.1	Cold Catastrophic Failure of Storage Vessel 1	Rupture	FBL	4.10E-07	9.00E-01	1.00E+00	3.69E-07
F1.1	Cold Catastrophic Failure of Storage Vessel 1	Rupture	VCE	4.10E-07	0.00E+00	1.00E+00	0.00E+00
F1.1	Cold Catastrophic Failure of Storage Vessel 1	Rupture	FFR	4.10E-07	1.00E-01	1.00E+00	4.10E-08
F1.2	Cold Catastrophic Failure of Storage Vessel 2	Rupture	FBL	4.10E-07	9.00E-01	1.00E+00	3.69E-07
F1.2	Cold Catastrophic Failure of Storage Vessel 2	Rupture	VCE	4.10E-07	0.00E+00	1.00E+00	0.00E+00
F1.2	Cold Catastrophic Failure of Storage Vessel 2	Rupture	FFR	4.10E-07	1.00E-01	1.00E+00	4.10E-08
F2.1	Cold Partial Failure of Storage Vessel 1	25	JFI	1.01E-05	5.00E-02	1.00E+00	5.03E-07
F2.1	Cold Partial Failure of Storage Vessel 1	25	BLEVE	1.01E-05	0.00E+00	1.00E+00	0.00E+00
F2.1	Cold Partial Failure of Storage Vessel 1	25	VCE	1.01E-05	0.00E+00	1.00E+00	0.00E+00
F2.1	Cold Partial Failure of Storage Vessel 1	25	FFR	1.01E-05	9.50E-01	1.00E+00	9.55E-06
F2.2	Cold Partial Failure of Storage Vessel 2	25	JFI	1.01E-05	5.00E-02	1.00E+00	5.03E-07
F2.2	Cold Partial Failure of Storage Vessel 2	25	BLEVE	1.01E-05	0.00E+00	1.00E+00	0.00E+00
F2.2	Cold Partial Failure of Storage Vessel 2	25	VCE	1.01E-05	0.00E+00	1.00E+00	0.00E+00
F2.2	Cold Partial Failure of Storage Vessel 2	25	FFR	1.01E-05	9.50E-01	1.00E+00	9.55E-06
F3	Cold Catastrophic Failure of Road Tanker	Rupture	FBL	6.89E-09	9.00E-01	1.00E+00	6.20E-09
F3	Cold Catastrophic Failure of Road Tanker	Rupture	VCE	6.89E-09	0.00E+00	1.00E+00	0.00E+00
F3	Cold Catastrophic Failure of Road Tanker	Rupture	FFR	6.89E-09	1.00E-01	1.00E+00	6.89E-10
F4	Cold Partial Failure of Road Tanker	25	JFI	1.75E-08	4.75E-02	1.00E+00	8.30E-10
F4	Cold Partial Failure of Road Tanker	25	BLEVE	1.75E-08	1.20E-02	1.00E+00	2.10E-10
F4	Cold Partial Failure of Road Tanker	25	VCE	1.75E-08	0.00E+00	1.00E+00	0.00E+00
F4	Cold Partial Failure of Road Tanker	25	FFR	1.75E-08	1.81E-01	1.00E+00	3.16E-09
F5.1	Guillotine Failure of Liquid filling Line to Vessel (fed from Tanker)	25	JFI	1.11E-07	5.00E-02	1.18E-04	6.51E-13
F5.1	Guillotine Failure of Liquid filling Line to Vessel (fed from Tanker)	25	BLEVE	1.11E-07	1.20E-04	1.18E-04	1.56E-15

Ref	Event Description	Hole Size (mm)	Outcome Event [Note 1]	Event Frequency per year	Outcome Probability	Probability of Failure to isolate	Total Outcome Frequency /year
F5.1	Guillotine Failure of Liquid filling Line to Vessel (fed from Tanker)	25	VCE	1.11E-07	0.00E+00	1.18E-04	0.00E+00
F5.1	Guillotine Failure of Liquid filling Line to Vessel (fed from Tanker)	25	FFR	1.11E-07	1.90E-01	1.18E-04	2.47E-12
F5.2	Guillotine Failure of Liquid filling Line to Vessel (fed from Vessel)	25	JFI	1.11E-07	5.00E-02	2.60E-03	1.43E-11
F5.2	Guillotine Failure of Liquid filling Line to Vessel (fed from Vessel)	25	BLEVE	1.11E-07	1.20E-04	2.60E-03	3.44E-14
F5.2	Guillotine Failure of Liquid filling Line to Vessel (fed from Vessel)	25	VCE	1.11E-07	0.00E+00	2.60E-03	0.00E+00
F5.2	Guillotine Failure of Liquid filling Line to Vessel (fed from Vessel)	25	FFR	1.11E-07	1.90E-01	2.60E-03	5.45E-11
F6	Guillotine Failure of Liquid Supply Line to Vaporizer	25	JFI	1.81E-05	5.00E-02	1.30E-01	1.17E-07
F6	Guillotine Failure of Liquid Supply Line to Vaporizer	25	BLEVE	1.81E-05	1.20E-04	1.30E-01	2.82E-10
F6	Guillotine Failure of Liquid Supply Line to Vaporizer	25	VCE	1.81E-05	0.00E+00	1.30E-01	0.00E+00
F6	Guillotine Failure of Liquid Supply Line to Vaporizer	25	FFR	1.81E-05	1.90E-01	1.30E-01	4.46E-07
F7	Guillotine Failure of Liquid Filling Line to Flexible Hose	25	JFI	1.60E-08	5.00E-02	7.80E-03	6.23E-12
F7	Guillotine Failure of Liquid Filling Line to Flexible Hose	25	BLEVE	1.60E-08	2.40E-04	7.80E-03	2.99E-14
F7	Guillotine Failure of Liquid Filling Line to Flexible Hose	25	VCE	1.60E-08	0.00E+00	7.80E-03	0.00E+00
F7	Guillotine Failure of Liquid Filling Line to Flexible Hose	25	FFR	1.60E-08	1.90E-01	7.80E-03	2.37E-11
F8	Vaporizer Failure	25	JFI	1.01E-05	5.00E-02	1.30E-01	6.55E-08
F8	Vaporizer Failure	25	BLEVE	1.01E-05	1.20E-06	1.30E-01	1.57E-12
F8	Vaporizer Failure	25	VCE	1.01E-05	0.00E+00	1.30E-01	0.00E+00
F8	Vaporizer Failure	25	FFR	1.01E-05	1.90E-01	1.30E-01	2.49E-07
F9.1	Guillotine Failure of Flexible Hose (fed from Tanker)	25	JFI	6.70E-06	5.00E-02	7.55E-03	2.53E-09
F9.1	Guillotine Failure of Flexible Hose (fed from Tanker)	25	BLEVE	6.70E-06	2.40E-04	7.55E-03	1.21E-11
F9.1	Guillotine Failure of Flexible Hose (fed from Tanker)	25	VCE	6.70E-06	0.00E+00	7.55E-03	0.00E+00
F9.1	Guillotine Failure of Flexible Hose (fed from Tanker)	25	FFR	6.70E-06	1.90E-01	7.55E-03	9.60E-09
F9.2	Guillotine Failure of Flexible Hose (fed from Vessel)	25	JFI	6.70E-06	5.00E-02	1.30E-03	4.35E-10

Ref	Event Description	Hole Size (mm)	Outcome Event [Note 1]	Event Frequency per year	Outcome Probability	Probability of Failure to isolate	Total Outcome Frequency /year
F9.2	Guillotine Failure of Flexible Hose (fed from Vessel)	25	BLEVE	6.70E-06	2.40E-04	1.30E-03	2.09E-12
F9.2	Guillotine Failure of Flexible Hose (fed from Vessel)	25	VCE	6.70E-06	0.00E+00	1.30E-03	0.00E+00
F9.2	Guillotine Failure of Flexible Hose (fed from Vessel)	25	FFR	6.70E-06	1.90E-01	1.30E-03	1.65E-09

Note 1: FBL – Fireball; BLEVE – Boiling Liquid Expanding Vapour Explosion; VCE – Vapour Cloud Explosion; JFI – Jet fire; FFR – Flash Fire

11.8 Consequences and Impact Analysis

Introduction

11.8.1 Consequence and impact analysis is conducted to provide a quantitative estimate of the likelihood and number of deaths associated with the range of possible outcomes (i.e. fireball, jet fire, flash fire) which are resulted from failure cases identified in previous sections. In this Study, PhastRisk 6.7 was used for such estimation.

11.8.2 The underground LPG storage vessels in the LPG Compound are situated inside a concrete chamber filled with washed sand. Literature published by The Netherlands Organisation (TNO) has considered this as a special provision. A BLEVE of the LPG tank as a result of a fire underneath the tank or a jet fire was considered impossible, and therefore no BLEVE occurrence was assumed for this scenario.

Modelling Input

11.8.3 Failure events identified in previous sections were considered and evaluated through consequence analysis. Taking into account the safeguard measures, layout plan of the LPG Compound and effect distances of failure events, some failure events would have insignificant off-site impact. Those failure events having potential off-site impact are listed as follows:

(a) Rupture of storage vessel

(b) Rupture of road tanker

(c) Partial failure of storage vessel

(d) Partial failure of road tanker

(e) Guillotine failure of liquid filling line to flexible hose

(f) Guillotine failure of flexible hose

(g) Guillotine failure of liquid filling line to storage vessel

(h) Guillotine failure of supply line to vaporizers

(i) Vaporizer failure

(j) BLEVE of road tanker

11.8.4 There are two storage vessels, each with a water capacity of 4.3 kL, at the LPG Compound. The storage vessels were assumed to be filled to a maximum permissible level (85% of the maximum capacity) in this Study. Replenishment of LPG was assumed to be arranged during either daytime or night-time each day for risk modelling purpose.

11.8.5 An instantaneous release mass of twice the flash fraction for cold catastrophic failure of the underground storage vessels was applied to the modelling of fireball consequence, as suggested by Reeves et al. [4]. The flash fraction of LPG in the storage vessels is around 0.26. Thus, the corresponding mass of 1.2 tonnes was applied for modelling fireball scenario due to rupture of storage vessels.

Ignition Source

11.8.6 In order to calculate the risk from flammable materials, information on ignition sources presented in the study area needs to be identified. Such data was included in the risk model for each type of ignition source (i.e. point sources, line sources and area sources). The risk calculation program (MPACT) is a module in PhastRisk. MPACT calculates the impact of the release of a toxic or flammable chemical on the population. It takes the results of the consequence calculations of the toxic and flammable effects, together with additional data on wind direction, ignition sources, event location and frequency and superimposes them on the population to calculate the fatality risk in the surrounding area. It then predicts the probability of a flammable cloud being ignited (delayed ignition) as the cloud moves downwind over ignition sources.

Point Sources

11.8.7 Since there is no significant ignition source at the LPG Compound, no point source was applied to the risk model.

Line Sources

11.8.8 Roads are defined as line sources in PhastRisk. The following assumptions were applied to estimate the presence factor of the line source and the ignition probability:

(a) Probability of ignition for a vehicle was taken as 0.4 in 60 seconds;

(b) Traffic density was based on the projected traffic flow adopted for population estimation, as detailed in **Appendix 11.2**.

11.8.9 Ignition line sources are summarized in Table 11.11 and Table 11.12.

Table 11.11 Summary of Line Ignition Source (Year 2033)

Line Source	Traffic Density (veh / hr)		Average Traffic Speed (km / hr)
	Daytime	Night-time	
Lion Rock Tunnel Road	8,001	3,521	80
Hung Mui Kuk Road	3,885	1,673	50
Chung Pak Road & Lung Pak Street	368	155	50
Fu Kin Street	213	92	50
Slip road (Lion Rock Tunnel Road to Hung Mui Kuk Road)	361	169	50
Slip road (Hung Mui Kuk Road to Lion Rock Tunnel Road)	291	115	50

Table 11.12 Summary of Line Ignition Source (Year 2041)

Line Source	Traffic Density (veh / hr)		Average Traffic Speed (km / hr)
	Daytime	Night-time	
Lion Rock Tunnel Road	8,114	3,567	80
Hung Mui Kuk Road	3,897	1,678	50
Chung Pak Road & Lung Pak Street	369	156	50
Fu Kin Street	214	92	50
Slip road (Lion Rock Tunnel Road to Hung Mui Kuk Road)	363	170	50
Slip road (Hung Mui Kuk Road to Lion Rock Tunnel Road)	291	116	50

Area Source

11.8.10 PhastRisk considers residential population as an ignition source (such as cooking, smoking, heating appliances etc.). The ignition probability was derived from population densities in the concerned area.

Ignition Probability

11.8.11 Immediate ignition probabilities of 0.9 and 0.05 [4] were adopted for instantaneous release and continuous release of LPG, respectively. These ignition probabilities were applied to event trees as shown in **Appendix 11.3**.

Protection Factors

11.8.12 With reference to previous practice of assessments with PhastRisk in Hong Kong, protection factors were considered and applied to the concerned population groups if applicable.

Protection afforded to persons indoors in a building

11.8.13 It was generally assumed that the respective outdoor/ indoor population are 5% and 95% at the time of an accident [4].

11.8.14 For flash fire consequence, the fatality rate for indoor persons was assumed to be one tenth of the outdoor fatality rate.

11.8.15 For fireball, it was assumed that 50% of indoor persons would be killed.

Protection afforded to persons by being on the upper floors of building

11.8.16 Cloud height decreases further away from the source. Most dispersed clouds for LPG will have a cloud height lower than 10m [4]. It is equivalent to have only population on the lowest two floors of a building (including ground level) being affected. The actual population affected by release events was dependent on gas dispersion results modelled in PhastRisk. Height protection factors were applied to various population types for flash fire events accordingly. The actual population affected by flash fire events are detailed in **Appendix 11.3**.

11.8.17 Jet fire events had been assumed to only affect population below 10m elevation in previous similar assessment, which was confirmed by the modelling results in this Study. All jet fires in the model were assumed to be horizontal or near-horizontal therefore reaching their maximum footprint radii. As with flashfires, only the population exposed (i.e. the population below 10m elevation) were considered in the risk summation for jet fire events, and the rest was excluded by the use of protection factor. The actual population affected by jet fire events are detailed in **Appendix 11.3**.

Shielding by buildings

11.8.18 Shielding protection factors for fireball events were applied to the population surrounding the LPG Compound [4].

11.8.19 For building wholly within the fireball diameter, population at the back of the building were considered protected.

11.8.20 For building wholly outside the fireball diameter, population without direct line of sight of the LPG facilities were considered protected.

11.8.21 While for building partly inside and partly outside of the fireball diameter, population outside the fireball diameter were considered shielded by the rest of the building.

11.8.22 The actual population affected by fireball events are detailed in **Appendix 11.3**.

11.9 Risk Assessment

Introduction

11.9.1 In this section, the risks arising from the LPG supply facilities are evaluated in terms of both individual and societal risks.

11.9.2 Individual risk is a measure of the risk to a chosen individual at a particular location. As such, this is evaluated by summing the contributions to that risk across a spectrum of incidents which could occur at a particular location.

11.9.3 Societal risk is a measure of the overall impact of an activity upon the surrounding community. As such, the likelihoods and consequences of the range of incidents postulated for that particular activity are combined to create a cumulative picture of the spectrum of the possible consequences and their frequencies. This is usually presented in the form of a FN curve and the acceptability of the results can be assessed against the societal risk criterion under the risk guidelines.

Individual risk

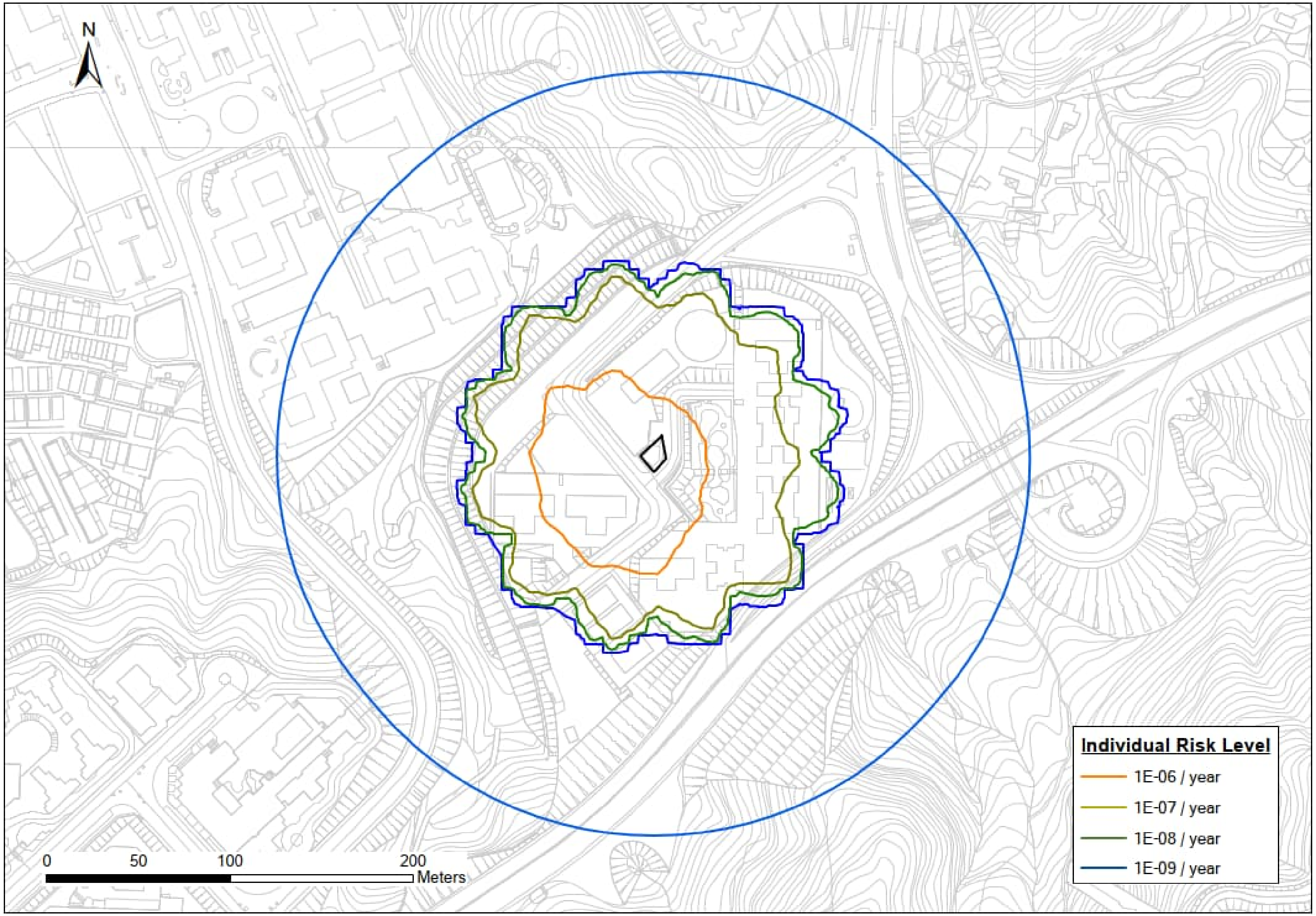
Risk Level

11.9.4 The predicted individual risk contours for the LPG Compound are shown in **Plate 11.4**. The associated risk levels were based on 100% occupancy with no allowance made for shelter or escape, as specified in the user manual of PhastRisk. Since construction activities or operation at the Project Site will not induce additional hazard to the LPG Compound, the individual risk plot is applicable to all assessed scenarios.

Acceptability

11.9.5 As observed in the figure, the 1×10^{-6}, 1×10^{-7}, 1×10^{-8} and 1×10^{-9} per year contours extend approximately 60m, 95m, 100m and 105m from the LPG Compound, respectively. Given that there was no offsite risk with frequency greater than 1×10^{-5} per year, the level of individual risk associated with the operation of the LPG Compound and the individual risk imposed to the Project Site is considered acceptable and in compliance with the Hong Kong Risk Guidelines.

Plate 11.4 Individual Risk Contours



Societal risk

Risk Level

11.9.6 The societal risks were evaluated for the range of incidents with the potential for fatalities in the vicinity of the LPG Compound. The FN Curves for Year 2033 – Base Case, Year 2033 – Construction Phase and Year 2041 – Operation Phase are presented in **Plate 11.5**. The societal risk is more complex than that for individual risk but, in essence, comprises three regions:

(a) Unacceptable – a region within which the risks may be regarded as unacceptable

(b) Acceptable – a region within which the risks may be regarded as acceptable

(c) ALARP – a region between the two in which measures should be taken to demonstrate the risks as "as low as reasonably practicable" (ALARP). In other words, consideration is given not only to the level of risk but also the cost and practicality of reducing it

11.9.7 Numerically, the upper bound of the ALARP region (and hence the borderline of "unacceptability") can be summarized as:

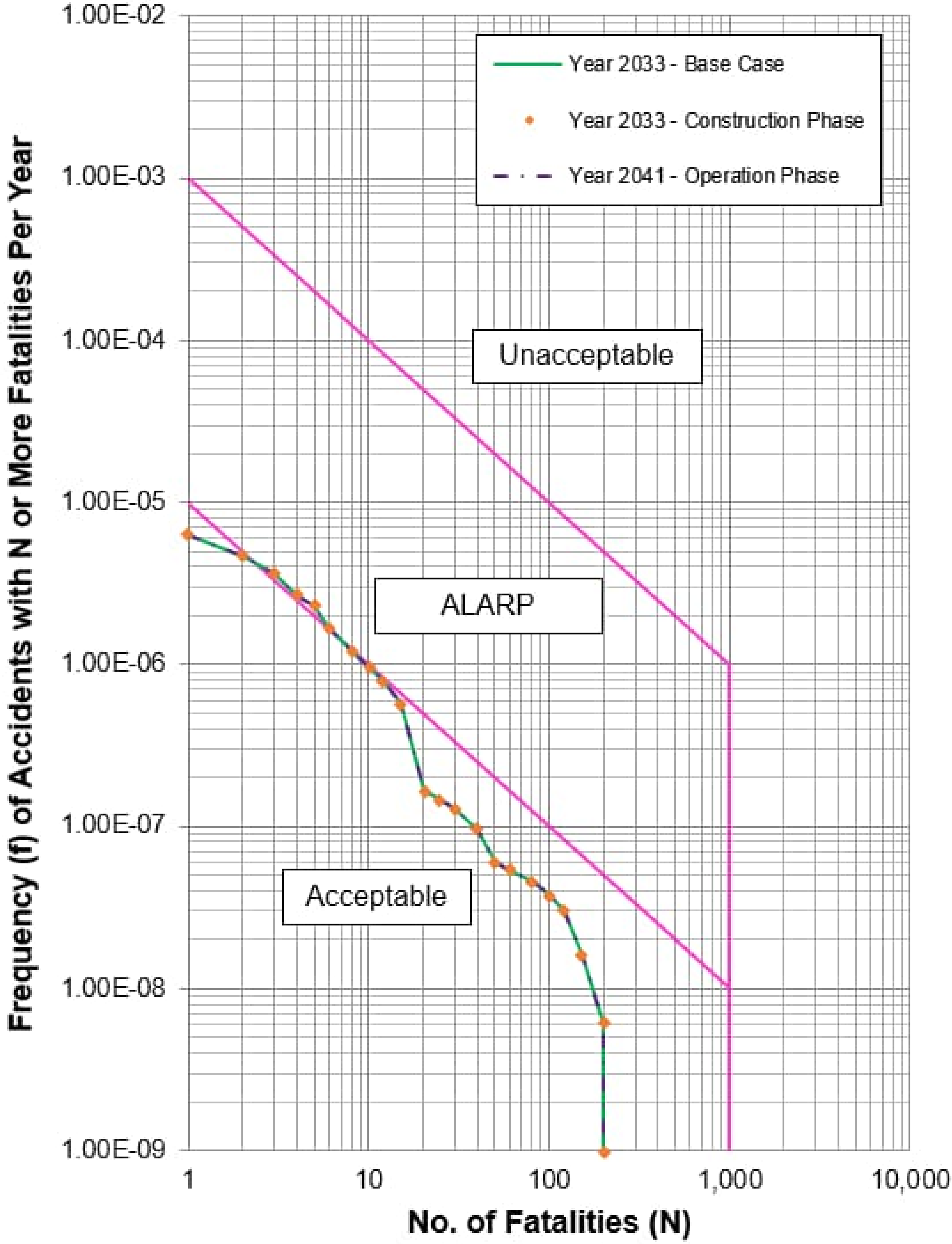
(a) 1 chance in 1,000 per year of an incident resulting in 1 or more fatalities;

(b) 1 chance in 10,000 per year of an incident resulting in 10 or more fatalities;

(c) 1 chance in 100,000 per year of an incident resulting in 100 or more fatalities; and

(d) not more than 1,000 fatalities at a frequency of greater than 1 chance in a billion (1,000,000,000) per year.

Plate 11.5 FN Curves for the LPG Compound



Acceptability

11.9.8 As shown in **Plate 11.5**, it was observed that part of the FN curve (i.e. between 3 and 6 fatalities) falls within the "ALARP" region and this trend is applicable for all assessed scenarios. Based on the societal risk data presented in

11.9.9 **Table 11.13**, minimal changes in frequency for a given number of fatalities was observed amongst the assessed scenarios. This is mainly due to the minimal change in population in close vicinity to LPG Compound and the construction workers will be located remotely away from the LPG Compound with a minimum separation of 85m.

Table 11.13 Societal Risk Data for the LPG Compound covering all Assessed Scenarios

No. Fatalities	Frequency (/year)		
	Year 2033 – Base Case	Year 2033 – Construction Phase	Year 2041 – Operation Phase
1	6.29E-06	6.29E-06	6.29E-06
2	4.64E-06	4.65E-06	4.64E-06
3	3.65E-06	3.65E-06	3.65E-06
4	2.68E-06	2.68E-06	2.68E-06
5	2.31E-06	2.31E-06	2.31E-06
6	1.68E-06	1.68E-06	1.68E-06
8	1.20E-06	1.21E-06	1.20E-06
10	9.58E-07	9.58E-07	9.58E-07
12	7.98E-07	7.99E-07	7.98E-07
15	5.72E-07	5.72E-07	5.72E-07
20	1.65E-07	1.65E-07	1.65E-07
25	1.47E-07	1.47E-07	1.47E-07
30	1.28E-07	1.28E-07	1.28E-07
40	9.48E-08	9.49E-08	9.48E-08
50	5.99E-08	6.00E-08	5.99E-08
60	5.36E-08	5.36E-08	5.36E-08
80	4.59E-08	4.59E-08	4.59E-08
100	3.79E-08	3.79E-08	3.79E-08
120	3.00E-08	3.00E-08	3.00E-08
150	1.64E-08	1.64E-08	1.64E-08
200	6.14E-09	6.14E-09	6.14E-09

Potential Loss of Life (PLL)

11.9.10 The total PLL and top ten most significant contributors for the assessed scenarios (i.e. Year 2033 – Base Case, Year 2033 – Construction Phase and Year 2041 – Operation Phase) are summarized in **Table 11.15**. The total PLLs for all assessed scenarios were found to be about 3.84×10^{-5} per year. The top ten most significant events were found to be common for all assessed scenarios. These included flash fire events of cold partial failure of storage vessels, which accounted for 3.36×10^{-5} per year (87.7% of total PLL), followed by fireball events of cold catastrophic failure of storage vessels, which accounted for 2.01×10^{-6} per year (5.24% of total PLL).

11.9.11 Additionally, the PLL breakdown by population groups for Year 2033 – Construction Phase is presented in

11.9.12 **Table 11.14**. It was found that the proposed Project works area accounted for 2.87×10^{-8} per year (0.07% of total PLL) during construction phase. Thus, the PLL contribution from the proposed Project works area as compared with the overall risk level was considered negligible.

Table 11.14 Breakdown of PLL for the LPG Compound by Population Groups (Year 2033 – Construction Phase)

Population		Potential Loss of Life (PLL) / per year	% of Total PLL
ID	Description		
8	Cypress Court, Worldwide Gardens	1.23E-05	31.96%
6	Anfield School	1.22E-05	31.90%
R3	Chung Pak Road & Lung Pak Street	8.01E-06	20.86%
5	Bauhinia Court, Worldwide Gardens	1.87E-06	4.88%
7	Begonia Court, Worldwide Gardens	1.64E-06	4.27%
4	Laurel Court, Worldwide Gardens	1.07E-06	2.80%
2	Hibiscus Court, Worldwide Gardens	5.00E-07	1.30%
3	Lily Court, Worldwide Gardens	4.54E-07	1.18%
R5	Slip road (Lion Rock Tunnel Road to Hung Mui Kuk Road)	1.66E-07	0.43%
1	Pine Court, Worldwide Gardens	1.25E-07	0.33%
12	Proposed Project Works Area	2.87E-08	0.07%
R1	Lion Rock Tunnel Road	3.14E-09	<0.01%
R2	Hung Mui Kuk Road	7.22E-10	<0.01%
10	Sheung Sum House, Lung Hang Estate	3.74E-10	<0.01%
R4	Fu Kin Street	1.78E-11	<0.01%
R6	Slip road (Hung Mui Kuk Road to Lion Rock Tunnel Road)	5.50E-12	<0.01%
11	Wai Sum House, Lung Hang Estate	1.97E-12	<0.01%
9	Pok Oi Hospital Chan Kai Memorial College	1.25E-13	<0.01%
	Total	3.84E-05	100%

Table 11.15 Breakdown of PLL for the LPG Compound by Major Events (All Assessed Scenarios)

Event Description	Outcome [Note 1]	Year 2033 – Base Case		Year 2033 – Construction Phase		Year 2041 – Operation Phase	
		Potential Loss of Life (PLL) / per year	% of Total PLL	Potential Loss of Life (PLL) / per year	% of Total PLL	Potential Loss of Life (PLL) / per year	% of Total PLL
Cold Partial Failure of Storage Vessel 2	FFR	1.68E-05	43.83%	1.68E-05	43.83%	1.68E-05	43.83%
Cold Partial Failure of Storage Vessel 1	FFR	1.68E-05	43.83%	1.68E-05	43.83%	1.68E-05	43.83%
Cold Catastrophic Failure of Storage Vessel 1	FBL	1.00E-06	2.62%	1.00E-06	2.62%	1.00E-06	2.62%
Cold Catastrophic Failure of Storage Vessel 2	FBL	1.00E-06	2.62%	1.00E-06	2.62%	1.00E-06	2.62%
Cold Catastrophic Failure of Road Tanker	FBL	8.15E-07	2.12%	8.15E-07	2.12%	8.15E-07	2.12%
Cold Partial Failure of Storage Vessel 1	JFI	6.12E-07	1.60%	6.12E-07	1.59%	6.12E-07	1.60%
Cold Partial Failure of Storage Vessel 2	JFI	6.12E-07	1.60%	6.12E-07	1.59%	6.12E-07	1.60%
Vaporizer Failure	FFR	2.48E-07	0.65%	2.48E-07	0.65%	2.48E-07	0.65%
Cold Catastrophic Failure of Storage Vessel 1	FFR	1.32E-07	0.34%	1.32E-07	0.34%	1.32E-07	0.34%
Cold Catastrophic Failure of Storage Vessel 2	FFR	1.32E-07	0.34%	1.32E-07	0.34%	1.32E-07	0.34%
Others	-	1.73E-07	0.45%	1.75E-07	0.45%	1.73E-07	0.45%
	Total	3.84E-05	100%	3.84E-05	100%	3.84E-05	100%

Note 1: FBL – Fireball; JFI – Jet fire; FFR – Flash Fire

11.10 Risk Mitigation Measures

Risk Mitigation Measure Identification

11.10.1 The assessment finding indicated that the risk level associated with the LPG Compound operation for all the assessed scenarios lies partially within the "ALARP" region of the risk guidelines. Following the ALARP principle, risk mitigation measures were proposed for implementation at the Project Site. Cost-benefit analysis was performed to assess the feasibility of the proposed risk mitigation measures.

11.10.2 The proposed risk mitigation measures to be considered include:

- Installation of onsite gas detectors at the construction site;
- Establishment of emergency response plans;
- Safety/ emergency response training and drills for all personnel at the construction site; and
- Maintain the number of construction workers onsite to a minimum.

Cost-Benefit Analysis

11.10.3 The cost effectiveness of the proposed mitigation measure was assessed by Cost-Benefit Analysis (CBA) using calculation of the Implied Cost of Averting Fatality (ICAF) for each mitigation measures identified. The ICAF was calculated using the equation as follows by taking into account the reduction in Potential Loss of Life (PLL):

$$\text{ICAF} = \frac{\text{Cost of Mitigation Measure}}{(\text{Reduction in PLL Value} \times \text{Design Life of Mitigation Measure})}$$

11.10.4 The ICAF can be compared with the value of life (proposed to be HK$33M in this Study) to determine whether the implementation of the identified mitigation measures is reasonably practicable.

11.10.5 The aversion factor indicates the level of aversion to accidents causing large numbers of fatalities [11]. Aversion factor of 20 (Maximum Aversion Factor for risks at the upper region of the Risk Guidelines) is proposed to adjust the Value of Life to reflect people's aversion to high risk. With this factor applied, the adjusted Value of Life of HK$660M was adopted.

Risk Mitigation Measure Evaluation

11.10.6 It was assumed that all onsite construction workers could escape successfully upon detection of LPG leakage by the gas detectors installed at the construction site. Thus, the maximum PLL reduction due to successful evacuation of construction workers for Year 2033 – Construction Phase was found to be 2.87×10^{-8} per year.

11.10.7 The cost for implementing the proposed mitigation measure would be around HK$100,000 and the design life of the mitigation measure was assumed to be 6 years, which is equivalent to the tentative duration of the construction period.

11.10.8 The ICAF for installing the gas detectors for Year 2033 was estimated to be HK$$5.82\times10^{11}$. Based on the cost-benefit analysis, the proposed mitigation measure to install gas detectors with PLL reduction of 2.87×10^{-8} per year was considered economically unviable since ICAF was found to be significantly larger than the adjusted Value of Life.

11.10.9 With consideration of the large separate distance between the LPG Compound and the Project Site (over 85m), the risk level posed to the populations of the Project would be insignificant as they are mostly located outside the 1×10^{-7} per year contour. The actual risk level posed to an individual would be less than 1×10^{-7} per year.

11.11 Environmental Monitoring and Audit Requirement

11.11.1 Good safety practices are recommended to further manage and minimize the potential risks during construction phase of the Project. Regular audit during construction phase is recommended.

11.12 Conclusions

11.12.1 A full quantitative risk assessment was carried out for the Project Site near the LPG Compound. The assessment was based on information collected from Census & Statistics Department, Hong Kong Observatory, Planning Department, Transport Department and site visits made by the Consultant.

11.12.2 The maximum individual risk contour of 1×10^{-6} per year contour extends approximately 60m from the LPG Compound. Given there is no offsite risk with frequency greater than 1×10^{-5} per year, individual risk is considered acceptable and in compliance with the Hong Kong Risk Guidelines. Part of the FN curve (i.e. between 3 and 6 fatalities) falls within the "ALARP" region and this trend is applicable for all assessed scenarios (i.e. Year 2033 – Base Case, Year 2033 – Construction Phase and Year 2041 – Operation Phase). The total PLLs for all assessed scenarios were found to be about 3.84×10^{-5} per year and the proposed Project works area accounts for 2.87×10^{-8} per year (0.07% of total PLL) during construction phase. Thus, the PLL contribution to the proposed Project works area as compared with the overall risk level was considered negligible. Nonetheless, risk mitigation measure, i.e. installation of gas detectors was proposed following the ALARP principle. Based on the cost-benefit analysis, the proposed mitigation measure to install gas detectors with PLL reduction of 2.87×10^{-8} per year was considered economically unviable since ICAF (i.e. HK\$$5.82\times10^{11}$) was found to be significantly larger than the adjusted Value of Life (i.e. HK$660M).

11.12.3 Although the proposed mitigation measure was considered economically unviable for PLL reduction during construction phase, the following "Good Practices" are proposed to limit the number of causalities and/ or fatalities:

- Establishment of emergency response plans;
- Safety/ emergency response training and drills for all personnel; and
- Maintain the number of construction workers onsite to a minimum.

11.13 References

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