Section 7B

QRA for Shell LPG Depot (PHI Assessment)

CONTENTS

1 INTRODUCTION

1.1 PURPOSE OF THE STUDY

The South Island Line (East) project (SIL(E)) is planned to be a medium capacity railway with stations at South Horizons (SOH), Lei Tung, Wong Chuk Hang, Ocean Park and Admiralty. Under Section 5(7) of the Environmental Impact Assessment (EIA) Ordinance (Cap. 499) (EIAO), the Director of Environmental Protection (Director) from the Environmental Protection Department (EPD) has issued a Study Brief No. ESB-181/2008 for this project (EIA Study Brief). Section 3.4.5 of the EIA Study Brief specifies Hazard to Life assessments to be conducted for the Project.

In Section 3.4.5.3 of the EIA Study Brief, it is stated that a hazard assessment should be carried out for aspects of the Project that fall within the Consultation Zone of the LPG Transit Depot/Bulk Domestic Supply at Lee Nam Road (the LPG Depot). For completeness, these requirements are repeated in *Table 1.1*. This Appendix addresses these requirements.

Table 1.1 EIA Study Brief - Hazard to Life Requirement

3.4.5	**Hazard to Life**
3.4.5.3	The Applicant shall carry out hazard assessment to evaluate potential hazard to life due to the construction and operation of those parts of the Project which fall within the Consultation Zone of the LPG Transit Depot/Bulk Domestic Supply at Lee Nam Road.
	The hazard assessment shall include the following:
	(i) Identify hazardous scenarios associated with the facilities/activities of the LPG Transit Depot/Bulk Domestic Supply at Lee Nam Road and then determine a set of relevant scenarios to be included in a Quantitative Risk Assessment (QRA);
	(ii) Execute a QRA of the set of hazardous scenarios determined in (i), expressing population risks in both individual and societal terms;
	(iii) Compare individual and societal risks with the criteria for evaluating hazard to life stipulated in Annex 4 of the TM; and
	(iv) Identify and assess practicable and cost-effective risk mitigation measures.
	The methodology of the hazard assessment shall be agreed and approved by the Director.

The layout of the South Horizons station in relation to the LPG Depot is shown in *Figure 1.1*. The LPG Depot is a Potentially Hazardous Installation (PHI) with two main facilities on the site: a Bulk Domestic Supply facility with 40 tonnes of LPG storage in two mounded tanks and a Transit Depot with storage shed for about 2000 LPG cylinders (up to 100 tonnes). A 500m Consultation Zone is defined around the facility as shown in *Figure 1.1*.

Societal risks from a PHI depend on population levels in the vicinity. Any development within the Consultation Zone 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. The criteria and guidelines for

assessing Hazard to Life are stated in Annexes 4 and 22 of the Technical Memorandum (EIAO-TM Criteria).

The proposed South Horizons station is located near Yi Nam Road, about 100m from the LPG Depot. This is situated within the Consultation Zone of the LPG Depot as shown in *Figure 1.1*. Some of the work sites and plant buildings also lie within the Consultation Zone.

1.2 GENERAL METHODOLOGY

An assessment was conducted previously for the LPG facilities at Ap Lei Chau as part of the Harbour Area Treatment Scheme (HATS) (ENSR, 2008). The methodology adopted in that study is followed closely in the current study although some refinements are made. These refinements are discussed as they arise in the report.

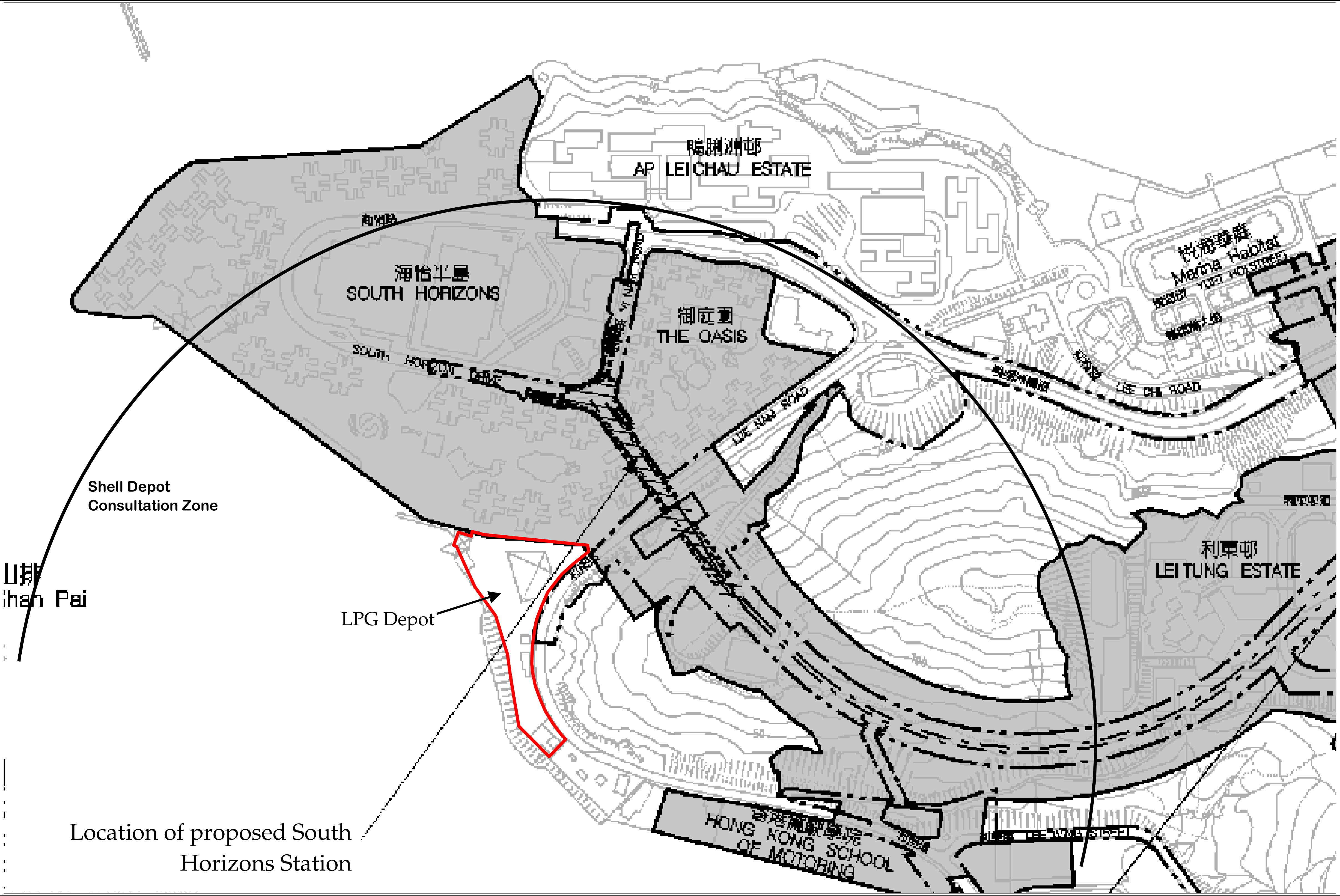
It should be noted that the separation between the South Horizons work sites and the PHI is such that activities at the work sites will not impact on the PHI. Blasting, for example, will all be underground and at distances significantly greater than that required to inflict damage to the LPG facilities. Potential impacts of construction activities on the LPG Depot are therefore not considered further in this assessment. On the other hand, incidents at the LPG Depot may extend up to a few hundred metres and may impact on the South Horizons station and/or worker population and needs to be assessed.

The South Horizons construction phase will overlap with construction work for the Preliminary Treatment Works (PTW) in Ap Lei Chau as part of the HATS project. The assessment therefore considers the increase in population due to both groups of workers. Three population cases are considered in the analysis:

- The current (2009) population;
- The construction phase (2014) population with overlapping construction activities between MTR South Horizons works and HATS works; and
- A future operational case with 2031 population.

Although the South Horizons construction phase may continue to 2015, the HATS construction is expected to be completed in 2014. Year 2014 was therefore selected as an appropriate year for the construction phase since the worker population will be at its highest during this time.

Figure 1.1 South Horizons Station Location

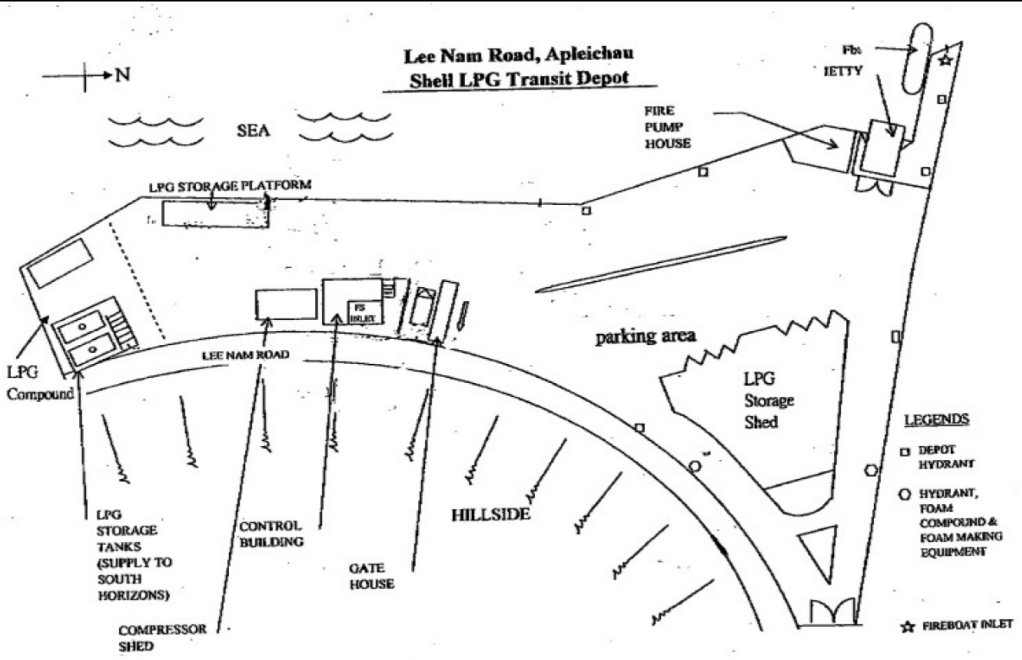


2 SITE DESCRIPTION

2.1 SHELL'S FACILITIES AT AP LEI CHAU

Shell's LPG site is defined in the 2000 PHI Register (Planning & Lands Bureau, 2000) as a PHI (Potentially Hazardous Installation) on account of storing Liquefied Petroleum Gas (LPG) in excess of 25 tonnes. The facility consists of an LPG Bulk Domestic Supply (LPG Compound) and a Transit Depot (*Figure 2.1*). The LPG Compound is located on the south side of the site while the Transit Depot (LPG Storage Shed) is situated on the north side. Deliveries are made by road tankers and cylinder wagons using Dangerous Goods ferries that berth at a jetty on the northwest of the site. An area for parking LPG road tankers and cylinder wagons is provided in front of the Storage Shed.

Figure 2.1 **LPG Depot Layout**

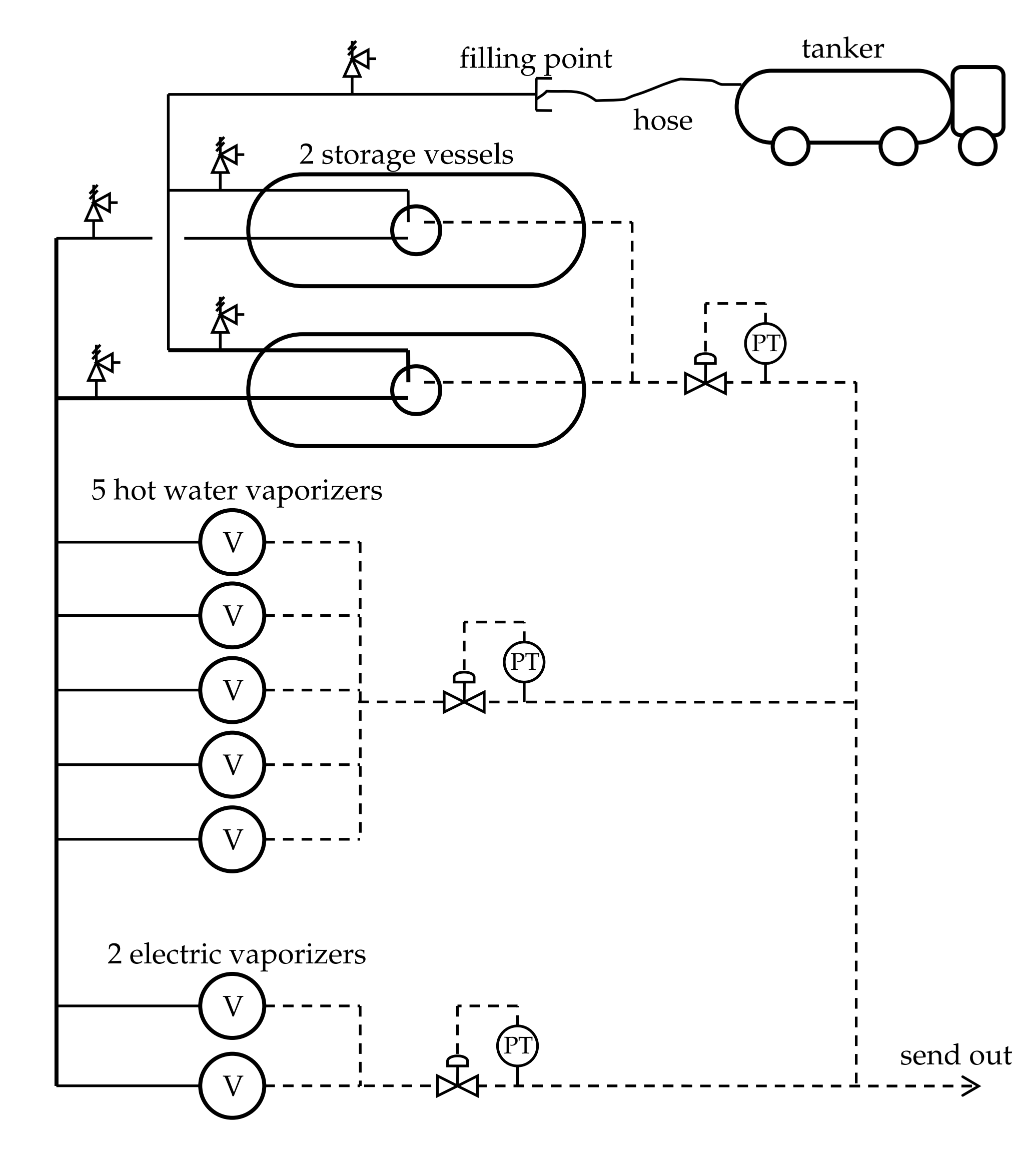


2.1.1 LPG Bulk Domestic Supply

A process flow diagram for the LPG compound is shown in *Figure 2.2*. LPG is stored in two 20 tonne mounded tanks. These tanks are filled to at most 85%, giving a maximum storage of 34 tonnes. LPG is vaporised in 5 water heated vaporisers and the pressure let down to 1 psi for send out to domestic customers in the area. 2 electrically heated vaporisers are available on standby. An unloading bay is provided for unloading LPG road tankers.

Three LPG road tanker deliveries are made per day, on a single DG ferry round trip.

Figure 2.2 **Storage Compound Process Flow Diagram**



A summary of the Bulk Compound operating data is provided in *Table 2.1*.

Table 2.1 **Bulk Domestic Supply Facility Operating Data**

Description	Number
LPG road tanker deliveries	3 per day (1 ro-ro ferry round trip)
LPG road tanker size	9 tonne
LPG storage	2 × 20 tonne mounded tanks (filled to 85% = 34 tonnes)
Storage pressure	~ 3.5 barg
Unloading time	2 hours
Vaporisers	5 hot water heaters + 2 electric heaters

2.1.2 LPG Transit Depot

The Transit Depot provides storage and transit for LPG cylinders. Cylinders are delivered to the store by ferry services. Cylinder capacities range from 2 kg

to 49 kg, with 13.5 kg being the most common size. Typically, around 2200 filled cylinders are stored within the shed at any time, with a further 900 empty cylinders. The LPG storage platform, near the waterfront, is used for temporary handling of cylinders.

Throughput at the Transit Depot amounts to 900 (max) cylinders per day, delivered on 3 cylinder wagons and a single DG ferry round trip. The depot operators also load/unload cylinder wagons of local distributors for delivery to customers in Hong Kong Island South. These distributors' wagons may be 5.5 tonne or 8 tonne in size.

Apart from LPG cylinder wagons, the ro-ro ferry pier is also the landing place for LPG tankers supplying the LPG Compound and bulk diesel /petrol tankers (4 ~ 5 trucks per day) serving public filling stations on Hong Kong Island. 5 cylinder wagons are parked on site overnight, with a further 2 LPG tankers on stand-by overnight during typhoons.

A summary of the Transit Deport operating data (Shell, 2009) is provided in *Table 2.2*.

Table 2.2 Transit Depot Operating Data

Description	Number
LPG cylinder wagon deliveries	3 per day (1 ro-ro ferry round trip)
Cylinder throughput	900 per day max (277,000 average per year)
Cylinder storage	Max 4,300, average 2,200
Cylinder transport to customers	Distributors' wagons. 5.5 tonne (65 cylinders) or 8 tonne (125 cylinders)
Cylinder size distribution	2kg – 8% 8kg – 24% 10.5kg – 5% 13.5kg – 39% 15kg – 8% 49kg – 16%
Storage pressure	~ 3.5 barg
Construction	Storage shed with open walls and natural ventilation
Safety systems	4 gas detectors with automatic water sprinklers and hydrants.

2.2 SURROUNDING POPULATION

Population in the vicinity of the LPG Depot is summarized in *Table 2.3* and *Figure 2.3*. Population was based on the HATS study (ENSR, 2008), data from the Census and Statistics Department for mid 2006 and site surveys. A population growth of 1% per year was assumed, consistent with previous studies in Hong Kong (ERM, 2009).

The future 2031 case considers the South Horizons MTR station during operational phase. Operation of the MTR will likely shift patronage away from buses and onto the trains. This may change outdoor population distributions at street level. Bus stops are currently distributed around the South Horizons residential development and considering that some waiting at

bus stops is necessary, the shift to usage of the MTR will likely cause a reduction in outdoor population. For simplicity, the analysis conservatively assumes outdoor population will grow at the same rate as indoor population i.e. by 1% per year. No redistribution in population is imposed due to construction of the MTR station.

It is possible the population in Horizon Plaza may increase beyond the 1% growth rate assumed in *Table 2.3* since visiting the area will be more convenient once SIL is operational. However, it was found in the analysis that none of the accident consequences have sufficient range to reach Horizon Plaza except for projectiles which are shielded by the neighbouring residential blocks. Therefore, increasing the Horizon Plaza population further to allow for increasing visitors will have no impact on the results.

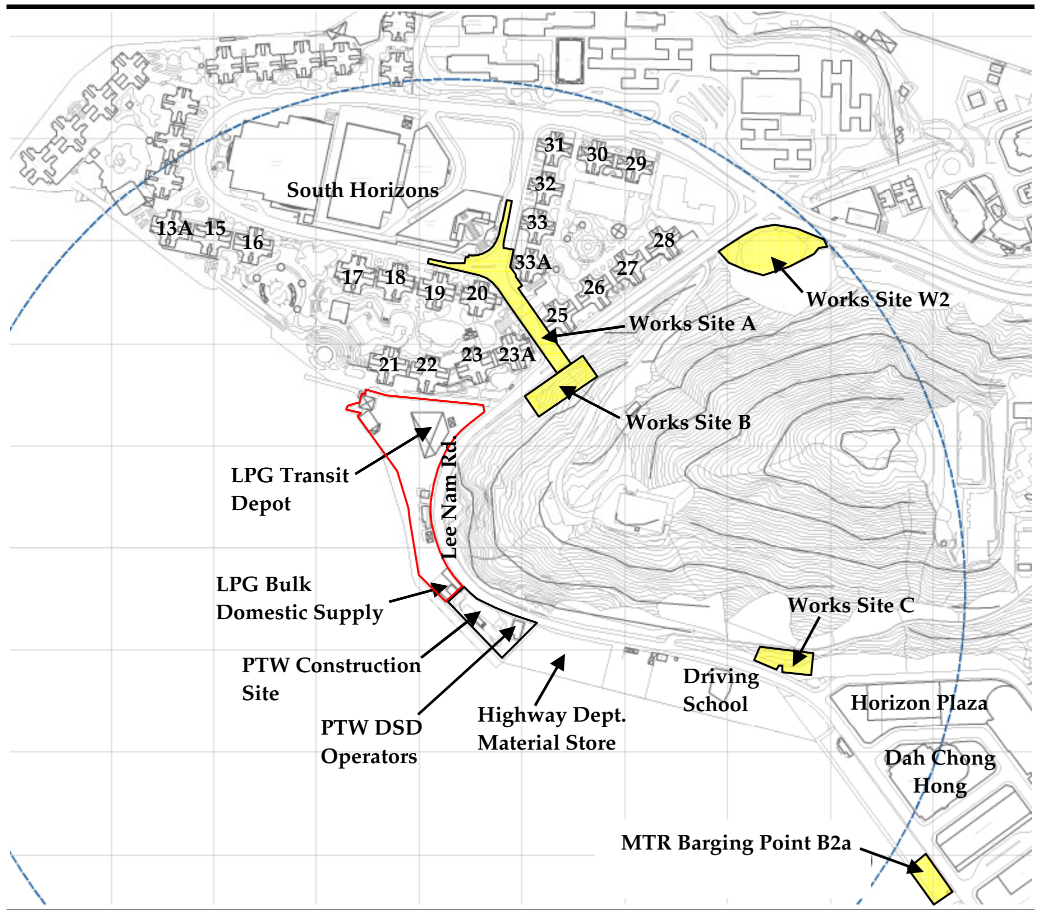
Table 2.3 Population in Vicinity of Shell Depot

Population Group	Current Population (Year 2009)	Construction Phase Population (2014)	Future Population (2031)
South Horizons Blocks 21 to 23A	3915	4074	4873
South Horizons Blocks 25 to 28	3270	3402	4070
South Horizons Blocks 29 to 33A	4508	4691	5611
South Horizons Blocks 17 to 20	4430	4610	5514
South Horizons Blocks 13A,15,16	3236	3366	4026
Horizon Plaza	3180	3309	3958
Dah Chon Hong	795	827	990
Driving School	50	50	50
Highway Dept. Material Store	2	2	2
Lee Nam Road Vehicle Pass.	20	21	25
Lee Nam Road Pedestrians	8	8	10
Sea population within 500m	10	10	12
PTW – DSD Operators*	4	3	4
PTW Construction Site	0	61	0
MTR Works Site A	0	200	0
MTR Works Site B	0	150	0
MTR Works Site C	0	250	0
MTR Works Site W2	0	100	0
MTR Barging Point B2a	0	100	0
South Horizons Station	0	0	280†

* DSD = Drainage Services Department

† Based on MTRC forecast of 63,600 passengers per day and assuming each person spends 5 minutes within the station and operations run for 19 hours per day. The station population is, however, all underground and will be unaffected by any incidents at the LPG Depot.

Figure 2.3 *Ap Lei Chau Population*



In order to reflect different populations at different times of the day, 4 time periods are used and the occupancy specified for each (*Table 2.4*). Daytime is defined as 07:00 to 19:00 and night-time from 19:00 to 07:00.

Since persons indoors will be offered some protection from fires and explosions, the analysis makes a distinction between those indoors and outdoors. The HATS study (ENSR, 2008) considered 5% of the population to be outdoors. This is refined in this study by adopting a more detailed breakdown for different types of population (*Table 2.4*), which is consistent with other studies in Hong Kong (ERM, 2006 for example).

Table 2.4 ***Population Occupancy and Indoor/Outdoor Fractions***

Population Type	Occupancy				% Outdoors			
	Weekday		Weekend		Weekday		Weekend	
	day	night	day	night	day	night	day	night
Residential	20 %	100 %	80 %	100 %	10 %	0 %	20 %	0 %
Industrial/Commercial	100 %	10 %	10 %	10 %	10 %	5 %	10 %	5 %
Shopping Centre	50 %	10 %	100 %	10 %	10 %	0 %	10 %	0 %
Road	100 %	20 %	100 %	20 %	0 %	0 %	0 %	0 %
Sea	100 %	0 %	100 %	0 %	100 %	100 %	100 %	100 %
PTW Construction	100 %	10 %	100 %	10 %	90%	5 %	90 %	5 %
MTR works sites	100 %	50 %	100 %	50 %	100 %	100 %	100%	100 %

2.3 METEOROLOGICAL CONDITIONS

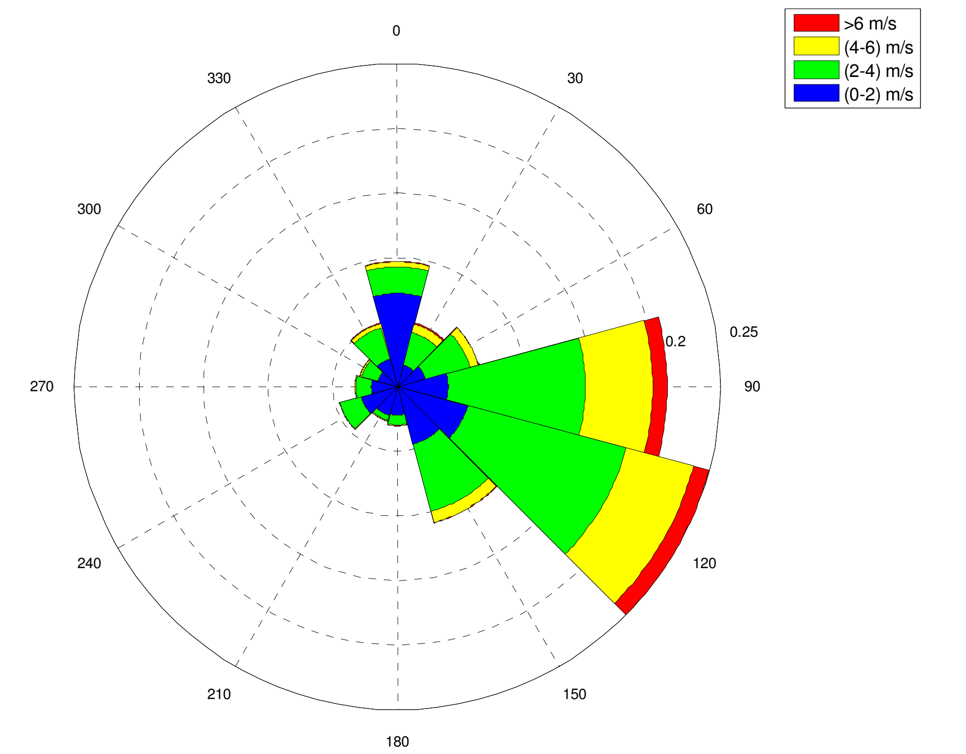
Meteorological conditions affect the dispersion behaviour of gas releases, particularly the wind speed, wind direction and atmospheric stability class. Weather data from the most recent 5 years (2004 to 2008) from Wong Chuk Hang weather station of the Hong Kong Observatory were used in the analysis. This weather data were rationalised into 5 categories to represent the range of weather conditions expected at the site. These categories were selected by reference to the HATS study (ENSR, 2008) and are denoted as 3B, 3D, 7D, 3E and 1.4F, where '3B' for example refers to a wind speed of 3 m/s and Pasquill atmospheric stability class of B.

The resulting probability of occurrence for each combination of wind speed, direction and stability class is summarised in *Table 2.5* and a wind rose plot is shown in *Figure 2.4*.

Table 2.5 ***Meteorological Data***

Wind Direction	Weather Category – Probability of Occurrence					
	3B	3D	7D	3E	1.4F	Total
Day						
0°	0.021	0.015	0.001	0.005	0.016	0.059
30°	0.014	0.012	0.002	0.006	0.006	0.040
60°	0.027	0.016	0.001	0.010	0.009	0.062
90°	0.080	0.050	0.020	0.022	0.016	0.189
120°	0.143	0.064	0.021	0.026	0.022	0.276
150°	0.099	0.026	0.001	0.010	0.018	0.154
180°	0.015	0.007	0.000	0.001	0.009	0.033
210°	0.008	0.005	0.000	0.001	0.007	0.022
240°	0.032	0.008	0.000	0.003	0.009	0.052
270°	0.022	0.006	0.000	0.003	0.005	0.035
300°	0.016	0.007	0.000	0.003	0.004	0.029
330°	0.020	0.012	0.001	0.009	0.006	0.048
Total	0.497	0.228	0.048	0.099	0.128	1.000
Night						
0°	0.000	0.008	0.002	0.014	0.116	0.140
30°	0.000	0.013	0.005	0.021	0.025	0.064
60°	0.000	0.013	0.002	0.021	0.032	0.068
90°	0.000	0.069	0.030	0.067	0.067	0.232
120°	0.000	0.058	0.028	0.062	0.072	0.220
150°	0.000	0.004	0.001	0.008	0.046	0.058
180°	0.000	0.000	0.000	0.001	0.026	0.027
210°	0.000	0.001	0.000	0.002	0.032	0.034
240°	0.000	0.001	0.000	0.004	0.035	0.040
270°	0.000	0.000	0.000	0.004	0.025	0.030
300°	0.000	0.003	0.000	0.006	0.022	0.031
330°	0.000	0.007	0.002	0.016	0.030	0.054
Total	0.000	0.179	0.069	0.224	0.528	1.000

Figure 2.4 *Wind Rose*



3 HAZARD IDENTIFICATION

3.1 REVIEW OF PAST ACCIDENTS

A survey of worldwide accidents involving LPG facilities and transport has been conducted and is presented below.

3.1.1 *Road Tanker Accident Review*

Kansas, USA, July 1952 – A discharge from a relief valve on the fuel tank of an LPG powered tanker at an LPG filling station ignited giving rise to a vapour-cloud explosion that killed two people and was heard 3.2 km away.

Netherlands, December 1981 – A road tanker containing 26 m^3 of LPG had been sealed by customs in Belgium. Both the storage box and valve of the line had been sealed. When commencing the unloading of the LPG at a fuelling station, the driver took hold of the line, breaking the seal. The rope connecting the seal, line and valve should have broken but did not and the valve was partly opened by the rope. Released LPG was ignited (source of ignition unclear) but despite the driver being engulfed in fire, he managed to close the valve and two other people extinguished the fire. The driver suffered first and second degree burns to his face.

Nijmgen, Netherlands, 18 December 1978 – A 27m^3 capacity LPG road tanker was refilling an above ground LPG storage tank at a refuelling station. Due to the cold weather, the tank driver went inside the office, leaving the refilling unattended. After a while a fire was seen, probably resulting from a leak during offloading. The safety valve on the tanker did not open and 45 minutes later the tanker suffered a BLEVE. Projectiles travelled up to 150m. The tanker and the fuelling station were destroyed. The safety valve on the LPG storage tank opened and up to 3000 litres of LPG burned off. The LPG storage tank did not explode. No injuries sustained.

Netherlands, March 1994 – A 20m^3 capacity underground LPG storage tank at a fuel station was being prepared for inspection when the remaining vapour in the tank was ignited by a petrol pump motor after the manway was opened. The ensuing flash fire severely injured two contractors. It was not clear to the investigation team whether the procedure for emptying the tank had been followed correctly.

Australia, 1999 – Approximately 10,000 litres of LPG escaped to atmosphere when the driver of a road tanker drove off without disconnecting the filling hose. Fortunately the gas did not ignite. Nearby residents were evacuated as a precaution. After an investigation the company was fined AU$2500 (1999), for the storage tank not meeting the Australian Standard.

New Jersey, USA, 21 Sep 1972 – A BLEVE of an LPG road tanker carrying 14te of propylene occurred on the New Jersey Turnpike. A collision at over 50 mph caused the tanker to cross the central divide and overturn. The pipework

on the tanker was not isolated and started to leak. The excess flow valve failed to isolate the leak because the leak was small. The trucks diesel tank was also damaged in the crash and the leaking diesel fuel ignited. This ignited the leaking propylene to form a jet fire that engulfed the tanker.

The fire caused the PRVs to lift but because the tanker was on its side, liquid propylene was released which ignited and spread across the highway. After 25 minutes had elapsed, with an estimated 10te of propylene still in the tank, a BLEVE occurred. The fireball extended at least 100m and passed over one occupied vehicle but the occupant was not injured. 28 bystanders were injured, including 7 policemen. One of the injuries occurred 180m from the tanker and the force of the blast propelled the main tank section 400m.

Ref: HCB, Sep 1984

Saint-Amand-les-Eaux, France, 1 Feb 1973 – A BLEVE of a road tanker carrying 20te of propane. An articulated tanker travelling at 30 mph overturned in a traffic accident. Propane leaked from a PRV damaged in the accident. The gas ignited within a minute forming a jet fire 10-30m long, which deflected from the ground and spread to nearby houses. Fire services tried to cool the tanker but after 10-15 minutes a BLEVE occurred. The tank disintegrated, destroying a house and sending fragments 450m. There were a total of 9 fatalities (some from the crash rather than related to the propane release), 23 serious injuries, 22 minor injuries and 9 vehicles and 13 houses destroyed. 100 spectators only 40m from the tanker survived.

Ref: OECD 1988, "Transporting hazardous Goods by Road"

Hubert P., 1989, "Sequence and Implications of the Accident at Saint-Amand-les-Eaux" (ACDS/MHT/TWP/44)

Casula, NSW, Australia, 21 Oct 1976 – Leak from an LPG road tanker. The vehicle's tail shaft broke and hit the liquid outlet line, breaking it and causing liquid LPG to escape. The damage to the pipe also prevented the excess flow valve from functioning and the shut-off valve only reduced the flow but did not stop it. The tank contents were transferred to other tankers but 2te of LPG was released. There was no ignition and no injuries reported.

Ref: Department of Environment and Planning, 1983, "hazard Study of Liquefied Petroleum Gas in Automotive retail Outlets", New South Wales, Australia.

San Carlos, Spain, 11 Jul 1978 – A fire occurred in an articulated propylene road tanker due to overfilling. The tanker was overloaded with 23.5te of propylene, compared to its permitted load of 19.4te and the tanker was not fitted with a PRV. The tank disintegrated, due to thermal expansion of the propylene, into 3 parts which were projected up to 220m. Ignition occurred after 1 minute leading to a flash fire (although some reports describe it as a BLEVE).

The incident occurred next to a camp site. The fire destroyed several buildings and killed 217 people with an additional 67 injuries.

Ref: Hymes I., 1983, "The Physiological and Pathological Effects of Thermal radiation", SRD Report R275.

Wispertal, Germany, 4 Jul 1985 – Controlled flaring from a propane tanker. An LPG road tanker overturned on a sharp bend and fell down a steep slope, coming to rest in a tree. The accident killed the driver but there was no leak. Recovering the tanker intact was deemed to be too dangerous and the nozzle of the filling valve only reached the vapour space. Thus the vapour had to be flared with vaporisation aided by spraying warm water on the tank. The operation lasted 2.5 days.

Ref: Droste B. and Mallon M., 1989, 'A statistical Review of the Reasons Leading to LPG Accidents", BAM, Berlin.

Memphis, Tennessee, USA, 23 Dec 1988 – Fireball after propane tanker collision with a bridge. A 36m^3 propane tanker overturned on a highway and slid along the road for 60m before colliding with a bridge buttress. The tank ruptured forming a vapour cloud that drifted 460m and then ignited in a fireball. Several vehicles on both carriageways were caught in the fire and most of their occupants died. Several buildings also caught fire and one occupant died. The tank shell was projected 120m, crushing a house and leading to secondary fires and 2 fatalities. There were a total of 9 fatalities and 12 injuries.

Ref: Loss Prevention Bulletin 094

MHIDAS

Candasnos, Spain, 31 Jan 1990 – Fireball after collision with bridge. An articulated tanker carrying 18te of propane veered off the highway after the driver fell asleep. The tanker struck a bridge buttress. Propane escaped and ignited forming a 500m radius fireball. The fireball enveloped 4 vehicles killing 6 people.

Ref: MHIDAS

Bangkok, Thailand, 24 Sep 1990 – Fire following road accident. A flat bed truck had been adapted into a tanker using 2 pressure vessels designed for static use. The tanker was unlicensed and was carrying 1.5te of LPG. The driver was under the influence of alcohol and drugs and was speeding when the vehicle overturned in an accident. LPG was released from the tanks and ignited in a flash fire that destroyed 40 vehicles. The fire also spread to adjacent shops and buildings and a squatter camp. A total of 68 people died and over 100 were injured. 48 shops and 57 cars were destroyed.

Ref: HCB, Nov 90

Toronto, Canada, 8 Apr 1991 – Leak after collision with a bridge. A 45m3 propane road tanker tried to pass under a low bridge following a diversion around a road accident. The bridge was too low and sheared off the 2 PRVs. Propane jets 3m high were formed above each valve. Over 2000 residents were

evacuated and a water curtain used to disperse the gas. The release was not ignited and there were no injuries.

Ref: HCB, Oct 91

Wandong, Victoria, Australia, 26 Jun 1991 – BLEVE of an LPG road tanker. The tanker was hit from behind in a road accident, causing a leak from the drain valve. The driver used his radio to warn on-coming traffic and stopped other vehicles and persuaded them to block the traffic. These actions ensured that when the BLEVE occurred, nobody was within range. There were no injuries or fatalities.

Ref: HCB, Oct 1991.

Agen, France, 25 Aug 1992 – Leak after road accident. An LPG road tanker was hit from behind in a road accident causing a rupture of the tankers pipework. $16m^3$ of LPG was released but no ignition occurred. Nearby residents were evacuated for 10 hours.

Ref: HCB, Nov 1992.

New York, USA, 27 Jul 1994 – Fireball after collision with bridge. A tanker carrying $35m^3$ of propane veered off the road and struck a bridge support column. The tank ruptured and caught fire. The main part of the tank was projected 100m and crushed 2 homes. The fireball set fire to 8 nearby homes. 23 people were injured.

Ref: HCB, Oct 1994.

Other incidents listed in MHIDAS for LPG are summarised in *Table 3.1* and in

Table 3.2 for the IchemE database. *Table 3.3* lists incidents specifically related to LPG cylinder vehicles.

Table 3.1 Worldwide Incidents with LPG Tankers

MHIDAS Ref	Date	Location	Accident Cause	Consequence	Fatalities	Injuries	Other Damage	Material
1815	22 Oct 1936	Crowley, Louisiana, USA	Butane leaked from snapped pipe connection	Flash fire	4			Butane
2517	18 Nov 1941	Hobart, Oklahoma, USA	Leak from pipe under truck by excessive vibration	Fire & explosion	0	4	1 house & 3 cars destroyed	Butane
1821	18 Jan 1943	Los Angeles, California, USA	Failure of bottom connection	Ignition of 400m diameter cloud	5			Butane
843	31 Mar 1944	Oklahoma City, USA	Leak from 1 of 4 tanks	BLEVE	5	21		Butane
1872	21 Nov 1944	Denison, Texas, USA	Excess flow valve damaged following collision	Ignition by water heater 60m away	10	Everyone within 90m		Butane
2569	23 Jun 1946	Louisiana, USA	Master valve between tank and pump left open	Jet fire 23m high	0	0		LPG
2570	12 Feb 1947	Hope, Arkansas, USA	Collision, rollover and damage to pipework	Fire	1	0		Butane
2571	13 Oct 1948	Sacramento, California, USA	Tanker was struck by a train	Fire	2	0	Train carriage burned	Butane
2572	13 mar 1949	Martinez, California, USA	Tanker overturned on road, breaking connection	Flash fire	0	0		Butane
1827	23 Aug 1950	Wray, Colorado, USA	Brake failure leading to rollover and damage to connection. Excess flow valve failed	Vapour ignited at nearby garage. Fire	2	3		Propane
2573	14 Jun 1951	San Fernando, California, USA	Tank ruptured following accident	Jet fire	1	0		Isobutane
1875	24 Jun 1952	Kansas City, USA	Vapour leak through PRV	Explosion	2			LPG
2120	14 Nov 1958	Los Angeles, USA	Tanker overturned and damaged instrument taping	Vapour cloud, no ignition	0	0		LPG
2635	22 Dec 1958	Brownfield, Texas, USA	Tanker rolled over followi9ng collision. PRVs torn off	Fire and BLEVE	4	160		Butane
2176	2 Jun 1959	Deer lake, Pennsylvania, USA	Collision	Fire and BLEVE after 45 min	11	10	Foliage burnt up to 150m away	LPG
2633	15 Dec 1960	Glen Loch, Pennsylvania, USA	Relief valve sheared off under low bridge	Ignition by passing train	0	0		LPG

MHIDAS Ref	Date	Location	Accident Cause	Consequence	Fatalities	Injuries	Other Damage	Material
2130	27 Apr 1961	Sidney, Nebraska, USA	Tanker overturned, breaking off valve	Ignition	0	1		LPG
825	25 Jul 1962	Berlin, New York, USA	Tanker collided with tree	Fire	10	17	Explosion in nearby houses	LPG
2124	31 Jul 1963	Memphis, Tennessee, USA	Hose broke during transit	Ignition by unknown source	1	1		LPG
2749	26 Feb 1965	Aylmer, Ontario, Canada	Collision caused crack between EFV and ball valve	Ignition by starter motor	0	2	7 buildings, 2 cars and 2 trucks destroyed	LPG
2223	15 Sep 1970	Hopkinton, Massachusetts, USA	Tanker ran off highway	Fire and BLEVE after 15min	1	0		LPG
HSC (1991)	23 Oct 1970	Hull, UK	Truck carrying static tank struck low bridge. Sheared off PRV	Flash fire (0.1 of 2te cargo)	2	0		Propane
590	9 mar 1972	Lynchburg, Virginia, USA	Tanker overturned and struck embankment causing 800mm tear	Fire	2	31		Propane
592	21 Sep 1972	New Jersey Turnpike, USA	Collision caused leak from pipework	Fire and BLEVE after 25 min	2	28		Propylene
1142	1 Feb 1973	St Amand-Les-Eaux France	Tanker overturned and ruptured	Jet fire and BLEVE after 15 min	6	37		Propane
1495	24 May 1973	Lynchburg, Virginia, USA	Tanker overturned and ruptured	Ignition after 2 min, fireball		7		LPG
118	Jan 1974	Florida, USA	Hose failure	Explosion	0	0	2 warehouses destroyed. Cars crushed with 4 block area	Propane
945	11 Jan 1974	Aberdeen, UK	PRV sheared off in accident	Immediate ignition & fireball		3		Butane
1797	6 Feb 1974	Albany, Georgia, USA	Tanker collision with train	Large fire	1	2		LPG
450	29 Apr 1975	Eagle Pass, Texas, USA	Semi-trailer overturned on highway	Fire	16	35	50 cars destroyed in used car facility	LPG
180	24 Jun 1976	Zaragoza, Spain	Gas seep from tanker	Ignition and explosion	>7	40	A warehouse and 2 workshops destroyed	Butane
2109	19 Aug 1976	Flint, Michigan, USA	Tanker ran off road and ruptured	Fire & explosion	1	7		LPG

MHIDAS Ref	Date	Location	Accident Cause	Consequence	Fatalities	Injuries	Other Damage	Material
1986	28 Dec 1977	Goldonna, Louisiana, USA	Collision with train caused tank rupture	Fireball	2	10		LPG
1999	11 Jul 1978	San Carlos, Spain	Tanker rupture due to overfilling & no PRV	Flash fire	217	67	Buildings destroyed	Propylene
2040	16 Jul 1978	Tula, Mexico City, Mexico	Tanker overturned and ruptured	Explosion & fire	10-15	>150		Butane
830	27 Jul 1979	Hayfield, Derbyshire, UK	Leak from overturned tanker	No ignition	0	0	Village evacuated	LPG
2303	10 Apr 1980	Pont A Mousson, France	Release after tanker crashed down embankment	No ignition	0	1	Neighbourhood evacuated	LPG
1728	2 May 1980	Patrington, Humberside, UK	Tanker overturned	Fire	1	0		Condensate
1981	7 Aug 1980	New York City, USA	Failure of PRV	No ignition	0	0	50km traffic jam	Propane
3264	20 Apr 1984	Westville, Indiana, USA	Tanker struck by train	Fireball	>2	6	12 railcars derailed	LPG
1025	13 Jun 1984	Salmon Arm, British Columbia, Canada	Tanker fell down embankment after collision	Explosion	1	23		Propane
3618	6 Sep 1985	Prince George's County, Maryland, USA	Tanker overturned & burst into flames	Fire			400 evacuated & road closed for 17 hours	Propane
1906	1 May 1986	Severna Park, Maryland, USA	Tanker overturned onto 2 petrol pumps. Leak from tanker's propane fuel tank, not cargo	Fire of petrol & propane. Flames 8m high	1	2	Fumes overcame person 800m away	Propane
2057	1 Jul 1986	Valley Falls, Kansas, USA	Collision with train	Explosion	3	2	13 train cars derailed	Propane
2593	16 Feb 1987	Winston-Salem, North Carolina, USA	Tanker crash	Fire	0	0	50 residents evacuated	LPG
2751	6 Apr 1987	Trenton, new Jersey, USA	Tanker overturned on highway	Explosion	0	7		LPG
3093	24 May 1988	Seaford, Long Island, USA	Tanker overturned after rear axle failed	Fire burned for 2 days	0		2000 people evacuated	LPG
3430	23 Dec 1988	Memphis, Tennessee, USA	Tanker accident & rupture	Fireball	9	4	Fire engulfed several other vehicles	Propane
3695	4 Apr 1989	Muswellbrook, NSW, Australia	Tanker leak from weld	No ignition	0	0		LPG

MHIDAS Ref	Date	Location	Accident Cause	Consequence	Fatalities	Injuries	Other Damage	Material
3884	25 Sep 1989	Aquidneck Island, Maryland, USA	Tanker struck low bridge and leaked	No ignition	0	0	Houses within 400m evacuated	Propane
4287	17 Oct 1989	Kangeroo Valley, Queensland, Australia	Tanker overturned on sharp bend	No ignition	0	0	Road closed	Condensate
4141	5 Jan 1990	Melbourne, Victoria, Australia	Leak from tanker	No ignition	0	0		Propane
4156	30 Jan 1990	Candasnos, Huesca, Spain	Tanker collided with bridge	No release	0	6		Propane
4127	24 Sep 1990	Bangkok, Thailand	Truck carrying 2 LPG tanks overturned	Fire	63	100	57 cars & 48 shops	LPG
4711	9 Mar 1991	Le Roy, new York, USA	Tanker overturned. No leak		0	0	Road closed for 10 hours	Propane
5411	29 Feb 1992	Greenwich, New Jersey, USA	Tanker struck train & overturned	No spill	0	0	60 homes evacuated	Propane
5465	3 Apr 1992	Warren, Vermont, USA	Tanker fell down steep embankment	No ignition	0	0	Residents evacuated	Butane
5651	23 Jul 1992	Muthill, Scotland, UK	Empty tanker collided with low archway. Sheared off PRV	No ignition	0	0		LPG
5931	27 Oct 1992	Sarnia, Ontario, Canada	Leak from packing gland nut of empty tanker	No ignition	0	0		LPG
5969	1 Dec 1992	Ankara, Turkey	Road traffic accident	Large fire and explosion	22			LPG
6003	29 Dec 1992	Port Coquitcam, British Columbia, Canada	Leak from valve	No ignition	0	0		LPG
6095	11 Mar 1993	Shakespeare, Ontario, Canada	Collision with train	No spill	0	0		LPG
1076	26 Feb 1993	Fakenham, Norfolk, UK	Empty tanker collision	No spill	0	0		Propane
12318	14 Jul 2003	Veldhoven, Netherlands	Cab of roadtanker caught fire following accident.	No spill	0	0	Offices within 500m evacuated as precaution	LPG
12513	13 Nov 2003	Bredbury, Cheshire, UK	LPG cargo was found to be leaking after roadtanker broke down on highway.		0	0	Road in both directions closed while leak repaired	LPG
12685	4 Feb 2004	Pune, India	Tanker exploded following accident and rollover	Explosion	3	15		LPG

Table 3.2 Road Tanker Incidents from the IchemE Database

IchemE Ref	Date	Location	Accident Cause	Consequence	Fatalities	Injuries	Other Damage	Material
9668	unknown	unknown	Hose leak on modified tanker. Leak was too small to activate excess flow valve	Fire	1	0		Propane
9666	unknown	unknown	Tank rupture during transit. Likely weld defects.	Explosion	10	17		Propane
50	11 June 1941	USA	8.7m³ tanker involved in collision.	Butane vapours covered large area. No ignition	0	0		Butane
185	12 Mar 1959	unknown	Operator error	BLEVE	0	0		Butane
1698	27 July 1978	Harton, Yorks, UK	1te cylinder broke lose after tank stuck on verge. Valve fractured and leaked	No ignition	0	0		Propane
1735	7 Sep 1978	Hartburn Bank, Stockton, UK	Tanker overturned but no release	None	0	0	Residents evacuated	Butane
1939	28 Dec 1979	Briton ferry, Wales, UK	Valve on tanker froze open	Vapour cloud. No ignition	0	0	Traffic stopped as precaution	Butane
2351	2 Jan 1982	Italy	Highway collision in foggy conditions leading to tanker explosion	Explosion	5	30		Propane
3272	1 Apr 1985	Dijon, France	Tanker crashed and caught fire	Fire	0	0		Propane
4367	30 Nov 1988	Elkridge, USA	Tanker overturned		0	0	Residents evacuated as precaution	Propane
4721	21 Sep 1989	Baltimore, USA	Leak from tanker wedged under bridge	Vapour release. No ignition	0	0	Residents evacuated	Propane
5300	8 Apr 1991	Toronto, Canada	2 PRVs sheared off when passing through underpass	Vapour release	0	0	2000 people evacuated	Propane
6646	27 Jul 1994	White Plains, New York, USA	Collision with bridge support. Leak ignited.	Explosion	1	23	10 houses destroyed	Propane
1224307	Mar 2000	Basingstoke, UK	Tanker hit by another vehicle after breaking down	20 out of 30 gas canisters exploded	1	1		Propane
1247317	Apr 2000	Fayette County, USA	Collision causing rollover	Vapour release	0	0	Residents evacuated as precaution	Propane

Table 3.3 Accidents with LPG Cylinder Wagons

Source	Date	Location	Description	Consequence	Fatalities	Injuries	Other Damage	Material
MHIDAS	7 Dec 1960	Nashua, New Hampshire, USA	Truck collided with train leading to cylinder ruptures	Fire	6	30		LPG
MHIDAS	7 May 1985	Pontypridd, West Glamorgan, UK	Truck carrying 102 cylinders exploded. The ensuing fire caused 12 cylinders to rupture.	Fire, BLEVE	0	0	Damage to supermarket	LPG
Fire Prevention Oct 1988	15 Feb 1987	Oldbury, UK	A portable boiler overturned and heated 3 LPG cylinders. 2 ruptured from the heat.	BLEVE	3	4		LPG
HCB	2 Nov 1987	Pine Grove, Pennsylvania, USA	Fire in truck caused propane cylinder to rupture	BLEVE	0	0		Propane
MHIDAS	22 Dec 1987	Exeter, UK	Collision caused truck to overturn. Several cylinders fractured	Vapour release	0	0		LPG
MHIDAS	21 Mar 1989	Maryborough, Queensland, Australia	Trailer carrying 190 cylinders involved in accident.	No ignition	6 (collision)			LPG
MHIDAS	20 Sep 1990	Blackwater, Queensland, Australia	Collision with train caused cylinder to rupture & explode.	Fireball	0	1		LPG
MHIDAS	14 Jun 1991	Patcham, UK	5 cylinders fell from a truck. 1 cylinder leaked but no ignition	Vapour release	0	0		LPG
MHIDAS	30 Sep 1992	Tsing Hhang Path, Tuen Mun, Hong Kong	Vandalism – setting fire to LPG truck while parked overnight	Multiple BLEVE	0	5 (during evacuation)	14 cars, 5 trucks, 3 taxis, buildings damaged	LPG

3.1.2 *LPG Storage Accidents*

New South Wales, Australia, 19 Sep 2001 – LPG bottles led to a series of explosions in an industrial estate. Firecrews responded and no injuries were reported.

Zambia, 1996 – Human error during special operations led to leak and explosion from an LPG storage tank. 5 fatalities and 3 injuries resulted.

Guangdong, China, 5 Aug 1993 – A fire and explosion at a warehouse spread to a storage tank at a nearby LPG storage depot. 15 fatalities and 160 injuries reported.

South Korea, 7 Jan 1993 – A fire detonated LPG storage tanks in basement of 4 storey apartment block and levelled the building. No injuries or fatalities.

Kuwait, 7 Dec 1987 – Act of sabotage led to a fire in an LPG storage depot. Fire fighting was effective and safety devices functioned, preventing escalation to the storage tanks. No injuries reported.

Mexico City, 18 Nov 1984 – A leak of LPG formed a vapour cloud which was ignited by a plant flare. A fierce fire developed engulfing the LPG spheres and bullets, with 4 spheres and many bullets failing one after the other in a series of BLEVEs. 50 (out of 54) vessels were destroyed. 540 people died, 7000 injured, 200,000 evacuated. A projectile hit and killed a person 1 km away.

Cleveland, UK, 1984 – A shrub fire spread to a chemical waste disposal site and caused a BLEVE of an LPG storage tank. No injuries or fatalities.

Rhode Island, USA, 6 Jun 1983 – 30 tanks of propane exploded at an LPG storage facility. 2 fire fighters injured.

Barking, Essex, UK, 21 Jan 1980 – Fire at a warehouse spread to LPG cylinder and numerous chemicals. 9 injured.

Turkey, 1979 – An LPG storage tank exploded at an oil refinery, showering a nearby town with flaming debris. 2 fatalities and 20 injuries reported.

Belgium, May 1979 – A release of LPG from a rail tanker resulted in an explosion at a railway station. The tanker is believed to have burst when the train arrived at the station. The dispersing vapour cloud reached 300m by 400m and was ignited by sparks from the overhead power lines when the train started to pull out of the station. The resulting explosion caused the tanker to rise 10m into the air and blew the manhole cover 100m. No injuries or fatalities were reported.

USA, 15 Sep 1977 – An LPG storage vessel was overfilled due to a faulty level gauge. The relief valve failed to open and the vessel ruptured. The resulting vapours ignited leading to fires and explosions involving 2 other vertical tanks and 4 horizontal bullet tanks. 2 fatalities reported.

Florida, USA, 6 Feb 1977 – A train derailed and crashed into a LPG cylinder store. The fire destroyed 9 cylinders. No injuries or fatalities.

Brazil, 30 March 1972 – An LPG tank constructed in 1961 was being filled with relatively high temperature LPG. The tank was fitted with only a single pressure relief valve and a single drain valve. Due to the temperature, the pressure within the tank rose rapidly above the safe working pressure but the relief valve failed to work. It was speculated that operators noticed the high pressure and opened the drain valve. LPG was released and the drain valve froze, preventing it from being closed. The gas spread and ignited, killing 37 people and inuring a further 37.

1972 – A high wall surrounding an LPG cylinder storage depot collapsed, crushing some 12 kg cylinders. A large quantity of gas escaped and ignited causing a fire. Three explosions occurred within the building and some cylinders exploded, scattering fragments over a distance of 100m. No injuries reported.

22 Oct 1971 – A butane sphere was overfilled due to a faulty level gauge. The pressure relief lifted and released liquid butane with formed a vapour cloud. Fortunately, the valve reseated and the vapour cloud was not ignited. No injuries were reported.

France, 4 Jan 1966 – An operator failed to follow procedures during the draining of water from an LPG sphere. The resulting vapour cloud spread until it reached a road and was ignited by a passing car. The fire spread back to the liquid pool that had formed within the bund, resulting in a BLEVE of the sphere. The incident escalated to cause a BLEVE of a neighbouring tank and rupture 3 other spheres. 21 fatalities and 52 injuries were reported.

California, USA, 1961 – During the draining of water from a horizontal LPG tank, a connection failed and released LPG through a 1” hole. The cloud was ignited within a minute resulting in a fire that caused the failure of all six storage tanks on site within 35 minutes, some failing violently. 2 injuries.

Kentucky, USA, Oct 1961 – A substandard installation of a 1,000 gallon LPG storage tank fell from its concrete block foundation. This damaged the outlet connection and produced a vapour cloud that spread over a large area. After 15 minutes, the cloud was ignited resulting in an explosion. No injuries or fatalities reported.

California, USA, 13 July 1954 – The driver of an LPG delivery tanker had filled his tanks from a storage tank and drove away without disconnecting the transfer and vent lines. LPG flooded the area and was ignited 10 minutes later. The flash fire caused secondary fires including one on top of the storage tank where the vapour connection had cracked. The storage tank eventually ruptured from the heat of the fire. 4 fatalities resulted from the flash fire.

USA, 27 Jan 1952 – A buried tank leaked into the surrounding earth through a threaded connection. The resulting fires and explosion damaged 216 buildings. Fortunately, occupancy was low and only 1 injury was reported.

Georgia, USA, 7 Oct 1950 – A transfer line between an LPG tanker and 1000 gall storage tank broke at the tank. The vapours were ignited. No injuries or fatalities.

USA, 25 April 1945 – Escaping vapours from a 100 tonne LPG storage tank ignited. The explosion shattered buildings and caused 5 fatalities.

3.2 *HAZARD IDENTIFICATION*

Based on the above review, the main hazard associated with an LPG facility is an uncontrolled release of LPG resulting in a fire or explosion upon ignition. There is also the potential for escalation of a fire event to cause a Boiling Liquid Expanding Vapour Explosion (BLEVE) of the LPG road tanker or the cylinders and this may produce fragments that can travel hundreds of metres. Connection/ disconnection errors and tanker drive away during unloading can also lead to leaks.

The initiating events leading to an LPG release could occur due to one of the following:

- Spontaneous failure of pressurised LPG equipment, i.e.:
  - Storage vessel failure;
  - Road tanker failure;
  - Pipework failure;
  - Hose failure;
  - Flange failure;
  - Valve leak; and
  - LPG cylinder failure.
- Loading failures, i.e. an LPG release that occurs as a direct result of the road tanker unloading operation.
  - Hose Failure;
  - connection/disconnection error (during tanker unloading);
  - Tanker drive away error;
  - Tanker impact;
  - Loading pipework overpressurisation; and
  - Storage tank overfilling/overpressurisation.
- External events, such as:
  - Earthquake;
  - Aircraft crash;
  - High wind loading;

  - External fire; and
  - Subsidence.

The following events could result from a release of LPG:

- Jet fire;
- Flash fire;
- Vapour Cloud Explosion (VCE);
- Fireball; and
- BLEVE

The likelihood or frequency of these events is discussed in *Section 4*.

Based on the considerations above, representative LPG release events considered in the assessment are as summarised in *Table 3.4*.

Rupture of vessels may result in fireballs, flash fires or vapour cloud explosions (VCE). Leaks may cause jet fires, flash fires or VCE, or may escalate leading to catastrophic failure of a vessel in a Boiling Liquid Expanding Vapour Explosion (BLEVE). BLEVE of the LPG Compound storage vessel is not considered possible since these are mounded tanks. BLEVE of road tankers and LPG cylinders is considered in the analysis however.

Leaks from all equipment are piping are taken to be 1" or 2", depending on the size of connections. Leaks from LPG cylinders are taken to be 1mm since anything larger would effectively lead to emptying of a cylinder in a matter of seconds and would essentially be the same as a rupture scenario.

VCE from LPG cylinders is not considered possible because of the very limited inventory in a cylinder. CCPS (1999) suggests that the minimum flammable mass required to allow transition from flash fire to VCE, based on experimental studies, is 100 kg. The inventory of all cylinders is less than this.

Additional risks potentially arise from the transit of petrol/diesel tankers through the site from the jetty. Petrol/diesel could be released from the tankers to form a liquid pool on the ground and a pool fire if ignited. These scenarios are included in the analysis.

Table 3.4 *Release Events Considered*

Equip. ID	Equipment Description	Event Description	Release Type	Hole Size	Potential Hazardous Event Outcomes*
1	Storage vessel	Catastrophic failure	Instantaneous	Rupture	Fireball, VCE, flash fire
		Partial failure	Continuous	1" leak	Jet fire, VCE, flash fire
2	LPG road tanker	Catastrophic failure	Instantaneous	Rupture	Fireball, VCE, flash fire
		Partial failure	Continuous	2" leak	Jet fire, VCE, flash fire, BLEVE
		Partial failure	Continuous	1" leak	Jet fire, VCE, flash fire, BLEVE
3	Filling line to storage vessel	Guillotine failure	Continuous	Pipe full bore	Jet fire, VCE, flash fire
		Partial failure	Continuous	1" leak	Jet fire, VCE, flash fire
4	Flexible hose	Guillotine failure	Continuous	Hose full bore	Jet fire, VCE, flash fire
		Partial failure	Continuous	1" leak	Jet fire, VCE, flash fire
5	Line from storage vessel to vaporizers	Guillotine failure	Continuous	Pipe full bore	Jet fire, VCE, flash fire
		Partial failure	Continuous	1" leak	Jet fire, VCE, flash fire
6	Vaporizer	Guillotine failure	Continuous	Pipe full bore	Jet fire, VCE, flash fire
7	Send-out piping downstream of vaporizers	Guillotine failure	Continuous	Pipe full bore	Jet fire, VCE, flash fire
		Partial failure	Continuous	1" leak	Jet fire, VCE, flash fire
8	LPG cylinder	Catastrophic failure	Instantaneous	Rupture	Fireball, flash fire
		Partial failure	Continuous	1mm leak	Jet fire, flash fire, BLEVE
9	Petrol/diesel road tanker	Catastrophic failure	Instantaneous	Rupture	Pool fire
		Partial failure	Continuous	1" leak	Pool fire

4 FREQUENCY ANALYSIS

4.1 BASE EVENT FREQUENCIES

The previous HATS study (ENSR, 2008) performed a detailed Fault Tree Analysis (FTA) to assess the frequency of each failure listed in *Table 3.4*. This included consideration of causes such as spontaneous failures, overfilling, truck collisions, connection/disconnection errors etc. and took credit for safety systems such as operator intervention, check valves, excess flow valves, pressure relief valves etc. The frequencies reported for this FTA were checked and found to be broadly consistent with those of previously approved studies in Hong Kong (for example, Maunsell 2006, ERM 2003, 2008). For conciseness, the FTA analysis has not been repeated here, since the frequencies have been largely adopted unaltered. Minor changes were made to scale frequencies to reflect updated information provided by the depot operators (Shell, 2009):

- Failure rates for LPG road tankers were increased to allow for 3 tanker deliveries per day instead of 2;
- Failure rates for LPG cylinders on wagons have been increased to allow for 3 wagon deliveries per day instead of 2. Also, the parking of 5 cylinder wagons on site overnight has been taken into account in the frequency calculations;
- Failure rates for 5 loaded bulk tankers (assumed to be three 20-tonne petrol tankers and two 20-tonne diesel tankers) have been included, and
- The number of cylinders in the Transit Depot has increased from 2000 to 2200. These cylinders have been further divided as 25% at 49kg and 75% at 13.5kg to reflect the actual size distribution (*Table 2.2*);

Base event frequencies adopted in this study are summarised in *Table 4.1* and *Table 4.2* for the LPG Compound and LPG Transit Depot respectively.

Table 4.1 ***Base Event Frequencies for the LPG Compound***

Event Description	Failure Rate (per year)
Cold catastrophic failure of storage vessel	6.72×10^{-7}
Cold partial failure of storage vessel	1.17×10^{-5}
Cold catastrophic failure of road tanker	1.48×10^{-7}
Cold partial failure of road tanker	3.62×10^{-7}
Rupture of filling line to storage vessel	5.14×10^{-7}
Leak of filling line to storage vessel	7.69×10^{-7}
Rupture of flexible hose	3.82×10^{-5}
Leak of flexible hose	3.92×10^{-5}
Rupture of line from storage vessel to vaporizers	4.00×10^{-6}
Leak of line from storage vessel to vaporizers	1.30×10^{-5}
Rupture of vaporizer	3.64×10^{-8}
Rupture of send-out piping downstream of vaporizers	4.00×10^{-6}
Leak of send-out piping downstream of vaporizers	1.30×10^{-5}
Rupture of LPG cylinder in storage shed	2.20×10^{-3}
Leak of LPG cylinder in storage shed	5.72×10^{-3}

Table 4.2 ***Base Event Frequencies for the Transit Depot***

Event Description	Failure Rate (per year)
Road Tanker / Cylinder Wagon Transport Events	
Cold rupture of road tanker	5.69×10^{-7}
Large liquid release from road tanker	3.94×10^{-6}
Large vapour release from road tanker	4.60×10^{-7}
Medium liquid release from road tanker	1.49×10^{-6}
Rupture of LPG cylinder on wagon	6.13×10^{-6}
Cold rupture of petrol tanker(1)	1.25×10^{-7}
Liquid release due to leak from petrol tanker(1)	3.13×10^{-7}
Cold rupture of diesel tanker(1)	8.33×10^{-8}
Liquid release due to leak from diesel tanker(1)	2.08×10^{-7}
Road Tanker/Cylinder Wagon Stationary Events	
Cold rupture of road tanker	2.08×10^{-9}
Large liquid release from road tanker	1.88×10^{-9}
Large vapour release from road tanker	1.88×10^{-9}
Medium liquid release from road tanker	1.88×10^{-9}
Rupture of LPG cylinder on wagon	3.54×10^{-7}
Rupture of LPG cylinder on wagon while parked overnight(2)	1.70×10^{-5}

- (1) Frequency calculated based on failure rate of 5×10^{-6} per tanker-year for a 1" leak, 2×10^{-6} per tanker-year for rupture (Crossthwaite, Fitzpatrick, and Hurst, 1988) and presence time of half an hour for each tanker.
- (2) Frequency calculated based on failure rate of 6.8×10^{-6} per vehicle-year, for 5 wagons parked overnight for 12 hours per day.

It may be noted that, following the HATS methodology, scenarios involving LPG cylinders are grouped with the LPG Compound (*Table 4.1*) to represent effectively the static facilities. LPG tankers during unloading are also included in *Table 4.1*. Events involving tankers and cylinder wagons during transit or parking outside the storage shed are listed under the Transit Depot (*Table 4.2*). Separate risk results are shown in *Section 6* for the Compound and Transit depot, in addition to results for the overall risks.

4.2 EVENT TREE ANALYSIS

Event tree analysis (ETA) is used to model the evolution of an event from the initial release through to the final outcome such as jet fire, fireball, flash fire etc. This may depend on factors such as whether immediate or delayed ignition occurs, or whether there is sufficient congestion to cause a vapour cloud explosion.

4.2.1 *Storage Vessel Scenarios*

The event tree for rupture of a storage vessel is shown in *Figure 4.1*. Immediate ignition is assigned a probability of 0.3 for large releases following Cox, Lees and Ang (Lees, 1996), see *Table 4.3*. Immediate ignition results in a fireball.

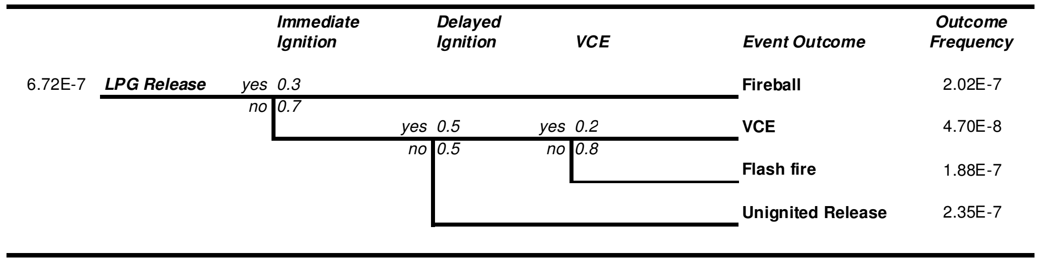
Table 4.3 Ignition Probabilities from Cox, Lees and Ang

Leak Rate	Probability of Ignition	
	Gas Release	Liquid Release
Minor (<1 kg/s)	0.01	0.01
Major (1-50 kg/s)	0.07	0.03
Massive (>50 kg/s)	0.3	0.08

Delayed ignition is assigned a probability of 0.5 (ENSR, 2008).

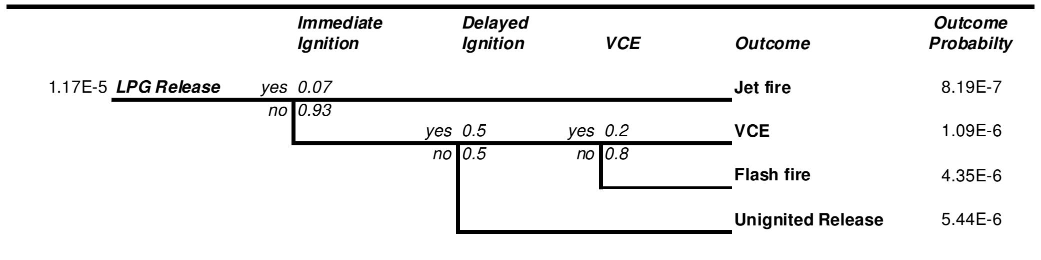
Delayed ignition may produce a flash fire or vapour cloud explosion (VCE). To achieve a VCE, a dispersing vapour cloud must accumulate in a confined and/or congested area and subsequently be ignited. Given the fairly open nature of the surroundings, an explosion probability of 0.2 was assumed.

Figure 4.1 Event Tree for Catastrophic Rupture of Storage Vessel



For smaller leaks, a lower immediate ignition probability of 0.07 is applied from *Table 4.3*. In other aspects, the event tree (*Figure 4.2*) is similar. Immediate ignition results in a jet fire, while delayed ignition may produce a flash fire or VCE.

Figure 4.2 Event Tree for Partial Failure of Storage Vessel

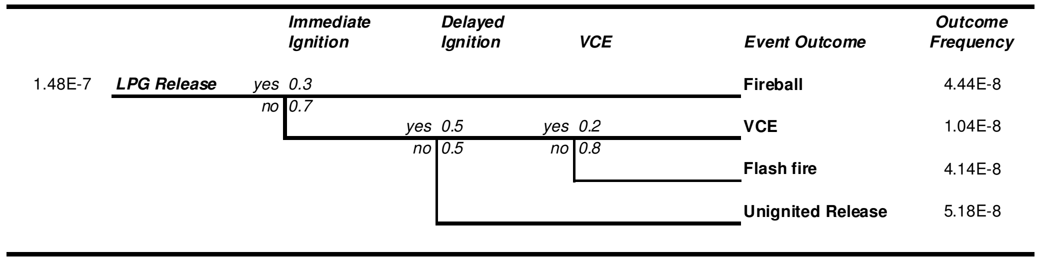


4.2.2 *Road Tanker Scenarios*

The event tree for catastrophic failure of an LPG road tanker is identical to that for the storage vessel (*Figure 4.1*), except for a different base frequency (see *Figure 4.3*).

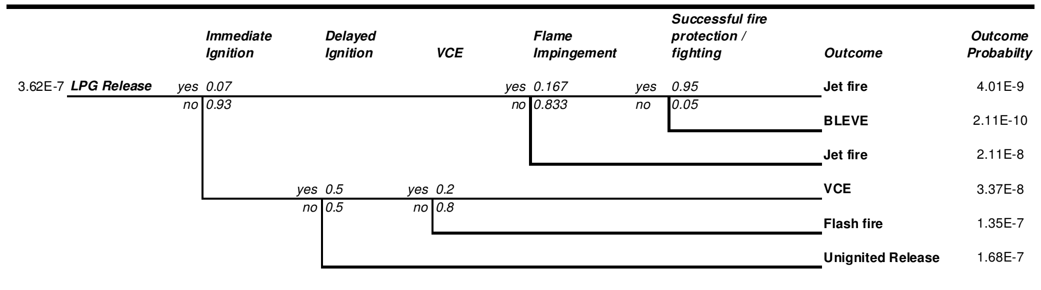
Partial failure of a road tanker is similar to the leak case for a storage vessel except that the possibility of flame impinging on the tanker and escalation to a BLEVE is also considered in the event tree (*Figure 4.4*). The probability of flame impingement is estimated at 1/6 (ERM, 2003). Credit is also taken for the passive fire protection (Chartek) coating on the road tankers, and time for emergency services to take action before a BLEVE occurs. The probability that Chartek will fail to prevent hot spots forming and leading to failure is assigned as 0.1 (Maunsell, 2006), and the probability that fire Services will be ineffective in preventing a BLEVE is assigned as 0.5 (Maunsell, 2006).

Figure 4.3 Event Tree for Catastrophic Rupture of LPG Road Tanker



Event tree applies to failure of road tanker in LPG Compound. Event trees for road tankers in the Transit Depot are similar except for the different base frequency (*Table 4.2*)

Figure 4.4 Event Tree for Partial Failure of LPG Road Tanker

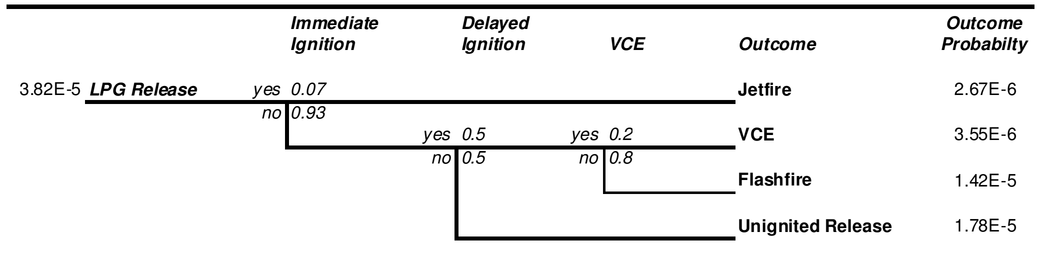


Event tree applies to failure of road tanker in LPG Compound. Event trees for road tankers in the Transit Depot are similar except for the different base frequency (*Table 4.2*)

4.2.3 *Hose and Piping Scenarios*

The event trees for leaks and ruptures of hoses, piping and vaporizers are essentially similar, except for different base frequencies. The event tree for a hose rupture is shown in *Figure 4.5*.

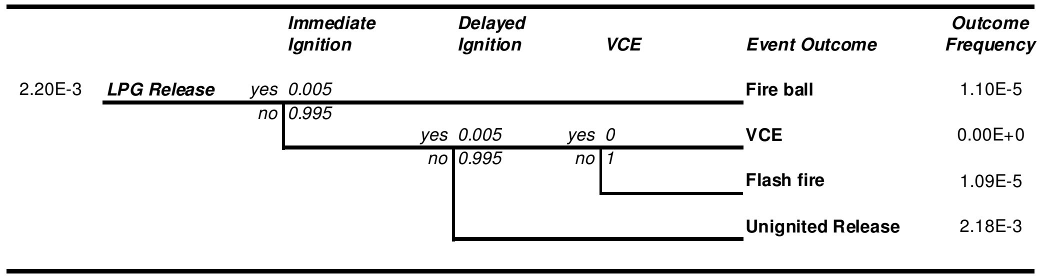
Figure 4.5 Event Tree for Hose Rupture



4.2.4 *LPG Cylinder Scenarios*

The event tree for cylinder rupture is shown in *Figure 4.6*. Immediate ignition results in a fireball while delayed ignition gives a flash fire. VCE is assigned a probability of zero since the inventory in a cylinder is too small to cause a VCE.

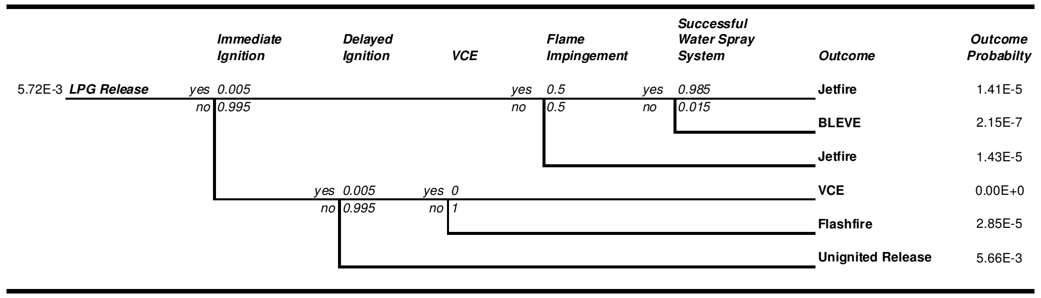
Figure 4.6 *Event Tree for LPG Cylinder Rupture*



Event tree applies to failure of cylinders in storage shed. Event trees for cylinders on wagons are similar except for the different base frequency (*Table 4.2*).

For leaks from a cylinder, the probability of impinging on a neighbouring cylinder is taken to be 0.5. This is a rather high probability to reflect that cylinders are stored in stacks. To escalate to a BLEVE, however, would require fire protection systems (gas detectors and water sprinklers) to fail which has been assigned a probability of 0.015 (Maunsell, 2006).

Figure 4.7 *Event Tree for LPG Cylinder Leak*



Event tree applies to failure of cylinders in storage shed. Event trees for cylinders on wagons are similar except for the different base frequency (*Table 4.2*).

4.2.5 *Transit Depot Scenarios*

The event trees for the LPG release at the Transit Depot are essentially similar to those for the bulk compound except for the different base frequencies (see *Table 4.2*).

Petrol/Diesel Tanker Scenarios

The event tree for petrol tankers is shown in *Figures 4.8*. Ignition probabilities are adopted from the values for liquids in *Table 4.3*, namely 0.08 for ruptures and 0.03 for leaks. Ignition of a spill will lead to a pool fire. The event tree for diesel tankers is shown in *Figure 4.9*. Given the high flash point of diesel, it is relatively more difficult to ignite. Diesel is actually classified as combustible rather than flammable. As such, a lower ignition probability is appropriate and a values ten times lower is assumed in the analysis.

Figure 4.8 *Event Tree for Petrol Tankers*

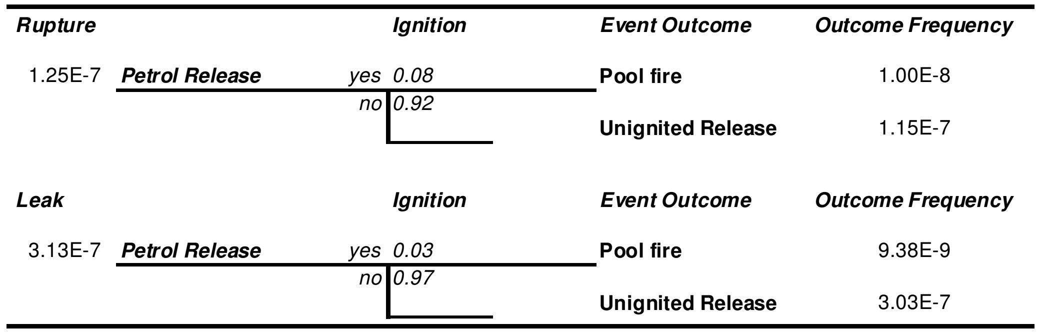
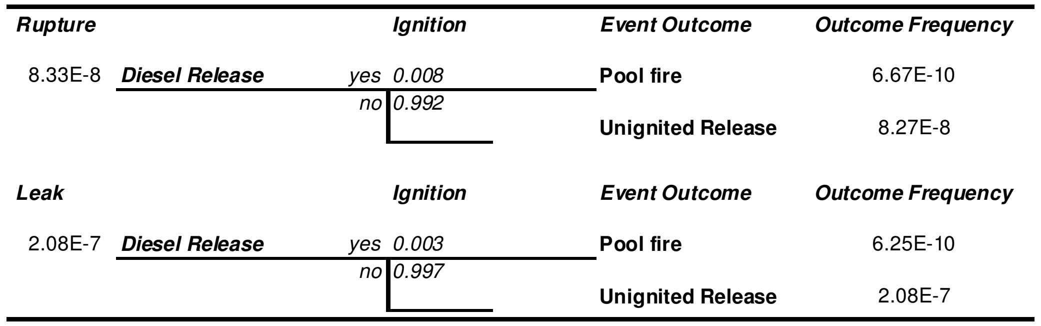


Figure 4.9 *Event Tree for Diesel Tankers*



4.3 PROJECTILES

Rupture of an LPG cylinder, due either to spontaneous failure or a BLEVE, may produce fragments that can cause fatal injuries hundreds of metres away. This is discussed further in this section.

4.3.1 *Cylinder Rupture Frequency*

Rupture of an LPG cylinder may be caused by spontaneous failures (material defects, overpressurisation, external damage etc. or by engulfment in a fire leading to a BLEVE.

Spontaneous failure of a cylinder is assigned a frequency of 1×10^{-6} per cylinder-year (Purple Book; ENSR, 2008). With 2200 cylinders in the store on average, the spontaneous rupture frequency is estimated at 2.2×10^{-3} per year.

An event tree for escalation of leaks to cause a major fire and multiple BLEVEs was shown in *Figure 4.7*. A cylinder leak frequency of 2.6×10^{-6} per cylinder-year (ENSR, 2008) is applied, which amounts to 5.72×10^{-3} per year for 2200 cylinders. An immediate ignition probability of 0.005 is used, based on ignition probabilities for small leaks from *Table 4.3*, assuming an even split between immediate and delayed ignition. If a leak is ignited, a jet fire will result. This will need to impinge directly on a neighbouring cylinder in order for the event to escalate (either by causing that cylinder to fail in a BLEVE or by causing its safety valve to open and add more fuel to the fire). Given that cylinders are stored in stacks, a relatively high flame impingement probability of 0.5 is assumed. The storage shed is equipped with gas detectors and automatic sprinkler systems. These would need to fail for the event to escalate

to a major fire. The probability of failure of the fire protection system is taken as 0.015 (Maunsell, 2006). This gives an overall frequency of major fire of 2.15×10^{-7} per year.

A major fire could lead to multiple, sequential BLEVEs. LPG cylinders, however, are fitted with safety valves to release the gas in case of overpressurisation. Not all cylinders will fail in a BLEVE. Conservatively assuming that 10% of cylinders will fail in a BLEVE gives 220 BLEVE events with a frequency of 2.2×10^{-7} per year. This is equivalent to one BLEVE with a frequency of 4.8×10^{-5} per year. This is small compared to the spontaneous failure rate, suggesting a total rupture frequency of 2.2×10^{-3} per year.

Number of Fragments

Brittle failure of LPG storage tanks have been known to produce up to 30 fragments in a catastrophic failure. However, brittle failures are not relevant to the current study since they generally occur under low temperatures. For ductile failures, Baum (1988) has reported that less than five projectiles will be produced. Holden and Reeves (1985) report that there is an 80% chance that a rupture will produce fragments and there will be 2 to 4 fragments for each failure. Most scenarios involve the valve being ejected so that there are 2 fragments (the valve and the cylinder). Assuming that 90% of incidents produce 2 fragments, 10% of incidents produce 5 fragments and only 80% of incidents produce any fragments, the average number of fragments may be estimated as 0.8×(0.9×2 + 0.1×5) = 2.

Cylinders are stored in stacks so that fragments produced from failure of inner cylinders are likely shielded by the outer cylinders. It is assumed that 50% of fragments will escape the stack and launch as a projectile (ENSR, 2008).

Fragment Range

In order to determine the range of the fragment, the initial velocity of the fragment must be determined. Range can then be found by solving equations for trajectory motion, allowing for the effects of drag.

Several models have been proposed to estimate the initial velocity of a fragment. The Brode and Baum models are described by Lees (1996) and the Center for Chemical Process Safety (CCPS, 1999) and were applied in this study.

Brode assumed that a portion of the total internal energy of a storage vessel is translated into kinetic energy of the fragment:

$$E_k = \frac{kp_1V}{\gamma-1}$$

$$k = 1-\left[\frac{p_o}{p_1}\right]^{(\gamma-1/\gamma)} + (\gamma-1)\frac{p_o}{p_1}\left[1-\left(\frac{p_o}{p_1}\right)^{(-1/\gamma)}\right]$$

$$v_i = \sqrt{\frac{2E_k}{M}}$$

where

v_i = initial fragment velocity (m/s)

E_k = kinetic energy (J)

M = total mass of the empty cylinder (kg)

k = fraction of internal energy converted to fragment kinetic energy

p_1 = absolute pressure in cylinder (Pa)

p_o = ambient pressure (Pa)

V = volume of the vessel (m^3)

γ = ratio of specific heats of the gas

The weakness of the Brode model is that it does not take into account the fragment size.

Baum developed empirical correlations for the initial velocity for an end cap breaking away from a cylindrical vessel, a cylindrical vessel breaking into two parts, and a single small fragment ejected from the vessel. As an example, the model for a single small fragment is presented in the equations below. The model for end cap and cylinder breaking into 2 parts are similar.

$$F = \frac{(p_1-p_o)Ar}{M_f a_o^2}$$

$$a_o = \sqrt{\frac{T\gamma R}{m}}$$

$$v_i = 2a_o\left(\frac{Fs}{r}\right)^{0.5}$$

where

F = parameter for calculation of initial velocity

A = area of the detached portion of the cylinder wall (m^2)

r = radius of the vessel

M_f = mass of fragment (kg)

a_o = speed of sound (m/s)

T = temperature of the gas inside cylinder at failure (K)

R = ideal gas constant (J/kmol-K)

m = molecular mass of cylinder contents (kg/kmol)

s = dimension of the fragment

With the initial velocities known, the maximum range can be estimated by solving the equations of motion. Baker et al. solved these computationally, incorporating drag effects, and presented the results graphically (Lees, 1996).

Applying the above models to LPG cylinders gives the results presented in *Table 4.4*. It can be seen that there is some variation in the predictions but a maximum range of about 350m is predicted which is consistent with most past incident reports.

Summary of assumptions used in the model:

LPG composition is 30% propane, 70% butane

Failure pressure of cylinder is taken as 1.21 times the design pressure (CCPS, 1996)

Cylinder design pressure is 1.86 Mpa (Shell, 2009)

The temperature of the gas at failure is taken to be 120°C (Stawczyk, 2003)

Drag coefficient for a spherical fragment = 0.47 (CCPS, 1996).

Empty cylinder mass is 10 kg and 30 kg for the 13.5 and 49 kg capacity cylinders

Cylinder volume is 30.5 L and 110 L respectively.

Table 4.4 ***Fragment Range***

				Brode		**Baum**	
Cylinder Type	**Fragment Case**	**Fragment Mass (kg)**	**Surface Area of Fragment (m^2)**	**Initial Velocity (m/s^2)**	**Maximum Range (m)**	**Initial Velocity (m/s^2)**	**Maximum Range (m)**
13.5 kg	end cap	2.05	0.087	127	154	252	230
13.5 kg	valve	0.5	0.012	127	270	173	352
13.5 kg	split	5	0.37	127	111	170	131
49 kg	end cap	2.05	0.087	140	165	252	230
49 kg	valve	0.5	0.012	140	287	173	352
49 kg	split	15	0.77	140	143	193	185

Many past incidents and experiments have been documented in the literature. Baker et al. reported 20 events that he classified into 6 event groups (Lees, 1996). The most relevant data is for cylindrical vessels containing 512 kg of propane gas, for which 98% of the fragments had a range of less than 500 m.

Another study by Holden and Reeves reviewed 27 events involving cylindrical vessels (Lees, 1996). The events are classified into 2 groups; vessels above 90 m^3 and vessels below 90 m^3. It was reported that 80% of the fragments travelled less than 200 m and that fragment ranges are much less than the maximum range from theoretical estimates. Also, it was found that smaller vessels projected fragments further. In contrast to Holden and Reeves, Birk (1996) suggested that smaller vessels produce lower projectile ranges.

Stawczyk (2003) found that the maximum range for 11 kg LPG cylinders is 300 m. This is perhaps the most relevant study since the size and contents of the cylinders are very close to that used in the Shell Depot. The maximum range of 300m is consistent with the predictions in *Table 4.4*.

The study of Baker et al. also provides information on the fragment range distribution, rather than simply the maximum fragment range. Although this study assessed data from larger storage vessels and gives a maximum range of 500m, it is conservatively applied in this study for lack of more relevant data. The distribution in fragment range is summarised in *Table 4.5*.

Table 4.5 ***Distribution of Fragment Range***

Range	**0-100 m**	**100-200 m**	**200-300 m**	**300-400 m**	**400-500 m**
Probability	0.54	0.30	0.10	0.04	0.02

Shielding Factors

Most of the buildings in South Horizons are partly shielded by three residential blocks, numbers 21, 22 and 23. These blocks are 70m from the storage depot and are 110m tall, so all projectiles launched with a takeoff angle of less than 58° will strike these nearest residential blocks. To travel over these buildings and fall on areas behind would require an initial launch angle of between 58 and 90°. It is therefore assumed that 36% of fragments will have this launch angle. The exposure factor for buildings and open areas lying behind the front row of residential blocks is therefore estimated at 0.36.

With reference to *Figure 4.10*, buildings with direct line-of-sight (shaded blue) are assigned an exposure factor of 1 (no shielding). Buildings highlighted in green are shielded and assigned an exposure factor of 0.36.

Buildings shown in gray are considered to be totally shielded by virtue of either being short buildings in the shadow of a tall building, or because they are located tightly behind another building. In either case, any fragments that impact these buildings will simply fall on the roof and have no impact on the occupants.

Figure 4.10 ***Shielding Factors***

Populated buildings/areas with direct line-of-sight to LPG depot

Partly shielded buildings/areas

Fully shielded buildings/areas

No shielding was applied to road and pedestrian population on Lee Nam Road, although the LPG Depot perimeter wall is about 2m tall and may provide some protection.

The analysis also neglects any shielding effects from the storage shed roof. This is a corrugated iron structure and is assumed to provide little protection.

Target Area

If a fragment strikes a critical part of the body such as head or torso, a fatality may result. Assuming a cylindrical shaped torso, about 1m long and 12" diameter (the chest size for the average Chinese male is 35" circumference (Alvanon, 2008), gives a target area of 0.3m^2.

The probability of a building being hit is estimated from the solid angle subtended by the building compared to the solid angle of a hemisphere (2π), taking into account the exposure (shielding) factor and the fraction of fragments that have sufficient range to reach the building (*Table 4.6*). Rupture fragments will not have sufficient energy to penetrate the concrete walls of residential buildings in Hong Kong, such that a person can only be hurt if the

fragment flies through a window. The ratio of window area to total wall area of the building in South Horizons is about 50% (Centamap, 2009).

The probability of a person being struck by a fragment is therefore calculated based on:

- The probability that the building will be hit, based on solid angles, shielding factor and the fraction of fragments that have sufficient range to reach the building;
- A probability of 0.5 that a fragment will pass through a window;
- A persons target area of 0.3m^2;
- The number of persons in a building estimated from number of units facing the LPG Depot and assuming 3 persons per unit; and
- A time average occupancy of 66% (from *Table 2.4*);

Calculations for outdoor population are a little more straightforward. The probability of a target being struck is calculation from the target area, fraction of fragments that have sufficient range to reach the target and the shielding (exposure) factors.

The results of this analysis are summarised in *Table 4.6*. It can be seen that for each projectile emanating from the LPG Depot, the probability of a person being struck and fatally injured is about 2×10^{-3}. This includes the construction phase population for MTR and PTW.

Table 4.6 ***Summary of Cylinder Projectile Analysis***

Area/Building	Exposure Factor	Probability of Area/Building being Hit	Probability of a Person being Hit
South Horizons Block 13A	0.36	1.30E-04	1.04E-06
South Horizons Block 15	0.36	4.33E-04	3.25E-06
South Horizons Block 16	1	1.56E-03	1.15E-05
South Horizons Block 17	0.36	2.75E-03	2.51E-05
South Horizons Block 18	0.36	2.99E-03	3.11E-05
South Horizons Block 19	0.36	3.31E-03	3.60E-05
South Horizons Block 20	0.36	3.33E-03	3.55E-05
South Horizons Block 21	1	4.75E-02	4.05E-04
South Horizons Block 22	1	5.65E-02	5.64E-04
South Horizons Block 23	1	4.65E-02	4.07E-04
South Horizons Block 23A	0.36	6.21E-03	4.80E-05
South Horizons Block 29	0.36	8.54E-05	6.41E-07
South Horizons Block 30	0.36	8.64E-05	7.29E-07
South Horizons Block 33A	0.36	1.63E-03	1.33E-05
Horizon Plaza	1	4.99E-05	3.46E-06
Dah Chong Hong	1	4.92E-05	6.61E-07
Outdoor Population (0 to 100 m)	1	3.41E-02	7.01E-05
Outdoor Population (100 to 200 m)	0.36	1.04E-02	1.17E-04
Outdoor Population (200 to 300 m)	0.36	2.00E-03	2.25E-05
Outdoor Population (300 to 400 m)	0.36	1.35E-03	1.51E-05
Outdoor Population (400 to 500 m)	0.36	3.29E-04	3.70E-06
Ap Lei Chau PTW	1	9.56E-03	2.86E-06
Driving School	1	4.40E-04	5.31E-07
Maine Population	1	4.00E-01	1.91E-06

Area/Building	Exposure Factor	Probability of Area/Building being Hit	Probability of a Person being Hit
MTR Works Site A	1	3.63E-03	3.18E-05
MTR Works Site B	1	1.79E-03	1.59E-05
MTR Works Site C	1	2.13E-04	3.98E-06
MTR Works Site W2	1	2.17E-04	1.06E-06
		Total	**1.87E-03**

Summary of Projectile Analysis

The frequency of cylinder ruptures was estimated at 2.2×10^{-3} per year. Each rupture was estimated to produce 2 fragments on average, but 50% of these will be trapped within cylinder stacks. This gives a frequency for fragments leaving the LPG Depot of 2.2×10^{-3} per year.

The probability that a fragment will cause a fatality was estimated at 1.87×10^{-3}. This is likely conservative since the analysis assumes all projectile impacts on a person will lead to a fatality. Combining the fragment frequency of 2.2×10^{-3} per year with the probability of 1.87×10^{-3} that a fragment will lead to fatality gives a projectile fatality rate of 4.1×10^{-6} per year.

A single point is therefore added to the FN curves at N=1 and $F=4.1\times10^{-6}$.

4.4 SUMMARY

The frequencies of hazardous outcomes assessed in this study are summarised in *Table 4.7* and *Table 4.8*.

Table 4.7 Event Outcome Frequencies for the LPG Compound

Equip. ID	Equipment Description	Event Description	Outcome	Outcome Frequency (per year)
1	Storage vessel	Rupture	Fireball	2.02×10^{-7}
			VCE	4.70×10^{-8}
			Flash fire	1.88×10^{-7}
		Leak	Jet fire	8.19×10^{-7}
			VCE	1.09×10^{-7}
			Flash fire	4.35×10^{-6}
2	Road tanker	Rupture	Fireball	4.44×10^{-8}
			VCE	1.04×10^{-8}
			Flash Fire	4.14×10^{-8}
		Leak	Jet fire	2.51×10^{-8}
			VCE	3.37×10^{-8}
			Flash fire	1.35×10^{-7}
		Escalation events	BLEVE	2.11×10^{-10}
3	Filling line to storage vessel	Full bore rupture	Jet fire	3.60×10^{-8}
			VCE	4.78×10^{-8}
			Flash fire	1.91×10^{-7}
		Leak	Jet fire	5.33×10^{-8}
			VCE	7.15×10^{-8}
			Flash fire	2.86×10^{-7}

Equip. ID	Equipment Description	Event Description	Outcome	Outcome Frequency (per year)
4	Flexible hose	Full bore rupture	Jet fire	2.67×10^{-6}
			VCE	3.55×10^{-6}
			Flash fire	1.42×10^{-5}
		Leak	Jet fire	2.74×10^{-6}
			VCE	3.65×10^{-6}
			Flash fire	1.46×10^{-5}
5	Line from storage vessel to vaporisers	Full bore rupture	Jet fire	2.80×10^{-7}
			VCE	3.72×10^{-7}
			Flash fire	1.49×10^{-6}
		Leak	Jet fire	9.10×10^{-7}
			VCE	1.21×10^{-6}
			Flash fire	4.84×10^{-6}
6	Vaporisers	Full bore rupture	Jet fire	2.55×10^{-9}
			VCE	3.39×10^{-9}
			Flash fire	1.35×10^{-8}
7	Send-out piping downstream of vaporisers	Full bore rupture	Jet fire	2.80×10^{-7}
			VCE	3.72×10^{-7}
			Flash fire	1.49×10^{-6}
		Leak	Jet fire	9.10×10^{-7}
			VCE	1.21×10^{-6}
			Flash fire	4.84×10^{-6}
8	LPG Cylinder *	Rupture	Fireball	1.10×10^{-5}
			Flash fire	1.09×10^{-5}
		Leak	Jet fire	2.84×10^{-5}
			Flash fire	2.85×10^{-5}
		Escalation events	BLEVE	2.15×10^{-7}

* 25% of cylinders are assumed to be 13.5kg and 75% are 49kg (see *Table 2.2*). Outcome frequencies are assigned proportionally

Table 4.8 Event Outcome Frequencies for the Transit Depot

Equipment Description	Event Description	Outcome	Outcome Frequency (per year)
Road Tanker/Cylinder Wagon Transport Events			
Road tanker	Rupture	Fireball	1.71×10^{-7}
		VCE	3.98×10^{-8}
		Flash Fire	1.59×10^{-7}
	Large liquid leak	Jet fire	2.74×10^{-7}
		VCE	3.66×10^{-7}
		Flash fire	1.47×10^{-6}
	Large vapour leak	Jet fire	3.22×10^{-8}
		VCE	4.28×10^{-8}
		Flash fire	1.71×10^{-7}
	Medium liquid leak	Jet fire	1.03×10^{-7}
		VCE	1.39×10^{-7}
		Flash fire	5.54×10^{-7}
	Escalation events	BLEVE	3.17×10^{-9}
Cylinder wagons *	Rupture	Fireball	3.07×10^{-8}
		Flash fire	3.05×10^{-8}

Equipment Description	Event Description	Outcome	Outcome Frequency (per year)
Petrol tankers	Rupture	Pool fire	1.00×10^{-8}
	Liquid leak	Pool fire	9.38×10^{-9}
Diesel tankers	Rupture	Pool fire	6.67×10^{-10}
	Liquid leak	Pool fire	6.25×10^{-10}
Road Tanker/Cylinder Wagon Stationary Events			
Road tanker	Rupture	Fireball	6.24×10^{-10}
		VCE	1.46×10^{-10}
		Flash fire	5.82×10^{-10}
	Large liquid leak	Jet fire	1.31×10^{-10}
		VCE	1.75×10^{-10}
		Flash fire	6.99×10^{-10}
	Large vapour leak	Jet fire	1.32×10^{-10}
		VCE	1.75×10^{-10}
		Flash fire	6.99×10^{-10}
	Medium liquid leak	Jet fire	1.31×10^{-10}
		VCE	1.75×10^{-10}
		Flash fire	6.99×10^{-10}
	Escalation events	BLEVE	2.20×10^{-12}
Cylinder wagon *	Rupture	Fireball	1.77×10^{-9}
		Flash fire	1.76×10^{-9}
Cylinder wagon whilst parked overnight *	Rupture	Fireball	8.50×10^{-8}
		Flash fire	8.46×10^{-8}

* 25% of cylinders are assumed to be 13.5kg and 75% are 49kg (see *Table 2.2*). Outcome frequencies are assigned proportionally

5 *CONSEQUENCE ANALYSIS*

5.1 *OVERVIEW*

Consequence analysis comprises of:

- Source term modelling;
- Physical effects modelling to determine the effects zone of the various hazardous outcomes such as jet fires and fireballs; and
- Assessment of the impact on the exposed population.

In this study, consequence analysis is performed using the PHAST suite of models, developed by DNV.

5.2 *SOURCE TERM MODELLING*

A source term is the information required by gas dispersion, fireball, vapour cloud explosion or other consequence models to describe the discharge rate and quantity of hazardous substance to be considered. Standard orifice type calculations are used to determine the rate of discharge, based on conditions of pressure, temperature and phase of material. Duration of discharge is determined from inventory and release rate.

LPG in Hong Kong is a mixture of 70% butane and 30% propane. Vessels are conservatively assumed to be full at time of failure; 17 tonnes for each storage vessel and 9 tonnes for an LPG road tanker.

LPG cylinders stored in the Transit Depot are refined into two groups, 25% at 49 kg and 75% at 13.5 kg (see *Table 2.2*). It is assumed that LPG cylinders loaded on wagons have the same size distribution.

LPG is stored in liquid form by pressurisation to moderate pressures of about 4 to 5 barg, depending on ambient temperature. A significant portion of LPG flashes upon release, forming a vapour cloud. Liquid droplets may be entrained with the vapour or rainout to the ground forming a liquid pool. In the current study, pool fires were not found to be significant compared to jet fires. The more serious jet fire consequences were therefore used in the analysis.

5.3 *PHYSICAL EFFECTS MODELLING*

PHAST is used for the modelling of:

- Fireballs;
- BLEVEs;
- Jet fires;
- Pool fires

- Gas dispersion and flash fires; and
- Vapour cloud explosions (VCE).

Each hazard is modelled for a range of meteorological conditions (see *Section 2.3*) to determine the size of the hazard footprint.

5.3.1 *Fireballs and BLEVEs*

Catastrophic failures are characterised by a rapid propagation of a crack leading to a sudden release of the contents inside a pressurised vessel. Immediate ignition results in a fireball, which gives a massive transient dose of thermal radiation. Due to its short duration, large size and high intensity, fireballs are not significantly influenced by weather, wind direction or wind speed. Its size, height, duration and thermal radiation flux are calculated using the HSE model within PHAST. People entrapped inside the fireball radius are seriously injured and the fatality is taken as 100%. Outside the fireball radius, radiation effects were found to be negligible due to the short duration of fireballs for the size of releases encountered in this study.

A BELVE is similar to a fireball except that it is caused by a hot failure from fire impingement and therefore occurs from escalation events. The physical effects are calculated in the same way as fireballs.

5.3.2 *Gas Dispersion and Flash Fires*

LPG evaporates rapidly following a release, generating a dispersing vapour cloud if there is no ignition source nearby. The cloud expands and migrates from its release point and may affect offsite locations. The built-in dispersion model in PHAST is used to predict the shape, size, concentration and migration of the vapour cloud.

The principal hazard arising from delayed ignition of an LPG vapour cloud is a flash fire. The flash fire envelope is modelled by calculating the dispersion distance up to the lower flammability limit (LFL).

It is considered that there is no scope for escape for persons within the flammable limits of a flash fire: a fatality probability of 100% is assumed. Flash fires are, however, short duration events with low levels of thermal radiation outside the flash fire. Persons outside the flash fire envelope are therefore assumed to be unaffected by a flash fire.

5.3.3 *Vapour Cloud Explosion*

If a dispersing vapour cloud undergoes delayed ignition in a confined and/or congested area, significant levels of overpressure (explosion) may occur. VCE effects were modelled using the Baker-Strehlow model (CCPS, 1999). This takes into account the reactivity of LPG and the volume, level of congestion and level of confinement in determining the explosion overpressures.

Given the generally open nature of the surrounding, the modelling assumed 3D confinement (i.e. the vapour cloud explosion is free to expand in 3

dimensions) and medium congestion. For explosions within the vaporizer room, a higher level of confinement, 2D, was assumed.

Fatality rates for persons outdoors are estimated from the HSE probit equation (Hurst et al. 1989):

$Y = 1.47 + 1.35 \ln(P)$

where

Y = probit

P = overpressure (psi)

For persons indoors, fatality rates if 55%, 15% and 3.5% are used for 5psi, 3psi and 2psi respectively, based on CIA (1998) guidelines. Fatality rates are higher for persons indoors because of the additional risk from projectiles such as breaking windows.

5.3.4 *Jet Fires and Pool Fires*

Jet fires occur from the immediate ignition of an LPG release from pressurised conditions. The flame length is determined from the initial momentum of the release. If a jet fire impinges on a LPG road tanker or a LPG cylinder, thermal intrusion and heat radiation could induce over-pressurization and the subsequent rupture of the container, releasing its inventory instantaneously to cause a BLEVE.

Pool fires are caused by the ignition of liquid pools spreading on the ground.

The major hazard from a jet fire or a pool fire is thermal radiation. Persons caught in the fire zone are assumed to suffer 100% fatality. Persons outside the flame zone are assigned a harm probability using the Green Book probit equation:

$Y = -36.38 + 2.56 \ln(tI^{4/3})$

Y = probit

I = radiation thermal flux (W/m^2)

t = exposure time, assumed to be 30 s

The exposure time for jet fires is taken to be 30s, the time assumed for an able person to seek shelter (ERM, 2008).

A summary of harm probabilities used in the current assessment is provided in *Table 5.1*. Persons indoors are expected to be offered some protection from fires due to shielding from the building structure; the indoor fatality is taken to be 10% that of the outdoor population. This is in line with previous studies in Hong Kong (ERM, 2006; ERM, 2008 for example).

The harm probabilities for persons indoors are somewhat different from those

used in the HATS study (ENSR, 2008). In that study, indoor harm probabilities for radiation effects are assumed to be 50% of those for outdoor population, and persons indoors who are within the flame envelope are assumed to have the same harm probability as those outdoors. These assumptions are considered to be very conservative and are the main difference between the previous HATS study and the current analysis. The HATS study also did not provide the probit equation/harm probabilities used for VCE effects although it may be discerned that the same harm probability was used for indoor and outdoor populations.

Table 5.1 ***Summary of Harm Probabilities***

Consequence Event	Endpoint Criteria	Outdoor Harm Prob.	Harm Prob. Inside Buildings
Flash fire	LFL	1	0.1
Jet fire/Pool fire	Fire zone	1	0.1
	20.9 kW/m²	0.9	0.09
	14.4 kW/m²	0.5	0.05
	7.3 kW/m²	0.01	0.001
Fireball and BLEVE	Fireball radius	1	0.1
VCE	5 psi overpressure	0.09	0.55
	3 psi overpressure	0.02	0.15
	2 psi overpressure	0.005	0.035

5.4 HAZARD IMPACT ON OFFSITE POPULATION

Population in the vicinity of the Shell depot can be potentially affected by the hazardous outcomes depending on the consequence distances. Fireballs from the LPG storage vessels have a radius of up to 71 m and a lift-off height of 142m, which covers the majority of the adjacent PTW construction site. Fireballs and BLEVEs of LPG road tankers have a radius of up to 60 m and a lift-off height of 121 m, which can reach the nearest residential high-rise buildings (South Horizons Blocks 21 & 22). Due to the lift-off and rise of fireballs, they are assumed to affect the full height of residential blocks facing the LPG Depot. Units that are not overlooking the LPG Depot are assumed to be unaffected by fireballs. Similarly, VCE are assumed to affect only units overlooking the LPG Depot.

The maximum height of a dispersing vapour cloud was found to be 36m. It was therefore assumed in the modelling that flash fires affect only the lowest 12 floors of residential blocks. Similarly, only 12 floors of population were taken for jet fires since radiation effects are unable to reach higher floors.

5.5 GAS INGRESS INTO SOUTH HORIZONS MTR STATION

The future 2031 case considers the South Horizons station during operational phase. All parts of the station will be underground, and as such, will be unaffected by any incident at the LPG Depot. Ventilation for the station will be via vents situated on the second level of the 2-storey plant building located on Lee Nam Road at the toe of Yuk Kwai Shan. This plant building is about 200m from the LPG Compound storage vessels and 123m from the road tanker parking area. Vapour clouds from ruptures of these vessels/tankers

can reach the plant building. The maximum vapour cloud depth at the plant building is predicted to be 8m for a tanker rupture and 12m for a storage vessel rupture. This compares to a vent height of about 8m above Lee Nam Road. Ingress into the vent is therefore possible although the transit time for the vapour cloud to blow past the plant building is only 17 seconds. For such a short transit time, there is no possibility for vapours to enter the station and achieve flammable concentrations. For example, typical ventilation rates for buildings are in the range of 5 to 10 volume changes per hour. This gives a time constant for concentration changes within the station of between 1/5 to 1/10 hours (6 to 12 minutes). It is not possible for a passing gas cloud to cause significant rise in concentration within the station in just 17 seconds.

No impact on South Horizons station population was therefore considered in the assessment.

Despite this, as an additional safeguard it is recommended to install gas detectors in the HVAC air intakes for the plant building that close the dampers in case of gas detection. Usually, three such gas detectors are provided with two-out-of-three voting logic to improve the reliability of the system.

5.6 CONSEQUENCE RESULTS

A summary of consequence results is listed in *Table 5.2*. Results for all consequences are presented in terms of 4 parameters, *d c s m*. These are defined as (*Figure 5.1*):

d: maximum downwind distance (m)

c: maximum half width (m)

s: offset between release point and start of hazard footprint (m) (value may be positive or negative)

m: distance from release point to position of maximum half width (m)

Figure 5.1 ***Hazard Footprint Notation***

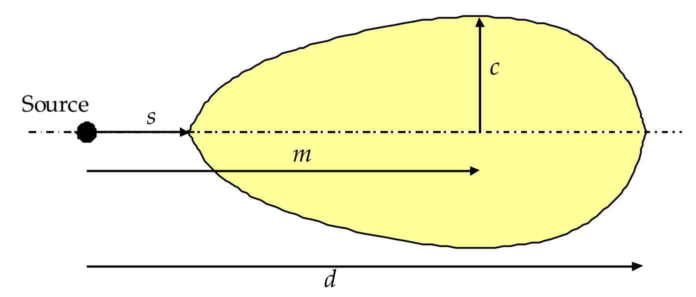


Table 5.2 ***Consequence Results***

Section No.	Description	Leak Size	Outcome	Criteria	Weather Conditions																			
					3B				3D				7D				3E				1.4F			
					d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m
1	Storage vessel	Rupture	Flash fire	LFL	153	51	-20	70	179	60	-24	88	264	54	-15	160	182	60	-20	90	120	62	-30	50
			VCE	5 psi	122	53	16	69	143	54	35	89	223	47	129	176	148	49	50	99	115	68	-21	47
				3 psi	203	134	-65	69	225	136	-47	89	303	127	49	176	230	131	-32	99	183	136	-89	47
				2 psi	273	204	-135	69	297	208	-119	89	384	208	-32	176	298	199	-100	99	255	208	-161	47
			Fireball	Fireball radius	71	71	-71	0	71	71	-71	0	71	71	-71	0	71	71	-71	0	71	71	-71	0
		Leak	Flash fire	LFL	38	2	8	28	40	2	8	30	30	1	8	20	42	2	8	32	47	4	8	36
			VCE	5 psi	10	10	-10	0	11	11	-11	0	9	9	-9	0	12	12	-12	0	13	13	-13	0
				3 psi	21	21	-21	0	23	23	-23	0	19	19	-19	0	24	24	-24	0	26	26	-26	0
				2 psi	32	32	-32	0	35	35	-35	0	30	30	-30	0	36	36	-36	0	40	40	-40	0
			Jet fire	Fire zone	37	13	1	19	37	13	1	19	33	14	1	17	37	13	1	19	43	12	2	22
				20.9 kW/m2	41	18	1	21	41	18	1	21	37	18	-1	18	41	18	1	21	46	18	2	24
				14.4 kW/m2	44	21	0	22	44	21	0	22	40	21	-2	19	44	21	0	22	49	22	1	25
				7.3 kW/m2	51	29	-1	25	51	29	-1	25	47	29	-3	22	51	29	-1	25	55	30	-1	27
2	LPG road tanker	Rupture	Flash fire	LFL	105	34	-20	55	110	34	-20	55	185	33	-15	110	112	35	-15	55	69	35	-25	30
			VCE	5 psi	67	36	-5	31	82	45	-8	37	122	34	54	88	85	47	-9	38	78	59	-40	19
				3 psi	167	136	-105	31	170	133	-96	37	188	100	-12	88	173	135	-97	38	155	136	-117	19
				2 psi	239	208	-177	31	239	202	-165	37	290	202	-114	88	243	205	-167	38	227	208	-189	19
			Fireball	Fireball radius	60	60	-60	0	60	60	-60	0	60	60	-60	0	60	60	-60	0	60	60	-60	0
		Leak	Flash fire	LFL	108	7	7	78	106	7	7	78	107	6	7	75	107	8	7	80	105	11	7	85
			VCE	5 psi	25	25	-25	0	25	25	-25	0	24	24	-24	0	27	27	-27	0	29	29	-29	0
				3 psi	49	49	-49	0	51	51	-51	0	48	48	-48	0	53	53	-53	0	59	59	-59	0
				2 psi	75	75	-75	0	77	77	-77	0	74	74	-74	0	81	81	-81	0	90	90	-90	0
			Jet fire	Fire zone	73	28	1	37	73	28	1	37	65	29	-1	32	73	28	1	37	83	27	1	42
				20.9 kW/m2	80	37	0	40	80	37	0	40	73	36	-1	46	80	37	0	40	89	37	1	45
				14.4 kW/m2	86	44	-2	42	86	44	-2	42	78	43	37	37	86	44	-2	42	95	45	-1	47
				7.3 kW/m2	100	61	-4	48	100	61	-4	48	92	60	-10	41	100	61	-4	48	108	61	-2	53
		Escalation	BLEVE	Fireball radius	60	60	-60	0	60	60	-60	0	60	60	-60	0	60	60	-60	0	60	60	-60	0
		Large liquid leak	Flash fire	LFL	108	7	7	78	106	7	7	78	107	6	7	75	107	8	7	80	105	11	7	85
			VCE	5 psi	25	25	-25	0	25	25	-25	0	24	24	-24	0	27	27	-27	0	29	29	-29	0
				3 psi	49	49	-49	0	51	51	-51	0	48	48	-48	0	53	53	-53	0	59	59	-59	0

Section No.	Description	Leak Size	Outcome	Criteria	Weather Conditions																			
					3B				3D				7D				3E				1.4F			
					d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m
				2 psi	75	75	-75	0	77	77	-77	0	74	74	-74	0	81	81	-81	0	90	90	-90	0
			Jet fire	Fire zone	73	28	1	37	73	28	1	37	65	29	-1	32	73	28	1	37	83	27	1	42
				20.9 kW/m2	80	37	0	40	80	37	0	40	73	36	-1	46	80	37	0	40	89	37	1	45
				14.4 kW/m2	86	44	-2	42	86	44	-2	42	78	43	37	37	86	44	-2	42	95	45	-1	47
				7.3 kW/m2	100	61	-4	48	100	61	-4	48	92	60	-10	41	100	61	-4	48	108	61	-2	53
		Large vapour leak	Flash fire	LFL	12	1	0	7	14	1	0	8	11	1	0	6	14	1	0	8	15	1	0	9
			VCE	5 psi	4	4	-4	0	4	4	-4	0	3	3	-3	0	4	4	-4	0	4	4	-4	0
				3 psi	8	8	-8	0	8	8	-8	0	7	7	-7	0	8	8	-8	0	8	8	-8	0
				2 psi	12	12	-12	0	12	12	-12	0	11	11	-11	0	12	12	-12	0	12	12	-12	0
			Jet fire	Fire zone	20	3	4	12	20	3	4	12	23	3	5	14	20	3	4	12	19	3	5	12
				20.9 kW/m2	22	6	4	13	22	6	4	13	25	6	5	15	22	6	4	13	20	5	4	12
				14.4 kW/m2	24	9	4	14	24	9	4	14	27	8	5	16	24	9	4	14	22	7	4	13
				7.3 kW/m2	28	13	4	16	28	13	4	16	29	13	3	16	28	13	4	16	27	14	3	15
		Medium liquid leak	Flash fire	LFL	37	1	6	28	40	2	6	30	32	1	6	22	42	2	6	32	47	3	6	34
			VCE	5 psi	25	25	-25	0	25	25	-25	0	24	24	-24	0	27	27	-27	0	29	29	-29	0
				3 psi	49	49	-49	0	51	51	-51	0	48	48	-48	0	53	53	-53	0	59	59	-59	0
				2 psi	75	75	-75	0	77	77	-77	0	74	74	-74	0	81	81	-81	0	90	90	-90	0
			Jet fire	Fire zone	39	14	1	20	39	14	1	20	35	14	1	17	39	14	1	20	39	14	1	20
				20.9 kW/m2	42	18	1	21	42	18	1	21	38	18	0	19	43	19	1	22	48	19	1	24
				14.4 kW/m2	45	21	1	23	45	21	1	23	41	21	-1	20	46	23	0	23	51	23	1	26
				7.3 kW/m2	53	31	-3	25	53	31	-3	25	50	31	-4	23	53	21	-1	26	58	32	0	29
3	Filling line to storage vessel	Full bore Rupture	Flash fire	LFL	19	1	0	13	20	1	0	14	16	1	0	10	21	1	0	16	23	1	0	18
			VCE	5 psi	6	6	-6	0	6	6	-6	0	4	4	-4	0	6	6	-6	0	7	7	-7	0
				3 psi	12	12	-12	0	13	13	-13	0	9	9	-9	0	13	13	-13	0	14	14	-14	0
				2 psi	18	18	-18	0	19	19	-19	0	14	14	-14	0	20	20	-20	0	22	22	-22	0
			Jet fire	Fire zone	25	8	1	13	25	8	1	13	22	9	1	11	25	8	1	13	29	8	3	16
				20.9 kW/m2	27	11	0	14	27	11	0	14	25	11	1	13	27	11	1	13	31	11	1	16
				14.4 kW/m2	29	14	-1	14	29	14	-1	14	27	14	-1	13	29	14	0	14	33	14	1	17
				7.3 kW/m2	34	19	-2	17	34	19	-2	17	31	19	-3	14	34	19	0	17	37	20	-1	18
		Leak	Flash fire	LFL	12	1	0	8	14	1	0	9	10	1	0	7	14	1	0	9	17	1	0	13
			VCE	5 psi	4	4	-4	0	4	4	-4	0	3	3	-3	0	4	4	-4	0	4	4	-4	0

Section No.	Description	Leak Size	Outcome	Criteria	Weather Conditions 3B				3D				7D				3E				1.4F			
					d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m
				3 psi	8	8	-8	0	8	8	-8	0	7	7	-7	0	8	8	-8	0	8	8	-8	0
				2 psi	12	12	-12	0	12	12	-12	0	11	11	-11	0	13	13	-13	0	13	13	-13	0
			Jet fire	Fire zone	20	6	2	11	20	6	2	11	17	7	1	9	20	6	2	11	23	6	3	12
				20.9 kW/m2	22	9	2	12	22	9	2	12	19	9	-1	9	22	9	2	12	24	9	2	12
				14.4 kW/m2	23	11	1	12	23	11	1	12	21	11	-1	10	23	11	1	12	26	11	2	14
				7.3 kW/m2	27	14	1	14	27	14	1	14	25	15	-1	12	27	14	1	14	29	15	-1	14
4	Line from storage vessel to vaporizers	Full bore Rupture	Flash fire	LFL	38	2	8	27	41	2	8	30	31	1	8	20	43	2	8	33	48	4	8	30
			VCE	5 psi	21	21	-21	0	21	21	-21	0	18	18	-18	0	22	22	-22	0	24	24	-24	0
				3 psi	33	33	-33	0	34	34	-34	0	29	29	-29	0	36	36	-36	0	39	39	-39	0
				2 psi	47	47	-47	0	48	48	-48	0	41	41	-41	0	51	51	-51	0	55	55	-55	0
			Jet fire	Fire zone	38	13	1	19	38	13	1	19	33	14	0	16	38	13	1	19	43	12	1	22
				20.9 kW/m2	42	18	1	21	42	18	1	21	38	18	0	19	42	18	1	21	46	18	1	23
				14.4 kW/m2	45	22	1	23	45	22	1	23	41	21	-1	20	45	22	1	23	49	22	1	25
				7.3 kW/m2	52	30	-2	25	52	30	-2	25	48	30	-4	22	52	30	-2	25	56	30	0	28
		Leak	Flash fire	LFL	12	1	0	8	14	1	0	9	10	1	0	7	14	1	0	9	17	1	0	13
			VCE	5 psi	7	7	-7	0	7	7	-7	0	7	7	-7	0	8	8	-8	0	8	8	-8	0
				3 psi	12	12	-12	0	12	12	-12	0	11	11	-11	0	12	12	-12	0	13	13	-13	0
				2 psi	17	17	-17	0	17	17	-17	0	15	15	-15	0	18	18	-18	0	18	18	-18	0
			Jet fire	Fire zone	20	6	2	11	20	6	2	11	17	7	1	9	20	6	2	11	23	6	3	12
				20.9 kW/m2	22	9	2	12	22	9	2	12	19	9	-1	9	22	9	2	12	24	9	2	12
				14.4 kW/m2	23	11	1	12	23	11	1	12	21	11	-1	10	23	11	1	12	26	11	2	14
				7.3 kW/m2	27	14	1	14	27	14	1	14	25	15	-1	12	27	14	1	14	29	15	-1	14
5	Vaporisers	Full bore Rupture	Flash fire	LFL	5	1	0	3	5	1	0	3	4	1	0	2	5	1	0	3	6	1	0	4
			VCE	5 psi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				3 psi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				2 psi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Jet fire	Fire zone	10	1	0	9	10	1	0	9	10	1	0	9	10	1	0	9	10	1	0	9
				20.9 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				14.4 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				7.3 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Flexible hose	Full bore Rupture	Flash fire	LFL	19	1	0	13	20	1	0	14	16	1	0	10	21	1	0	16	23	1	0	18

Section No.	Description	Leak Size	Outcome	Criteria	Weather Conditions 3B				3D				7D				3E				1.4F			
					d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m
			VCE	5 psi	6	6	-6	0	6	6	-6	0	4	4	-4	0	6	6	-6	0	7	7	-7	0
				3 psi	12	12	-12	0	13	13	-13	0	9	9	-9	0	13	13	-13	0	14	14	-14	0
				2 psi	18	18	-18	0	19	19	-19	0	14	14	-14	0	20	20	-20	0	22	22	-22	0
			Jet fire	Fire zone	25	8	1	13	25	8	1	13	22	9	1	11	25	8	1	13	29	8	3	13
				20.9 kW/m2	27	11	0	14	27	11	0	14	25	11	1	13	27	11	1	13	31	11	1	16
				14.4 kW/m2	29	14	-1	14	29	14	-1	14	27	14	-1	13	29	14	0	14	33	14	1	17
				7.3 kW/m2	34	19	-2	17	34	19	-2	17	31	19	-3	14	34	19	0	17	37	20	-1	18
		Leak	Flash fire	LFL	12	1	0	8	14	1	0	9	10	1	0	7	14	1	0	9	17	1	0	13
			VCE	5 psi	4	4	-4	0	4	4	-4	0	3	3	-3	0	4	4	-4	0	4	4	-4	0
				3 psi	8	8	-8	0	8	8	-8	0	7	7	-7	0	8	8	-8	0	8	8	-8	0
				2 psi	12	12	-12	0	12	12	-12	0	11	11	-11	0	13	13	-13	0	13	13	-13	0
			Jet fire	Fire zone	20	6	2	11	20	6	2	11	17	7	1	9	20	6	2	11	23	6	3	12
				20.9 kW/m2	22	9	2	12	22	9	2	12	19	9	-1	9	22	9	2	12	24	9	2	12
				14.4 kW/m2	23	11	1	12	23	11	1	12	21	11	-1	10	23	11	1	12	26	11	2	14
				7.3 kW/m2	27	14	1	14	27	14	1	14	25	15	-1	12	27	14	1	14	29	15	-1	14
7	Send-out piping downstream of vaporizers	Full bore Rupture	Flash fire	LFL	14	1	0	10	16	1	0	11	11	1	0	6	17	1	0	12	23	2	0	16
			VCE	5 psi	5	5	-5	0	7	7	-7	0	4	4	-4	0	8	8	-8	0	12	12	-12	0
				3 psi	11	11	-11	0	14	14	-14	0	9	9	-9	0	16	16	-16	0	25	25	-25	0
				2 psi	17	17	-17	0	22	22	-22	0	13	13	-13	0	24	24	-24	0	38	38	-38	0
			Jet fire	Fire zone	24	1	0	23	24	1	0	23	24	1	0	23	24	1	0	23	24	1	0	23
				20.9 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				14.4 kW/m2	24	2	2	13	24	2	2	13	24	2	2	13	24	2	2	13	19	2	1	10
				7.3 kW/m2	25	4	1	13	25	4	1	13	25	4	1	13	25	4	1	13	20	5	0	10
		Leak	Flash fire	LFL	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	3	1	0	2
			VCE	5 psi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				3 psi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				2 psi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Jet fire	Fire zone	5	1	0	4	5	1	0	4	5	1	0	4	5	1	0	4	5	1	0	4
				20.9 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				14.4 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				7.3 kW/m2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Section No.	Description	Leak Size	Outcome	Criteria	Weather Conditions																			
					3B				3D				7D				3E				1.4F			
					d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m
8	LPG Cylinder 13.5kg	Rupture	Flash fire	LFL	11	3	-2	2	11	3	-2	2	15	3	-2	4	11	4	-2	5	6	4	-3	2
			Fireball	Fireball radius	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0
		Leak	Flash fire	LFL	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
			Jet fire	Fire zone	2	0	0	1	2	0	0	1	2	0	0	1	2	0	0	1	2	0	0	1
				20.9 kW/m2	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
				14.4 kW/m2	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
				7.3 kW/m2	3	1	0	1	3	1	0	1	3	1	0	1	3	1	0	1	3	1	0	1
		Escalation	BLEVE	Fireball radius	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0
9	LPG Cylinder 49kg	Rupture	Flash fire	LFL	19	6	-4	8	19	6	-4	8	29	5	-3	16	17	6	-4	7	11	6	-5	3
			Fireball	Fireball radius	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0
		Leak	Flash fire	LFL	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
			Jet fire	Fire zone	2	0	0	1	2	0	0	1	2	0	0	1	2	0	0	1	2	0	0	1
				20.9 kW/m2	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
				14.4 kW/m2	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1	2	1	0	1
				7.3 kW/m2	3	1	0	1	3	1	0	1	3	1	0	1	3	1	0	1	3	1	0	1
		Escalation	BLEVE	Fireball radius	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0
10	Cylinder Wagon 13.5kg	Rupture	Flash fire	LFL	11	3	-2	2	11	3	-2	2	15	3	-2	4	11	4	-2	5	6	4	-3	2
			Fireball	Fireball radius	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0
		Escalation	BLEVE	Fireball radius	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0	7	7	-7	0
11	Cylinder Wagon 49kg	Rupture	Flash fire	LFL	19	6	-4	8	19	6	-4	8	29	5	-3	16	17	6	-4	7	11	6	-5	3
			Fireball	Fireball radius	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0
		Escalation	BLEVE	Fireball radius	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0	11	11	-11	0
12	Petrol tanker	Rupture	Pool fire	Fire zone	42	42	-42	0	42	42	-42	0	42	42	-42	0	42	42	-42	0	42	42	-42	0
				14.4 kW/m2	44	44	-44	0	44	44	-44	0	43	43	-43	0	44	44	-44	0	44	44	-44	0
				7.3 kW/m2	68	54	-44	12	68	54	-44	12	79	60	-43	18	68	54	-44	12	59	50	-45	7
		Leak	Pool fire	Fire zone	18	18	-18	0	18	18	-18	0	18	18	-18	0	18	18	-18	0	18	18	-18	0
				14.4 kW/m2	19	19	-19	0	19	19	-19	0	19	19	-19	0	19	19	-19	0	19	19	-19	0
				7.3 kW/m2	38	26	-19	11	38	26	-19	11	45	29	-19	15	38	26	-19	11	34	25	-19	8
13	Diesel tanker	Rupture	Pool fire	Fire zone	40	40	-40	0	40	40	-40	0	40	40	-40	0	40	40	-40	0	40	40	-40	0
				14.4 kW/m2	41	41	-41	0	41	41	-41	0	41	41	-41	0	41	41	-41	0	41	41	-41	0
				7.3 kW/m2	65	51	-41	12	65	51	-41	12	76	57	-42	17	65	51	-41	12	56	48	-44	6

Section No.	Description	Leak Size	Outcome	Criteria	Weather Conditions																			
					3B				3D				7D				3E				1.4F			
					d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m	d	c	s	m
		Leak	Pool fire	Fire zone	22	22	-22	0	22	22	-22	0	22	22	-22	0	22	22	-22	0	22	22	-22	0
				14.4 kW/m2	26	23	-22	3	26	23	-22	3	25	23	-22	2	26	23	-22	3	26	23	-22	3
				7.3 kW/m2	43	30	-22	12	43	30	-22	12	50	34	-22	15	43	30	-22	12	37	28	-22	8

6 RISK RESULTS

6.1 RISK SUMMATION

Risk summation combines the estimates of the consequences of an event with the event frequencies to give an estimate of the resulting risk of fatalities. The Consultants in-house software RISKPLOT™ has been used for risk summation. The inputs to the software comprise a number of files:

- *Release cases file* detailing all identified hazardous events and their frequencies;
- *Release location file* containing the locations of hazardous events either at given points or along given routes;
- *Consequences file/effect zone dimensions*, which inputs the calculated consequences of each event under each possible weather condition, as appropriate;
- *Weather frequencies file* that details the local meteorological data according to a matrix of weather class (speed/stability combinations) and wind directions;
- *Population data file*. The population data are divided into geographical areas of polygonal shape dependent on the population density within that area. Point and line populations may also be defined.

RISKPLOT™ takes into account all of the above information and models each event under each combination of conditions (weather, location, etc.). It calculates the number of fatalities from each event with a given probability of occurrence. The number of fatalities is based upon the proportion of each population area overlapped by the hazard effect.

The two types of risk measures considered are societal risk and individual risk.

6.2 SOCIETAL RISK

Societal risk is defined as the risk to a group of people due to all hazards arising from a hazardous installation or activity. The simplest measure of societal risk is the Rate of Death or Potential Loss of Life (PLL), which is equivalent to the predicted number of fatalities per year.

The frequency (f) and fatalities (N) associated with each outcome event are derived as described in earlier sections. The Potential Loss of Life is then calculated as follows:

$$PLL = f_1N_1 + f_2N_2 + f_3N_3 + \ldots + f_nN_n$$

The PLL results are presented in *Table 6.1* for the existing, construction and

future phases. The highest risks are associated with the construction phase due to the additional worker population. The PLL for this year amounts to 3.39×10^{-5} per year, or equivalently, one fatality every 30,000 years.

The future 2031 case is marginally higher than the existing risks, in line with the general growth in residential population assumed in the analysis. This increase is not due to MTRC operations however, since all station population will be below ground and unaffected by any incidents at the LPG Depot.

Table 6.1 Potential Loss of Life

Project Phase	PLL (per year)		
	LPG compound	LPG transit	Overall
Existing risk (2009)	5.96×10^{-6}	1.25×10^{-5}	1.84×10^{-5}
Construction phase (2014)	1.99×10^{-5}	1.41×10^{-5}	3.39×10^{-5}
Future operational phase (2031)	6.38×10^{-6}	1.55×10^{-5}	2.19×10^{-5}

A breakdown of PLL by population group for the construction year 2014 is shown in *Table 6.2*. It can be seen that a major component of the societal risks arise from the Preliminary Treatment Works construction workers. This is due to the close proximity of these workers with the LPG Compound. The additional population injected from MTR workers contribute only 1% to the societal risks since they are located further from the LPG Depot. This is a negligible increase in risks.

Table 6.2 PLL Breakdown by Population Group for Construction Phase

Population Group	PLL	% of Total
MTR construction workers	1.88×10^{-7}	1 %
PTW construction workers	1.46×10^{-5}	43 %
Other population	1.92×10^{-5}	56 %
Total	3.39×10^{-5}	100 %

Societal risk can also be expressed in the form of an F-N curve, which represents the cumulative frequency (F) of all event outcomes leading to N or more fatalities. This representation of societal risk highlights the potential for accidents involving large numbers of fatalities.

FN curves for the LPG Depot are shown in *Figure 6.1*. The risks for the current year, construction phase and future operational phase all lie in the acceptable region. It may be noted that the curves are in good agreement with the previous HATS study (ENSR, 2008). Although the current analysis made some refinements to the methodology, the approach is essentially very similar to that adopted by ENSR (2008). The main difference is in the indoor harm probabilities and the inclusion of projectile effects from the LPG Transit Depot. A test was conducted using the same indoor harm probabilities as those used in the previous HATS study. This increased the risks marginally and further improved the agreement between the two studies, but the differences are not significant.

Comparing the existing risks (2009) with the future operational phase (2031), it

can be seen that the societal risks increase slightly. As discussed above, this is due to the general increase in population in the surrounding area, modelled as a 1% increase per year. The population within South Horizons station does not contribute to this increase since the population is underground and will not be impacted by incidents at the LPG Depot.

The highest risks are again observed during the construction phase, due to the additional outdoor population on work sites. A breakdown of risks by population group for the construction phase is shown in *Figure 6.2*. It can be seen that the increase is predominantly due to workers at the Preliminary Treatment Works (PTW) which is immediately adjacent to the LPG Compound site. Risks to MTR construction workers are very much smaller and make negligible contribution to the overall societal risks.

Separate results for the LPG Compound and LPG Transit depot are shown in *Figures 6.3* and *6.4*.

Figure 6.1 Societal Risk Results

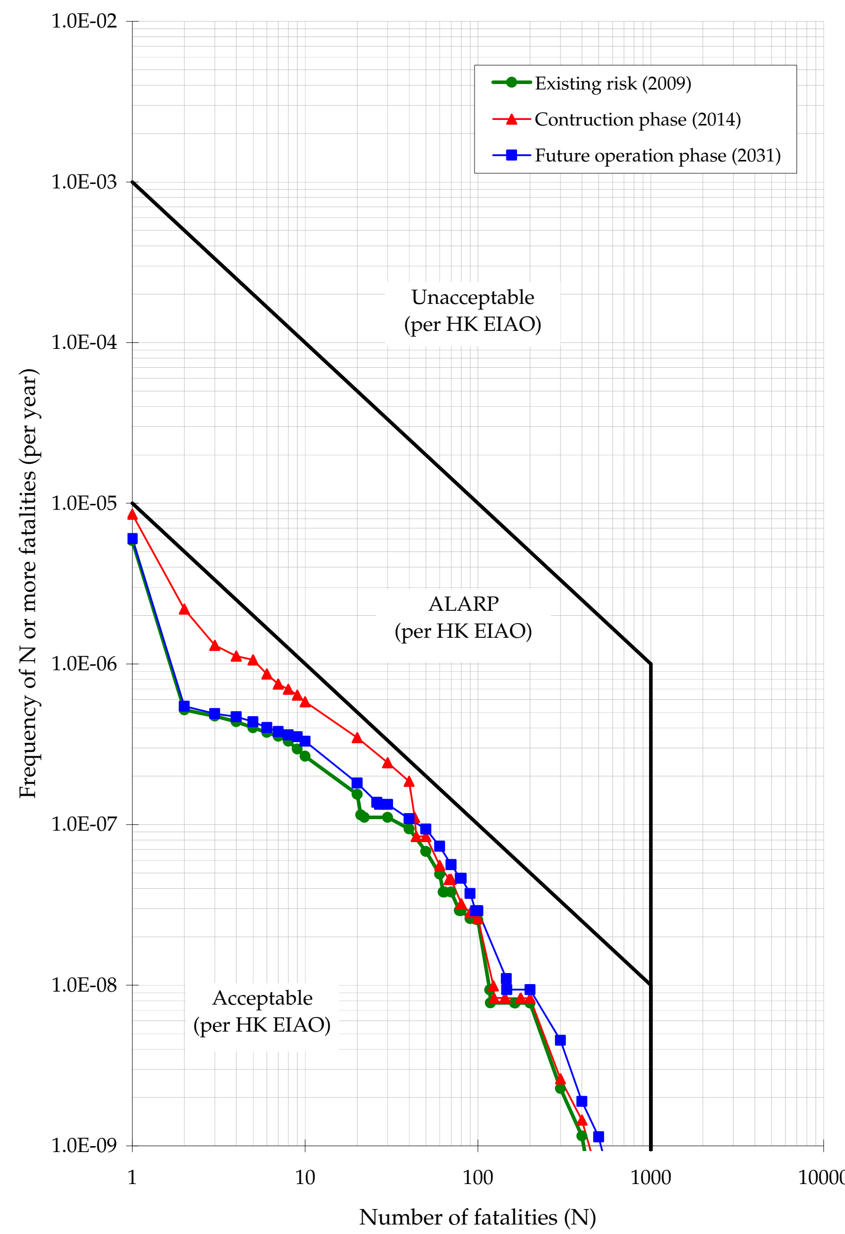


Figure 6.2 Construction Phase Risk Breakdown by Population Type

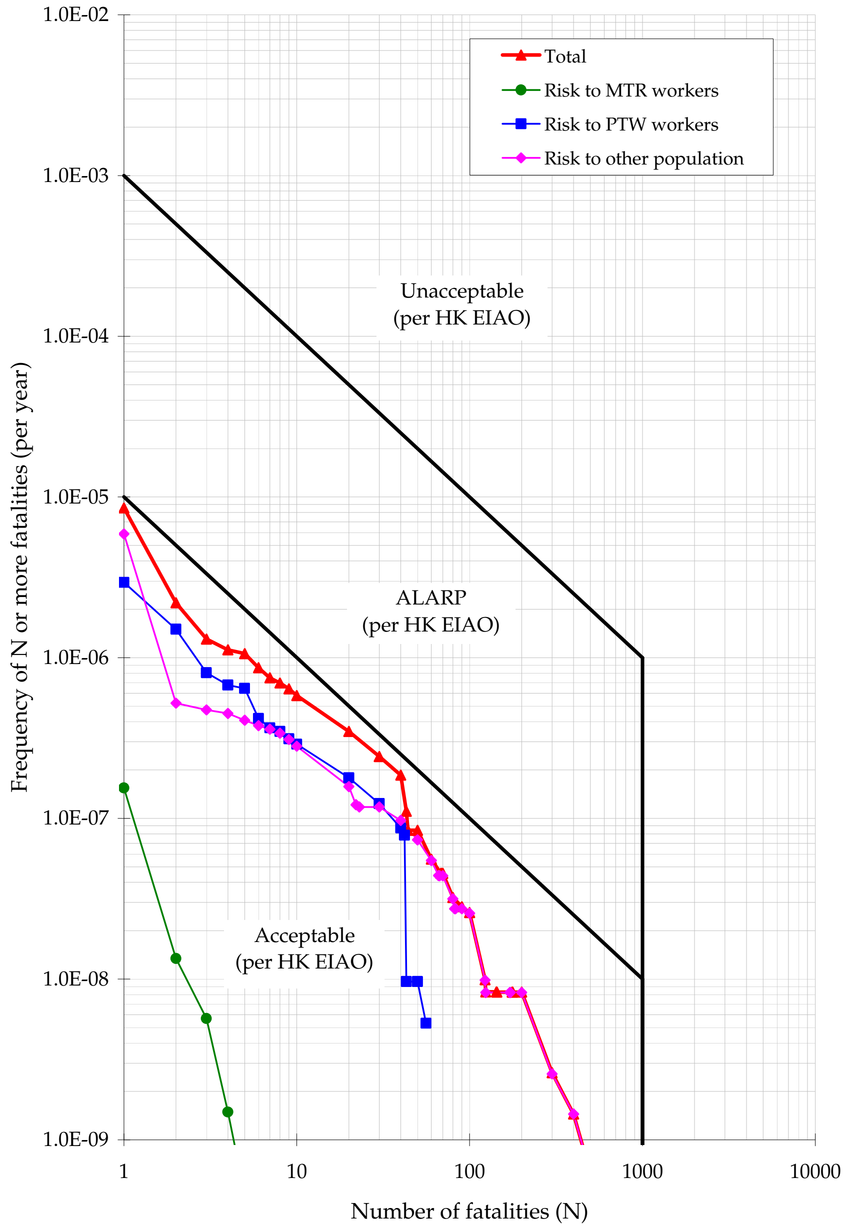


Figure 6.3 Societal Risk Results (LPG Compound)

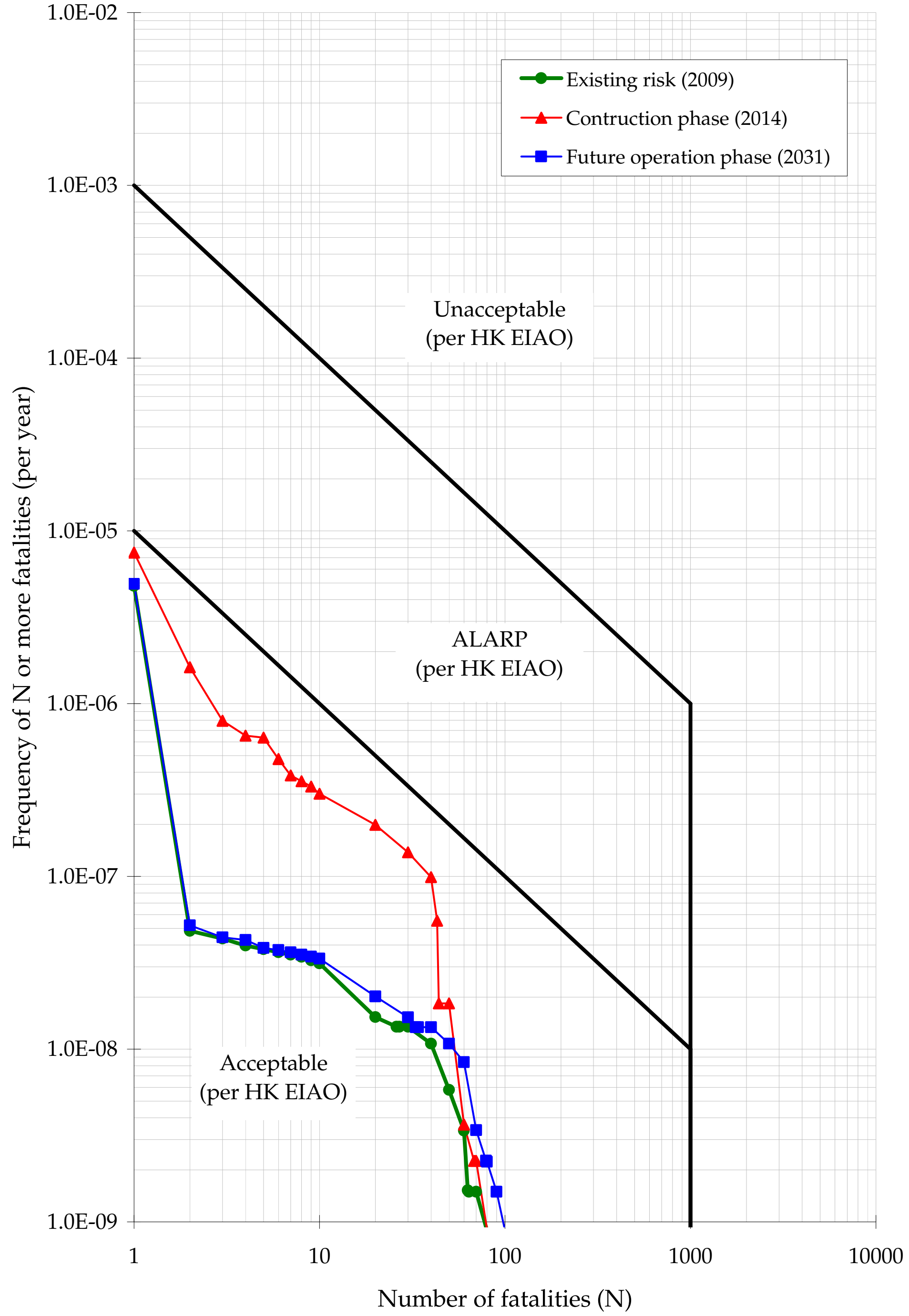
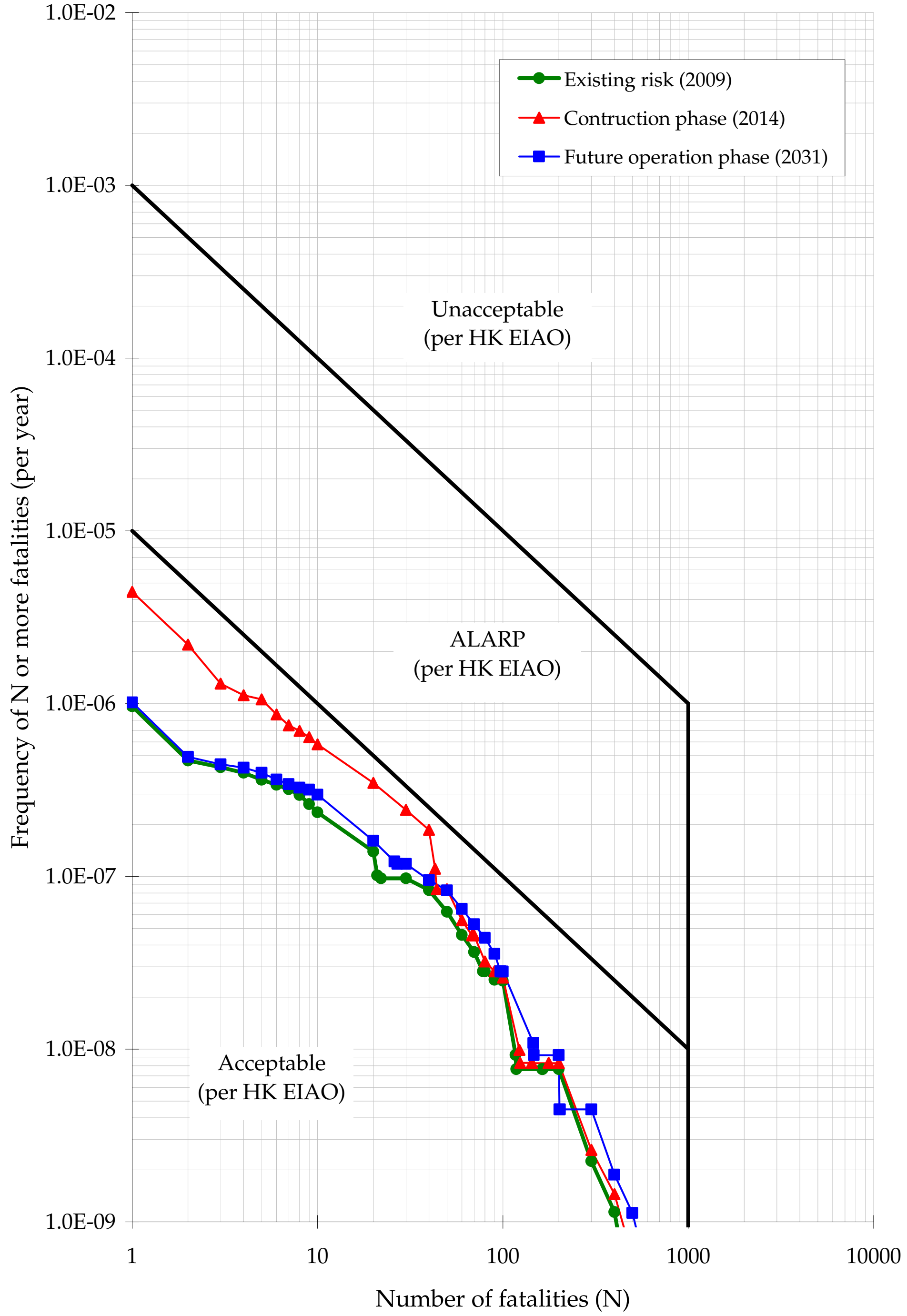


Figure 6.4 ***Societal Risk Results (LPG Transit Depot)***



6.3 INDIVIDUAL RISK

Individual risk may be defined as the frequency of fatality per individual per year due to the realisation of specified hazards. Individual Risk may be derived for a hypothetical individual present at a location 100% of time or a named individual considering the probability of his presence etc. (the latter case is known as Personal Individual Risk).

Individual risk contours for the LPG Depot are presented in *Figure 6.5, Figure* 6.6 *and Figure* 6.7. The 1×10^{-5} per year risk contour lies inside the depot boundary and therefore meets the Hong Kong risk criterion for individual

risk.

It may be noted that individual risk, unlike societal risk, is a property of the LPG Depot alone and is unaffected by surrounding population. As such, individual risk is unchanged by any changes in population that may arise from the project.

The highest individual risk occurs in the Storage Shed area due to the large number of cylinders stored there. However, incidents involving LPG cylinders have only short range effects and the risks diminish quickly away from the Storage Shed. The risks at greater distances from the facility are caused by flash fires from releases from larger inventories such as road tankers and storage vessels.

Figure 6.5 ***Individual Risk Contours***

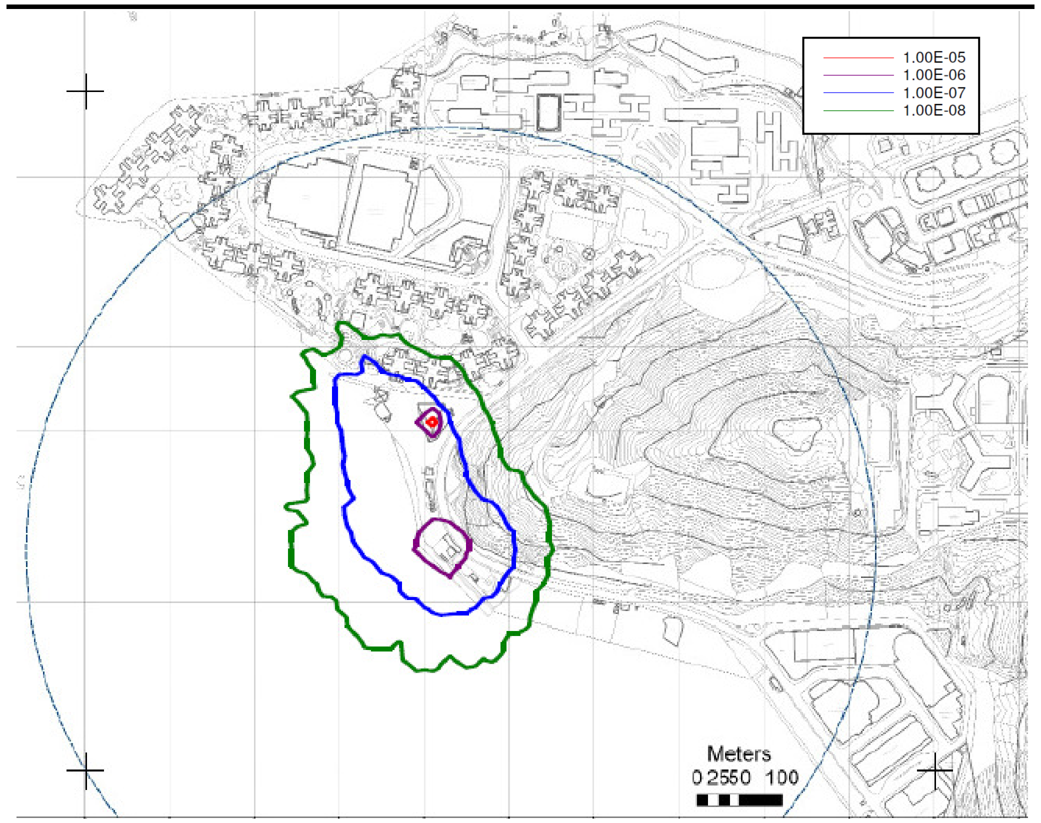


Figure 6.6 Individual Risk Contours (LPG Compound)

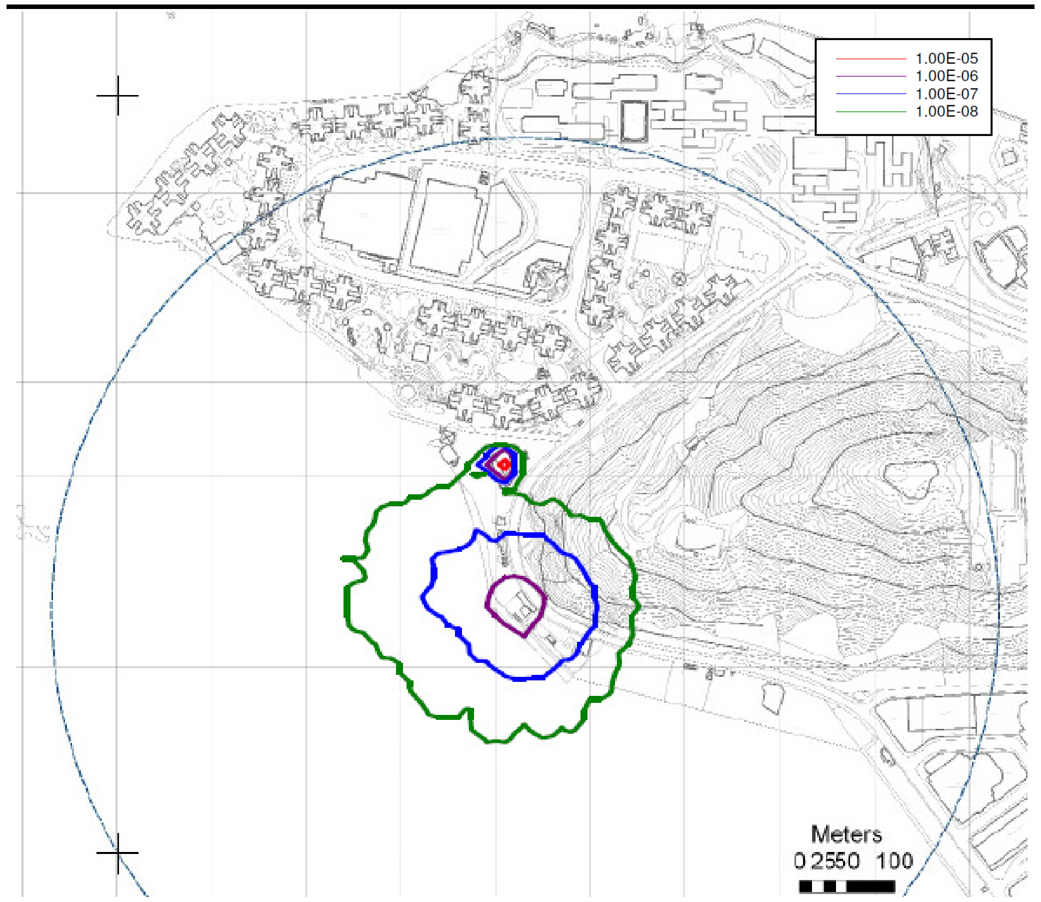
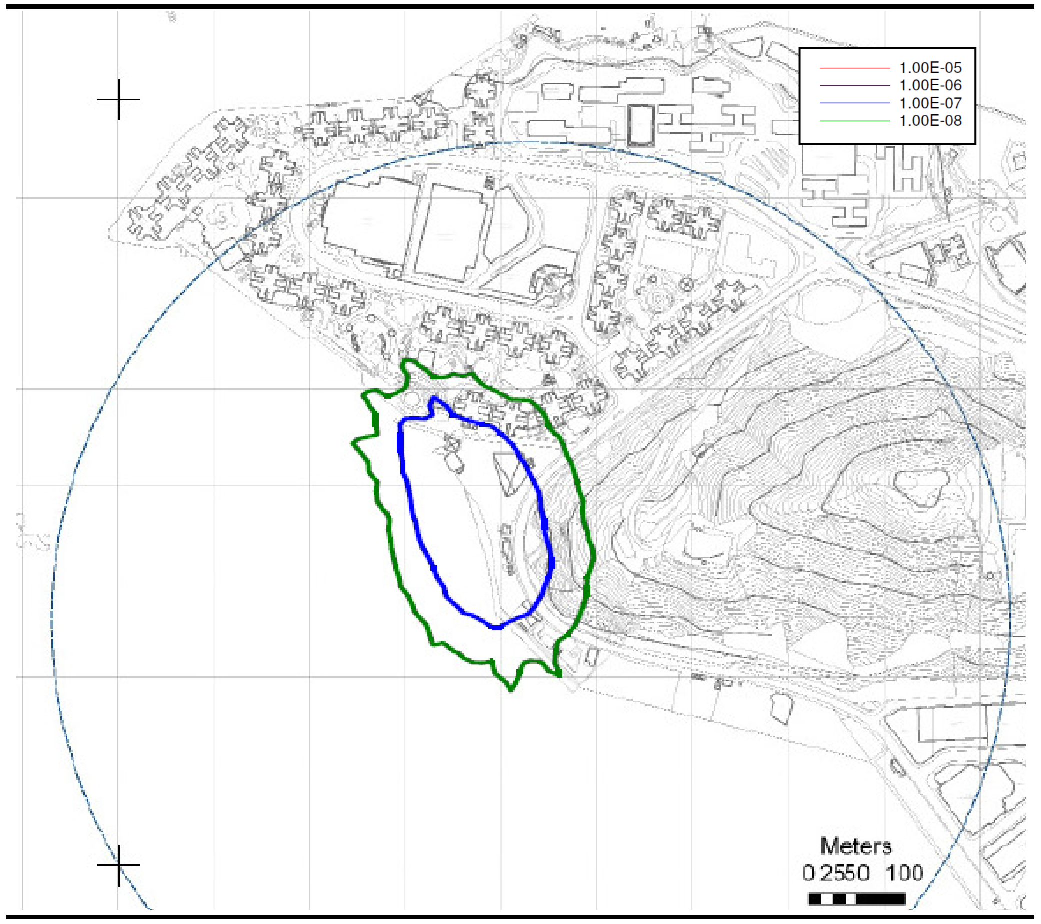


Figure 6.7 Individual Risk Contours (LPG Transit Depot)



6.4 *THE LPG DEPOT AND EXPLOSIVES DELIVERIES VIA LEE NAM ROAD*

Explosives deliveries from the Chung Hom Shan Magazine to the Ap Lei Chau delivery point will use Lee Nam Road, a section of which adjoins the LPG Depot. In the event of an explosives vehicle detonation within this road section, there could be an impact on the LPG containing equipment inside the depot. Conversely an explosion in the LPG facility could impact on the explosives vehicle. This section presents an assessment of the risk that the explosives vehicle poses to or suffers from the LPG Depot.

Since the entire LPG Depot is enclosed by a 2.4 m high solid boundary wall, damage to the LPG facilities is considered only possible if the explosion overpressure is sufficient to damage the wall and the fragments generated strike the equipment inside.

Lees suggests an overpressure of 2.3 psi as the lower limit of serious structural damage and an overpressure of 2 -3 psi could shatter concrete (not reinforced) or cinder block walls (Lees, 1996). It is therefore deemed appropriate to assume an overpressure of below 2 psi would not affect the equipment inside the boundary wall. For comparison, an overpressures below 2 psi is expected to result in only minor damage such as slight distortion of the steel frame of a clad building (1.3 psi), shattering of windows (0.5 – 1 psi) and minor structural damage (0.4 psi).

In the worst case the maximum quantity of explosives to be transported along Lee Nam Road will be 207 kg TNT equivalent. Based on the TNT explosion model from the Yellow Book, an overpressure of 2 psi could reach up to a distance of 62 m from the source of explosion.

The two concerned road sections to be considered are a 10 m route along the boundary of the LPG compound and a 40 m route along the cylinder shed. For the LPG compound, the vulnerable length of the road can be calculated as 134 m (i.e. 10m + 62m + 62m). Based on the maximum foreseeable usage of Lee Nam Road of 787 trips per year and the probability of initiation of explosives during road transport (non-expressway) of 7.96×10^{-10} per km, the probability of truck explosion impacting the LPG compound is 8.4×10^{-8} per year. Similarly, the frequency of impacting the LPG shed can be calculated as 1.0×10^{-7} per year.

It should be noted that in the ALARP case a maximum 250 kg load (258kgTNT equivalent) can be transported for a maximum of 670 trips, with a 2 psi overpressure distance of 67m, giving corresponding impact frequencies of 7.7×10^{-8} and 9.3×10^{-8}, which is less than in the worst case.

Even without considering that the tanks are mounded, the probability of the equipment being struck, and then being struck with a high energy fragment sufficient to rupture the steel vessels or piping, these explosion impact frequencies are already about 3 to 4 orders of magnitude lower than the base event frequencies assumed for the QRA (*Table 4.1* and *4.2*). For example, the failure rate of LPG vessels is 1.24×10^{-5} per year and for LPG cylinders it is

7.92×10^{-3} per year. Therefore, the increased risk of a truck explosion impacting the equipment inside the depot is considered negligible.

The scenario of a major fire or explosion within the LPG depot leading to an initiation of explosives in the truck is also considered negligible from the risk standpoint. The presence time of an explosives truck on the road along the LPG Depot is estimated to be about 3.5 hours per year (assuming a driving speed of 50km/hr for a 250m road), this equates to a presence factor of 3.98×10^{-4}. Combining this presence factor with the event frequencies of a jet fire, explosion or flash-fire of between 10^{-5} and 10^{-7} per year (*Table 4.7*), and considering the directional probability of a jet fire impinging on the explosives truck, the protection from the boundary wall, and that a flash-fire would not ingress into the truck, would give frequency values of well below 10^{-9} per year.

It is therefore concluded that the explosives truck travelling alongside the LPG Depot on Lee Nam Road poses negligible additional risk to the LPG Depot and vice versa.

7 CONCLUSIONS

A QRA was conducted on Shell's LPG Depot in Ap Lei Chau to assess the increase in societal risk from the SIL(E) construction and operation. The methodology adopted followed closely that of an earlier study conducted for the same facility as part of the Harbour Area Treatment Scheme (HATS) assessment. Refinements to the methodology were applied in a few respects, but nevertheless, the results obtained are closely consistent with those obtained from the previous study.

Results for the existing risks, construction phase and future operational phase all lie in the acceptable region of the FN curves, although they lie close to the ALARP region. Societal risks are highest during the construction phase which overlaps with construction for the Preliminary Treatment Works. The additional population from these groups of workers increases the societal risks but risks remain in the acceptable region. This increase in risk is predominantly due to workers at the Preliminary Treatment Works site which is immediately adjacent to the LPG Depot. Additional risks from the MTR construction workers are negligible and amount to about 1%.

The South Horizons station, once complete, is also expected to make negligible contribution to societal risks since the station population will be below ground and will be unaffected by possible incidents at the LPG Depot.

Assessment of large gas releases from road tanker or storage tank ruptures suggest that it is not possible for flammable gas to ingress into the South Horizons Station through vent ducts in significant quantities. Nevertheless, as an additional precaution, it is recommended to provide gas detectors in the air intakes which automatically close the HVAC dampers in case of gas detection.

The 10^{-5} per year individual risk contour remains on site and meets Hong Kong Risk Guidelines criteria.

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