13. Hazard to Life Assessment

13.1 Introduction

13.1.1 Background

Water Supplies Department (WSD) of HKSAR proposes to construct and operate a desalination plant (hereafter referred to as "the Desalination Plant") using Seawater Reverse Osmosis (SWRO) technology in Tseung Kwan O (TKO) Area 137, together with the associated fresh water transfer facilities to the existing TKO Fresh Water Primary Service Reservoir (TKOFWPSR) (hereafter referred to as "the Project").

The Project comprises the following components/works:

(i) A new desalination plant in TKO Area 137 with an initial capacity of 135 Mld, expandable to an ultimate capacity of 270 Mld in the future.

(ii) A dedicated trunk feed system for the transfer of fresh water output from the Desalination Plant to the existing TKOFWPSR in Po Lam. The system consists of a new pumping station, a new treated water storage tank, about 9 km of 1200 mm diameter fresh water mains along Wan Po Road, Po Hong Road and Tsui Lam Road, and the associated pipeworks and ancillary facilities including fittings/valves, leakage, flow and pressure monitoring facilities etc. The exact location and details of the new pumping station will be identified during the EIA study.

(iii) Natural slope mitigation works including construction of debris barriers and boulder traps at the toe of the slope and stabilization of natural slopes and boulders on the natural slope within the Clear Water Bay Country Park, which overlooks the northeast boundary of the new desalination plant at TKO Area 137.

(iv) All the associated civil, structural, geotechnical, landscaping, electrical, and mechanical works.

The location and general layout of the Project are shown in Figure 13.1.

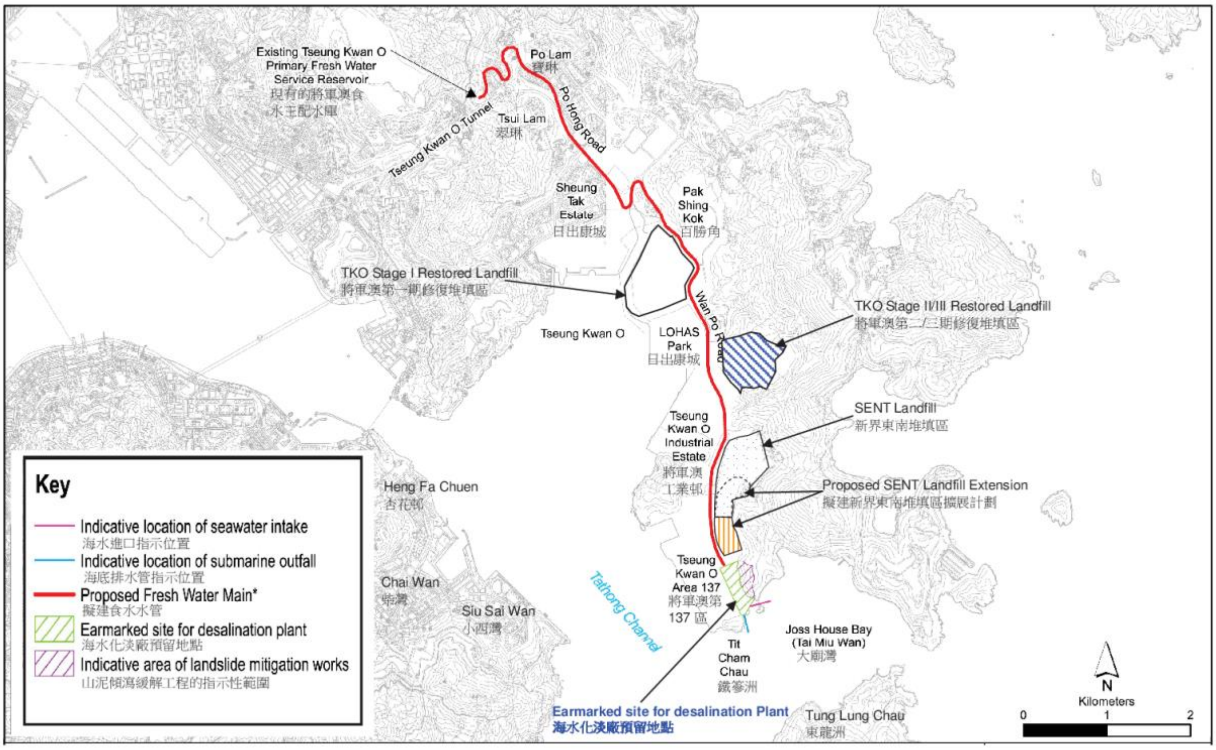


Figure 13.1 Location of the Proposed Desalination Plant at Tseung Kwan O

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-266/2013 for this Project (EIA Study Brief). Section 3.4.11 of the EIA Study Brief requires a Hazard to Life assessment to be conducted for storage, handling and transport of chlorine and other dangerous goods (DGs) associated with the Desalination Plant, which is identified as a Potentially Hazardous Installations (PHI).

Black & Veatch Hong Kong Ltd (B&V) is the main consultant of this EIA study, and undertakes the above captioned Hazard to Life Assessment for storage, handling and transport of chlorine and other dangerous goods (DGs) associated with the Desalination Plant and propose risk mitigation measures if necessary. The criteria and guidelines for assessing Hazard to Life are stated in Annexes 4 and 22 of the TM (EIAO-TM Criteria).

As part of the EIA Study Brief, the Hazard to Life assessment methodology has been agreed with the Director taking into account relevant previous studies. The Hazard to Life assessment requirements of the EIA Study Brief are shown below.

Requirements for Hazard to Life Assessment

1. *The Applicant shall investigate methods to avoid and/or minimize risks from chlorine and other DGs. The Applicant shall carry out hazard assessment to evaluate potential hazard to life during construction and operation stages of the Project. The hazard assessment shall include the following:*

   (i) *Identify hazardous scenarios associated with the transport (on-site and off-site), storage and use of chlorine and other DGs at the Project 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.

2. *The hazard assessment shall also include a cumulative risk assessment of the Project, through interaction or in combination with other existing, committed and planned developments involving DGs in the vicinity of the Project (e.g. explosive stores and transport routes in TKO).*

3. *The methodology to be used in the hazard assessment shall be agreed with the Director and be consistent with previous studies having similar issues (e.g. Shatin to Central Link [2] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3]).*

This document presents the methodology and results of the Hazard to Life assessment for storage, handling and transport (on-site and off-site) of chlorine and other dangerous goods (DGs) associated with the Desalination Plant, and cumulative risk assessment in the vicinity of the proposed Desalination Plant as part of the EIA study.

13.1.2 Study Objectives, Scope and Risk Criteria

Study Objectives and Scope

The main objective of this Hazard to Life assessment is to assess the risks associated with storage, handling and transport of chlorine and other dangerous goods (DGs) for the desalination plant operation. Risk results were compared to EIAO-TM Criteria and practical mitigation measures, where applicable, were identified to satisfy the EIAO-TM Criteria.

The study is particularly focused on the following:

- Potentially Hazardous Installations (PHI) QRA: Storage, Use and On-site Road Transport of Chlorine (from TKO Area 137 Pier to Chlorination Store of the Desalination Plant)[1];
- Off-site Marine Transport of Chlorine (from Sham Shui Kok Dock to TKO Area 137 Pier);
- Storage, Use and Transport of Sodium Hypochlorite associated with the Desalination Plant Operation;
- Transport (On-site and off-site), Storage, Handling of Cryogenic and Pressurised Liquid Carbon Dioxide; and
- Other Risk Associated Issues, including:
  - Storage, Use and Transport of other DGs associated with the Desalination Plant Operation;
  - Explosive Transport in TKO Area 137 (Existing, Committed and Planned Projects Requiring Explosive Transport from TKO 137 Pier); and
  - Explosive Offloading Operation at TKO Area 137 Pier.

Technical and Geographical Scope of the PHI QRA Study

[1] The Desalination Plant is next to the TKO Area 137 Pier, which is fenced to avoid trespass. It is assumed the transportation route from TKO Area 137 Pier to Chlorination Store as **on-site road transport** while transportation route from Sham Shui Kok Dock to TKO Area 137 Pier as **off-site marine transport**.

The technical and geographical scope of the PHI QRA study is defined as follows:

- The study is concerned with the Desalination Plant operated at its ultimate design capacity (representing the highest chlorine storage and handling activities in the Desalination Plant);
- The study is concerned with off-site risk to the general public near the Desalination Plant. Risk posed to on-site population such as operating staff of the Desalination Plant is excluded from the chlorine assessment, but included in the explosives and cumulative assessment; and
- The study assesses the risk to the future population at operation stage in 2036. Chlorine storage and handling are not anticipated during the construction stage of the Desalination Plant. Chlorine will be required for the Testing and Commissioning (T&C) period for the Chlorination Systems. T&C period for the Chlorination Systems will start after the completion of all civil and electrical & mechanical (E&M) works. No construction workers will be present at the Desalination Plant at that time and be affected by accidental chlorine release. The maximum chlorine storage quantity will be about 6 tonnes during T&C period, which is less than that in operation stage (37 tonnes). The risk associated with chlorine during T&C period will be lower than that during operation stage and thus not considered in this study.

The Chlorination Store in the Desalination Plant is designed to store maximum 37 tonnes of liquid chlorine which are contained in 1-tonne chlorine drums. It is classified as a Potentially Hazardous Installations (PHI) according to Hong Kong Planning Standards and Guidelines (HKPSG).

The storage quantity is provided for the disinfection of treated water. It is estimated based on the ultimate plant throughput of 270 Mld desalinated water with the design continuous dosage of 1.5 mg/L chlorine gas and 90 days of storage.

Reference to previous QRA studies of eight Water Treatment Works (8 WTWs) [1], the geographical scope is defined as the area affected by the Lethal Dose (LD) 03 contour of chlorine dispersion (see Section 13.2.8). Population data within the LD03 contour were gathered for inclusion, as appropriate, in the QRA for the Desalination Plant.

<u>EIAO-TM Criteria</u>

The individual risk guidelines and societal risk guidelines specified in Annex 4 of the EIAO-TM are shown below.

<u>Individual Risk (IR)</u>

Individual risk is defined as the frequency of fatality per year to a specific individual due to the realisation of specified hazards, with account taken of presence factors.

The maximum level of off-site individual risk should not exceed 1 in 100,000 per year, i.e. 1×10^{-5} per year.

<u>Societal Risk (SR)</u>

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

Societal risk is also expressed in the form of an FN 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.

The societal risk guidelines expressed in the form of FN curve is shown in Figure 13.2. There are three regions identified:

- Unacceptable region where risk is so high that it should be reduced regardless of the cost of mitigation or the hazardous activity should not proceed;
- ALARP region where risk is tolerable providing it has been reduced to a level As Low As Reasonably Practicable (ALARP); and
- Acceptable region where risk is broadly acceptable and does not require further risk reduction.

The risk guidelines incorporate a special requirement (as seen in Figure 13.2), that no hazardous scenario shall cause more than 1,000 fatalities. If so, the risks are deemed 'Unacceptable' and need to be reduced regardless of the cost.

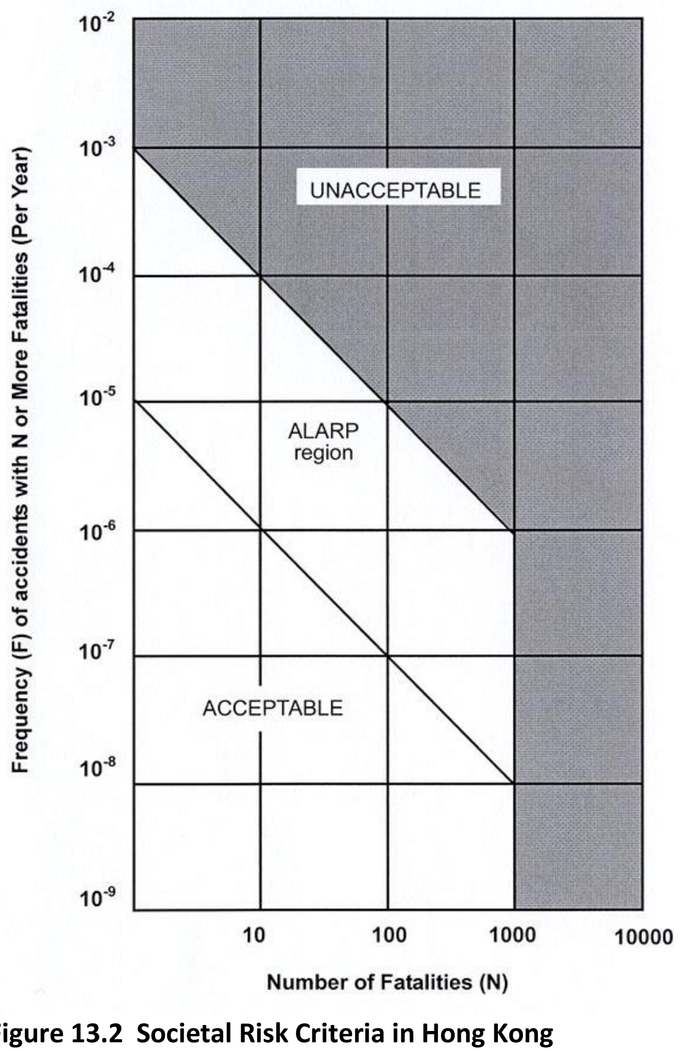


Figure 13.2 Societal Risk Criteria in Hong Kong

13.1.3 Structure of the Report

The report is divided into the following sections:

- Section 13.2 presents the risk results for the storage, handling and on-site transport of chlorine for the Desalination Plant operation;
- Section 13.3 presents the risk results for the off-site transport of chlorine (marine transport from Sham Shui Kok Dock to TKO Area 137 Pier);
- Section 13.4 presents the risk results for the storage, use and transport of sodium hypochlorite associated with the Desalination Plant operation;
- Section 13.5 presents the risk results for the storage, use and transport of carbon dioxide associated with the Desalination Plant operation;
- Section 13.6 presents other risk issues associated with the proposed Desalination Plant;
- Section 13.7 presents the results for cumulative risk assessment;
- Section 13.8 presents the uncertainty analysis of the study;
- Section 13.9 presents the conclusions and recommendations of the study; and
- Section 13.10 presents the references adopted in this study.

13.2 QRA for the On-site Transport, Storage and Use of Chlorine at the Proposed Desalination Plant

13.2.1 Introduction

This section of the report addressed risks associated with on-site transport, storage and use of chlorine at the proposed Desalination Plant.

13.2.2 Scope of On-site Chlorine Risk Assessment

The main objective of this Hazard to Life assessment is to assess the risks associated with storage, handling and transport of chlorine for the Desalination Plant operation. Risk results were compared to EIAO-TM Criteria, and practical mitigation measures have been identified where applicable. In this section, the study is particularly focused on the following:

- Potential Hazardous Installations (PHI) QRA: storage, use and on-site road transport of chlorine (from TKO Area 137 Pier to Chlorination Store of the Desalination Plant)[1]

13.2.3 Approach to the Study

The overall approach to this QRA study is shown in Figure 13.3.

The methodology proposed reflects the most advanced and robust, yet the pragmatic approach required in a major QRA study. The methodology is intended to be as realistic as possible, consistent with previous assessments, and derive the risk using cost-effective techniques available nowadays.

[1] The Desalination Plant is next to the TKO Area 137 Pier, which is fenced to avoid trespass. It is assumed the transportation route from TKO Area 137 Pier to Chlorination Store as **on-site road transport** while transportation route from Sham Shui Kok Dock to TKO Area 137 Pier as **off-site marine transport**.

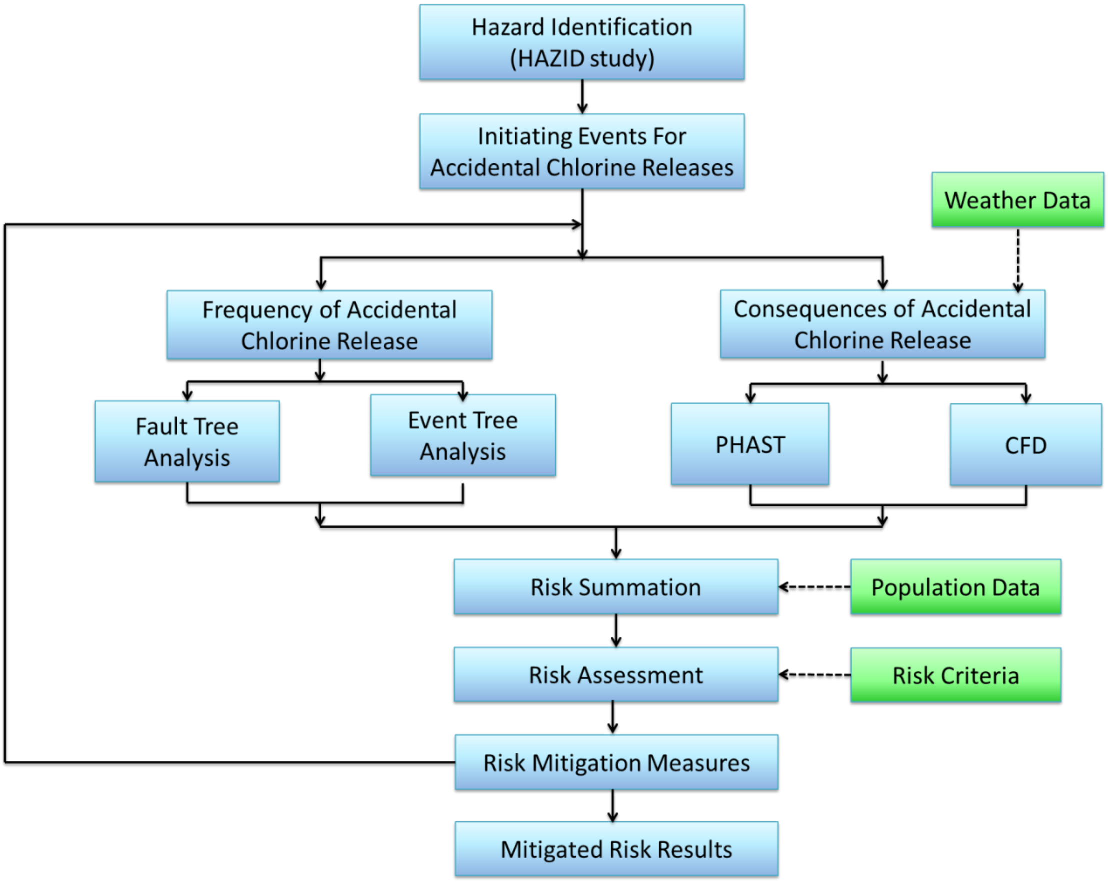


Figure 13.3 Approach to On-site Chlorine PHI QRA

13.2.4 Description of Site, Location and Operations

<u>Location and Surrounding Topography</u>

The proposed Desalination Plant is located at south-east corner of the TKO Area 137 (Figure 13.4). Access to the site is via Wan Po Road or TKO Area 137 Pier at the southern coast of Area TKO 137. To the immediate east of the plant there are hills of the Clear Water Bay Country Park. To the west and north of the plant there are TKO Area 137, South East New Territories Landfill, and Tseung Kwan O industrial estate. To the south is Tathong Channel. Most areas surrounding the Desalination Plant in the north, west and south are flat. The earmarked site for Desalination Plant site currently forms part of a temporary fill bank and the work area of an explosive magazine store. Such temporary uses will be terminated when the sites are required for the site formation and construction of the Desalination Plant.

The layout plan and sectional view are shown in Figure 13.5 and Figure 13.6. The Chlorination Store is located at the middle of the proposed Desalination Plant.

Figure 13.4 Surrounding Topography of the Proposed Desalination Plant

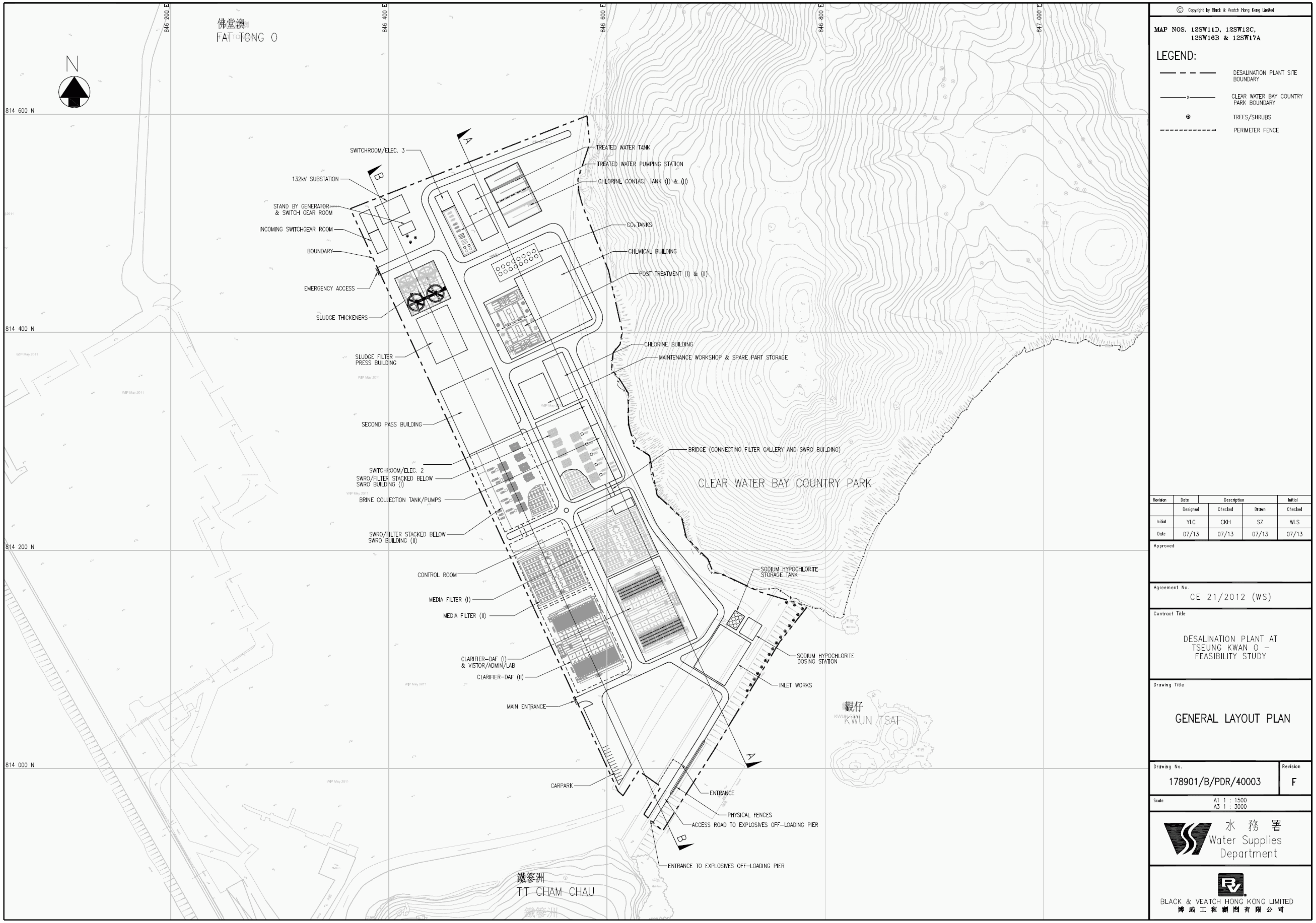


Figure 13.5 Layout Plan of the Proposed Desalination Plant

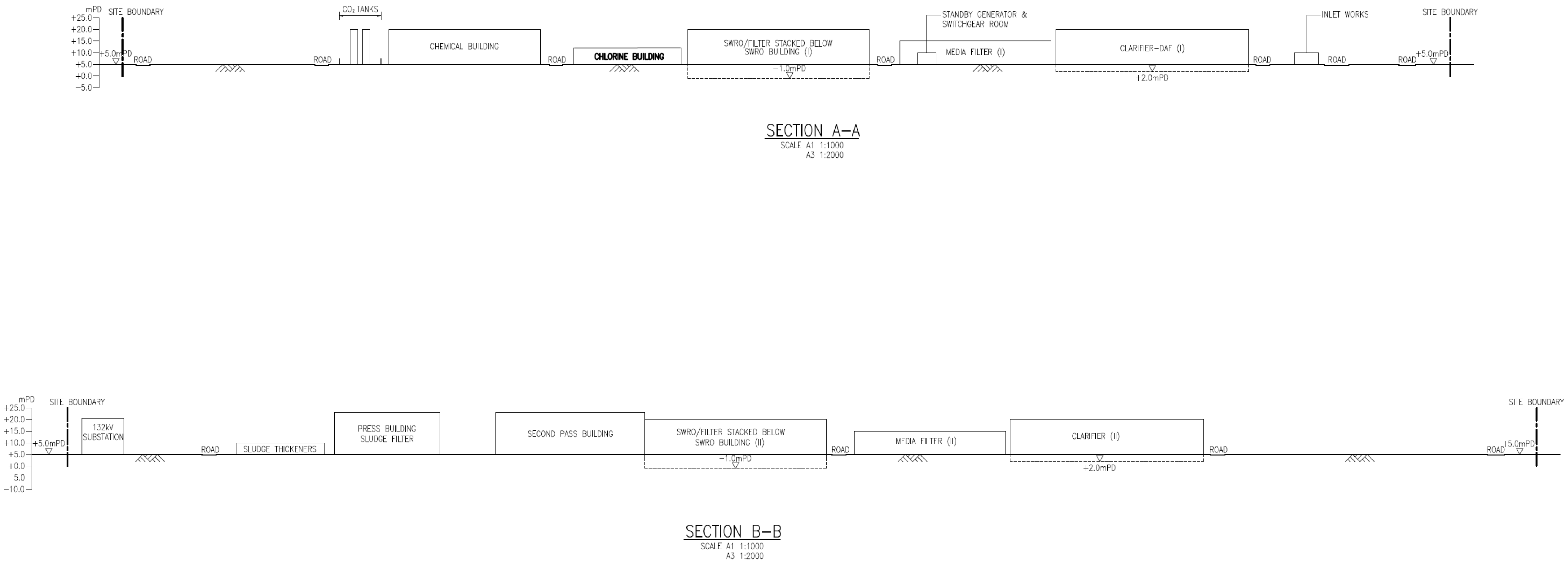


Figure 13.6 Sectional View of the Proposed Desalination Plant

Number of Population at the Desalination Plant

- Construction stage: During construction stage, about 160 construction workers will be present at the desalination facility. The 160 construction workers include the Resident Site Staff (RSS), main contractor staff, sub-contractor staff, WSD site staff and site visitors.
- Operation stage: During operation stage, about 40 operation and maintenance staff including plant manager, operation staff, maintenance staff and laboratory staff will be present at the desalination facility.

  There will be a reception facility for visitors as an integrated part of the Desalination Plant. The visitor reception facility will be located within the boundary fence of the proposed Desalination Plant, which walk-in visitors will not be allowed. Only visitors permitted by WSD will be allowed to enter into the boundary of the Desalination Plant. In addition, visitors will be briefed on the safety and emergency procedures in case of fire and chlorine leak. Visitors will also be escorted by WSD staff during visits.

Operation of the Chlorination Store

Provision and operation of the chlorine facilities in the proposed Desalination Plant will be similar to other 8 WTWs [1]. Safety features, such as redundant chlorine scrubbing system, will be provided to this new chlorine facility to reduce the risk from accidental chlorine release.

(i) Delivery, Storage and Handling of Chlorine

Chlorine is delivered to the Chlorination Store of the Desalination Plant in batches of 1-tonne drums. Unloading takes place inside the Chlorination Store with the doors closed in a designated truck unloading bay. The movement of drums within the storage area and unloading bay is carried out using either an electrically-operated overhead travelling crane (EOTC) or a hoist/monorail system with a purpose-built lifting beam. Prior to usage, the drums are stored on cradles within the chlorine storage area.

Figure 13.7 shows the on-site chlorine road delivery route from TKO Area 137 Pier to Chlorination Store at the proposed Desalination Plant.

(ii) Chlorination System

The draw-off units comprise pairs of drums, one drum on duty, the other serving as standby. The number of drums on line is subject to the permeate water quantity and quality following reverse osmosis and the seawater quantity and quality entering the plant via intake.

Changeover panels automatically change the draw-off from duty to standby when the draw-off pressure falls below a preset level. The changeover is achieved by electrically actuated isolating valves provided for each drum.

Liquid chlorine is drawn from the 1-tonne drums and is passed to the evaporators for conversion into the gaseous state. The gaseous chlorine passes through the chlorinators where it is dissolved in water to form a chlorinated water solution for feeding into the bulk water stream during the treatment process.

The chlorinators are of vacuum venturi type and thus the section of line between the regulator and the chlorinator is at negative pressure. Double non return valves are provided within the chlorinator units.

Shock Chlorination of seawater intake is periodically conducted via injection of sodium hypochlorite solutions.

(iii) Ventilation System

The chlorine drum storage area, evaporator and chlorinator rooms are normally ventilated via a supply of fresh air at high level and extracted at low level. There are two chlorine detection levels, i.e. "low chlorine leak" alarm for 1 ppm and "high chlorine leak" alarm for 3 ppm and above. When low chlorine leak is detected, both visual and audible alarms would be triggered. When high chlorine leak is detected, in addition to the two alarms, ventilation system would be shut with ventilation fans stopped and ventilation louvers shut.

Figure 13.7 Road Transport Route from TKO Area 137 Pier to the Chlorination Store

(iv) Chlorine Scrubbing System

Emergency chlorine scrubbing system is installed to remove any leaked chlorine in the chlorine handling and storage areas. The system is either a wet-type with packed tower/

horizontal type utilising sodium hydroxide as the neutralising agent or a dry-type using alumina oxide substrate as the neutralising agent. The plant and equipment are installed in a separate scrubber room.

On detection of chlorine content at a level of 3 ppm or above in the chlorine handling or storage areas, the scrubbing system will activate automatically. The air/ chlorine mixture in the affected areas is drawn into the scrubber by the scrubber fan via ducting which may be the same as (or entirely separate from) the ducting provided for the normal ventilation system.

An electrically-operated isolating damper is provided in the scrubber intake and recycle which opens automatically when the scrubber fan starts up. An additional isolating damper is provided to isolate the normal ventilation system when the scrubber system is operating.

The scrubber system is normally set to recycle air back to the drum storage area. The treated air may be discharged to atmosphere at roof level when the chlorine concentration is below 3 ppm (in accordance with the FSD requirements DG/TS/llOA, 3rd Revision). This is affected by means of a pair of electrically operated change-over dampers controlled manually from the local control panel. A continuous chlorine monitor is installed at a point downstream of the chlorine scrubber and upstream of the vent/recycle changeover dampers. It has a high level alarm which sounds at both the local control panel and in the main control room when the chlorine concentration exceeds a pre-set level.

Typical setup of a wet-type packed tower chlorine scrubbing system is described in the following paragraphs as an example.

The sodium hydroxide solution is of approximately 10% (w/v) concentration and is held in a solution tank. When the system is in operation, the sodium hydroxide is recirculated by a pump to the distributor to provide adequate irrigation. Sufficient solution is provided to absorb 1 tonne of chlorine.

A mist eliminator is provided upstream of the chlorine scrubber outlet to prevent entrainment of liquid into the treated air in the scrubber before it is discharged to the atmosphere or returned to the drum storage area.

The scrubber is provided with the following additional features: a sampling point, a mixer (for preparation the sodium hydroxide solution), a direct reading transparent level gauge, an inspection window and level indication with high and low level alarms and a temperature measurement device for monitoring the temperature of caustic solution during preparation process.

Table 13.1 provides the basic plant operating data for the Desalination Plant.

Table 13.1 Plant Operating Data for the Desalination Plant

Items	Units	Desalination Plant
Type of container in use	-	1 tonne drum
Operational Phase – Year 2036		
Design capacity of plant	Mld	270
Estimated chlorine usage	tonnes per year	148
Chlorine dosage (average)	mg/L	1.5

Items	Units	Desalination Plant
Chlorine storage capacity (including duty and standby containers)	tonnes	37
Number of draw-off units	--	2
General		
Chlorine container lifting device	--	Electrically-operated overhead travelling crane (EOTC) or a hoist/ monorail system
Scrubber capacity	tonnes chlorine	1
Distance travelled by chlorine truck along site on-site access road	km	0.55

13.2.5 Meteorological Data

The meteorological data used in this study are the data recorded at the Kai Tak weather station in 2003 – 2012 by the Hong Kong Observatory. Weather data in nearby weather stations (Kai Tak, North Point and Tseung Kwan O) have been reviewed and it is deemed weather data in Kai Tak weather station largely represent TKO Area 137 site considering the topographical features. The weather data have been rationalised into different combinations of wind direction, speed and atmospheric stability class. The probabilities of occurrence of each combination during day and night are presented in Table 13.2. The Pasquill-Gifford stability classes range from A through F. Class A represents extremely unstable conditions which typically occur under conditions of strong daytime insolation. Class F on the other hand represents moderately stable conditions which typically arise on clear nights with little wind. Turbulent mixing, which will affect the dispersion of a chlorine cloud, increases through the stability class range from F to A.

Table 13.2 Meteorological Data (Kai Tak Weather Station, Year 2003 – 2012)

		Probability							
		Day				**Night**			
	Wind Speed (m/s)	**3**	**2**	**4.5**	**1.5**	**2**	**4.5**	**1.5**	
Direction	**Atmospheric Stability**	**B**	**D**	**D**	**F**	**D**	**D**	**F**	**Total**
N		0.0068	0.0056	0.0107	0.0042	0.0055	0.0113	0.0155	**0.0597**
NE		0.0082	0.0080	0.0152	0.0048	0.0079	0.0161	0.0176	**0.0779**
E		0.0296	0.0095	0.1094	0.0054	0.0122	0.1295	0.0323	**0.3279**
SE		0.0496	0.0199	0.0655	0.0097	0.0175	0.0414	0.0668	**0.2703**
S		0.0122	0.0064	0.0055	0.0037	0.0029	0.0046	0.0257	**0.0609**
SW		0.0246	0.0071	0.0115	0.0033	0.0030	0.0090	0.0195	**0.0780**
W		0.0149	0.0070	0.0110	0.0045	0.0037	0.0113	0.0200	**0.0724**
NW		0.0061	0.0065	0.0095	0.0040	0.0054	0.0085	0.0128	**0.0528**
Total		**0.1521**	**0.0700**	**0.2383**	**0.0396**	**0.0582**	**0.2316**	**0.2102**	**1**

13.2.6 Population Data

<u>Overview</u>

Figure 13.8 presents the population for the area surrounding the Desalination Plant PHI. The population data have been gathered from a variety of sources as follows:

- Planning Department;
- Social Welfare Department;
- Education Department;
- Transport Department; and
- Surveys undertaken by the Consultants.

The population data which is included in the Hazard Assessment is all population which can be affected by the LD03 contour of chlorine dispersion (see Section 13.2.8).

No chlorine storage and handling is anticipated at the construction stage. As mentioned in Section 13.1.2, T&C stage will not be considered in this assessment. Only population at the operation stage (2036) will be considered. "Year 2036" represents the operation year of the Desalination Plant by taking the maximum population from the latest population forecast between 2011 and 2041 for each population area. This future scenario is considered the most pessimistic situation in the assessment.

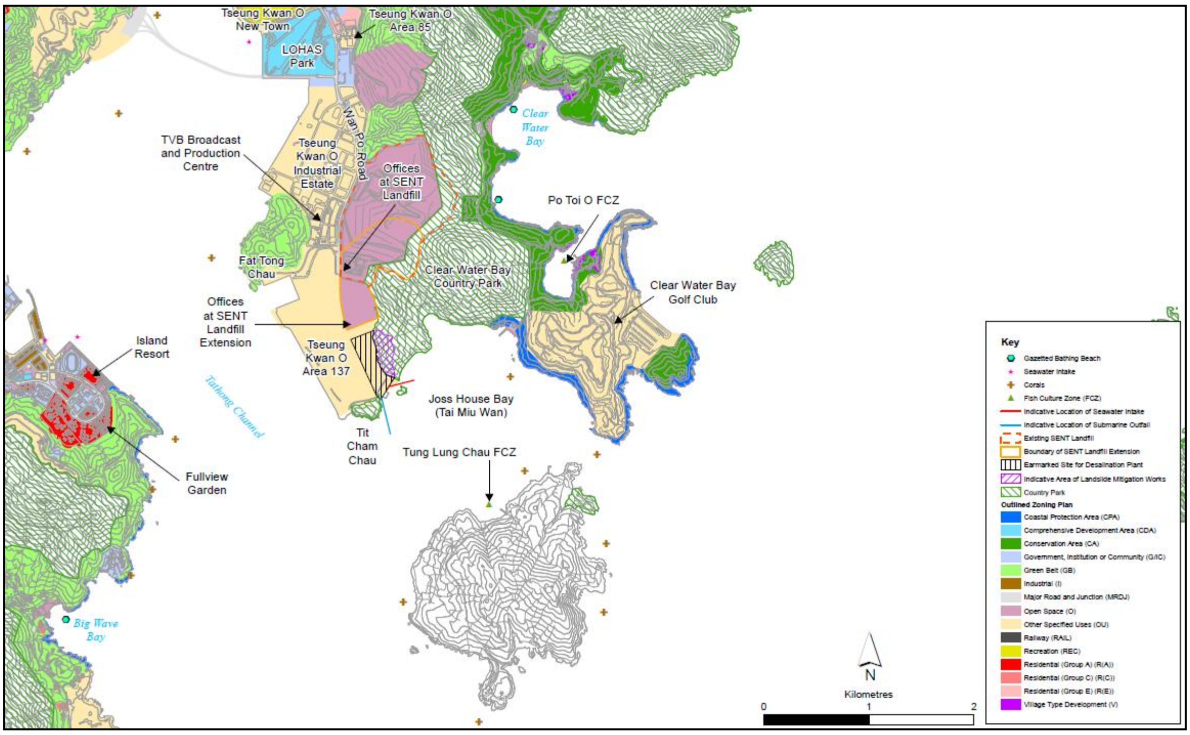


Figure 13.8 Population Surrounding the Chlorine PHI (Desalination Plant)

<u>Surrounding Population Distribution</u>

During the population review through aerial maps, it is found that the surrounding populated areas are industrial areas in the north and west of the Desalination Plant, including Tseung Kwan O Industrial Estate, Green Valley Landfill Limited, and TKO Area 137.

Residential Developments at Tseung Kwan O

Residential developments, including LOHAS Park and the Beaumount, are found to the north and over 2 km away from the Desalination Plant. Population data is extracted from the "land Hong Kong resident population" dataset of the latest (2011-based with adjustment) Territorial Population and Employment Data Matrix (TPEDM).

Tseung Kwan O Industrial Estate

Site survey reveals that the industrial buildings in Tseung Kwan O Industrial Estate (TKOIE) are of average 5 storeys (ceiling height around 4.5 m each storey). The latest (2011-based with adjustment) TPEDM data for employment population is utilized for the estimation of population in the TKOIE. The estimation of employment population is supplemented with information from government department and desktop/site / telephone survey where it is appropriate.

TKO Area 137 Future Land Use (OZP No. S/TKO/21)

TKO Area 137 where the proposed Desalination Plant is located is zoned "Other Specified Uses" annotated "Deep Waterfront Industry" in the draft Tseung Kwan O Outline Zoning Plan (OZP) No. S/TKO/21. According to the Notes of the OZP, the zone is intended primary for special industries which required marine access, access to deep water berths or water frontage. Industries to be accommodated within this zone are usually capital intensive, land intensive and cannot be accommodated in conventional industrial buildings.

This area is in close vicinity of the Desalination Plant, therefore, is anticipated as the main risk receptor of accidental chlorine release. According to Planning Department, the working population in the area is estimated to be in the range of about 1,450 to 1,800 workers upon full development. Since types of industry in TKO Area 137 have not yet been finalized, population at the TKO Area 137 is assumed to be 1,800 and evenly distributed in the area.

SENT Landfill & Extension

Work force at SENT Landfill & Extension site was gathered from Environmental Protection Department. The population was estimated according to the existing SENT Landfill operation and projected operation conditions for the extension site.

TKO Area 137 Pier

The pier is mainly used by Mines Division of CEDD for the delivery of explosives. The pier will also be used for delivery of chlorine to the desalination plant. It will be fenced for authorized access only. Population for delivery of explosives was provided by Mines Division.

Tathong Channel

Maritime population of Tathong Channel within 3-km range is estimated from site survey results. In the survey, marine traffic was counted by taking into account vessel types and their typical occupancies. Details estimation of maritime population is provided in Annex D.

Siu Sai Wan

Residential developments, education institutes, industrial/commercial developments at Siu Sai Wan are found to the west of the Desalination Plant over 2 km range. Datasets "land Hong Kong resident population", "number of full-time school places" and "employment" of the latest

(2011-based with adjustment) TPEDM are adopted for the estimation of residential, student and employment population in Siu Sai Wan.

Future Residential Developments and School Sites

According to the latest (2011-based with adjustment) TPEDM data and Planning Department, there will be future residential developments and schools within the study by referring to PDZ 391. They are also included in the assessment.

Transient Population

Modelling of the impact of chlorine releases on road populations follows the Health and Safety Executive (HSE) approach, as described in the previous 8 WTWs Reassessment Study. Road Traffic Population associated with the road vehicles will be modelled as 100% outdoor.

Current average daily traffic is estimated from Annual Traffic Census (ATC) 2013 from Transport Department. Traffic variation and average vehicle occupancy is estimated from major traffic stations and site survey. The average traffic population is calculated from the following formula:

$$Traffic\ \ Population = \frac{\frac{No.\ of\ \ ppl}{vehicle} \times \frac{No.\ of\ \ vehicle}{hr} \times Road\ \ length\ \ (km)}{Traffic\ \ speed\ \ (km/hr)}$$

It is assumed vehicle speeds under normal traffic conditions are 50 km/hr and 70 km/hr for non-expressways and expressways respectively, according to the HK Road Traffic Ordinance. Vehicle speed during peak hours and jammed peak cases will be reduced due to traffic congestion, which is estimated from site traffic survey.

Wan Po Road is the major road being considered in the assessment. The most appropriate traffic census data is available for the section of Wan Po Road between Chiu Shun Road and Chun Yat Street. The data captures traffic of TKOIE and nearby residential developments and is considered to give conservative traffic estimation for the southern section of Wan Po Road. Traffic along this section of road (3 km length) is mainly composed of goods vehicle and traffic congestion is not anticipated. Population at jammed-peak is estimated by assuming jammed condition in one direction and free-flow in the opposite direction. Free flow traffic is estimated from Annual Average Daily Traffic (AADT) of ATC 2013 data by referring to temporal distribution for Tseung Kwan O Tunnel. Also, the average occupancy of 3.4 persons/vehicle and speed of 50 km/hr are assumed. The average occupancy is derived from vehicle type distribution data during peak hour period (1800-1900) in Annual Traffic Census 2013 for core station “TKO Tunnel” by referring to Table 13.3,

Table 13.3 Calculation of Average Occupancy for Vehicles

Vehicle Type	% Total	Occupancy	Weighed Occupancy
MC	4.1	1.1	0.0451
PC	55.2	1.5	0.828
taxi	15.1	2.2	0.3322
Private LB	1	3.2	0.032
PLB	4.5	12	0.54
LGV	11.9	1.3	0.1547
M&HGV	4.3	1.2	0.0516
Non Fr. Bus	1.5	23	0.345

Vehicle Type	% Total	Occupancy	Weighed Occupancy
SD	0.1	23.8	0.0238
DD	2.3	45	1.035
		Average Occupancy	3.4

Note:
MC=motorcycle; PC=passenger car; LB=light bus; PLB=public light bus; LGV=light goods vehicle; M&HGV=medium & heavy goods vehicle; Non Fr. Bus= non franchised bus; SD=single decker; DD=double decker.

Sensitive Population

Sensitive populations such as homes for the elderly, kindergartens and hospitals (vulnerable population factor 3.3) are separately identified from other populations (vulnerable population factor 1).

Population Forecast

In general, future population data for those population areas are directly adopted from the latest (revised 2011-based) TPEDM without detailed breakdown into individual building or development. Projected population data is available for Years between 2011 and 2041 in a 5-year interval. Adopting a conservative approach, the maximum population between 2011 and 2041 is adopted. Population data in TPEDM is divided into Planning Data Zones (PDZ). Mapping of PDZ to population areas in the assessment is listed in Table 13.4.

Table 13.4 Mapping of PDZ Data

PDZ	Population Area [1]
34	Siu Sai Wan (D, E, F); Tathong Channel (07)
391	TVB (08); Tseung Kwan O Industrial Estate / Industrial & government facilities at south of the Wan Po Road and Pak Shing Kok Road junction (A); LOHAS Park & The Beaumount and future residential developments in TKO Area 85 (B), TKO schools (G1, G2); Proposed Broadcasting House of Radio Television Hong Kong (H); Proposed 3 data centre sites (J)
392	TKO Area 137 pier (04); SENT landfill extension (05); TKO Area 137 (06); Tseung Kwan O Industrial Estate / Industrial & government facilities at south of the Wan Po Road and Pak Shing Kok Road junction (A)

Notes:
[1] Ref. nos. for population areas are shown in brackets.

Time Periods

The population data is presented in five time periods: night, working day, weekend day, peak hour and 'jammed peak', the last time period representing conditions under which traffic on road is at a standstill, 'bumper-to-bumper'. The definition of the time periods is given in Table 13.5

Table 13.5 Definitions of Time Periods

From	To	Mon-Fri	Sat	Sun	
00:00	01:00	Night	Night	Night	
01:00	02:00	Night	Night	Night	
02:00	03:00	Night	Night	Night	
03:00	04:00	Night	Night	Night	
04:00	05:00	Night	Night	Night	
05:00	06:00	Night	Night	Night	
06:00	07:00	Night	Night	Night	
07:00	08:00	Peak	Peak	Weekend day	
08:00	08:15	Jammed Peak	Jammed Peak	Weekend day	
08:15	09:00	Peak	Peak	Weekend day	
09:00	10:00	Working day	Working day	Weekend day	
10:00	11:00	Working day	Working day	Weekend day	
11:00	12:00	Working day	Working day	Weekend day	
12:00	13:00	Working day	Working day	Weekend day	
13:00	15:00	Working day	Peak	Weekend day	
15:00	16:00	Working day	Weekend day	Weekend day	
16:00	17:00	Working day	Weekend day	Weekend day	
17:00	19:00	Peak	Weekend day	Weekend day	
19:00	20:00	Night	Night	Night	
20:00	21:00	Night	Night	Night	
21:00	22:00	Night	Night	Night	
22:00	23:00	Night	Night	Night	
23:00	00:00	Night	Night	Night	
Summary		**Mon-Fri**	**Sat**	**Sun**	**% Time**
Peak		18.75 hr	3.75 hr	0 hr	13.4%
Jammed Peak		1.25 hr	0.25 hr	0 hr	0.9%
Working day		40 hr	4 hr	0 hr	26.2%
Weekend day		0 hr	4 hr	12 hr	9.5%
Night		60 hr	12 hr	12 hr	50.0%

Details of the population data adopted in the assessment for population areas as shown in Figure 13.9 are summarized in Table 13.6.

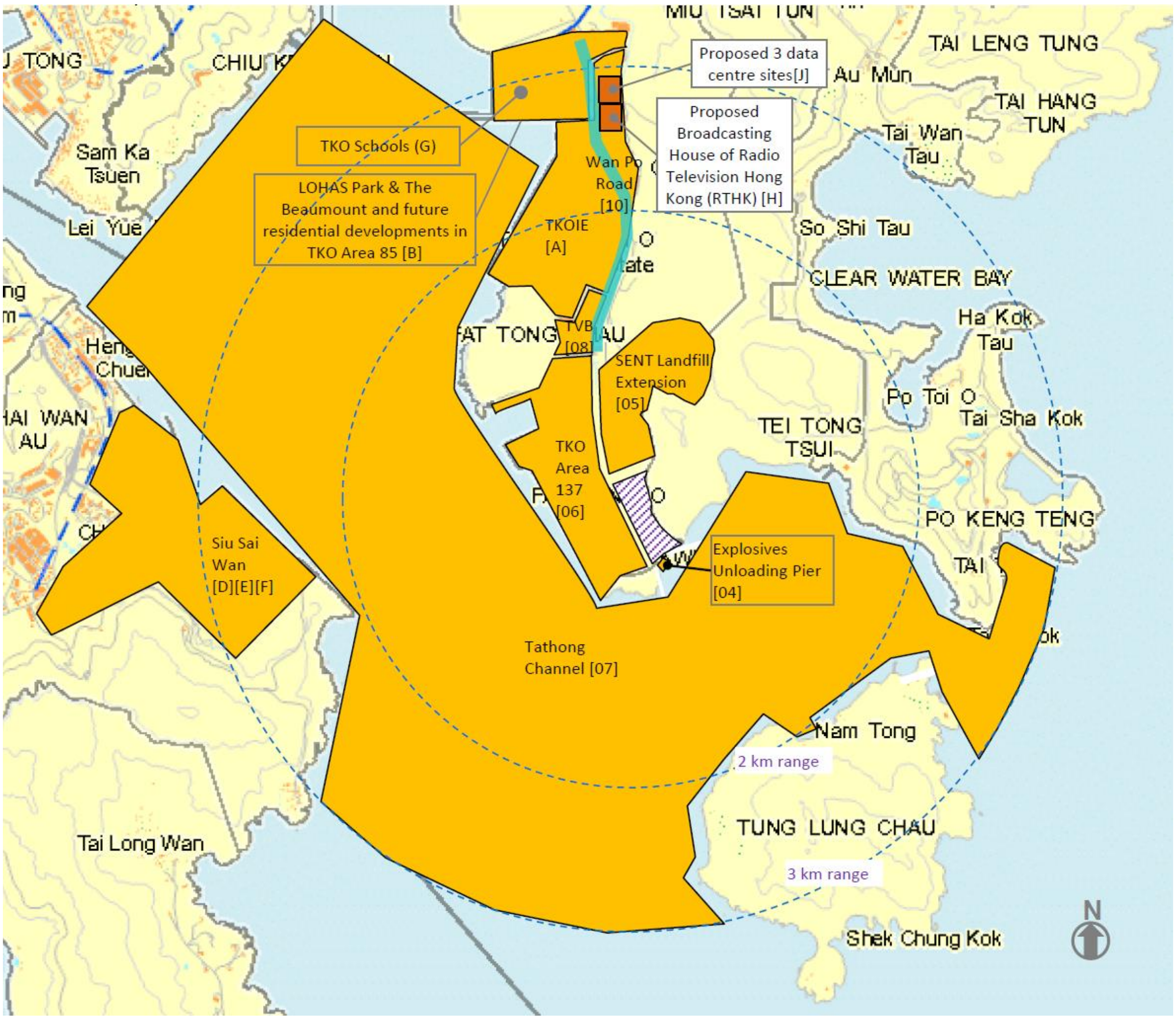


Figure 13.9 Population Areas

Table 13.6 Population Data

Ref no.	Name	Population (Base Year 2011 [Note 1])	Population (Operation, Year 2036)	Occupancy (%)					Indoors Fraction	Vulner-ability Factor	No. of Floors	Remarks
				Night	Jammed Peak	Peak Hour	Weekend Day	Working Day				
04	TKO Area 137 Pier	12	12	0	0	0	0	13	0	1	0	Population source: Info supplied by Mines/CEDD; No concurrent explosives/chlorine unloading operation; Occupancy and indoor fraction: 1 operation takes place between 11:00 - 13:00 (Mon-Sat). It takes 1 hour for each operation (i.e. 1/8 of working day = 13% occupancy for "working day"); outdoor environment i.e. indoor fraction = 0; No. of floors: 0 refers to ground floor only without building structure;
05	SENT Landfill Extension	-	129	19	64	64	52	79	0.39	1	2	Population source: info supplied by EPD; numbers under the population columns represent the total employment; Occupancy and indoor fraction: population data is supplied for each time period. Occupancy is calculated from (number of population at a time period)/(total employment); indoor fraction provided by EPD; No. of floors: based on 2-storey container office.
06	TKO Area 137	-	1671	20	20	20	100	100	0.9	1	1	Population source: max. population 1,800 for the whole TKO Area 137 - supplied by PlanD; population for SENT Landfill extension is subtracted from the total population; Occupancy and indoor fraction: estimated from TKO Bio-diesel EIA [17]; No. of floor: taken as 1 by adopting a conservative approach.
07	Tathong Channel	124	124	50	100	100	100	100	0	1	0	Population source: based on marine traffic survey in 2014 - population density=7.90E-6 ppl/m^2 ; area considered= 15.7E+6 m^2; Occupancy and indoor fraction: conservatively assume that marine traffic and ferry services in night-time is 50% of day-time; No. of floors: 0 refers to ground floor / sea level only without building structure.
08	TVB	4600	4600	20	20	20	100	100	0.9	1	5	Population source: estimated from information as given on TVB's company website; Occupancy and indoor fraction: estimated from TKO Bio-diesel EIA [17]; No. of floors: ranging from approximately 5 to 10, 5-storey is assumed by taking a conservative approach such that the number of fatalities in chlorine releases is predicted at the high side.
10	Wan Po Road	1894	1894	10	100	23	19	16	0	1	0	Population source: Except jammed-peak, based on Annual Average Daily Traffic (AADT) of Wan Po Road and traffic distribution for TKO Tunnel in Annual Traffic Census 2013; 3.4 ppl/veh; speed 50km/hr; road length 3km; Jammed-peak - assumed jammed condition in one direction and free-flow in the opposite direction; Occupancy and indoor fraction: Occupancy is calculated from (number of population at a time period)/(total employment); indoor fraction is 0 by assuming no protection inside vehicles; No. of floors: 0 refers to ground floor only without building structure.
A	TKOIE/industrial & government facilities at south of the Wan Po Road and Pak Shing Kok Road junction	7150	14550	20	20	20	100	100	0.9	1	5	Population source: 2011-based TPEDM (w/ adjustment) PDZ 391 & PDZ 392 employment population [2]; The projected population for year 2021 is the largest and is adopted for year 2036[3]; population for 'TVB' is subtracted from TPEDM data; Occupancy and indoor fraction are estimated from TKO Bio-diesel EIA [17]; No. of floors: based on low rise buildings in TKOIE in general.
B	LOHAS Park & the Beaumount and future residential developments in TKO Area 85	11500	78630	100	50	50	70	50	0.99	1	38	Population source: 2011-based TPEDM PDZ 391 (w/ adjustment) (residential population) for Year 2011 [2]; Info is given by Planning Department; Occupancy and indoor fraction: refers to residential population in SCL EIA; No. of floors: 38 (The Beaumount) – 59 (LOHAS Park); 38-storey is assumed by taking a conservative approach such that the number of fatalities in chlorine releases is predicted at the high side;

Ref no.	Name	Population (Base Year 2011 [Note 1])	Population (Operation, Year 2036)	Occupancy (%)					Indoors Fraction	Vulner-ability Factor	No. of Floors	Remarks
				Night	Jammed Peak	Peak Hour	Weekend Day	Working Day				
D	Siu Sai Wan (residential)	70350	71750	100	50	50	70	50	0.99	1	28	Population source: 2011-based TPEDM (w/ adjustment) PDZ 34 (residential population) [2]; The projected population for year 2041 is the largest and is adopted for year 2036; Occupancy and indoor fraction: refers to residential population in SCL EIA; No. of floors: 28 - 51 storeys (for most of buildings); 28-storey is assumed by taking a conservative approach such that the number of fatalities in chlorine releases is predicted at the high side.
E	Siu Sai Wan (employment)	32300	37800	20	20	20	100	100	0.9	1	10	Population source: 2011-based TPEDM (w/ adjustment) PDZ 34 employment population [2]; The projected population for year 2026 is the largest and is adopted for year 2036 [3]; Occupancy and indoor fraction: estimated from TKO Bio-diesel EIA [17]; No. of floors: Most of industrial buildings >10 stories; 10-storey is assumed by taking a conservative approach such that the number of fatalities in chlorine releases is predicted at the high side; the population mainly comes from the industrial area;
F1	Siu Sai Wan (kindergartens and primary schools)	3400	3400	0	50	50	0	100	0.95	3.3	5	Population source: 2011-based TPEDM (w/ adjustment) PDZ 34 (school places); There is no change in projected population for years 2011 - 2041; Occupancy and indoor fraction: refers to school population in SCL EIA; No. of floors: makes reference to typical school.
F2	Siu Sai Wan (secondary schools)	7650	7650	0	50	50	0	100	0.95	1	5	Population source: 2011-based TPEDM (w/ adjustment) PDZ 34 (school places); There is no change in projected population for years 2011 - 2041; Occupancy and indoor fraction: refers to school population in SCL EIA; No. of floors: makes reference to typical school.
G1	TKO Schools (primary schools)	0	2300	0	50	50	0	100	0.95	3.3	5	Population source: 2011-based TPEDM (w/ adjustment) PDZ 391 (school places); The projected population for year 2041 is the largest and is adopted for year 2036[3]; Occupancy and indoor fraction: refers to school population in SCL EIA; No. of floors makes reference to typical school.
G2	TKO Schools (secondary schools)	0	3600	0	50	50	0	100	0.95	1	5	Population source: 2011-based TPEDM (w/ adjustment) PDZ 391 (school places); The projected population for year 2041 is the largest and is adopted for year 2036 [3]; Occupancy and indoor fraction: refers to school population in SCL EIA; No. of floors: makes reference to typical school.
H	Proposed Broadcasting House of Radio Television Hong Kong (RTHK)	0	941	20	20	20	100	100	0.9	1	10	Population source: population data given by RTHK; Occupancy and indoor fraction: estimated from TKO Bio-diesel EIA; No. of floors: estimated from the existing broadcasting house.
J	Proposed 3 data centre sites	0	900	20	20	20	100	100	0.9	1	5	Population source: population data given by Planning Department; Occupancy and indoor fraction: estimated from TKO Bio-diesel EIA; No. of floors: based on low rise buildings in TKOIE in general.
	Total	**138980**	**229951**									

Notes:
[1] Population is based on year 2011 data unless it is specified in the 'remarks' column
[2] TPEDM - Territorial Population and Employment Data Matrix; PDZ - Planning Data Zone
[3] Take the largest number from TPEDM data between year 2011 and 2041 for individual population groups

13.2.7 Hazard Identification

This section presents the hazard identification summary for the on-site chlorine risk at the Chlorination Store of the Desalination Plant, leading to development of a set of 'failure cases' for the Hazard Assessments.

Hazardous Properties of Chlorine

The following represent some of the key hazards associated with chlorine, drawn from the ICI Chlorine Handbook [11]:

- Chlorine gas is heavier than air. As a result it will tend to accumulate in low places when released to the atmosphere and flow downhill in still air. However, slight breezes or thermal turbulence will cause it to move upward, so people are not necessarily safe simply because they are above the point of release.
- At high concentrations, chlorine gas has a greenish-yellow colour which is only visible at levels many times greater than the danger level.
- Liquid chlorine has a high rate of expansion with increase of temperature. Liquid chlorine should never be trapped between two valves in a pipe or vessel because, if the temperature rises, the pipe may burst, e.g. when welding near chlorine lines, great care should be taken to protect them from weld spatter and radiated heat.
- Liquid chlorine supplies should never be connected together – one cylinder (or drum) may be overfilled by transfer from the other one. If the valve is then closed, the cylinder may burst when the temperature rises.
- Liquid chlorine produces very large volume of gas when released to the atmosphere. A liquid leak is, therefore, very much more dangerous than a gas leak.
- Chlorine reacts strongly with combustible materials -sometimes with explosive violence.
- Chlorine attacks oils and greases forming gummy deposits that, for example, block up flow-meters.
- Chlorine has a characteristic pungent odour that can be detected down to a level of about 3mg/ m^3.
- Chlorine gas is a respiratory irritant. Symptoms caused by inhalation of chlorine include: headaches, pain, difficult breathing, burning sensation of the chest, nausea and watering of the eyes. If exposed to chlorine at 30 ppm for one minute severe toxic effects would occur.
- Some important properties are:
  - Molecular weight: 70.91
  - Boiling point at 1 atm: -34.05°C
  - Density of gaseous chlorine at 20°C and 1 atm: 2.9 kg/m^3
  - Density of air at 20°C and 1 atm: 1.2 kg/m^3
  - Density of liquid chlorine at 0°C and 1 atm: 1.467 kg/L
  - 1 volume of liquid chlorine will give 456 volumes of gas at 0°C & 1 atm

The physiological effects of chlorine are summarised in Table 13.7.

Table 13.7 Physiological Effects of Chlorine

Concentration (ppm)	Effects
0.2-3.5	Threshold of odour perception in most individuals
3-5	Tolerated without undue ill effect for half to one hour.
5-8	Slight irritation of the mucous membranes of the upper respiratory tract and of the eyes.
15	Effects are immediate. Irritation of nose, throat and eyes with cough and lachrymation.
30	Immediate cough with a choking sensation, retrosternal chest pain and a sense of constriction in the chest.
40-60	Development of a chemical tracheo-bronchitis and pulmonary oedema.
1000	Concentration likely to be fatal after a few deep breaths.

Review of Past Incidents

A survey of worldwide incidents involving chlorine drums and cylinders is presented in the previous 8 WTWs Reassessment Study [1].

Referring to recent EIA studies [2][3], review of past incidents was conducted to identify any new hazardous scenarios. In particular, the world wide accident database MHIDAS was independently reviewed in order to update the Hazard Identification conclusions. However, only a few relevant chlorine incidents occurred worldwide since the previous review, and after examination of their nature was concluded that no revision of the previously identified hazard scenarios.

The following reference data were searched and consulted in the previous 8 WTWs Reassessment Study [1]:

- MHIDAS Database (MHIDAS is a Major Hazard Incident Data Service developed by the Safety and Reliability Directorate of the UK Atomic Energy Authority. MHIDAS contains incidents from over 95 countries particularly the UK, USA, Canada, Germany, France and India. The database allows access to many other important sources of accident data, such as the Loss Prevention Bulletin, and is continuously updated);
- HSELine (The Library and Information Services of the UK Health and Safety Executive has accumulated in a computer database documents relevant to health and safety at work. HSELine contains citations to HSE and Health and Safety Commission publications, together with documents, journal articles, conference proceedings, etc.);
- Lees (2012);
- AQUALINE;
- Chlorine Institute;
- Chlorine Transport Risk Study, DNV Technica (1996); and
- Provision of Services for Risk Assessment of the Transport of Liquid Chlorine from Sham Shui Kok of North Lantau & Tuen Mun Area 40 to Various Waterworks Potentially Hazardous Installations – Quantitative Risk Assessment Report, Atkins (2006) [4].

The search undertaken is for all incidents involving chlorine 'drums' or incidents occurring at Desalination Plant/ treatment works.

The primary causes of worldwide chlorine release incidents identified from previous 8 WTWs Reassessment Study [1] include:

- Equipment Failure;
- Human Error;
- Corrosion;
- Fire/Overheating;
- Contamination;
- Road accident;
- Marine Accident;
- Rail accident;
- Loadshedding; and
- Unknown/not specified.

Hazard Identification Review (HAZID)

As confirmed with WSD, there is no chlorine leak incident recorded by WSD since previous 8 WTWs Reassessment Study [1], i.e. 2001.

In previous 8 WTWs Reassessment Study, a Hazard and Operability (HAZOP) study has been conducted for each of the 8 WTWs to provide a full and systematic identification of the hazards associated with the delivery, storage and handling of chlorine. The HAZOP technique provides a means of examining deviations from the design intent, their causes, consequences and safeguards, in a structured manner.

Hazard identification review has been conducted for the chlorine facilities of the proposed Desalination Plant, which are similar to the HAZOP study of previous 8 WTWs Reassessment Study [1], through desktop review of identified scenarios from previous HAZOP study.

A set of hazardous chlorine release scenarios has been selected as results of HAZID review. The major categories of hazardous scenarios identified in the previous 8 WTWs Reassessment Study [1] include:

- Access road;
- Containers handling;
- Containers in storage;
- Connection and disconnection of chlorine containers; and
- Chlorination system.

Failure cases are grouped as follows:

- Internal failure cases: These are releases occurring within the Chlorination Store for which the Contain and Absorb system should ensure that there is no significant release to atmosphere. (The assessment has been considered the possibility of failure of the Contain and Absorb system.);
- External failure cases (at Chlorination Store): These are releases occurring due to some external events (e.g. earthquake, tsunami and aircraft crash) in which the containment provided by the building would be expected to be lost; and

- External failure cases (on access road): These are releases occurring during transportation of 1-tonne drums along the site access road.

(i) Earthquake and Aircraft Crash

Earthquake and aircraft crash are considered in the external failure cases. These events are of remote possibility but have potential to cause failures of multiple chlorine drums in the Chlorination Store. Since the Desalination Plant is a new facility, reinforced concrete structure with latest available earthquake-resistant/crash-resistant designs will be implemented to the new chlorine facilities to minimize/eliminate the impact from earthquake and aircraft crash.

Apart from being damaged by heavy structures, chlorine drums may be punctured by non-structural components. Although high-bay lighting and over-head ventilation duct can be avoided in the design of the Chlorination Store, overhead crane will still be used for transferring chlorine drums within the Chlorination Store. Reference has been made to the Reassessment Study for 8 WTWs [1] and Arup's 2001 seismic hazard assessment report [37] for the dislodged crane scenario.

(ii) Tsunami

The proposed Desalination Plant is near the water front and may be subject to potential impact of tsunamis. Damages may be caused by hydrostatic force and hydrodynamic force of tsunamis as well as buoyant force and impact force of debris etc. On the other hand, the Chlorination Store is protected from the direct impact of tsunamis by other civil structures between the store and the waterfront such as 15m high clarifiers, 5m high media filter buildings and 15m high SWRO buildings. Cluster of buildings would increase friction and decrease damage due to hydrodynamic force.

The wave height for the worst case is assumed equal to the water depth near shore of the TKO Area 137. The integrity of the chlorine building is considered being compromised under this circumstance such that outdoor chlorine release is resulted. While drums on cradle would not be affected by water current, it is assumed that on-duty chlorine drums would be damaged leading to valve connecting to the draw-off unit failure. Taking into account the solubility of chlorine in seawater, it is anticipated that chlorine discharged from damaged chlorine drums would completely dissolve into seawater and would not release to atmosphere causing hazard to the surrounding population. Details of the chlorine release estimation due to Tsunami are presented in Annex F.

According to the calculation in Annex F, the water flow in a tsunami would completely dissolve chlorine discharging from damaged drums and chlorine would not release to atmosphere affecting surrounding population and therefore, chlorine release in the tsunami event is not further assessed.

(iii) External Explosion

Explosives off-loading operation at the TKO Area 137 Pier and explosive truck delivery route are external explosion sources. The setback distance between the chlorine building and explosive trucks / TKO Area 137 Pier shall provide sufficient clearance so that the overpressure resulting from explosion of explosive trucks or the explosives offloading operation that reaches the chlorine building is less than 2 psi. Therefore, the chlorine building would not be subject to structural damages in explosions caused by explosive trucks or explosive unloading operation. Damage to chlorine drums inside the Chlorination Store is not expected because sufficient separation distance will be provided between the Chlorination Store and TKO Area 137 Pier/explosive truck delivery route. Also, other civil structures of the Desalination Plant provide shielding protection to the chlorine building. Moreover, concurrent delivery of explosives and chlorine is not allowed such that these explosive sources do not affect chlorine drums outside of the chlorine building during chlorine delivery.

On the other hand, there are no storage of other explosion sources e.g. LPG cylinder inside the chlorine building and nearby. Therefore, it is anticipated that external explosion presents negligible risk.

Considering similarity of chlorine operation and improved Chlorination Store design, the following chlorine release scenarios within the Chlorination Store have been reviewed:

(i) Rupture of a Single 1-tonne Drum

In the 1-tonne instantaneous release scenario, pressurization due to the flashing chlorine liquid results in the release of chlorine to the atmosphere through weak points of the Chlorination Store. The amount of chlorine discharged to the atmosphere has been estimated from the corresponding values for existing water treatment works of similar building volume (e.g. Sheung Shui WTW) according to the 8 WTWs Reassessment Study.

(ii) Rupture of Multiple 1-tonne Drums in Case of High Intensity Earthquake or Aircraft Crash

The likelihood of aircraft crash has been reviewed and the frequency is less than 1×10^{-9} per year (Section 13.2.9). It is deemed that aircraft crash at the Desalination Plant is very unlikely to occur and thus multiple drums release in an aircraft crash will not be further considered in the study.

Seismic hazard assessment is undertaken to estimate the impact of earthquakes to the chlorine building and develop the chlorine release scenarios in earthquakes. The assessment estimates that probabilities of 10% and 50% roof collapse would be resulted in earthquakes at ground peak acceleration of 0.7g and 1.0g respectively. The total number of 6 chlorine drums in average would be ruptured by the collapsed roof. The seismic hazard assessment adopts the same methodology as Arup (2001) and is detailed in Annex E.

(iii) Leakage from chlorine drum and associated pipework in the Chlorination Store

Referring to the previous 8 WTWs Reassessment Study, Chlorination Store has a significant effect in modifying the release of chlorine to the atmosphere due to dilution with building air in the case of failure of the Contain and Absorb system. Similar to the ‘rupture of single 1-tonne drum’, the chlorine release rate to the atmosphere is estimated from the corresponding value for existing water treatment works of similar building volume (e.g. Sheung Shui WTW).

Failure modes, ‘ventilation remains on’ and ‘a door is left open’, are considered for indoor continuous release in the previous 8 WTWs Reassessment Study. Also, chlorine release rate to the atmosphere is considered higher in ‘ventilation remains on’ case than in ‘a door is left open’ case. Similar to point (i) ‘rupture of single 1-tonne drum’ above, the chlorine release rates to the atmosphere in this assessment has been estimated from the corresponding values for existing water treatment works of similar building volume according to the 8 WTWs Reassessment Study.

Hazard distance of internal release events is assumed to be similar to that of existing WTW of similar size and has been compared with the separation distance between the Chlorination Store and the nearest boundary of the Desalination Plant to determine whether the scenarios have offsite impact.

A set of chlorine release scenarios, referenced from previous 8 WTWs Reassessment Study [1], are summarised in Table 13.8 and Table 13.9.

Table 13.8 Hazards Identified for Previous 8 WTWs Reassessment Study Using 1 tonne Chlorine Drums

Ref.	Hazard
1	**ACCESS ROAD**
1.1	Fire on the truck leading to melting of the fusible plugs on one or more containers
1.2	Fire on the roadside leading to melting of the fusible plugs on one or more containers
1.3	Impact with object during truck manoeuvring
1.4	Lorry over-turns
1.5	Collision with another vehicle
1.6	Loadshedding
1.7	Spontaneous container failure
2	**CONTAINERS HANDLING**
2.1	Dropped container
2.2	Collision of container with another object
2.3	Accidental impact of drum on pigtail during setdown at standby position
2.4	Overextension during use of truck crane (not normally used)
2.5	Section of monorail track incorrectly aligned leading to a dropped drum
3	**CONTAINERS IN STORAGE**
3.1	Leaking chlorine containers
3.2	Overfilled containers leading to overpressurisation on thermal expansion
3.3	Impurities in chlorine containers, in particular nitrogen trichloride (leading to explosion) or moisture (causing accelerated corrosion)
3.4	Object falls onto chlorine containers
3.5	Fire (external or internal)
3.6	External explosion
3.7	Lightning strike
3.8	Extreme wind
3.9	Flooding/ Tsunami (1)
3.10	Construction activities
3.11	Subsidence
3.12	Landslide due to heavy rain
3.13	Earthquake
3.14	Aircraft / helicopter crash
3.15	Sabotage
3.16	Vehicle crash
3.17	Electromagnetic interference
4	**CONNECTION AND DISCONNECTION OF CHLORINE CONTAINERS**
4.1	Human error or equipment failure during connection/disconnection of containers
5	**CHLORINATION SYSTEM**
5.1	Trapping of liquid chlorine between closed valves and subsequent thermal expansion leading to overpressurisation of pipework
5.2	Pigtail failure
5.3	Failure of fixed chlorine pipework
5.4	Open end on pipework due to operator or maintenance error
5.5	Corroded pipework
5.6	Presence of nitrogen trichloride in evaporator leading to explosion
5.7	Presence of moisture in evaporator leading to accelerated corrosion

(1) Tsunami is considered in this project as the site location is close to the waterfront.

Table 13.9 Failure Modes of Contain and Absorb System

Ref.	Failure Mode
1	**LEAK DETECTION SYSTEM**
1.1	Chlorine leak detector 'cell' malfunction
2	**CONTAIN SYSTEM**
2.1	Door left open
2.2	Air inlet louvres fail to close on demand
2.3	Normal ventilation system left in manual mode, therefore does not shutdown on detection of chlorine leak
2.4	Failure of chlorine absorption system (see below) with dampers set to 'exhaust to atmosphere' position and failure to detect chlorine breakthrough
2.5	Failure of door seals
2.6	Outage due to maintenance
2.7	System disabled by operator
3	**CHLORINE ABSORPTION SYSTEM**
3.1	Caustic pump failure
3.2	Blockage in caustic pipework
3.3	Overloading of scrubber
3.4	Caustic valve inadvertently closed
3.5	No caustic in tank
3.6	Caustic pipe leakage
3.7	Scrubber nozzles blocked
3.8	Initial make-up of caustic incorrect
3.9	Leakage of water into tank causing dilution of caustic and reduced efficiency
3.10	Degradation of caustic over a period of time
3.11	Wrong chemical in tank
3.12	Failure due to power failure
3.13	Outage due to maintenance
3.14	System disabled by operator

The physical state of the release may be gas, liquid or two-phase depending on the precise location, e.g. a small leak downstream of the evaporator is likely to be gas, a leak from the 'pigtail' connection is likely to be two-phase (due to flashing in the line), whereas a leak from the container shell itself is likely to be liquid. The release may arise from failure of the chlorine equipment itself or failure induced by an external event such as an earthquake or landslide. The quantity of chlorine released may vary from a few kilograms released continuously to several tonnes released instantaneously, e.g. in the case of a severe external event such as an aircraft crash. For releases occurring within the Chlorination Store, a Contain and Absorb system is provided to minimise the likelihood of the release escaping to atmosphere.

Characterisation of Chlorine Release Scenarios

Following the Hazard Identification (HAZID) review process, the next step in the study is to characterise the release scenarios identified in HAZID in terms of the releasing inventory, hole size and phase of release (Table 13.10). This follows the approach outlined in the Methodology Report for the previous 8 WTWs Reassessment Study [12], Shatin to Central Link [2] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3]. Table 13.10 also screens out those scenarios considered to present negligible off-site risk.

Table 13.10 Characterisation of Chlorine Release Scenarios

Ref.	Scenario	Outcome	Releasing Inventory (tonne)	Hole Size (diameter)	Phase
1	***ACCESS ROAD***				

Ref.	Scenario	Outcome	Releasing Inventory (tonne)	Hole Size (diameter)	Phase
1.1	Truck fire	Considered to result in the melting of the fusible plugs on up to 3 drums (1):	3	3×6 mm	liquid
1.2	Fire on the roadside	Considered to present negligible risk as truck does not park on site other than within chlorine building	-	-	-
1.3	Manoeuvring accident	As manoeuvring takes place at slow speed, considered to result in a single drum –small leak (e.g. valve gland failure)	1	3 mm	liquid
1.4	Rollover	Single drum – small leak (e.g. valve gland failure)	1	3 mm	liquid
		Single drum – medium leak (e.g. guillotine failure of drum valve)	1	8 mm	liquid
		Three drums – medium leak (e.g. guillotine failure of drum valves on three drums)	3	3×8 mm	liquid
		Fire (outcomes as item 1.1 above)	-	-	-
1.5	Collision	Single drum – rupture	1(inst)	-	liquid
		Fire (outcomes as item 1.1 above)	-	-	-
1.6	Load- shedding	Single drum – small leak	1	3 mm	liquid
		Single drum – medium leak	1	8 mm	liquid
1.7	Spontaneous container failure	Single drum – medium leak	1	8 mm	liquid
		Single drum – large leak (e.g. dislodgement of a fusible plug)	1	20 mm	liquid
		Single drum – rupture	1(inst)	-	liquid
2	***DRUM HANDLING***				
2.1	Dropped drum	Single drum – medium leak	1	8 mm	liquid
		Single drum – large leak (e.g. dislodgement of a fusible plug)	1	20 mm	liquid
		Single drum – rupture	1 (inst)	-	liquid
2.2	Collision of drum with another object	Single drum - medium leak	1	8 mm	liquid
2.3	Accidental impact of drum on pigtail during setdown at standby position	Pigtail – guillotine failure	1	4.5 mm	two- phase
2.4	Dropped drum due to overextension of truck crane	Single drum - medium leak	1	8 mm	liquid
2.5	Dropped drum due to incorrect alignment of rail track	As item 2.1 above	-	-	-
3	***CONTAINERS IN STORAGE***				
3.1	Leaking chlorine drums	Single drum – medium leak	1	8 mm	liquid
		Single drum – large leak	1	20 mm	liquid
		Single drum – rupture	1 (inst)	-	liquid
3.2	Overfilled drums leading to over-pressurisation on thermal expansion	As item 3.1 above	-	-	-
3.3	Impurities in chlorine drum leading to explosion or leak	As item 3.1 above	-	-	-
3.4	Object falls onto	Considered to present negligible risk as there are no	-	-	-

Ref.	Scenario	Outcome	Releasing Inventory (tonne)	Hole Size (diameter)	Phase
	chlorine containers	objects likely to fall which could cause significant damage to the drums			
3.5	Fire (external or internal)	Considered to present negligible risk as chlorine stores are 2 hour fire-rated structures. The most significant internal source of fire is considered to be the chlorine truck. However, pessimistically, all truck fires are modelled as occurring outdoors, thus this scenario is already included in Item 1.1. Although the slope at the Clear Water Bay Country Park in vicinity of the desalination plant is covered by vegetation, branches of trees or shrubs will not reach the desalination plant. There is negligible risk of hill fire impact to the chlorine facility.	-	-	-
3.6	External explosion	Considered to present negligible risk as there are no storage of other explosion sources e.g. LPG cylinder inside the chlorine building and nearby. The setback distance between the chlorine building and explosive trucks / TKO Area 137 Pier shall provide sufficient clearance so that the overpressure resulting from explosion of explosive trucks or the explosives offloading operation that reaches the chlorine building is less than 2 psi. Insignificant escalation risk due to CO_2 storage tank BLEVE, referring to CO_2 assessment section.	-	-	-
3.7	Lightning strike	Considered to present negligible risk as the chlorine store is lightning protected; and a lightning, while can result in electrical damage, is unlikely to cause a chlorine release	-	-	-
3.8	Extreme wind	Considered to present negligible risk as chlorine store is designed for typhoon loading	-	-	-
3.9	Flooding/Tsunami	Considered to pose negligible risk as flooding could only affect empty drums. "Empty" drums contain gaseous residual chlorine. They float when the chlorine store is flooded. However, "empty" drums are stored with protective caps in place. It is considered damage to flowing "empty" drums would be insignificant and would not lead to chlorine leakage. In tsunamis, chlorine released would vastly dissolve into seawater. The probability of fatality due to chlorine released into the atmosphere is insignificant (referring to Annex F).	-	-	-
3.10	Construction activities	No construction activities inside the chlorine store are anticipated during the construction and operational phases of this project.	-	-	-
3.11	Subsidence	The chlorine store will be built on piles. Therefore, subsidence risk should be ruled out from the release scenarios.	-	-	-
3.12	Landslide due to heavy rain	Considered to present negligible risk. The chlorine building is sited on a flat reclamation final formation level at +5.5mPD. There is a natural slope overlooks the site. A defense wall will be installed as natural terrain hazard mitigation measures to safeguard facilities within the desalination plant for the worst credible event in accordance with GEO Report No. 138. The slope failure could be due to sliding failure, boulder / rock fall or washout. Impacts of the slope failure would be confined within a zone of about 50m from the toe of the slope. This 50m zone refers to how far debris flow from the slope failure may reach as a general guideline.	-	-	-

Ref.	Scenario	Outcome	Releasing Inventory (tonne)	Hole Size (diameter)	Phase
		Having reviewed the site specific data, it is anticipated that the fail volume would be less than 200m³ referring to GEO Report No. 138. Considering the distance 34m between the chlorine building and the toe of the slope from the toe of the slope, the depth of debris reaching the chlorine building would be a shadow one, say around 1m. There would be no structural damage to the chlorine building due to the loading of the debris flow even without the defense wall. Eventually, a defense wall will be constructed to protect from landslide impact. Therefore, landslide risk should be ruled out from the release scenarios.			
3.13	Earthquake	Roof collapse: Multiple drum-rupture	6	-	liquid
		Overhead crane dislodged from rails: The impact energy is not sufficient to cause drum failure, referring to Annex E.	-	-	-
3.14	Aircraft / helicopter crash	There is no public helipad or helicopter facility in vicinity of the desalination plant. No helicopter crash risk is anticipated. Aircraft crash is considered to present negligible risk due to low event frequency (The frequency analysis is shown in Section 13.2.9)	-	-	-
3.15	Sabotage	Considered to present negligible risk. The following security measures will be implemented in the proposed Desalination Plant, - apart from the normal staff patrol, the proposed chlorine store will be under 24-hour CCTV surveillance in the main control room. - access doors to the chlorine store are locked at all times. - Implementation of log in-log out procedure for all personnel and visitors.	-	-	-
3.16	Vehicle crash	Considered to present negligible risk due to robustness of chlorine store, and chlorine storage area can be separated from unloading bay with barrier wall/kerb or drop-level unloading bay design	-	-	-
3.17	Electromagnetic interference	Considered to present negligible risk as suitable precautions are adopted in the design of the electrical systems	-	-	-
4	***CONNECTION AND DISCONNECTION OF CHLORINE CONTAINERS***				
4.1	Human error or equipment failure during connection or disconnection of drums	Pigtail – guillotine failure	1	4.5 mm	two- phase
5	***CHLORINATION SYSTEM***				
5.1 – 5.5	Failures associated with the chlorination system pipework	Liquid chlorine pipework – guillotine failure	1.05(2)	4.5 mm(3)	two- phase
5.6 – 5.7	Failure of Evaporation	Evaporator – leak or rupture	1.05	4.5 mm	two- phase

Notes:
(1) All existing drums have a single fusible plug on each drum. The fusible plug has a 6mm fusible core.
(2) Inventory of drum (1 tonne) and evaporator (50kg).
(3) Diameter of liquid chlorine pipework is 20mm but limiting orifice size is that of pigtail, i.e. 4.5mm.

13.2.8 Consequence Analysis

Methodology

The assessment of the consequences of a chlorine release essentially involves three steps:

(i) Source Term Modelling: Modelling the initial release of chlorine (whether inside or outside the chlorine building).

(ii) Dispersion Modelling: Modelling the dispersion of chlorine in the atmosphere.

(iii) Toxic Impact Assessment: Assessing the toxic impact to people off-site (whether indoors or outdoors).

Chlorine vapour, which is of almost 2.5 times density of air, tends to migrate, disperse and accumulate to lower areas. The concentration profile of chlorine vapour is significantly dependent on the topography near the release source and the weather conditions (wind speeds and stability classes). In previous 8 WTWs Reassessment Study [1], three dispersion modelling techniques were applied:

- Flat terrain dispersion modelling ('DRIFT' model);
- Wind tunnel simulations; and
- Computational Fluid Dynamics (CFD).

The following most advance and robust techniques for dense gas dispersion have been applied in this risk assessment:

- Flat terrain dispersion modelling (PHAST model); and
- Computational Fluid Dynamics (CFD).

PHAST is the world's most comprehensive process industry hazard analysis software tool for flat terrain dispersion modelling. The software examines the progress of a potential incident from the initial release to far-field dispersion including modelling of pool spreading and evaporation, and flammable and toxic effects. PHAST software contains DNV's proprietary discharge and dispersion model, Unified Dispersion Model (UDM), which could simulate dispersion of flammable and toxic gas releases.

CFD is an advanced technique to provide the rigorous means of dense gas dispersion simulation for a variety of atmospheric conditions, fully taking account of the effects of on-site buildings and complex terrain. Intensive computational power is required for CFD simulations, which is the major obstacle of applying CFD methodology in the past but becomes achievable with recent advances on computer hardware and software. In the past decade, the time required for CFD simulation considering complex terrain and objects has been significantly reduced, and a large number of studies have been conducted to accurately predict the actual gas dispersion for a variety of hazardous gases (flammable and toxic gases). With rapid increase of computing power by orders of magnitude and extensive research work in the past decade, nowadays CFD gains popularity in industrial risk assessment area and provides relatively high accurate prediction for situations with complex terrain and geometry in a reasonable time and cost compared with wind tunnel simulations.

PHAST and CFD are widely adopted gas dispersion techniques in the Health and Safety Executive (HSE) safety & risk management in the oil & gas, petrochemical and chemical industry, which have been accepted by UK HSE. Their application in dense gas dispersion modelling has been extensively validated.

The two analytical techniques are complimentary in this risk assessment study. This is because of the large number of individual simulations which may be required for each site when considering all possible combinations of chlorine release rate and duration, wind direction, wind speed and atmospheric stability. Time required for CFD simulations is considerable higher than PHAST modelling to model all required scenarios.

PHAST has the advantage that it can provide results very quickly for prediction of near-field and far-field dispersion concentration calculations. PHAST has very limited capability ('Surface Roughness' factor) to handle the effects of terrain and geometry which will have a significant impact on far field dispersion patterns of dense gases such as those proposed to be studied here. Complex terrain models incorporating buildings, hills, etc. can be accounted for in CFD modelling which can also take into account all the full scale physics that determine the way plumes disperse. CFD methods require significantly more time and skills to get the gas dispersion concentration profiles.

Wind Tunnel Testing is not further recommended considering its extreme cost (requiring standard wind tunnel facilities), time (requiring several months to build the physical models and several days to prepare for each test), limitation to near-neutral atmospheric conditions, as well as accuracy problem due to scaling from the representative miniature models.

(i) Source Term Modelling

The source term comprises the application of appropriate discharge rate models to define the release rate, duration, quantity of release and also the extent of flash or vapourisation which may occur from a liquid release. The source term outputs form the inputs to the dispersion model.

DNV PHAST was adopted for Source Term Modelling in this study. It has been used to model the transient release of chlorine in the near vicinity of the leak location. PHAST can take into account the high pressure and multi-phase physics that may be present in liquid and gas releases (e.g. flashing and rain-out). The results of the PHAST dispersion simulations at a small distance downstream of the leak location were used as input conditions for the subsequent dispersion modelling.

(ii) Dispersion Modelling

Dispersion calculations are required in order to evaluate the concentration of chlorine as a function of distance from the point of release (for continuous releases) and as a function of both distance and time (for instantaneous releases). This information is required as part of the toxic impact assessment which is described below.

The risk assessment requires a large number of individual gas dispersion calculations (plus re-runs for risk mitigation measures, if any). The individual calculations cover a range of release scenarios (instantaneous releases of different quantities and continuous releases from different hole sizes), together with a range of weather conditions. In order for this to be feasible, it is necessary to use a dispersion calculation method which is relatively quick, whilst still adequately modelling the physical processes which occur during heavy gas dispersion. These requirements necessitate the use of an 'integral' dispersion model PHAST in conjunction with the CFD simulation.

Similar to previous 8 WTWs Reassessment Study [1], CFD has been used to determine the chlorine gas dispersion concentration profiles, taking in account of ground terrain and obstacles (e.g. buildings) as input parameters. A three-dimensional (3D) model of the proposed Desalination Plant, surrounding terrain and buildings has been constructed to cover the areas of interest. Figure 13.10 shows the surrounding natural terrains and buildings of the Desalination Plant.

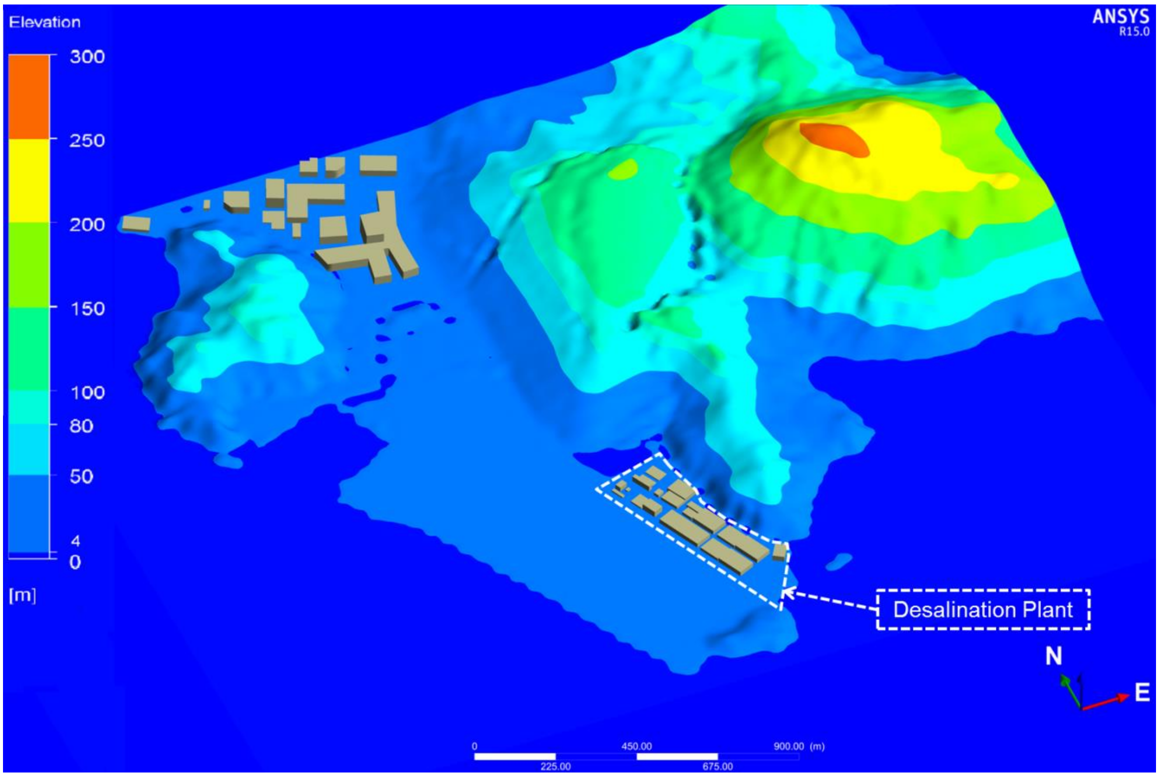


Figure 13.10 Surrounding Natural Terrains and Buildings of the Desalination Plant

Simulations of continuous and instantaneous releases were run and gas concentrations were monitored at points of interest downwind of the release. Contour maps of gas concentration have been produced and presented in Annex B1 and Annex B2. CFD is to provide modelling results with high accuracy by rigorous calculation of gas concentration at each location using principles of thermodynamics, heat and material balance, for a set of selected release scenarios at various conditions (discharge rate, atmospheric stability, wind direction and wind speed), and in conjunction with PHAST to provide all the consequence data needed for the risk assessment input.

PHAST dispersion modelling was run for all combinations of release rates and weather conditions, as listed in Table 13.11, to derive a relationship between the chlorine release rate/ quantity and the hazard range. These relationships have been used to scale the LD contours generated by CFD according to the release rate/ quantity of interest. Detailed results of PHAST modelling are shown in Annex A. According to the preliminary hazard identification in Table 13.10, chlorine release rates/ quantities as shown in Table 13.11 are considered sufficient to cover release scenarios with potential off-site impact which are applicable to the Desalination Plant.

Table 13.11 PHAST Flat Terrain Dispersion Modelling Cases

Release Case	Weather Class	Remarks
1.4 kg/s continuous	B3, D2, D4.5, F1.5	Typical Release Scenario: Accidental release on Access Road, Unisolated release from 1 tonne drum, Single Drum failure, Medium Leak Size
4.2 kg/s continuous	B3, D2, D4.5, F1.5	Typical Release Scenario: Accidental release on Access Road, Unisolated release from 1 tonne drum, Multiple Drum failure, Medium Leak Size
1 tonne instantaneous	B3, D2, D4.5, F1.5	Typical Release Scenario: Accidental release on Access Road, Unisolated release from 1 tonne drum, Single Drum failure, Rupture
4.2 tonnes instantaneous	B3, D2, D4.5, F1.5	Typical Release Scenario: Accidental release at Chlorination Store due to roof collapse upon high-intensity earthquake (0.7g and 1.0g), Unisolated release from 1-tonne drum, Multiple Drum failure, Rupture
57 kg instantaneous	B3, D2, D4.5, F1.5	Typical Release Scenario: Accidental release inside Chlorination Store due to drum handling, Unisolated release from 1-tonne drum, Single Drum failure, Rupture

The discharge rates and dispersion distances of identified hazard scenarios in Table 13.11 have been calculated by PHAST.

CFD dispersion simulation were conducted by ANSYS CFX, which originates from AEA Technology *CFX-4* adopted in the previous 8 WTWs Reassessment Study [1], for a combination of runs including release scenarios (continuous/ instantaneous), wind directions, wind speed/ stability and release location (access road and Chlorination Store). Conclusions of CFD simulation from previous 8 WTWs Reassessment Study [1] are considered in the list of CFD simulation runs in Table 13.12. The details of ANSYS CFX are presented in Annex C of Methodology Report of this study.

Similar to previous 8 WTWs Reassessment Study [1], Shatin to Central Link [2] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3]:

- A relationship between the chlorine release rate/ quantity and the hazard range has been developed from PHAST results. These relationships were used to scale the LD contours generated by CFD dispersion modelling according to the release rate/ quantity of interest.
- Consequences for other directions have been estimated by simple rotation of the cloud shape from the CFD study for a total of 36 wind directions at several points along the access road (approximately one release point every 50 m).

Table 13.12 CFD Dispersion Modelling Cases

Release Case	Weather Class (Wind Direction)	Remarks
Access Road, 1.4 kg/s continuous, aerosol	D2 (N, NE, E, SE, S, SW, W, NW)	Continuous release of 4.2 kg/s has been estimated by applying a scale factor, which is estimated from PHAST Flat Terrain Dispersion Modelling. The relationship between the chlorine hazard range and release rate/ quantity of chlorine is presented in Annex A.
	F2 SE B2 SE	With reference to Section 4.2.2 and Annex D of previous 8 WTWs Reassessment study, simulations have been undertaken for atmospheric stability classes (B, D and F) for wind direction SE to study the effect of atmospheric stability class on the chlorine hazard range. Wind direction SE is selected because it is the critical wind direction towards the TKO Industrial Estate and LOHAS Park, which are the closest populated area in the proximity of the proposed Desalination Plant.
	D4.5 (E, SE)	Simulations have been undertaken for wind speeds (4.5 m/s) for two major wind directions E and SE (accounts for 60% of occurrence probabilities, critical wind directions towards industrial/ residential/ commercial areas of TKO and HK Island). Scale factor has been derived from PHAST and CFD adopted for other wind directions. [Note 1]
Access Road, 1 tonne instantaneous, aerosol	D2 (N, NE, E, SE, S, SW, W, NW)	
	F2 SE B2 SE	With reference to Section 4.2.2 and Annex D of previous 8 WTWs Reassessment study, simulations will be undertaken for atmospheric stability classes (B, D and F) for wind direction SE to study the effect of atmospheric stability class on the chlorine hazard range. Wind direction SE is selected because it is the critical wind direction towards the TKO Industrial Estate and LOHAS Park, which are the closest populated area in the proximity of the proposed Desalination Plant.
	D4.5 (E, SE)	Simulations have been undertaken for wind speeds (4.5 m/s) for two major wind directions E and SE (accounts for 60% of occurrence probabilities, critical wind directions towards industrial/ residential/ commercial areas of TKO and HK Island). Scale factor has been derived from CFD and adopted for other wind directions. [Note 1]
Chlorination Store, 57 kg instantaneous, vapour	D2 N, NE, E, SE, S, SW, W, NW	
	D4.5 E, SE	Simulations have been undertaken for wind speeds (4.5 m/s) for two major wind directions E and SE (accounts for 60% of occurrence probabilities, critical wind directions towards industrial/ residential/ commercial areas of TKO and HK Island). Scale factor has been derived from CFD and adopted for other wind directions. [Note 1]

Release Case	Weather Class (Wind Direction)	Remarks
Chlorination Store, 4.2 tonnes instantaneous, vapour	D2 N, NE, E, SE, S, SW, W, NW D4.5 E, SE	Simulations have been undertaken for wind speeds (4.5 m/s) for two major wind directions E and SE (accounts for 60% of occurrence probabilities, critical wind directions towards industrial/ residential/ commercial areas of TKO and HK Island). Scale factor has been derived from CFD and adopted for other wind directions. [Note 1]

Note 1: In the previous 8 WTWs Reassessment Study [1], the scale factors for different wind speeds are derived from wind tunnel test results. In this study, CFD dispersion modelling results have been used to derive the scale factors. Both wind tunnel test and CFD dispersion modelling are advanced techniques taking into account ground terrain and obstacles around the release source.

<u>Consequence Analysis Results</u>

(i) Initial Release of Chlorine

The initial release of chlorine or 'source term' is modelled using standard discharge rate formulae as detailed in Methodology Report of 8 WTWs Reassessment Study [12]. Releases direct from the chlorine container are the most significant and, in the case of chlorine drums, these are modelled as liquid releases.

The rapid flashing of chlorine which occurs following a liquid leak from a drum is conservatively assumed to result in 100% entrainment of the liquid as aerosol with no rain-out. For catastrophic (instantaneous) liquid releases, the rapid boiling of chlorine on contact with the ground is assumed to result in entrainment of twice the initial flash fraction as aerosol, following Lees [16]. The remainder of the liquid chlorine is modelled as a spreading, evaporating pool.

The results of the 'source term' modelling of chlorine releases are summarised in Table 13.13 below.

Table 13.13 Summary of Source Term Modelling Results for Proposed Desalination Plant

Release Case	Hole Size – Diameter (mm)	Phase	Mode of Release to Atmosphere (for Internal Release Cases only)	Release Rate to Atmosphere or Instantaneous Release Quantity	Release Duration [Note 1]
External Releases (1 tonne Drum)					
Small leak	3	Liquid	-	0.2 kg/s	83 mins
Medium leak	8	Liquid	-	1.4 kg/s	12 mins
Large leak	20	Liquid	-	8.8 kg/s	114 s
Rupture	-	Liquid	-	1000 kg	-
Internal Releases (1 tonne Drum or Chlorine Pipework)					
Pigtail–guillotine failure	4.5	2-phase	Normal ventilation remains on	0.027 kg/s	10 mins [Note 2]
			Door left open	0.012 kg/s	10 mins
Medium leak from drum	8	Liquid	Normal ventilation remains on	0.30 kg/s	10 mins
			Door left open	0.13 kg/s	10 mins
Large leak from drum	20	Liquid	Normal ventilation remains on	0.56 kg/s	10 mins
			Door left open	0.30 kg/s	10 mins

Release Case	Hole Size – Diameter (mm)	Phase	Mode of Release to Atmosphere (for Internal Release Cases only)	Release Rate to Atmosphere or Instantaneous Release Quantity	Release Duration [Note 1]
Rupture	-	Liquid	Pressurisation of Chlorination Store – release via weak points [Note 4]	5.7 kg/s	10 s [Note 3]

Note 1: Assumes no intervention by operating staff.
Note 2: Upper limit of 10 min set for duration of releases from chlorine building (by which time action would be taken to shut-off ventilation, close doors etc.).
Note 3: Assumed release duration for catastrophic failure of a drum, e.g. a split along a weld (QRA not sensitive to this assumption).
Note 4: 'Normal ventilation remains on' and 'Door left open' are not included for this mode of release since 'Pressurisation of Chlorination Store – release via weak points' will be more dominant in the study.

It is also apparent that the Chlorination Store at Desalination Plant has a significant effect in modifying the release of chlorine to the atmosphere, given failure of the Contain and Absorb system. The rate of chlorine release is reduced dramatically (e.g. for a medium leak the rate of chlorine to atmosphere is reduced from 1.4 kg/s to 0.3 kg/s or 0.13 kg/s) and the chlorine becomes diluted in the building air.

The failure mode of the Contain and Absorb system 'Normal ventilation remains on' is a more severe case than 'Door left open' in terms of the chlorine release rate to atmosphere. This is because the normal ventilation (typically 2.6 air changes per hour) provides a more rapid release of chlorine to the environment than if a door is left open (normal ventilation shutdown, chlorine scrubber system in operation).

(ii) Toxic Impact Assessment

Similar to the previous QRAs [1][2][3], the following Probit equation in TNO Green Book [22] has been used in this study to estimate the likelihood of fatality due to exposure to chlorine:

Chlorine Probit Equation

The following Probit equation is used to estimate the likelihood of fatality due to exposure to chlorine:

$Pr = -14.3 + \ln C^{2.3} t$

where
Pr = probit value
C = chlorine concentration (mg/m^3)
t = exposure time (minutes)

Table 13.14 shows the relationship between the chlorine concentration and the probability of fatality for the TNO Probit, assuming 10 minutes exposure duration.

Table 13.14 Chlorine Toxicity Relationship

Chlorine Concentration (ppm)	Probit Value for 10 min Exposure (TNO Probit)	Probability of Fatality (LD = Lethal Dose)
251	3.12	0.03 (LD03)
557	5.00	0.50 (LD50)
971	6.28	0.90 (LD90)

Dispersion of Chlorine in the Atmosphere

(i) CFD Modelling Results

The major results of the CFD modelling for proposed Desalination Plant are summarised in Table 13.15 below. Full result details and LD contours are presented in Annex B.

Table 13.15 Summary of CFD Results for Desalination Plant

Release Case	Weather Class (Wind Direction)	Maximum Extent of LD Contour (m)		
		LD03	LD50	LD90
1.4 kg/s continuous	D2 (W) (Note 1)	307	254	177
	D2 (SE)	163	135	134
	D4.5 (E) (Note 2)	168	121	86
	B2 (SE)	191	110	93
	F2 (SE)	112	87	86
1 tonne instantaneous	D2 (NW) (Note 1)	549	412	317
	D2 (SE)	272	193	140
	D4.5 (E) (Note 2)	347	236	194
	B2 (SE)	241	145	115
	F2 (SE)	284	220	154
57 kg instantaneous	D2 (NW) (Note 1)	122	83	48
	D4.5 (SE) (Note 2)	70	34	27
4.2 tonnes instantaneous	D2 (NW)(Note 1)	964	563	447
	D4.5 (SE) (Note 2)	526	276	221

Note 1: The wind direction of largest LD03 hazard range for weather class D2.
Note 2: The wind direction of largest LD03 hazard range for weather class D4.5.

From Table 13.15 and Annex B1, the key findings of the CFD modelling are summarised as follows:

- atmospheric stability does not significantly influence the hazard range of either a 1.4 kg/s continuous release of chlorine or a 1 tonne instantaneous release of chlorine for the three weather conditions of most interest in this study (i.e. B – unstable conditions, D - neutral stability and F - stable conditions) for wind direction SE. This is because, in the presence of buildings inside the Desalination Plant, atmospheric stability has relatively less influence on chlorine dispersion;
- for B (unstable conditions) and F (stable conditions), the CFD results for the Desalination Plant indicate that, whilst the chlorine hazard range is not significantly affected by atmospheric stability, the shape of the chlorine cloud (i.e. impacted area) may be affected. D (neutral conditions) impacts relatively larger area than B (unstable conditions) and F (stable conditions) for LD03, LD50 and LD90 contours, i.e. a factor of 1.0 ~ 2.7 for 1.4kg/s continuous release and 1.0 ~ 1.2 for 1 tonne instantaneous release. The factors were obtained by comparing the impacted area ratio of chlorine dispersion at different lethal concentrations under stability class of D2 respective to various stability classes (i.e. D/B and D/F). This aspect is considered further in the uncertainty analysis (Section 13.8).

(ii) Flat Terrain Dispersion Modelling Results

The results of flat terrain dispersion modelling using PHAST (weather class: D2) is summarised in Table 13.16 below. Full details and LD contours can be found in Annex A.

Table 13.16 Summary of PHAST Results for Desalination Plant

Release Case	Weather Class	Maximum Extent of LD Contour (m)		
		LD90	LD50	LD03
1.4 kg/s continuous	D2	265	319	398
4.2 kg/s continuous	D2	440	523	647
1 tonne instantaneous	D2	330	397	498
57 kg instantaneous	D2	114	133	164
4.2 tonnes instantaneous	D2	597	696	858

From the results in Table 13.16 it is possible to derive a relationship between the chlorine release rate (or release quantity) and the downwind hazard range. The relationship is used in the QRA, as described below.

(iii) Comparison of Results of CFD and PHAST Modelling

Table 13.17 compares the key results from CFD modelling and PHAST flat terrain dispersion modelling.

Table 13.17 Comparison of CFD and PHAST Results (Weather Class: D2)

Release Case	Maximum Extent of LD03 Contour (m)	
	CFD	PHAST
1.4 kg/s continuous	307	398
1 tonne instantaneous	549	498
57 kg instantaneous	122	164
4.2 tonnes instantaneous	967	858

From Table 13.17, for releases of 1.4 kg/s continuous and 57 kg instantaneous, the chlorine hazard range predicted by the CFD modelling is greatly shorter than that predicted by the PHAST dispersion modelling (which only flat terrain was considered). While for very large amount of releases (1 tonne and 4.2 tonnes instantaneous), the hazard ranges are comparable for CFD and PHAST dispersion modelling. This highlights the importance of modeling the effects of buildings and complex terrain, which act to increase turbulence and cause greater mixing of the chlorine. From Annex B, it can be seen dispersion of chlorine vapour cloud is significantly affected by the building layout and nearby hill thus does not always follow the wind direction. Such effect is more obvious for releases of 1.4 kg/s continuous and 57 kg instantaneous which cloud height is comparable to the height of buildings thus vapour cloud reaches the maximum extent along the 'gaps' between the buildings and the hill.

(iv) Rationalisation of Chlorine Dispersion Modelling Results

The preceding sections have discussed the results arising from the various strands of work on chlorine dispersion modelling. The following paragraphs summarise how these results have been applied in the QRA.

CFD modelling: the CFD modelling results in Table 13.15 show no significant influence of atmospheric stability on the chlorine hazard range (for B, D and F conditions), therefore this parameter is not further considered in this study. The CFD results for the 1.4 kg/s continuous release case (D2 weather conditions), which are consistent for previous 8 WTWs Reassessment Study [1], are used in the QRA in preference to those from the PHAST modelling.

PHAST modelling: the PHAST flat terrain dispersion modelling results are not used directly in this study. However the relationships derived from the PHAST modelling for the chlorine release rate/quantity versus hazard range are used to scale the CFD results for the complete range of release scenarios which need to be considered in this study. One further aspect which needs to be considered in applying the results of the CFD in the QRA is the number of individual wind directions which are considered. In the CFD up to eight (8) wind directions were modelled for the 1.4 kg/s continuous and 1 tonne instantaneous release scenarios for weather class of D2. However, in a QRA, it is usually necessary to consider a greater number of possible directions, in order to eliminate any spurious, numerical error in the risk results. The process of interpolating between the modelled wind directions is called 'wind smoothing' (achieved mathematically in software such as GIS*Risk* the Consultants proprietary risk integration tool).

The application of wind smoothing in this study was considered in detail in Technical Note 1 of 8 WTWs Reassessment Study [23]. It was concluded that for sites with relatively flat surrounding terrain, wind smoothing could be achieved by the simple method of cloud 'rotation' (i.e. rotation of clouds to fill the directional 'gaps' left by the CFD modelling). With reference to Sha Tin WTW, as the building and terrains in the vicinity of the Desalination Plant is not complicated and it is deemed that sufficient number of wind directions were considered in the CFD modelling, such that further wind smoothing was either not necessary or could be achieved easily by the method of cloud rotation without introducing any significant additional error.

(v) Chlorine Cloud Height

Chlorine cloud heights for continuous and instantaneous releases have been obtained from the CFD modellings. This is useful for determining the impact on populations within high rise buildings. Takes into account the terrain offset, the chlorine cloud height of dose concentration for LD03 contour for continuous and instantaneous releases obtained by CFD modelling is determined, as presented in Table 13.18.

The current study directly uses CFD simulation results which take into account the actual building layout and terrain to calculate the total dose during chlorine gas dispersion (i.e. integration of Probit via time). The maximum cloud height of LD03 is then determined accordingly. In the previous 8WTWs Reassessment Study, the cloud height was given by considering equivalent cloud height based on conversion of mass, scaling factors from DRIFT results and a relatively simple geometry.

Assuming 3 m per storey, the maximum cloud heights obtained from CFD modelling and adopted in this study for are 51 m (equivalent to 17 storeys), 69 m (equivalent to 23 storeys), 24 m (equivalent to 8 storeys) and 90 m (equivalent to 30 storeys) for 1.4 kg/s continuous release, 1 tonne instantaneous release, 57 kg instantaneous release and 4.2 tonnes instantaneous release respectively.

Table 13.18 Chlorine Cloud Height Prediction from CFD Modelling

Release Cases	Chlorine Cloud Height at LD03 (Note 1)		
	Weather Class	LD03 Cloud Height (m) (Note 2)	No. of Storeys (Note 3)
1.4 kg/s continuous	D2	39	13
	D4.5	51	17
4.2 kg/s continuous	D2	-	-
	D4.5	-	-

Release Cases	Chlorine Cloud Height at LD03 (Note 1)		
1 tonne instantaneous	D2	63	21
	D4.5	69	23
57 kg instantaneous	D2	24	8
	D4.5	24	8
4.2 tonnes instantaneous	D2	90	30
	D4.5	78	26

Note 1: Note that the chlorine cloud height is estimated based on the dose concentration ($C^{2.3}t$) for LD03 contour (i.e. 3.68×10^{7} $(mg\ m^{-3})^{2.3}min$).
Note 2: The value has taken into account the terrain offset.
Note 3: Assumes 3 m per storey.

(vi) Vertical Scaling Factors

As described above, the relationship between the horizontal chlorine hazard range and release rate/quantity of chlorine is presented in Annex A. However, the same relationship could not be applied in the vertical dimension because of the smaller extent of mixing in the z direction.

Based on the PHAST dispersion modelling results, an approximation of 1/3 power law is applied to 1.4 kg/s continuous release to estimate the cloud height of 4.2 kg/s continuous release. The calculation is shown below:

Cloud height of 1.4 kg/s continuous release from CFD simulation = 51 m (i.e. 17 storeys).

Cloud height of 4.2 kg/s continuous release = $(4.2/1.4)^{1/3} \times 51$= 75 m (i.e. 25 storeys).

The same approach is described in the previous QRA studies of 8 WTWs Reassessment Study [1].

(vii) Modelling of Escape from the Chlorine Cloud

In risk assessments for toxic gas releases it is common practice to take into account the possibility of escape of exposed persons. This is because at lower concentrations of the gas, people may be able to obtain protection by moving indoors or directly out of the cloud.

Annex F1 of 8 WTWs Reassessment Study [1] provides details of the modelling of escape from a chlorine cloud which is also followed in this study. The methodology is similar to that developed by the UK Health and Safety Executive (HSE) [24]. It assumes that a person outdoors will have a probability of escape dependent on the chlorine cloud concentration, with escape occurring either directly out of the cloud or to a nearby building. The methodology takes into account the dose received during escape as well as the subsequent dose in the place of refuge. Suitable conservative assumptions are made for the time of escape bearing in mind the debilitating effect of the chlorine gas.

Incorporating all the above considerations it is possible to calculate an 'effective' outdoors fatality probability, i.e. the fatality probability that can be applied to the total outdoor population at any given location taking into account the probability of escape.

The consequence analysis gives three fatality probability contours for each release scenario, corresponding to 3%, 50% and 90% nominal outdoor fatality probability. The effective outdoors fatality probabilities corresponding to these levels of fatality are shown in Table 13.19.

Table 13.19 Effective Outdoors Probability of Fatality

Nominal Outdoor Fatality Probability (for a Person Remaining Outdoors)	% of Population Attempting Escape	Effective Outdoor Fatality Probability (Taking into Account the Probability of Escape)
90%	0%	90%
50%	80%	31%
3%	80%	0.7%

(viii) Protection for Persons Indoors

Following similar previous studies [1][2][3] undertaken in Hong Kong and elsewhere, it is assumed that the probability of fatality for a person indoors is 10% of that for a person remaining outdoors, i.e. nominal outdoor fatality probability.

Protection is also considered for people on the upper floors of high rise buildings. This is based on data on the typical height of a chlorine cloud provided by the dispersion modelling.

(ix) Sensitive Populations

Certain groups of people, i.e. the primary student, the elderly and the infirm will be more sensitive to the effects of chlorine than others [1]. This is taken into account in the QRA by increasing the fatality rate applied to certain sensitive receivers such as primary schools (see Table 13.6).

In line with data published by Withers and Lees [25] and risk criteria applied to sensitive developments in the UK and Australia, the fatality rate for these groups of people is set a factor of 3.3 higher than for the average population.

(x) Transient Population

The approach to modelling the effect of chlorine releases on transient populations, in particular road vehicles, essentially follows that developed under research work undertaken on behalf of the UK HSE, as described in the previous 8 WTWs Reassessment Study [1].

<u>Rationalization of Chlorine Release Scenarios and Estimation of Scenario Frequencies</u>

<u>Release Scenarios Considered</u>

With reference to previous studies (e.g. previous 8 WTWs Reassessment Study [1], Shatin to Central Link [2] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3]), Table 13.20 considers each release scenario in turn and, based on the results of the consequence analysis in Table 13.15 and Table 13.16, determines whether the scenario poses an off-site hazard.

This study follows the approach in the previous 8 WTWs Reassessment Study [1]. In the previous 8 WTWs Reassessment Report [1], it stated that only certain, severe types of chlorine release scenarios (i.e. external continuous releases of 1.4 kg/s or more and instantaneous releases of 1 tonne or more whether external or internal) could produce fatal off-site impact. Based on the reasons described in Section 13.2.7, it is deemed appropriate to apply the previous finding in this study.

Table 13.21 then summarises the results of the analysis in Table 13.20 by grouping the release scenarios into 'events' having identical release characteristics (i.e. the same release rate, duration and phase of release).

Table 13.22 shows the events grouped according to the leak quantity.

Table 13.20 Rationalisation of Chlorine Release Scenarios

Ref.	Scenario	Outcome	Hole Size - Diameter	Phase	Source Release Rate (kg/s)	Release Qty. (tonnes)	Release Rate/ Qty. to Atmosphere	Off-site Hazard [Note 3 & 4]	Event Ref. [Note 5]
1	**ACCESS ROAD**								
1.1	Truck fire	Considered to result in the melting of the fusible plugs on up to three drums	3×6mm	Liquid	2.4	3	2.4 kg/s (2)	Y	RU1TMML
1.3	Manoeuvring accident	Single drum - small leak	3mm	Liquid	0.2	1	0.2 kg/s	N	-
1.4	Rollover	Single drum – small leak	3mm	Liquid	0.2	1	0.2 kg/s	N	-
		Single drum – medium leak	8mm	Liquid	1.4	1	1.4 kg/s	Y	RU1TSML
		Three drums – medium leak	3×8mm	Liquid	4.2	3	4.2 kg/s	Y	RU1TMML
		Fire (outcomes as item 1.1 above)		Liquid					
1.5	Collision	Single drum – rupture	-	Liquid	-	1 (inst)	1 tonne	Y	RU1TSRU
		Fire (outcomes as item 1.1 above)		Liquid					
1.6	Loadshedding	Single drum – small leak	3mm	Liquid	0.2	1	0.2 kg/s	N	-
		Single drum – medium leak	8mm	Liquid	1.4	1	1.4 kg/s	Y	RU1TSML
1.7	Spontaneous container failure	Single drum – medium leak	8mm	Liquid	1.4	1	1.4 kg/s	Y	RU1TSML
		Single drum – large leak	20mm	Liquid	8.8	1	8.8 kg/s (1)	Y	RU1TSRU
		Single drum – rupture	-	Liquid	-	1 (inst)	1 tonne	Y	RU1TSRU
2	**CONTAINERS HANDLING**								
2.1	Dropped drum	Single drum – medium leak	8mm	Liquid	1.4	1	0.3 kg/s	N	-
		Single drum – large leak	20mm	Liquid	8.8	1	0.56 kg/s	N	-
		Single drum – rupture	-	Liquid	-	1 (inst)	57 kg	Y	IU1TSRU
2.2	Collision of drum with another object	Single drum – medium leak	8mm	Liquid	1.4	1	0.3 kg/s	N	-
2.3	Accidental impact of drum on pigtail during setdown at standby position	Pigtail – guillotine failure	4.5mm	2-phase	0.12	1	0.027 kg/s	N	-
2.4	Dropped drum due to overextension of truck crane	Single drum – medium leak	8mm	Liquid	1.4	1	0.3 kg/s	N	-
2.5	Dropped drum due to incorrect alignment of rail track	As item 2.1 above							
3	**CONTAINERS IN STORAGE**								
3.1	Spontaneous chlorine drums failure – leaking chlorine drums	Single drum – medium leak	8mm	Liquid	1.4	1	0.3 kg/s	N	-
		Single drum – large leak	20mm	Liquid	8.8	1	0.56 kg/s	N	-

Ref.	Scenario	Outcome	Hole Size - Diameter	Phase	Source Release Rate (kg/s)	Release Qty. (tonnes)	Release Rate/ Qty. to Atmosphere	Off-site Hazard [Note 3 & 4]	Event Ref. [Note 5]
		Single drum – rupture	-	Liquid	-	1 (inst)	57 kg	Y	IU1TSRU
3.2	Overfilled drums leading to over-pressurisation on thermal expansion	As item 3.1 above							
3.3	Impurities in chlorine drum leading to explosion or leak	As item 3.1 above							
3.13	Earthquake	Roof collapse: Multiple drum rupture	-	Liquid	-	6 (inst)	4.2 tonnes [Note 6]	Y	EU1TMRU EU1TMRU1G
4	**CONNECTION AND DISCONNECTION OF CHLORINE CONTAINERS**								
4.1	Human error or equipment failure during connection/ disconnection of drums	Pigtail – guillotine failure	4.5mm	2-phase	0.12	1	0.027 kg/s	N	-
5	**CHLORINATION SYSTEM**								
5.1 – 5.5	Failures associated with the chlorination system pipework	Liquid chlorine pipework – guillotine failure	4.5mm	2-phase	0.12	1.05	0.027 kg/s	N	-
5.6 – 5.7	Failure of Evaporator	Evaporator – leak or rupture	4.5mm	2-phase	0.12	1.05	0.027 kg/s	N	-

Note:

[1] Release duration for large leak is less than 2 minutes and is considered rupture release

[2] This release (2.4 kg/s) treated as a multiple medium leak for simplification (conservative assumption)

[3] Verified by CFD modeling results

[4] CFD simulations for 0.56kg/s and 0.3kg/s continuous chlorine releases have been conducted (Annex B2). It can be concluded that chlorine release scenario with continuous release rate of 0.56kg/s and 0.3kg/s will have insignificant or no impact to the off-site populated area (i.e. TKO 137 Area). As such, these scenarios (with continuous release rate ≤ 0.56 kg/s) are not further considered in the study.

[5] Key to event ref

R	*Road or E (Earthquake) or I (Internal)*
U	*U (Unisolated) or I (Isolated)*
1T	*1T (1 tonne drums)*
M	*S (Single) or M (Multiple)*
RU	*RU (Rupture), LL (Large Leak), ML (Medium Leak) or SL (Small Leak)*
1G	*Earthquake of higher ground acceleration*

[6] After the instantaneous discharge of chlorine from ruptured drums, it is estimated that 70% of the chlorine is released to atmosphere as vapour and entrained aerosol. The chlorine vapour cloud is contributed by the initial vapour flash fraction (19%), the entrained aerosol (2 x 19%) and evaporating chlorine pool over the first minute (10% depending on the chlorine pool size).

Table 13.21 Release Scenarios Included in QRA

Event Ref	Component Scenarios	Release Rate (or Quantity) to Atmosphere	Type of Release	Release Location
IU1TSRU	Spontaneous failure Dropped drum	57 kg	Instantaneous	Chlorination Store
RU1TSML	Rollover Loadshedding Spontaneous leak	1.4 kg/s	Continuous	Access road
RU1TMML	Rollover Truck fire	4.2 kg/s	Continuous	Access road
RU1TSRU	Truck impact Spontaneous container failure	1 tonne	Instantaneous	Access road
EU1TMRU	Earthquake: roof collapse, ground acceleration 0.7g	4.2 tonnes	Instantaneous	Chlorination Store
EU1TMRU1G	Earthquake: roof collapse, ground acceleration 1.0g	4.2 tonnes	Instantaneous	Chlorination Store

Table 13.22 Release Scenarios Categorised by Leak Quantity

Leak Quantity (kg)	Event Ref
0 - 10	None
10 - 100	IU1TSRU
100 - 1000	RU1TSML
	RU1TMML
	RU1TSRU
> 1000	EU1TMRU
	EU1TMRU1G

13.2.9 Frequency Estimation

Next step in the Hazard Assessment is to determine the frequency of occurrence of scenarios listed in Table 13.21. This is based on the approach outlined in the Methodology Report of previous 8 WTWs Reassessment Study [12]. Failure frequencies adopted in this hazard to life assessment (HA) have made reference to the reports of "Reassessment of Chlorine Hazard for Eight Existing Water Treatment Works" and a more recent HA about Water Treatment Works of "In-Situ Reprovisioning of Sha Tin Water Treatment Works (STWTW) South Works Project".

The latest traffic accident data (2009 to 2013) has been reviewed and the involvement rates of chlorine truck accident with significant impact are found to be 0.224 and 0.229 for 2007 and 2013, respectively. Such change is considered insignificant comparing to the involvement rate used in the current PHI QRA (0.59 per million vehicle-km). That said, the variation in transport accident rate should not result in noticeable change to the PHI QRA.

<u>Frequency Estimation Results</u>

Table 13.23 summarises the base data which has been used in the frequency calculations. Following the fault tree analysis adopted in Methodology Report of previous 8 WTWs Reassessment Study [12] and also applied in Shatin to Central Link [2] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3], actual frequencies are then determined based on these base failure data and the operational parameters of the Desalination Plant such as chlorine use, chlorine delivery frequency, chlorine delivery truck

speed, and length of the access road or, in the case of the aircraft crash event, the proposed Desalination Plant location in relation to the flight path, number of flights into Chek Lap Kok International Airport etc.

Table 13.23 Base Failure Rate Data

Data item	Value	Units	Source
1. *Chlorine Drum*			
(i) Spontaneous drum failure frequency (ii) Conditional probability of catastrophic failure (iii) Conditional probability of large leak (iv) Conditional probability of medium leak	1.5E-4 2.7E-2 8.1E-2 2.2E-1	per year - - -	*Methodology Report* of 8 WTWs Reassessment Study [1], based on review of worldwide failure data for chlorine containers and generic pressure vessel failure data
(v) Probability of dropped drum (vi) Probability of leak following dropped drum (vii) Conditional probability of rupture	7.7E-6 1 1.0E-4	per lift - -	*Methodology Report* of 8 WTWs Reassessment Study [1], based on Hong Kong data for number of lifts which have occurred without incident.
2. *Chlorine Delivery Vehicle*			
(i) Spontaneous container failure frequency (ii) Conditional probability of catastrophic failure (iii) Conditional probability of large leak (iv) Conditional probability of medium leak	1.5E-4 2.7E-2 8.1E-2 2.2E-1	per year - - -	*Methodology Report* of 8 WTWs Reassessment Study [1], based on review of worldwide failure data for chlorine containers and generic pressure vessel failure data
(v) Frequency of loadshedding (vi) Conditional probability of a medium leak	1.1E-7 6.3E-2	per truck-km -	*Methodology Report* of 8 WTWs Reassessment Study [1], based on Chlorine Transport Risk Study, DNV (1997) [13]
(vii) Frequency of rollover (viii) Conditional probability of a small leak from a single drum (ix) Conditional probability of a medium leak of a single drum (x) Conditional probability of medium leak of multiple drums	1.9E-7 2.4E-1 1.5E-1 1.1E-2	per truck-km - - -	*Methodology Report* of 8 WTWs Reassessment Study [1], based on Chlorine Transport Risk Study, DNV (1997) (Note 1) [13]
(xi) Frequency of vehicle impact (xii) Conditional probability of drum rupture	4.0E-7 1.7E-2	per truck-km -	Chlorine Transport Risk Study, DNV (1997) (Note 1) [13]
(xiii) Frequency of spontaneous truck fire (xiv) Conditional probability of a medium leak of multiple drums	4.0E-9 1	per truck-km -	Chlorine Transport Risk Study, DNV [13]
3.Extenal Events			
(i) Frequency of earthquake of 0.7g ground acceleration (1) (ii) Probability of roof collapse in an earthquake of 0.7g ground acceleration (iii) Frequency of earthquake of	4.0E-7 0.1 2.5E-8	per year - per year	Estimated based on Water Treatment Works Seismic Hazard Assessment, Ove Arup (2000) [37]

Data item		Value	Units	Source
	1.0g ground acceleration (1)			
(iv)	Probability of roof collapse in an earthquake of 1.0g ground acceleration	0.5	-	
(v)	Frequency of aircraft crash	5.52E-17	per year	Frequency analysis presents in Table 13.24

Note 1: The DNV (1997) rollover and impact frequencies were derived from the general truck accident involvement rate on Hong Kong roads. This is a very conservative assumption considering the very low traffic volume and very low chlorine truck speed on the access road.

(i) Frequency of Hazardous Scenarios on Access Road and at Chlorination Store

The probabilities of hazardous scenarios due to chlorine deliver and drum handling identified in Table 13.21 have been estimated using fault tree analysis and is summarised in Table 13.25.

(ii) Frequency of Earthquake

The probability of hazardous scenarios due to earthquake is presented in Annex E.

(iii) Frequency of Aircraft Crash

The probability of a civilian aircraft crashing on-site can be estimated using the HSE methodology [26]. The same model has been used in previous assessments of aircraft accidents [2][27]. The model takes into account specific factors such as the target area of the proposed site and its longitudinal (x) and perpendicular (y) distances from the airport runway thresholds of the Hong Kong International Airport (Figure 13.11).

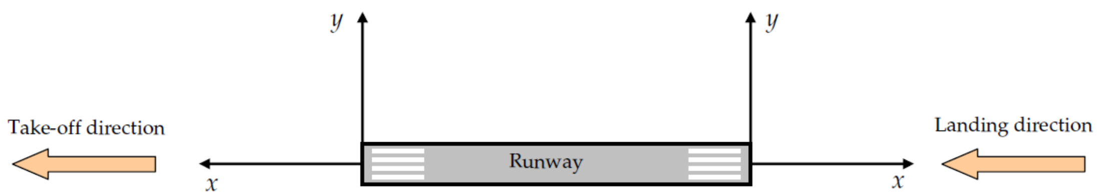


Figure 13.11 Aircraft Crash Coordinate System

The crash frequency per unit ground area (per km²) is calculated as:

$$g(x,y) = NRF(x,y) \qquad \text{(Equation 1)}$$

where N is the number of runway movements per year and R is the probability of an accident per movement (landing or take-off). F(x,y) gives the spatial distribution of crashes and is given by:

Landings

$$F_L(x,y) = \frac{(x+3.275)}{3.24} e^{\frac{-(x+3.275)}{1.8}} \left[\frac{56.25}{\sqrt{2\pi}} e^{-0.5(125y)^2} + 0.625 e^{-\frac{|y|}{0.4}} + 0.005 e^{-\frac{|y|}{5}} \right] \quad \text{(Equation 2)}$$

for $x > -3.275$ km

Take-off

$$F_T(x,y) = \frac{(x+0.6)}{1.44} e^{\frac{-(x+0.65)}{1.2}} \left[\frac{46.25}{\sqrt{2\pi}} e^{-0.5(125y)^2} + 0.9635 e^{-4.1|y|} + 0.08 e^{-|y|} \right] \quad \text{(Equation 3)}$$

for $x > -0.6$ km

Equations 2 and 3 are valid only for the specified range of x values, as defined in Figure 13.11 for take-offs and landings. If x lies outside this range, the impact probability is zero.

National Transportation Safety Board (NTSB) data for fatal accidents in the US involving scheduled airline flights during the period 1986-2005 show a downward trend with recent years showing a rate of about 2×10^{-7} per flight. However, only 13.5% of accidents are associated with the approach to landing, 15.8% are associated with take-off and 4.2% are related to the climb phase of the flight [28]. The accident frequency for the approach to landings hence becomes 2.7×10^{-8} per flight and for take-off/climb 4.0×10^{-8} per flight. The Civil Aviation Department (CAD) reports annual numbers of flights at Chek Lap Kok in the past years. The annual number of flights at Year 2014 is estimated as 377,560.

Chek Lap Kok has 2 runways, but with take-offs and landings from each direction, the runway designations are 07L, 07R, 25L and 25R. Half the plane movements are taking-offs (188,780 per year) and half are landings (188,780 per year). Assuming each runway is used with equal probability, the frequency of crashes at the Chlorination Store of the proposed Desalination Plant sites is calculated in. The footprint area of the Chlorination Store is estimated at 28m × 20m = 560 m^2, suggesting a target area of 1000 m^2.

From Table 13.24, the combined frequencies of all take-off and landing crashes amount to much less than 10^{-9} per year for the Chlorination Store of the proposed Desalination Plant. The risk of aircraft crash is therefore negligible and so will not be further considered in the study.

The resulting total event frequencies are presented in Table 13.25. The details of frequency estimation analysis are presented in Annex G.

Table 13.24 Airplane Crash Frequencies

Desalination Plant	Distance from Runway Threshold (km)				Crash Frequency (per km^2-year) (Note 1)					Chlorination Store Area (m^2) (Note 2)	Impact Frequency (per year)
	07L/25R		07R/25L		07L	25R	07R	25L	Total	-	-
	x	*y*	*x*	*y*	Take-off	Landing	Take-off	Landing	-	-	-
Chlorination Store	27.6	16	27.6	14.5	1.19E-21	4.57E-14	1.19E-19	9.50E-15	5.52E-14	1000	5.52E-17

Note 1: Take-offs to the west on runways 25L/R, and landings from the west on runways 07L/R will not contribute to the crash frequencies impacting on the Desalination Plant
Note 2: Size of Chlorination Store of the proposed Desalination Plant is about 28m×20m =560 m^2. It is conservatively assumed the area of Chlorination Store as 1000 m^2.

Table 13.25 Event Frequencies On-site Chlorine of Hazardous Scenarios

Event Ref	Component Scenarios	Frequency (per year)	Time Periods during Which Event Could Occur
IU1TSRU	Dropped drum	2.29E-7	All except Night
	Spontaneous drum failure	1.50E-4	All
	Total	***1.50E-4***	
RU1TSML (Note 1)	Rollover	4.01E-7	All except Night
	Loadshedding	9.45E-8	All except Night
	Spontaneous leak	3.11E-8	All except Night
	Total	***5.27E-7***	
RU1TMML (Note 1)	Rollover	2.87E-8	All except Night
	Truck fire	5.50E-8	All except Night
	Total	***8.37E-8***	
RU1TSRU (Note 1)	Truck impact	9.38E-8	All except Night
	Spontaneous container failure (Note 2)	1.50E-8	All except Night
	Total	***1.09E-7***	
EU1TMRU	Earthquake (0.7 g ground acceleration)	4.00E-8	All
EU1TMRU1G	Earthquake (1.0 g ground acceleration)	1.25E-8	All
AU1TMRU	Aircraft crash	5.52E-17 (Note 3)	All

Note 1: Frequencies of events occurring on the access road are calculated from the number of chlorine truck delivery per year and the length of the on-site truck access route. Maximum storage of 37 tonnes is assumed for the Chlorination Store for provision of 3-month storage capacity. Correspondingly the maximum annual consumption of chlorine is 148 tonnes (= 37/ 3 x 12), which requires 25 truck deliveries annually (148 drums/ 6 drums per truck).
Note 2: Includes large leak and rupture spontaneous container failure.
Note 3: Not further considered in QRA analysis due to frequency < 1E-9 per year.

13.2.10 Risk Summation

Methodology

For each outcome of each individual event, the results of the consequence and frequency analysis have been combined to give a measure of risk of each outcome. By summing all the events' risk contribution, the total risk for the facility can be obtained. This step has been done by using suitable risk summation software. This study has been undertaken using **ERM GIS*Risk***.

The main outputs from the software are as follows:

- Individual risk in the form of iso-risk contours overlaid on a base map of the area;
- Societal risk in the form of an FN curve, which is a graphical representation of the cumulative frequency (F) of N or more fatalities plotted against N on a log-log scale; and
- Societal risk in the form of a Potential Loss of Life (PLL) value, which expresses the risk to the population as a whole and for each scenario and its location. The PLL is an integrated measure of societal risk obtained by summing the product of each f-N pair, as below:

$$PLL = f_1N_1 + f_2N_2 + \cdots + f_nN_n$$

The individual and societal risk guidelines are described in Section 13.1.2.

Societal Risk Result for on-site chlorine risk at the proposed Desalination Plant

The FN curve for the operational phase scenario (Year 2036) is presented in Figure 13.12. The maximum N numbers derived from the figure is around 10 for $F > 1\times10^{-9}$ per year. Table 13.26 presents the overall PLL values, together with a breakdown of the PLL by release scenario and affected population. The breakdown of the PLL by population group is presented in Table 13.27. As can be seen in Figure 13.12, the F-N curve for risk from on-site chlorine at the proposed Desalination Plant lies within the "Acceptable" region.

Table 13.26 Breakdown of PLL by Release Scenario for On-site Chlorine Assessment

Event Ref	Operational Phase	
	Per Year	%
IU1TSRU	0	0.0%
RU1TSML	7.08E-8	9.4%
RU1TMML	9.42E-8	12.5%
RU1TSRU	3.43E-8	4.6%
EU1TMRU	5.24E-7	69.7%
EU1TMRU1G	2.89E-8	3.8%
Total	**7.52E-7**	**100.0%**

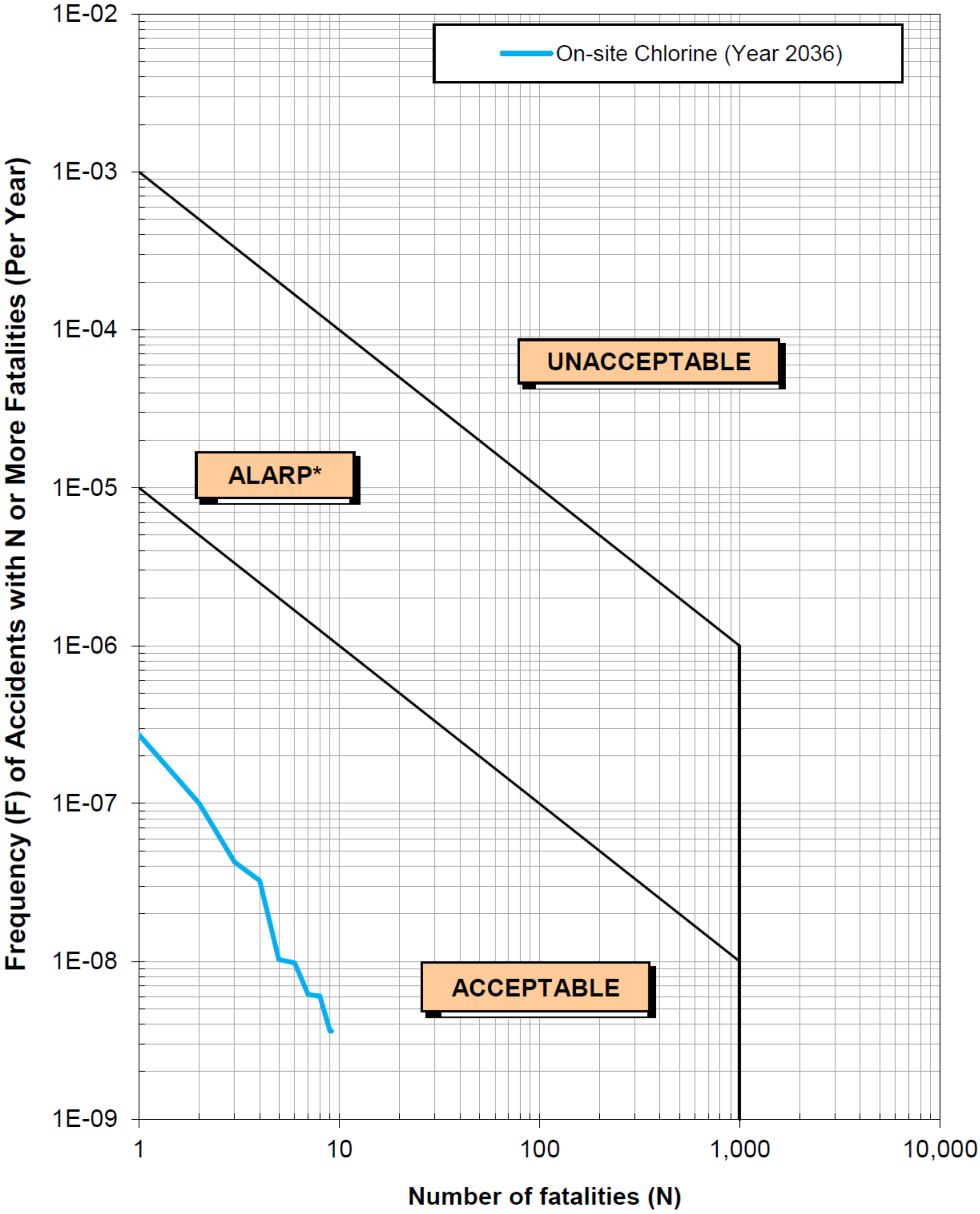


Figure 13.12 FN Curve of Operational Phase of the Desalination Plant for On-site Chlorine Assessment

Table 13.27 Breakdown of PLL by Population for On-site Chlorine Assessment

Location Ref (Note 1)	Operational Phase	
	Per Year	%
04 TKO Area 137 Pier	1.27E-7	16.8%
05 SENT Landfill Extension	4.78E-8	6.4%
06 TKO Area 137	5.74E-7	76.4%
07 Tathong Channel	2.87E-9	0.4%
Total	**7.52E-7**	**100.0%**

Note 1: For descriptions and locations of population units, refer to Table 13.6 and Figure 13.9

<u>Individual Risk Result for on-site chlorine risk at the proposed Desalination Plant</u>

The individual risk is defined as the probability of a fatality for a hypothetical person spending 100% of their time outdoors in the vicinity of the proposed Desalination Plant. As noted in Section 13.1.2, HK Risk Guidelines stipulate that the maximum level of off-site risk should not exceed 1 in 100,000 per year, i.e. 1×10^{-5} per year.

Figure 13.13 presents the individual risks obtained for the worst case scenario assuming the maximum chlorine storage of 37 tonnes. The contours near the chlorination store (i.e. 1×10^{-5} and 1×10^{-6}) is dominated by the event IU1TSRU (internal release due to drum handling and spontaneous drum failure) due to its high event frequency whilst the 1×10^{-7} contour is contributed by earthquake event due to its large consequence distance.

As can be seen, the individual risk due to on-site chlorine risk is low, and nowhere outside the Desalination Plant site boundary does the individual risk exceed 1×10^{-5} per year. It is therefore concluded that the on-site chlorine risk at the proposed Desalination Plant at TKO Area 137 complies with the individual risk criteria.

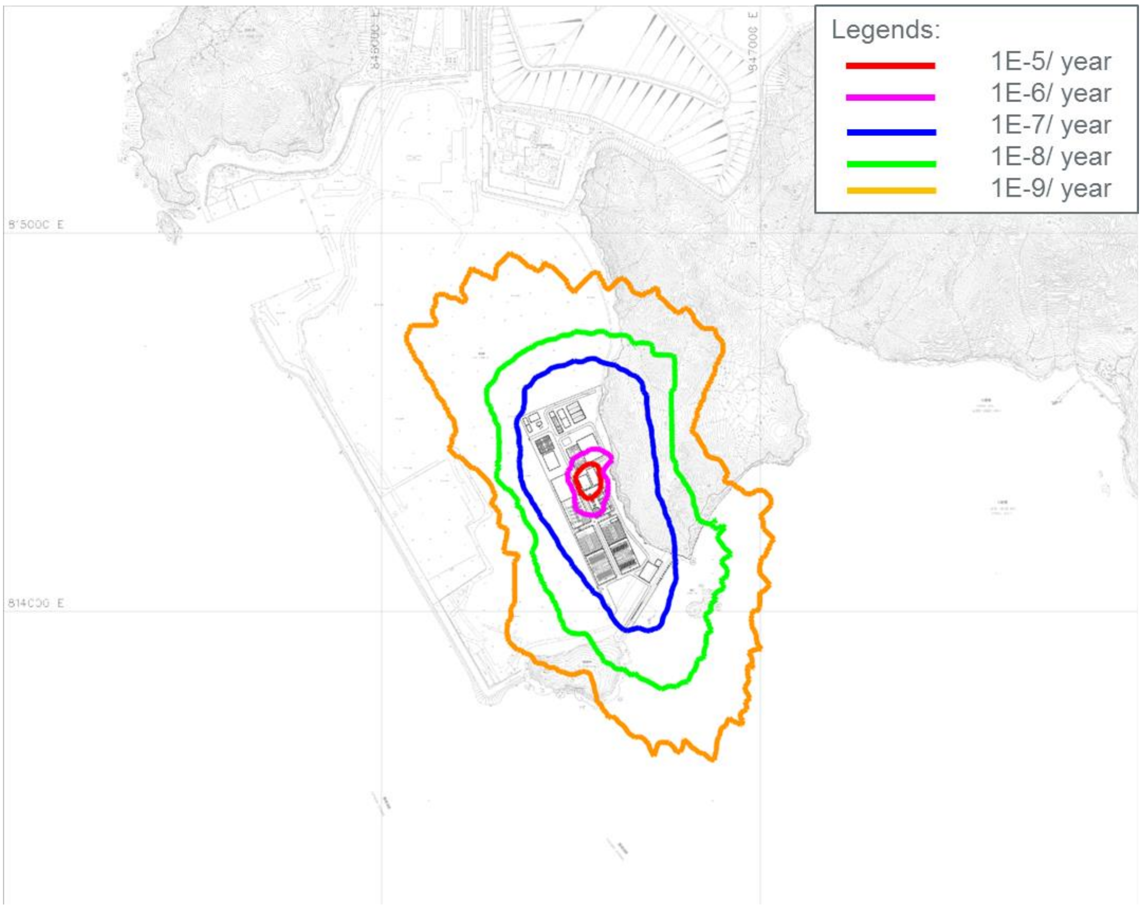


Figure 13.13 Individual Risk Contours for On-site Chlorine Assessment

<u>Result Summary</u>

A Hazard Assessment of the risks associated with the storage, use and on-site Road Transport of chlorine (from TKO Area 137 Pier to the Chlorination Store) at the proposed Desalination Plant at TKO Area 137 has been conducted for the Operational Phase.

Following the Study Brief of the project, the methodology adopted in the hazard assessment is consistent with previous studies having similar issues, i.e. 8 WTWs Reassessment Study [1], Shatin to Central Link [2] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3].

For operational phase (Year 2036), the Individual Risk complies with the Hong Kong Risk Guidelines (HKRG) and the societal risk expressed in the form of FN curve, lies in the "Acceptable" region of the HKRG.

The assessment concludes individual risk and societal risk associated with the storage, use and on-site Road Transport of chlorine (from TKO Area 137 Pier to the Chlorination Store) at the proposed Desalination Plant at TKO Area 137 are acceptable for operational phase (Year 2036). The overall risk (in terms of individual risk and societal risk) lies within the acceptable level.

13.3 QRA for Off-site Transport of Chlorine

13.3.1 Overview

The scope of off-site transport of chlorine is defined to include the following three elements:

(i) Marine transport route between Sham Shui Kok Chlorine Dock and TKO Area 137 pier

(ii) Unloading and Loading at TKO Area 137 pier

(iii) Road transport from TKO Area 137 pier to the proposed Desalination Plant

It is assumed that the liquid chlorine drums required for the proposed Desalination Plant are delivered to TKO Area 137 pier and then to proposed Desalination Plant by dedicated marine vessels and trucks operated by the chlorine supplier. Off-site transport of chlorine (liquid chlorine contained in 1-tonne chlorine drums) poses a risk to the general public from accidental release and dispersion of toxic chlorine vapour along the transport route from Sham Shui Kok Chlorine Dock to the Desalination Plant.

A risk assessment on off-site transport of chlorine was undertaken in the 2006 Study [4]. In the study, risks associated with marine transport within Hong Kong waters and road transport of 1-tonne drums as well as chlorine dock operation were investigated for different options of chlorine dock location. A set of chlorine release scenarios was identified. Failure frequencies were derived using fault tree analysis. Consequence analysis was carried out using ALOHA (referring to Section 13.3.6 for more information on ALOHA) to give impact zones. Results were presented in terms of:

- Individual risk contours for marine transport and chlorine dock operation
- FN curves and Potential Loss of Life (PLL) for societal risk with breakdown by activity (i.e. road, dock and marine). PLL by failure case for each activity was also presented in to show major contributors as supplementary information.

Considering the availability of relevant previous study [4], risk assessment on off-site chlorine transport is based on methodology, findings and data of the study as far as possible to minimize the use of new modelling data. Hence, the amount time for assessment and approval process can be reduced. Following sections describe how this assessment adopts the 2006 Study [4] and the rationale.

<u>Off-site Marine Transport</u>

The marine transport covers transport of chlorine drums between Sham Shui Kok Chlorine Dock and TKO Area 137 pier using dedicated marine vessels by sea. The proposed route (primary route, segments 1-2-4-8) and an alternative route (segments 1-3-5-6-7-9) are depicted in Figure 13.14. Although the traveling distance for the alternative route (via Lamma Island) is longer than the primary route (via Kowloon Bay), the inclusion of the alternative route is to evaluate the amount of risk reduction due to avoiding relatively heavy marine traffic (i.e. higher marine traffic population density) in the Victoria Harbour.

Since most part of the marine transport route is covered by the scenario “Existing Route Using Kowloon Bay Dock (Based Case)” under the 2006 Study, the methodology of the 2006 Study is adopted for off-site marine transport from Sham Shui Kok Chlorine Dock to TKO Area 137 pier.

Figure 13.14 Marine Transport Routes from Sham Shui Kok to TKO Area 137 Pier

Unloading/Loading at TKO Area 137 Pier

Unloading and loading at TKO Area 137 Pier covers transfer operation of chlorine drums from the dedicated marine vessels to chlorine trucks.

The unloading/loading operation at the TKO Area 137 follows the existing procedures for Sham Shui Kok chlorine dock operation.

Off-site Road Transport

The road transport covers transport of chlorine drums using trucks by road.

The southern boundary of the Desalination Plant adjoins the northern boundary TKO Area 137 Pier. Based on the preliminary plant layout, it is feasible for chlorine trucks entering directly from TKO Area 137 Pier to the Desalination Plant without passing through local roads as shown in Figure 13.7. It is considered that off-site road transport is not applicable to the routing.

The methodology accounts for relevant previous studies including:

- Transport of Liquid Chlorine from Sham Shui Kok of North Lantau & Tuen Mun Area 40 to Various Waterworks Potentially Hazardous Installations – Quantitative Risk Assessment (2006) [4]
- The Risk Assessment of the Transport of Non Fuel Gas Dangerous Goods in Hong Kong (1996) [5]
- Risk Assessment of Liquid Chlorine Transport (1990)[6]
- Hazard to Life Assessment for *In-situ Reprovisioning of Sha Tin Water Treatment Works* [3]

The 2006 Study [4] is the primary reference source for off-site chlorine transport. References [5] and [6] provided study basis for the 2006 Study [4]. Frequency analysis for off-site road transport in this assessment will make reference to [3] for updated base frequencies.

To carry out the Hazard to Life Assessment, Quantitative Risk Assessment (QRA) is be conducted following the generic assessment steps listed below:

- Hazard identification, scenario definition and survey of potentially impacted population
- Frequency assessment
- Consequence assessment
- Risk summation
- Risk mitigation as applicable

13.3.2 Chlorine Transport Route

Sham Shui Kok Chlorine Dock to TKO 137 Pier

The primary route starts from Sham Shui Kok chlorine dock through Ma Wan Channel, Victoria Harbour, Lei Yue Mun and arrives at TKO 137 Pier (refers to segments 1, 2, 4 and 8 in Table 13.28). An alternative route is also selected and assessed to avoid heavy marine traffic in the Victoria Harbour. The alternative route, along the south-western waters of Hong Kong via East Lamma Channel and Tathong Channel (refers to segments 1, 3, 5, 6, 7 and 9 in Table 13.28). Segmentation of the marine transport route is based on an initial estimation of marine traffic. The marine transport routes are indicated in Figure 13.14

Table 13.28 Segmentation of Marine Transport Route

Ref.	Segment Name	Location	Segment Length (km)
1	Sham Shui Kok	Sham Shui Kok – Ma Wan	7.93
2	Tsing Ma	Ma Wan – Victoria Harbour	12.98
3	Tsing Ma	Ma Wan – Cyberport	13.75
4	Victoria Harbour	Victoria Harbour – Lei Yue Mun	12.97
5	East Lamma Channel	Cyberport – Chung Hom Kok	8.34
6	Island South	Chung Hom Kok – Hok Tsui Wan	12.40
7	Tathong Channel	Hok Tsui Wan – Tung Lung Chau	3.87
8	Tseung Kwan O	Lei Yue Mun – TKO 137 pier	4.28
9	Tseung Kwan O	Tung Lung Chau – TKO 137 pier	1.91

13.3.3 Population Definition

Off-site Marine Transport (From Sham Shui Kok Chlorine Dock to TKO Area 137 Pier)

Referring to the 2006 Study [4], each marine route section requires the following definitions:

- Route section length
- Amount of chlorine being transported along the section per year
- Meteorological data
- Marine population

Marine population is estimated from vessels count in surveys. Surveys were undertaken at various locations including Tsing Lung Tau, Ma Wan Channel, Victoria Harbour, East Lamma Channel), Island South, Tathong Channel (Tung Lung Chau) and Tathong Channel (Lei Yue

Mun). The survey used the same technique as in the Atkins 2006 [4] by taking 3 snapshots at a survey location for each route section. Records of the surveys and estimation of traffic population are detailed in Annex D. The estimated marine traffic population is summarized in Table 13.29. The updated marine population is combined with consequence modeling results for the number of fatalities estimation.

Table 13.29 Estimated Marine Traffic Population

Segment Name	Survey Location	Population Density (ppl/m^2)
Sham Shui Kok	Tsing Lung Tau	1.41E-5
Tsing Ma	Ma Wan Channel	3.35E-5
Victoria Harbour	Victoria Harbour (Tsim Sha Tsui)	6.66E-4
East Lamma Channel	Cyberport	1.53E-5
Island South	Chung Hom Kok	2.93E-6
Tathong Channel	Tathong Channel (Tung Lung Chau)	7.90E-6
Tseung Kwan O	Tathong Channel (Lei Yue Mun)	7.44E-6

Unloading/Loading at TKO Area 137 Pier

In the Atkins 2006 [4], the risk impact of Kowloon Bay/Sham Shui Kok Chlorine Dock was assessed. Population surrounding the chlorine docks was accounted for in the study. Similar to the Atkins 2006 [4], population surrounding the TKO Area 137 Pier except staff of the Desalination Plant is included in the assessment. Details of population estimation are described in the previous sections about population for storage, use and on-site transport of Chlorine (PHI).

13.3.4 Meteorological Data

Wind direction and wind speed have direct effects on chlorine gas dispersion. However, the off-site transport route passes through variation locations in Hong Kong waters. The wind conditions vary from one location to another. For simplification, wind distribution is assumed uniform in all directions. Also, the transport operation is carried out during daytime and at open area. Wind speed of 5 ms^{-1} and atmospheric stability class D were selected as representative weather class (weather class 5D) for marine transport assessment in the Akins 2006 [4]. Detailed meteorological conditions for dispersion modeling are listed as follows and in Table 13.30,

- Open/Urban Area
- Ambient temperature. 23 ^{o}C
- Relative humidity. 75%
- Wind speed, 5 ms-^{1};
- Atmospheric stability class, D

Table 13.30 Wind Direction Probability

Wind Direction (Relative to the Traveling Direction)	Probability (Open Area)
0^o	8.33%
30^o	8.33%
60^o	8.33%
90^o	8.33%
120^o	8.33%
150^o	8.33%
180^o	8.33%

Wind Direction (Relative to the Traveling Direction)	Probability (Open Area)
210^o	8.33%
240^o	8.33%
270^o	8.33%
300^o	8.33%
330^o	8.33%

13.3.5 Hazard Identification

A comprehensive review of hazardous properties of liquid chlorine, review of historical incidents with respect to transportation of liquid chlorine both in Hong Kong and overseas, review of relevant previous studies is carried out to identify hazards applicable for the off-site transportation of liquid chlorine from TKO Area 137 pier to the proposed Desalination Plant as part of this project. Based on the hazard identification, a list of scenarios is developed.

Properties of Chlorine

The hazardous properties of chlorine were discussed for PHI. This is also applicable to hazards associated with off-site transport.

Incidents Review

Extensive reviews of the past chlorine incidents were conducted in previous studies [1][5]. In general, only a small number of such incidents involved chlorine releases from drums during their road transport. For example, methodology report for ERM (2001) [1] attributes 14% of the 86 chlorine incidents recorded worldwide over 77 years to the road transport, but about half of these occurred during the loading/unloading operations.

The most recent review of past incidents for the period 1995 – 2004 worldwide was conducted by Atkins (2006) [4]. While it was noted that one major incident (involving a 35-tonne road tanker rather than chlorine drums) occurred during that time, the report concluded that no changes in the study methodology, and in particular in the incident frequencies derived from the generic worldwide data was necessary. There is no change or new operation on the chlorine transport operation since the Atkins (2006) [4]. Therefore, review results from the previous studies are considered valid and applicable to current chlorine transport operation.

Release Scenarios

Hazard scenarios have been developed in the Atkins 2006 [4] in which covers leak failure as well as rupture failure of chlorine drums and cylinders. Failure cases applicable to this study and the corresponding release sizes are selected and tabulated in Table 13.31 and Table 13.32. This set of release scenarios are adopted for consequence and risk analyses.

Table 13.31 Failure Cases of Chlorine Drum

Failure Case Code		Description
by release size	by failure mode	
SVC&D	SVC&DS	Small vapour leak (successful isolation)
	SVC&DF	Small vapour leak (isolation failure)
SLD	SLDS	Small liquid leak (successful isolation)
	SLDF	Small liquid leak (isolation failure)
MVD	MVD	Medium vapour leak

Failure Case Code		Description
by release size	by failure mode	
MLD	MLD	Medium liquid leak
LVD	LVD	Large vapour leak
LLD	LLD	Large liquid leak
RD	RD	Rupture
RDM1	RDM1	Multiple drum failure due to impact
RDM2	RDM2	Multiple drum failure due to fire
Empty	Empty	Release from "empty" drum

Table 13.32 Failure Cases of Chlorine Drum Grouped by Release Size

Release Size	Representative Hole Size (mm)	Representative Release Rate (kg/s)/Quantity	
		Liquid	Gas
Small	2.5	0.1	0.01
Medium	7.5	1	0.1
Large	22.5	10	1
Rupture	-	1,000 kg	
Multiple Failure due to Damage [1]	3 x 7.5	3 (3 drums x 1 medium leak per drum)	
Multiple Failure due to Fire [2]	6 x 10	6 (6 drums x 1 leak through fusible plug)	
Release from "empty" drum	22.5	See Note [3] below	

Notes:
[1] Failure of drums due to impacts in road accidents and load shedding are likely to be small or medium leaks from crack leaks or a burst valve. It is modeled as 3 medium leaks (i.e. 3 kg/s).
[2] For releases in a fire, the scenario is represented by rapid leaks through fusible plugs and valves on 6 drums with equivalent hole size of 10mm each. According to WSD, old drums (3 fusible plugs per drum) have been replaced by new drums (1 fusible plug per drum).
[3] According to the Atkins 2006[4], the quantity of residual chlorine left in a drum marginally is about 3 - 4 kg. Under this storage condition, chlorine is in vapour phase. The release rate from a 22.5mm hole is approximately 0.015 kg/s and is considered a small leak. This is different from the Atkins 2006 (release rate of 1 kg/s) due to too conservative assumption.

13.3.6 Consequence and Vulnerability Assessment

The hazard footprint for each hazard scenario is established from consequence modeling using ALOHA (Areal Locations of Hazardous Atmospheres) model which was developed by US Environmental Protection Agency (EPA) for chemical releases resulting in toxic gas dispersions, fires and/or explosions. This model was previously used in chlorine transport hazard assessment study in 2006 [4].

ALOHA is designed for use during accidental chemical spills to help assess the risk to human populations associated with toxic air hazards, thermal radiation from fires, and blast effects. It is designed to provide a close upper bound to the threat distances associated with chemical spills of a scale typical of transportation accidents, with typical threat zones in the range of 100 to 10,000 meters. ALOHA deals specifically with human health hazards associated with inhalation of toxic chemical vapours, thermal radiation from chemical fires, and the effects of the pressure wave from vapour-cloud explosions.

<u>Hazard Distances</u>

ALOHA presents model outcomes in graphical plots and maximum downwind distances. To enable the textual description of consequence results, LD contours are generalized using 4 parameters as shown in Table 13.33.

Table 13.33 Hazard Distances from ALOHA for Weather Class 5D

Case Code	Release Rate (kg/s)	Lethal Dose (LD)	Distances (m) [1]			
			d	c	a	s
SLD/MVD	0.1	90 [2]	-	-	-	-
		50 [2]	-	-	-	-
		3	66	5	27	0
MLD/LVD	1	90	100	9	56	0
		50	135	11	61	0
		3	211	15	106	0
LLD	10	90	302	34	133	0
		50	433	41	172	0
		3	707	53	251	0
RD	1,000	90	389	44	196	0
		50	557	52	215	0
		3	892	71	389	0
RDM1	3	90	169	17	49	0
		50	241	21	79	0
		3	373	28	183	0
RDM2	6	90	235	26	124	0
		50	340	31	177	0
		3	543	41	244	0

Notes:
[1] d = downwind distance : measured from the release source to the downwind end of the LD contour
c = crosswind distance : maximum half width of a LD contour; measured from the centre line
a = downwind distance to max width: measured from the release source to the maximum crosswind distance
s = offset distance : measured from the release source to the upwind end of the LD contour
[2] ALOHA did not give hazard zone because effects of near-field patchiness. Dispersion predictions are less reliable for short distances.

Since the hazard distance for a small leak is insignificant, small size release and release from 'empty' drum are not further assessed.

Chlorine Cloud Height

Outputs from ALOHA do not consist of cloud height information. The prediction of chlorine cloud height makes reference to the Reassessment Study [1] in which wind tunnel data, CFD and DRIFT model results were applied to give the correlation between release mass and cloud height. According to the Atkins 2006 [4], cloud heights for the selected release scenarios were interpolated from findings of the Reassessment Study [1]. The estimated cloud heights are tabulated in Table 13.34 and adopted in this assessment.

Table 13.34 Chlorine Cloud Height

Case Code	Release Rate (kg/s)	Duration (s)	Quantity Released (tonne)	Cloud Height [3]		
				LD3	LD50	LD90
SLD/ MVD [1]	0.1	500	0.05	1	1	1
MLD/ LVD [1]	1	50	0.05	1	1	1
LLD [1]	10	100	1	3	2	2
RD [2]	1,000	1	1	3	2	2
RDM1 [1]	3	240	0.72	2	1	1
RDM2 [1]	6	210	1.26	3	2	2

Notes:
[1] For the continuous release cases, it is assumed that the chlorine cloud will reach a certain level and become saturated and stable such that continuous release will not further increase the height but maintain the current shape. The saturated time can be estimated using the ALOHA model where it is observed that for a particular release case, the footprint area will remain constant and will not increase further with the increase in release duration.
[2] For instantaneous release cases, it is assumed that the duration is 1 second.
[3] The Cloud Height is assumed to be at least 1 floor height (i.e. 3m) for any release.

The hazard footprint is overlaid on the population polygons to establish overlap areas from which the number of fatalities can be estimated. A series of hazard footprints are used in the computation of the number of person impacted for a given scenario.

Marine population and road population are considered 100% outdoor. Since people on a moving vessel are at speed faster than human escape speed, fatality probabilities derived from the Reassessment Study [1] for building population are considered slightly conservative and applicable to off-site transport. The approach of the Reassessment Study is consistent with the Atkins 2006 [4] by taking into account the escape factor. The fatality probabilities are adopted from the corresponding values for PHI.

13.3.7 Frequency Assessment

Off-site Marine Transport (From Sham Shui Kok Chlorine Dock to TKO Area 137 Pier)

The chlorine delivery frequency is approximately once per month, i.e. 12 deliveries per year. The number of chlorine drums in each delivery is estimated on average 13 drums per delivery (i.e. 148/12). Failure frequencies for different release scenarios are derived from fault trees that were developed in the 2006 Study [4] as shown in Figure D.1 of the study report.

Unloading/Loading at TKO Area 137 Pier

Using on the same approach as off-site marine transport, failure case frequencies are derived from fault trees as shown in Figure D.2 of the 2006 Study report. The number of chlorine drums per delivery and the delivery frequency have already described in the previous section. Moreover, time taken for loading/unloading operation was assumed 16 hours, the same amount of time adopted in the 2006 Study. According to the 2006 Study, the average time a chlorine vessel staying at a chlorine dock is 16 hours for cargo load of 66 drums and 70 cylinders. It is anticipated that the average time a chlorine vessel staying at TKO Area 137 Pier would be less than the figure adopted in the 2006 Study. The average time is adjusted according to the number of drums being handled in each delivery i.e. (13/66). Therefore, the average time a vessel staying at TKO Area 137 Pier is assumed 3.2 hours.

According to WSD, there is no new chlorine release incident involving local marine transport of chlorine drums since the 2006 Study [4]. Considering the longer operating drum year without new incident, the frequency of chlorine release should be lower than the one adopted in the 2006 Study. Therefore, it is appropriate to adopt frequency data from the 2006 Study by following the conservative approach. However, marine traffic accident rate is upward adjusted by applying a safety factor according to statistical data supplied by Marine Department. Frequencies for selected failure cases are summarized in Table 13.35. Fault trees and base frequency data are given in Annex H.

Table 13.35 Summary of Failure Case Frequencies

Case Code	Description	Frequency		
		Marine [1] (per km per vessel)	Marine [2] (per km per vessel)	Dock (per vessel)
SLDS	Small liquid leak (successful isolation)	6.43E-08	1.78E-08	3.73E-07
SLDF	Small liquid leak (isolation failure)	2.57E-07	7.12E-08	1.48E-06
MVD	Medium vapour leak	3.82E-06	1.38E-06	9.73E-07
MLD	Medium liquid leak	2.04E-07	5.70E-08	8.70E-07
LVD	Large vapour leak	5.33E-10	5.33E-10	4.90E-09
LLD	Large liquid leak	4.81E-09	4.81E-09	4.40E-08
RD	Rupture	3.70E-09	3.70E-09	3.40E-08
RDM1	Multiple drum failure due to impact	1.21E-08	2.11E-09	1.92E-08
RDM2	Multiple drum failure due to fire	1.95E-07	7.33E-08	9.61E-09

Notes:
[1] Ma Wan Channel section with vessel collision frequency 6 times higher than the rest of route section
[2] Marine transport route except the Ma Wan Channel section

13.3.8 Risk Summation

The individual risk and societal risk in terms of F-N curve are evaluated in the risk summation process, for all hazardous events and then summed to determine the total transport related risk. The results are compared to Annex 4 of the EIAO TM Criteria to determine if the risk level is acceptable.

<u>Off-site Marine Transport (From Sham Shui Kok Chlorine Dock to TKO Area 137 Pier)</u>

Individual risk contours of off-site marine transport for primary route and alternative route are shown in Figure 13.15 and Figure 13.16 respectively. The individual risk along the both routes is below 1E-6/year and the 1E-7/year, 1E-8/year and 1E-9/year contours are plotted. No off-site risk is larger than 1E-5/year. Therefore, the risk due to marine transport of chlorine is considered acceptable.

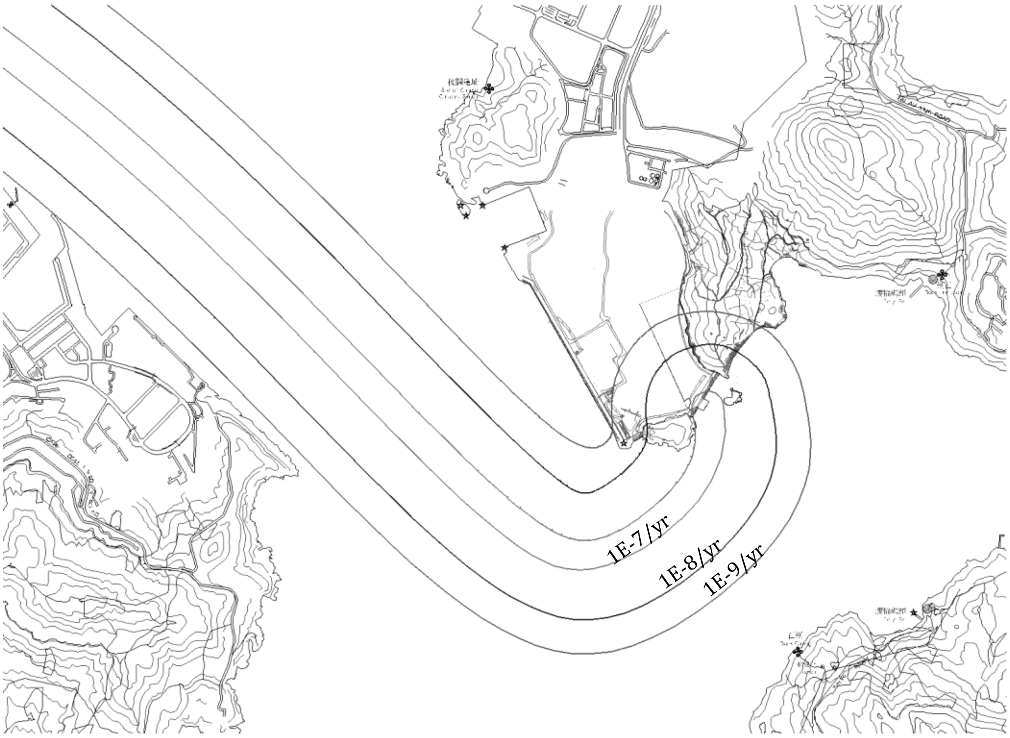


Figure 13.15 Individual Risk Contours for Off-site Marine Transport (Primary Route)

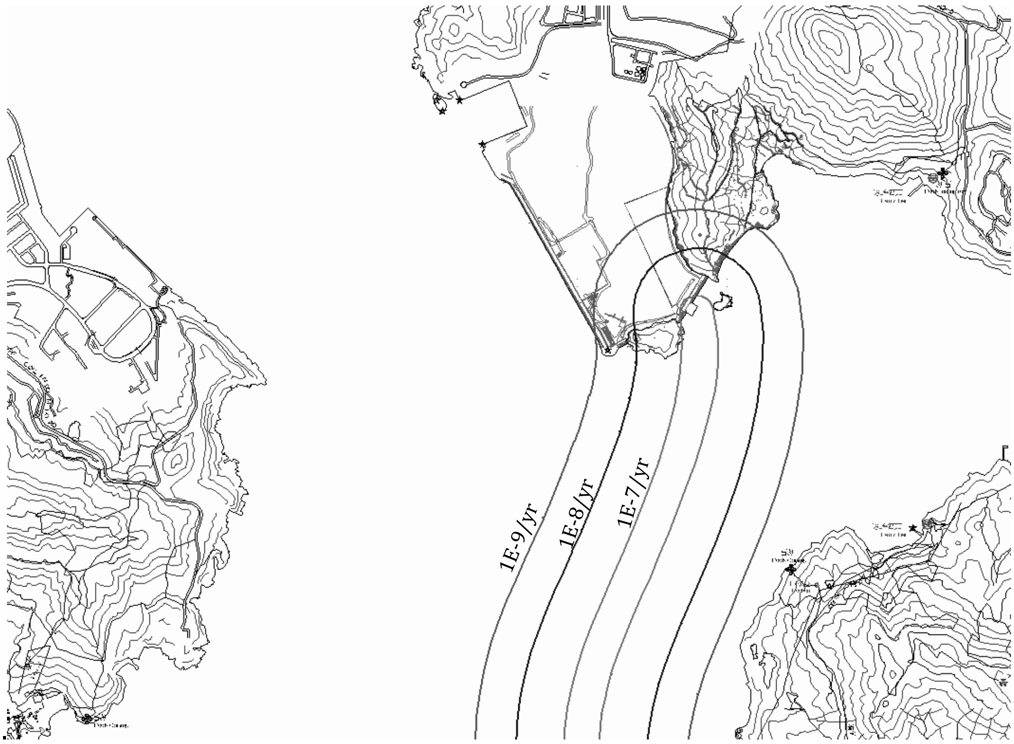


Figure 13.16 Individual Risk Contours for Off-site Marine Transport (Alternative Route)

The societal risk of off-site marine transport of chlorine for a 3-km section of transport route approaching the TKO Area 137 Pier is plotted in Figure 13.17 in form of FN curve. The potential loss of life (PLL) breakdown by release scenario and location are summarized in

Table 13.36 and Table 13.37 respectively. The FN shows the societal risk falls within the Acceptable region.

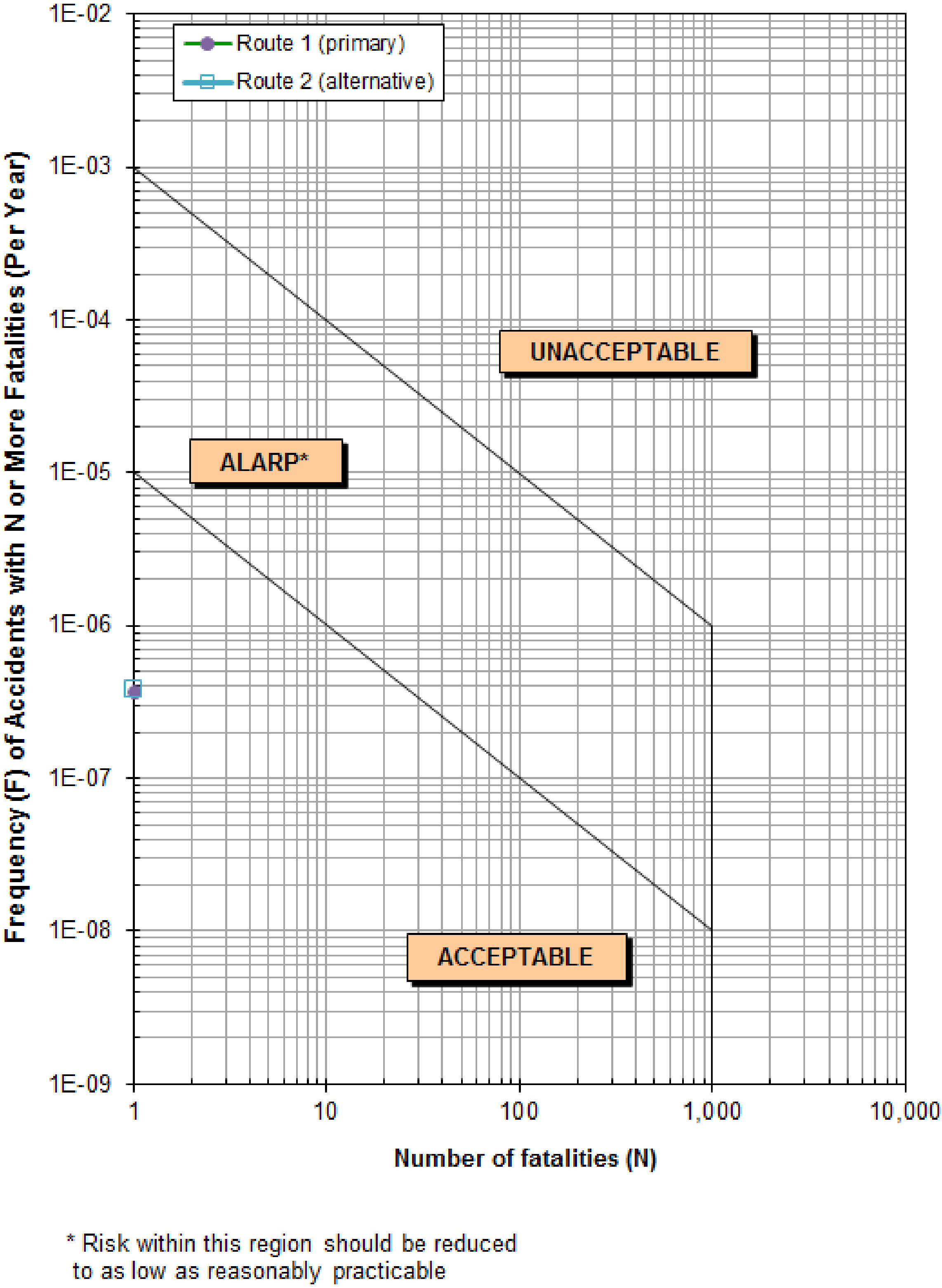


Figure 13.17 FN Curves for Off-site Marine Transport Risk (3-km section)

Table 13.36 PLL Breakdown by Release Rate for Off-site Marine Transport Risk (the Whole Transport Route)

Case Code	Description	Primary Route		Alternative Route	
		PLL	%	PLL	%
SLD/MVD	Small liquid leak/Medium vapour leak	3.96E-06	2.4	6.41E-07	2.7
MLD/LVD	Medium liquid leak/Large vapour leak	1.33E-05	8.1	2.52E-06	10.5
LLD	Large liquid leak	1.21E-05	7.4	1.03E-06	4.3
RD	Rupture	1.58E-05	9.7	1.34E-06	5.6
RDM1	Multiple drum failure due to impact	1.84E-06	1.1	4.82E-07	2.0
RDM2	Multiple drum failure due to fire	1.16E-04	71.2	1.81E-05	75.1
	TOTAL (1)	1.63E-04	100	2.41E-05	100

Notes:
(1) The total may not exactly the same the sum of individual rows due to rounding.

Table 13.37 PLL Breakdown by Segment for Off-site Marine Transport Risk (the Whole Transport Route)

Ref.	Segment Name	Location	PLL	%
	Primary Route			
1	Sham Shui Kok	Tsing Lung Tau	1.85E-06	1.1
2	Tsing Ma	Ma Wan – Victoria Harbour	1.77E-05	10.9
4	Victoria Harbour	Victoria Harbour – Lei Yue Mun	1.43E-04	87.7
8	Tseung Kwan O	Lei Yue Mun – TKO 137 pier	5.28E-07	0.3
		TOTAL (1)	1.63E-04	100
	Alternative Route			
1	Sham Shui Kok	Tsing Lung Tau	1.85E-06	7.7
3	Tsing Ma	Ma Wan – Cyberport	1.88E-05	78.0
5	East Lamma Channel	Cyberport – Chung Hom Kok	2.11E-06	8.8
6	Island South	Chung Hom Kok – Hok Tsui Wan	6.02E-07	2.5
7	Tathong Channel	Hok Tsui Wan – Tung Lung Chau	5.07E-07	2.1
9	Tseung Kwan O	Tung Lung Chau – TKO 137 pier	2.36E-07	1.0
		TOTAL (1)	2.41E-05	100

Notes:
(1) The total may not exactly the same the sum of individual rows due to rounding.

Unloading/Loading at TKO Area 137 Pier

Individual risk contours due to chlorine unloading/loading operation at the TKO Area 137 Pier is presented in Figure 13.18. Since the maximum individual risk is below 1E-5/year, only 1E-6/year and lower contours are plotted.

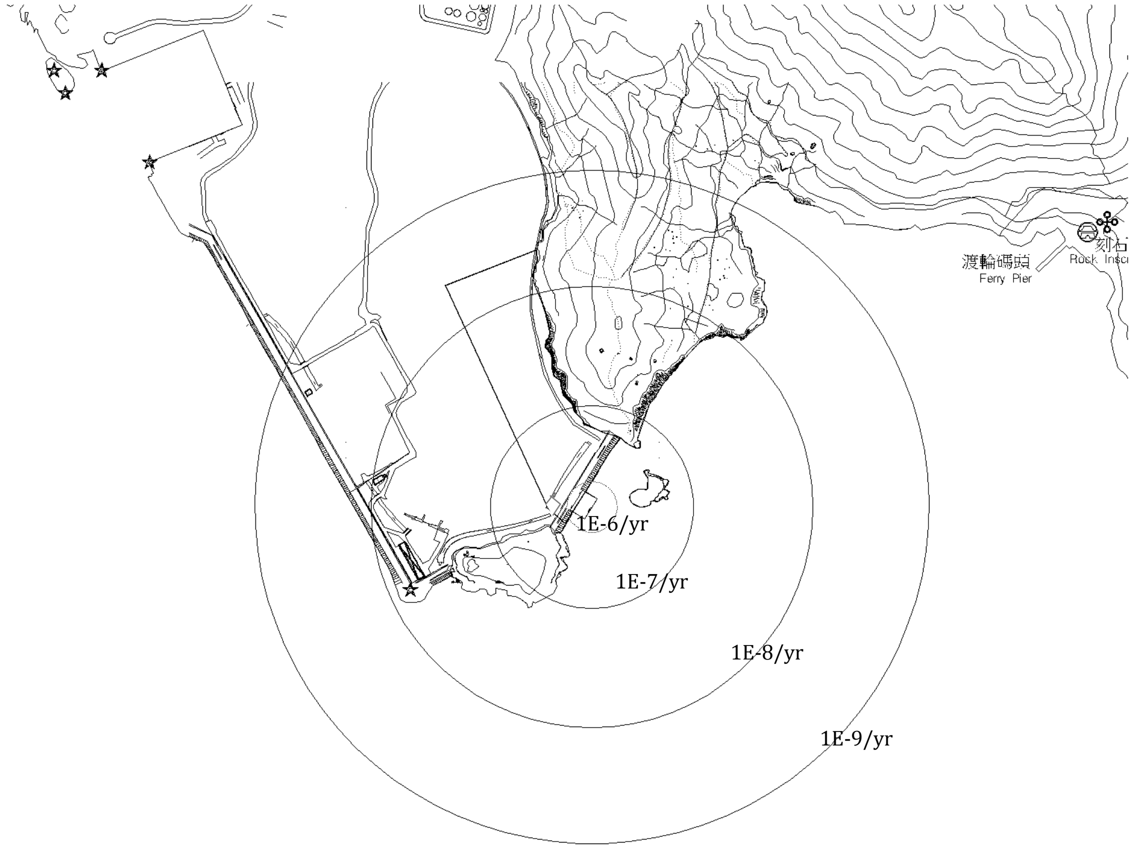
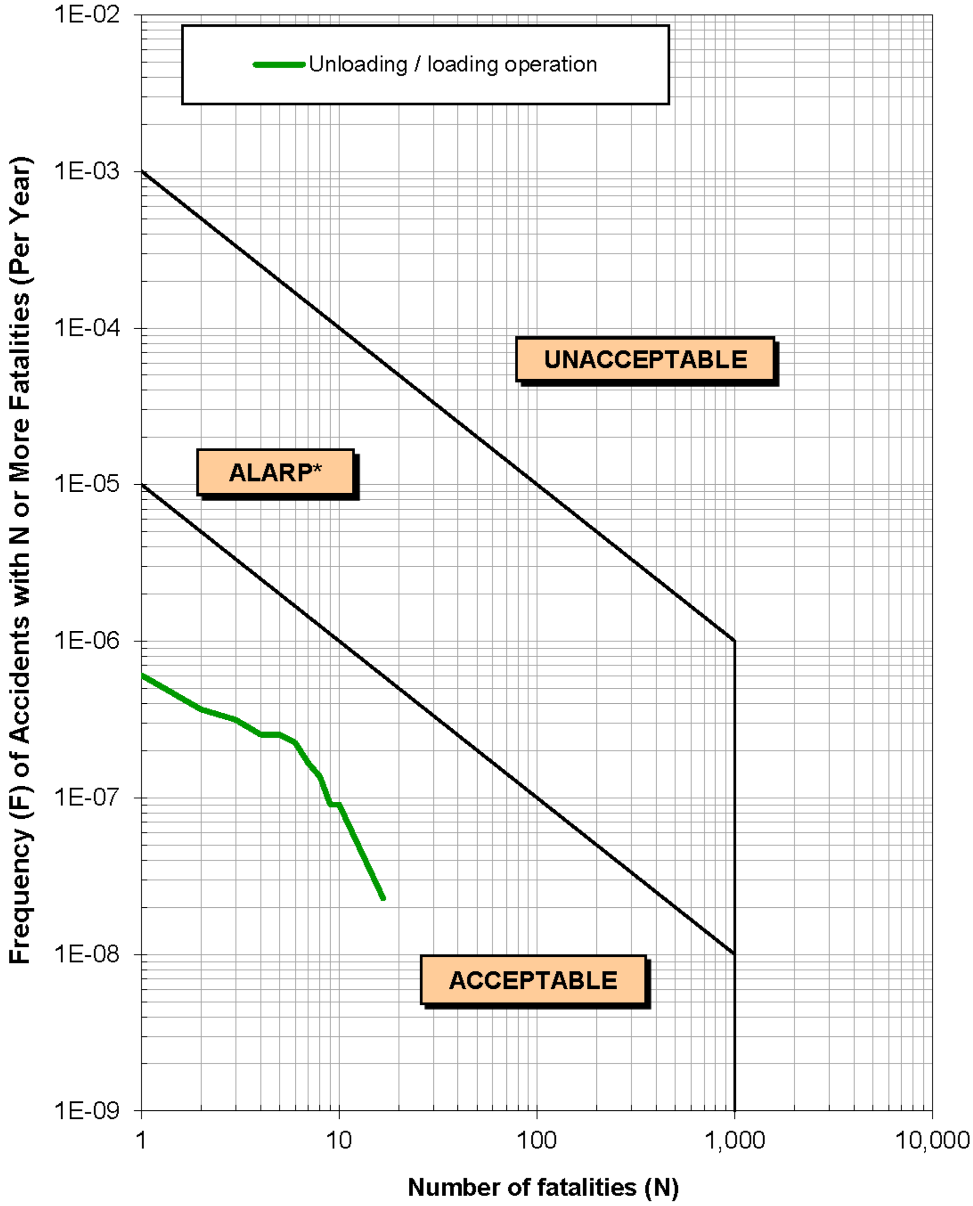


Figure 13.18 Individual Risk Contours for Chlorine Unloading / Loading at TKO Area 137 Pier

Considering there is no permanent population in vicinity of the TKO Area 137 Pier, surrounding population would spend 33% of time (8 hours a day and 7 days a week) at workplace. Therefore, the extent of 1E-6/year contour should be further reduced within the TKO Area 137 Pier at the land side.

FN curve for chlorine unloading/loading operation at the TKO Area 137 Pier is shown in Figure 13.19. The risk level falls within the "Acceptable" region. Breakdown of PLL by release case is tabulated in Table 13.38.



* Risk within this region should be reduced to as low as reasonably practicable

Figure 13.19 FN Curves for Unloading/Loading Operation at TKO Area 137 Pier

Table 13.38 PLL breakdown for Unloading/Loading Operation at TKO Area 137 Pier

Case Code	Description	PLL	%
		Pier	
SLD/MVD	Small liquid leak/Medium vapour leak	0.00E+00	0.0
MLD/LVD	Medium liquid leak/Large vapour leak	3.62E-8	1.2
LLD	Large liquid leak	1.07E-6	34.8
RD	Rupture	1.9E-6	61.8
RDM1	Multiple drum failure due to impact	2.05E-8	0.7
RDM2	Multiple drum failure due to fire	4.74E-8	1.5
	TOTAL	**3.07E-6**	**100.0**

The combined individual risk and the combined FN curve for chlorine unloading/loading operation at the TKO Area 137 Pier and off-site marine transport of chlorine for a 3-km section of transport route approaching the TKO Area 137 Pier is shown in Figure 13.20 and Figure 13.21. The risk level falls within the "Acceptable" region.

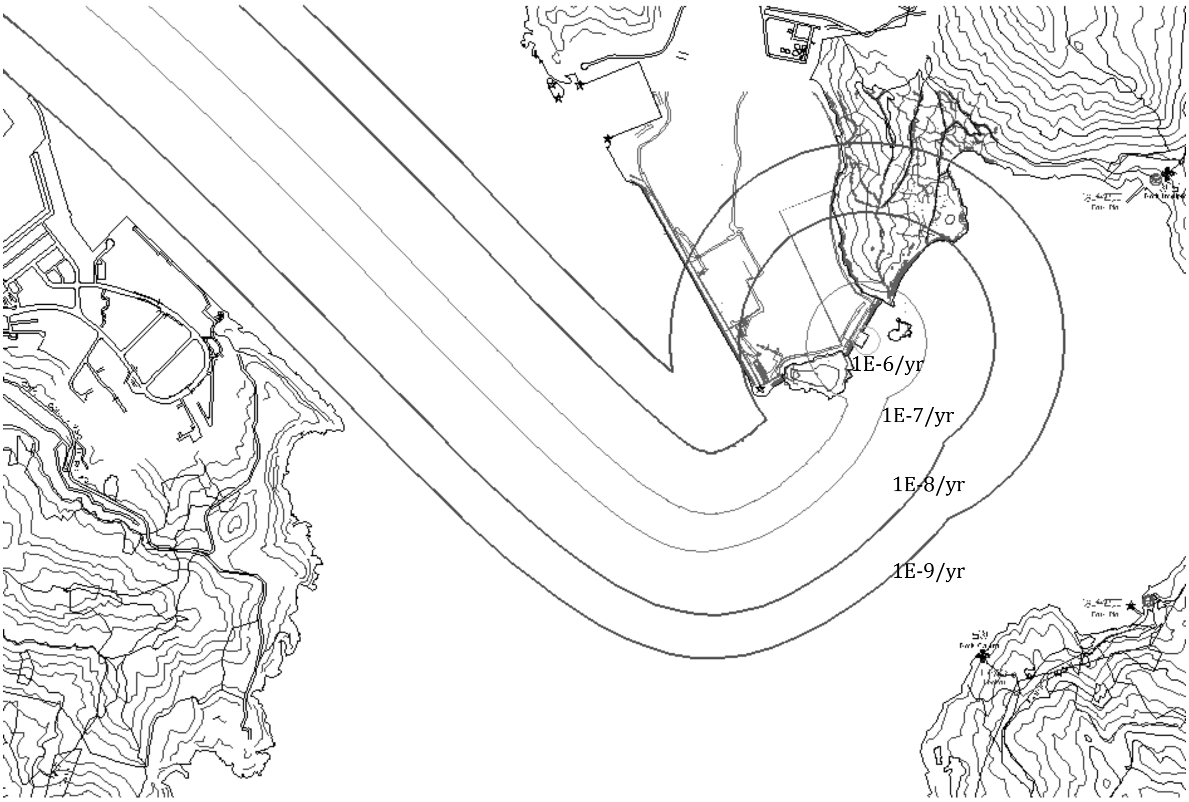
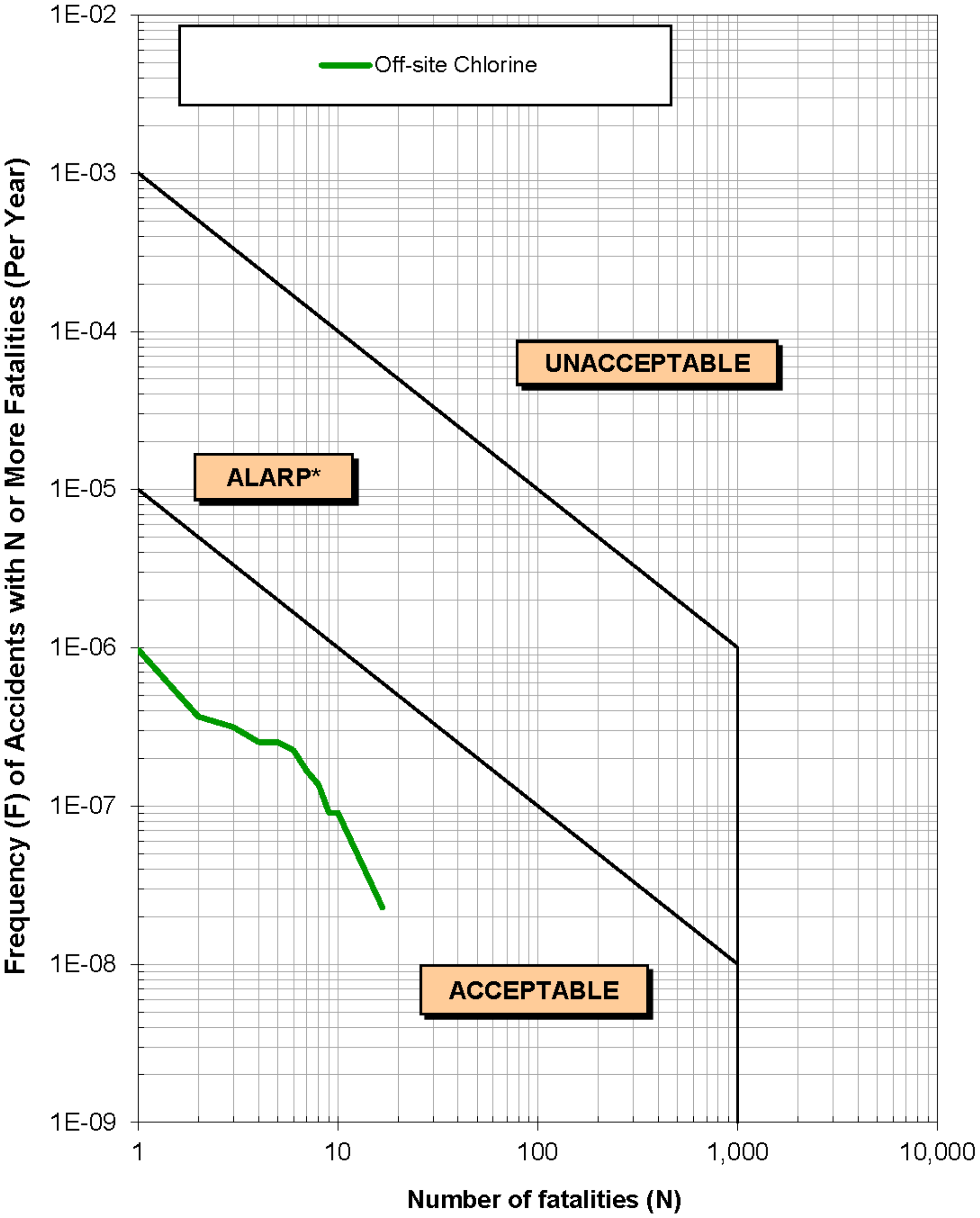


Figure 13.20 Individual Risk for Offsite Transport of Chlorine



* Risk within this region should be reduced to as low as reasonably practicable

Figure 13.21 FN Curve for Offsite Transport of Chlorine

13.4 QRA for Use, Storage and Transport of Sodium Hypochlorite

13.4.1 Introduction

Earlier sections of the report addressed risks associated with use, storage and transport of chlorine. This chapter of the report addresses risks associated with the use, storage and transport of sodium hypochlorite for the proposed Desalination Plant.

13.4.2 Scope of Sodium Hypochlorite Risk Assessment

The EIA Study Brief requires risk assessment of use, storage and transport of other DGs associated with the proposed Desalination Plant. Sodium hypochlorite (NaOCl) is classified as Category IV Class 1 Dangerous Goods (DG) under the Dangerous Goods Ordinance in Hong Kong. Therefore, the potential risk of NaOCl hazards has been assessed in the study.

The scope of this section includes the following elements:

<u>*Off-site hazard:*</u>

- Off-site sodium hypochlorite delivery from chemical suppliers to the entrance of the Desalination Plant.

<u>*On-site hazard:*</u>

- Transportation of sodium hypochlorite from entrance of the Desalination Plant to the dedicated unloading bay;
- Unloading operation of sodium hypochlorite to bulk storage tanks; and
- On-site storage and use of sodium hypochlorite.

13.4.3 Approach to the Study

The Hazard to Life Assessment for NaOCl has been conducted following the generic assessment steps listed below:

- Hazard identification, scenario definition and survey of potentially impacted population;
- Frequency assessment;
- Consequence assessment;
- Risk summation; and
- Risk mitigation (as applicable).

References are also made to the following approved EIAs relevant to NaOCl risk assessments,

- Harbour Area Treatment Scheme (HATS) Stage 2A Environmental Impact Assessment [29]; and
- Construction of an International Theme Park in Penny's Bay of North Lantau together with its Essential Associated Infrastructures (Theme Park EIA) [30].

Operations involving NaOCl and relevant plant facilities have been reviewed and described in the assessment report. Population data and meteorological data in Section 13.2.5 and 13.2.6 of On-site Chlorine PHI QRA section of this study have been adopted for sodium hypochlorite risk assessment for consistency.

13.4.4 Description of Sodium Hypochlorite Operation

Sodium hypochlorite solution of minimum 10% (w/w) is a disinfection agent, which is dosed periodically into the intake seawater to control the biological growth at intake and screens (shock chlorination of seawater intake). Sodium hypochlorite solution will be purchased directly from off-site chemical suppliers and no onsite generation of sodium hypochlorite is proposed. On-site sodium hypochlorite facilities include a bulk storage area and a dosing station which are located close to the intake pumping station (location of application) near the waterfront, as shown in Figure 13.22.

The bulk storage area consists of 6 bulk storage tanks for the ultimate design and provides total storage capacity of 138 m^3 (approximately 15 tonnes active chlorine equivalent). Each storage tank has capacity of approximately 25 m^3. The storage tanks will reside in a bund to contain spillage from tank failures. The internal dimensions of the bund are 14.5m (L) x 10m (W) x 1.7m (H) or equivalent to minimum capacity of 100% containment of total spillage of sodium hypochlorite. Moreover, proper drainage at the perimeter of the storage area (Figure 13.22) will be provided to collect spillage of sodium hypochlorite outside of the bund area. Therefore, chemical spillage to the sea is not anticipated. Besides, spills will be properly handled for disposal in accordance with the Waste Disposal Ordinance.

Sodium hypochlorite solutions have limited storage stability. Loss of active chlorine through the decomposition process is a function of storage time and temperature. Therefore, the total storage quantity is sufficient for 30-day consumption. It is estimated that about 1 replenishment operation every 15 days would be carried out under the ultimate operation scenario. The replenishment of sodium hypochlorite is required when 3 storage tanks are emptied (i.e. $138\ m^3 \times \frac{15}{30} = 70\ m^3$). Sodium hypochlorite solution will be delivered to the Desalination Plant by DG barges twice per month. The chemical could then be fed to the storage tanks by direct pumping from the barge using dedicated chemical feedline with connection points as shown in Figure 13.22. No other chemicals will be delivered with NaOCl by the same barge at the same time. Other chemicals will be delivered by road transport. Different delivery mode for sodium hypochlorite and other chemicals could reduce the risk of human error leading to accidental mixing of sodium hypochlorite and incompatible chemical at the Desalination, which are identified as hydrochloric acid (HCl), ferric chloride ($FeCl_3$, which contains 5wt.% of HCl), sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$). These incompatible chemicals are stored at the Chemical Building.

The use of sodium hypochlorite involves a simple dosing process. Metering pumps at the dosing station draw sodium hypochlorite solution from the bulk tank at the designed flow rate within the specified interval. Sodium hypochlorite is then delivered to the seawater intake for application. The dosing process involves only sodium hypochlorite. Sodium hypochlorite would not be possible in contact with other incompatible chemicals.

The sodium hypochlorite storage, associated facilities and pipelines are located away from other chemicals including acids (HCl, H_2SO_4 and $C_6H_8O_7$) and $FeCl_3$, which are stored at the chemical building, to avoid accidental mixing of incompatible chemicals. The locations of sodium hypochlorite facilities and chemical building are shown in Figure 13.22.

Table 13.39 provides the basic sodium hypochlorite (NaOCl), hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) operation data for the proposed Desalination Plant.

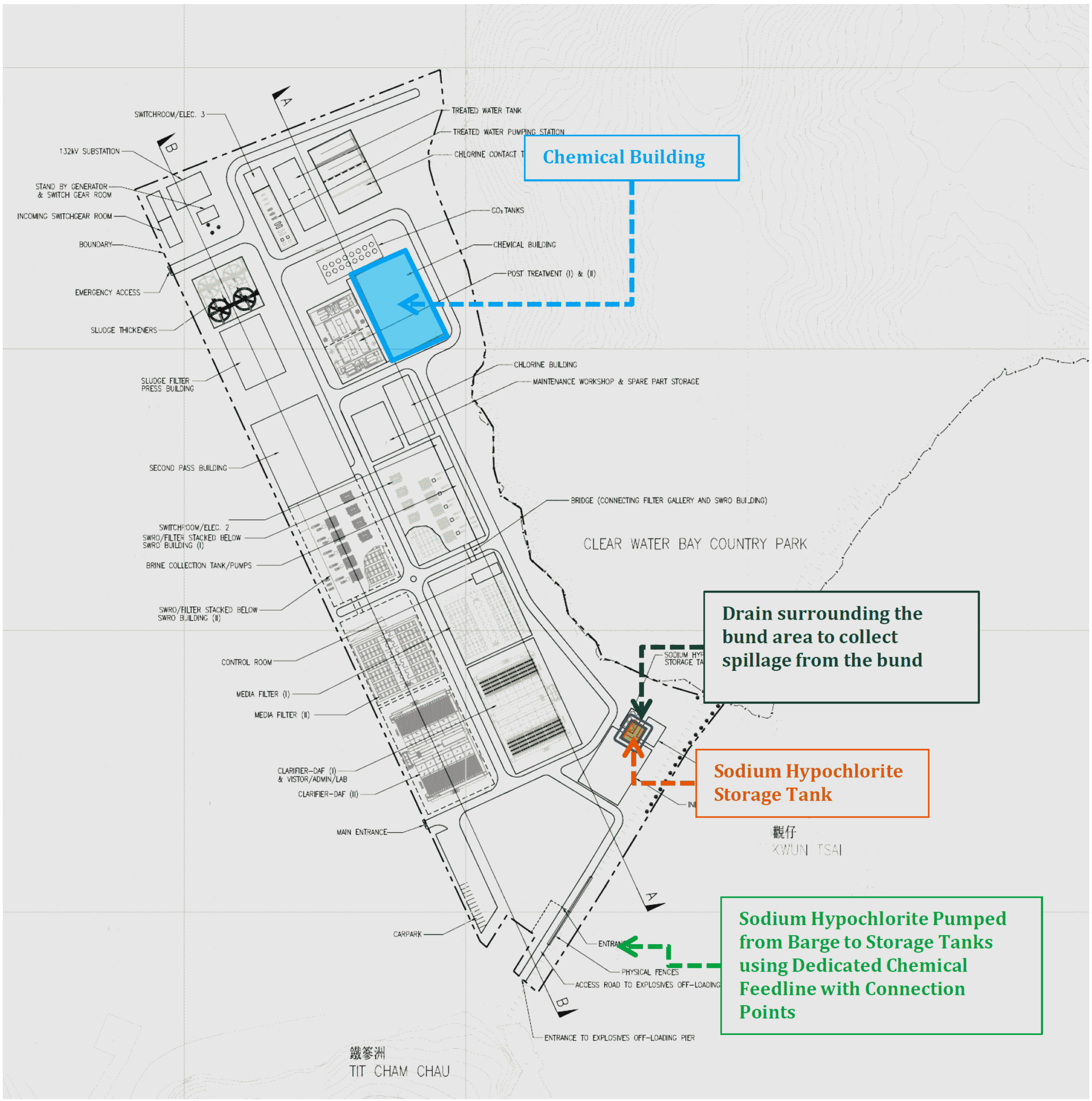


Figure 13.22 Location of On-site Sodium Hypochlorite Facilities and Chemical Building

Table 13.39 Summary of Sodium Hypochlorite, Hydrochloric Acid, Ferric Chloride, Sulphuric Acid and Citric Acid Operations

Items	Value	Units	Remarks
Sodium Hypochlorite (NaOCl):			
Concentration of NaOCl solution	10-12	% (wt)	Minimum concentration is 10% (wt), 12% (wt) is the worst case
Number of NaOCl storage tanks	6	-	Separated tanks, not connected
Volume of NaOCl storage tank (each)	~25	m^3	
Bund volume for NaOCl tanks	~247	m^3	With bund wall; or equivalent to minimum capacity of 100% containment of total spillage
Number of Deliveries of NaOCl	24	per year	Twice per month; Delivered by dedicated barge via marine

Items	Value	Units	Remarks
			and dedicated feedline; 30-day storage
Feedline unloading rate of NaOCl solution to tank	10	L/s	
Hydrochloric Acid (HCl):			
Concentration of HCl solution	10	% (wt)	
Number of HCl storage tanks in chemical building	2	-	Separated tanks, not connected
Volume of HCl storage tank (each)	40	m^3	Total storage quantity is $80m^3$
Number of Deliveries of HCl	9	per year	9 road tanker deliveries per year; 3 road tanker deliveries each time
Road tanker unloading rate of HCl solution to tank	10	L/s	
Ferric Acid ($FeCl_3$)			
Concentration of $FeCl_3$ solution	28-43	% (wt)	
Concentration of HCl in $FeCl_3$ solution	<5	% (wt)	
Number of $FeCl_3$ storage tanks in chemical building	8		Separated tanks not connected
Volume of $FeCl_3$ storage tank (each)	190	m^3	Total storage quantity is $1520m^3$
Number of Deliveries of $FeCl_3$	243	per year	243 road tanker deliveries per year
Road tanker unloading rate of $FeCl_3$ solution to tank	10	L/s	
Sulphuric Acid (H_2SO_4)			
Concentration of H_2SO_4 solution	98	% (wt)	
Number of H_2SO_4 storage tanks in chemical building	4		Separated tanks not connected
Volume of H_2SO_4 storage tank (each)	62	m^3	Total storage quantity is $248m^3$
Number of Deliveries of H_2SO_4	42	per year	42 road tanker deliveries per year
Road tanker unloading rate of H_2SO_4 solution to tank	10	L/s	
Citric acid ($C_6H_8O_7$)			
Concentration of citric acid solution	50	% (wt)	
Number of citric acid storage tanks in chemical building	1		
Volume of citric acid storage tank	8	m^3	
Number of Deliveries of citric acid	4	per year	4 road tanker deliveries per year
Road tanker unloading rate of citric acid solution to tank	10	L/s	

Safety measures:	
1.	Specific hose connection, the use of different sizes of hose and coupler for NaOCl, HCl, $FeCl_3$, H_2SO_4 and $C_6H_8O_7$ unloading facilities.
2.	Warning signs will be displayed at the inlet of each storage tank to show chemical name and to warn the potential hazards of mixing incompatible chemicals.
3.	NaOCl will be delivered by barges. Dedicated chemical feedline with connection points will be used for transferring NaOCl from barges to storage bulk tanks. HCl, $FeCl_3$, H_2SO_4 and $C_6H_8O_7$ will be delivered by road tankers. No other chemicals will be delivered with NaOCl by the same barge at the same time.
4.	HCl, $FeCl_3$, H_2SO_4 and $C_6H_8O_7$ will be stored in double containment tanks.
5.	HCl, $FeCl_3$, H_2SO_4 and $C_6H_8O_7$ flowing outside of the chemical building will be collected by road side drains. Moreover, road humps will help to prevent acids moving towards the NaOCl storage area.
6.	Perimeter drain will be installed surrounding the NaOCl bund to collect spill from overtopping. Temporary storage tank will be connected to the drainage system for the NaOCl storage area to prevent from mixing with HCl / $FeCl_3$ / H_2SO_4 / $C_6H_8O_7$ or discharging directly to the sea.
7.	NaOCl facilities are located 290 m far away from the chemical building.

13.4.5 Hazard Identification

Hazardous Properties of Sodium Hypochlorite

Sodium hypochlorite (NaOCl) solution is a corrosive substance in clear light yellow to greenish-yellow liquid form with a chlorine-like odour. It is not flammable. It decomposes and releases corrosive chlorine gas when it is in contact with acids. It is classified as Category IV Dangerous Goods under the Hong Kong Dangerous Goods Ordinance due to giving off a poisonous gas or vapour.

The following health hazards would be caused in contact with the substance:

- Dermal contact – causes severe skin irritation with blistering and ulceration;
- Eye contact – causes severe irritation of the mucous membranes of the eyes and may cause severe eye damage;
- Ingestion – causes burning of the mouth and throat, abdominal cramps, nausea, vomiting, diarrhea, shock and may lead to convulsions, coma, and even death; and
- Inhalation – causes irritant of the nose and throat, coughing, difficulty breathing and pulmonary edema.

According to the aforementioned health hazards, inhalation is the major pathway for human to life issue. Mists are not formed under normal operation environment or in accidental release although they can probably cause mild to severe irritation of the nose and throat. With vapour pressure of 0.016 atm at 20^{o}C, sodium hypochlorite does not easily form a vapour. According to typical product information, active chlorine in initial concentration of 160g/L solution will drop to 137g/L at 20^{o}C in 30 days. Assuming that all active chlorine lost in the form of chlorine gas, the estimated chlorine release rate is about 2.2E-4 kg/s for the quantity of 25m^3.

Review of Past Incidents

Review of historical incidents and relevant previous studies [29][30] with respect to operation of sodium hypochlorite has been carried out to identify hazardous scenarios associated with sodium hypochlorite operation at the proposed Desalination Plant as part of this project.

Besides, a search was also carried out on Major Accident Reporting System (eMARS) [33] to identify recent incidents involving sodium hypochlorite operations. The results are summarised in Table 13.40.

Based on the review from previous studies [29][30] and eMARS database [33], it is found that almost all the incidents were due to accidental mixing of incompatible chemicals with sodium hypochlorite leading to toxic chlorine generation causing injuries.

Table 13.40 Incidents involving Sodium Hypochlorite from eMARS

Date	Injuries	Accident Description
2007-06-16	6	Explosion and release of substances in the waste water treatment plant of an electro-plating installation causing material damage of approx. 2.500.000 EUROn Saturday 16. 06. 2007 by 03:30 the fire detection system triggered alarm in the control room. Subsequently the fire prevention coordinator inspected the affected section. When he opened the staircase-door leading to the waste water treatment room he saw that the room was filled with fumes. He alerted immediately the onsite fire brigade. The fire brigade intervened and sprayed the room with water. The lid of a batch tank in the waste water treatment plant had been ripped off and displaced. The 4 daily-service tanks placed on the tank, containing hydrogen chloride (HCl CAS 7647-01-0), hydrogen

Date	Injuries	Accident Description
		peroxide (H2O2, CAS 8007-3-5), sodium hypochlorite (NaOCl, CAS 7681-52-9) and sodium hydroxide solution (NaOH, CAS 1310-73-2), were displaced and tilted. Piping of the batch tank and the daily-service tanks had ripped off. The batch tank with a volume of approximately 15m^3 was filled up to 78% corresponding to a volume of 11,7m^3. The daily service tank with a volume of 300l are filled to maximally 70%, this corresponds to a maximal volume per tank of 210 litres. The tank rupture was caused by the exothermic reaction of waste water with added H2O2 (overdosage), inducing an explosion type foam (gas) formation. Consequent to piping rupture the chemicals in the daily service tanks leaked out, HCl and NaOCl reacted forming chlorine gas. The leaked chemicals and the fire brigade''s spray-water were collected in a retention pond and disposed externally. The volume of the polluted water amounts to 21m^3 with a pH of 1.1 and an HCl content of 3.5 g/l. 6 persons were hospitalised as precautionary measure and dismissed the next day fit for work.
1996-06-01	70	In a vertical depot charged with 6000 l of sodium hypochlorite (12%) a lateral leak occurred, for the crack of the upper side and damaging a pipe in which flowed hydrochloric acid (36%). A chlorine cloud and its by-products formed which affected various persons and the environment.
1993-05-18	7	A 5 m^3 mobile tank, normally filled only with sodium hypochlorite (NaOCl), which during summer had exceptionally been filled with diluted acid, labeled and after use was parked externally for 9 months, was to be filled again with NaOCl. Because of the meteorological influence the label fell off. At the beginning of the filling procedure the tank contained still a rest of not identified diluted acid. It reacted with the filled in NaO3 to Chlorine gas of which about 10 m^3 were released from the tank sited externally to the environment. The chlorine gas expanded on the on-site road and in the on-site surroundings of the transfer zone. The release reached also a building with a staying room for personnel. About 30 seconds after the chlorine gas release the alarm was given by loud speaker system to evacuate the company building. The chlorine gas reached 7 persons some of them were external contractors workers personnel which had not left the staying room immediately and were hospitalised. The inflow of NaOCl was stopped immediately and the open nozzle of the tank covered in order to avoid the unhindered chlorine escaping.

Hazard Identification (HAZID)

Sodium hypochlorite is non-acutely toxic. With reference to previous EIAs [29][30] and eMARS database [33], the only identified hazardous scenario that may cause potential off-site impact is accidental mixing of sodium hypochlorite and incompatible chemicals. Toxic gas (i.e. chlorine) would be evolved if sodium hypochlorite accidentally mixes with incompatible chemicals, i.e. hydrochloric acid (HCl), ferric chloride ($FeCl_3$) sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) in this study. There are three sources of incompatible chemicals, which are HCl solution (10% by weight), ferric chloride solution (HCl contents is <5% by weight), and sulphuric acid (~98% by weight) and citric acid (~50% by weight).

Based on the preliminary operation data for the proposed Desalination Plant, accidental mixing of sodium hypochlorite and incompatible chemicals, which is identified as hydrochloric acid (HCl), ferric chloride ($FeCl_3$),sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) in this study, can be avoided. At the current layout, the sodium hypochlorite storage tanks and its associated facilities, and pipelines are located away from chemical building for other chemicals storage. Preventive measures could be built into the design such as using different colour code and/or size for sodium hypochlorite storage tank inlets. Operating procedures include use of different entrances and internal access roads to avoid mixing of incompatible chemicals. It is deemed that accidental mixing due to right product in wrong tank (i.e. hydrochloric acid (HCl), ferric chloride ($FeCl_3$)), sulphuric acid (H_2SO_4) or citric acid ($C_6H_8O_7$) is inadvertently unloaded into the sodium hypochlorite tank or sodium hypochlorite is inadvertently unloaded into the hydrochloric acid (HCl), ferric chloride ($FeCl_3$),sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) tanks) is very unlikely and so, will not be further assessed in this study.

In addition, to avoid accidental mixing of sodium hypochlorite and its hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) during off-site transport, sodium hypochlorite solution will be delivered to the Desalination Plant in bulk using DG barges whilst hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) will be delivered by road transport. No other chemicals will be delivered by the same DG barge at the same time. Generation and release of hazardous gas due to accidental mixing of sodium hypochlorite with hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) or citric acid ($C_6H_8O_7$) during off-site transport is considered very unlikely and so, will not be further assessed in this study.

Other causes for accidental mixing such as failure of both the tanks are deemed very unlikely to occur due to (1) sodium hypochlorite facilities are located 290 m away from the chemical building and (2) bund wall will be installed around sodium hypochlorite tanks to prevent spillage of sodium hypochlorite outside its boundary. As a result, these scenarios are ruled out and will not be further considered in this study.

To summarise, the possible hazardous events leading to accidental mixing of sodium hypochlorite with hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) or citric acid ($C_6H_8O_7$) solution causing generation of toxic chlorine gas at the proposed Desalination Plant have been identified and possible causes are listed below:

- Scenario 1 – wrong product (HCl) is delivered and unloaded to the right tank (NaOCl tank) (wrong product in right tank – Human error by supplier);
- Scenario 2 – wrong product (NaOCl) is delivered and unloaded to the right tank (HCl tank) (wrong product in right tank – Human error by supplier);
- Scenario 3 – wrong product ($FeCl_3$) is delivered and unloaded to the right tank (NaOCl tank) (wrong product in right tank – Human error by supplier); and
- Scenario 4 – wrong product (NaOCl) is delivered and unloaded to the right tank ($FeCl_3$ tank) (wrong product in right tank – Human error by supplier).
- Scenario 5 – wrong product (H_2SO_4) is delivered and unloaded to the right tank (NaOCl tank) (wrong product in right tank – Human error by supplier); and
- Scenario 6 – wrong product (NaOCl) is delivered and unloaded to the right tank (H_2SO_4 tank) (wrong product in right tank – Human error by supplier).
- Scenario 7 – wrong product ($C_6H_8O_7$) is delivered and unloaded to the right tank (NaOCl tank) (wrong product in right tank – Human error by supplier); and
- Scenario 8 – wrong product (NaOCl) is delivered and unloaded to the right tank ($C_6H_8O_7$ tank) (wrong product in right tank – Human error by supplier).

13.4.6 Frequency Estimation

Fault tree analysis has been used to estimate the frequency of identified hazardous scenarios due to failure of sodium hypochlorite/ hydrochloric acid / ferric chloride / sulphuric acid / citric acid operating procedures. These are then summed to give the overall frequency of toxic chlorine releases due to accidental mixing of sodium hypochlorite (NaOCl) and with hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) or citric acid ($C_6H_8O_7$) solution. The fault trees developed in the approved EIAs [29][30] have been reviewed and updated as appropriate for this study. As referenced from the approved Theme Park EIA [30], a simple fault tree has been developed to quantify the human error probability resulting in the top event which is defined as “Accidental Mixing of NaOCl and Incompatible Chemicals due to Operational Error” and subsequent chlorine release.

Frequency Estimation Results

The base frequency/ probability of human errors adopted in fault tree are presented in Table 13.41.

Table 13.41 Base Frequencies or Probabilities of Human Error

Item	Value	Units	Source
Driver drives the tanker to the wrong tank	0.001	per operation	Hunns and Daniels 1980 [31]
Driver fails to rectify the error	0.1	-	Hunns and Daniels 1980 [31]
Wrong product delivered by supplier	0.0001	per operation	Hunns and Daniels 1980 [31]
Operator fails to check product sample	0.0001	-	Hunns and Daniels 1980 [31]
Wrong product (NaOCl) delivered by supplier	0.0001	per operation	Hunns and Daniels 1980 [31]
Wrong product (HCl) delivered by supplier	0.0001	per operation	Hunns and Daniels 1980 [31]
Wrong product ($FeCl_3$) delivered by supplier	0.0001	per operation	Hunns and Daniels 1980 [31]
Wrong product (H_2SO_4) delivered by supplier	0.0001	per operation	Hunns and Daniels 1980 [31]
Wrong product ($C_6H_8O_7$) delivered by supplier	0.0001	per operation	Hunns and Daniels 1980 [31]
Operator and WSD staff fail to identify the empty tank for refill	0.01	-	Guide to Practical Human Reliability Assessment [32]
WSD staff fails to recover the error*	0	per operation	N/A

*Not possible to deliver right product in wrong tank due to proper connection design, i.e. different sizes of hose and coupler of different chemicals.

The probability of accidental mixing of sodium hypochlorite and hydrochloric acid / ferric chloride / sulphuric acid / citric acid is made up of the human errors from supplier/driver/operator/WSD staff.

The probability of "Operator and WSD staff fail to identify the empty tank for refill", i.e. 0.01, is taken as the operator and WSD staff fail to identify the error and unload the chemicals to non-empty tanks in which they are supposed to check and fill the empty tanks only. Release of chlorine will occur only if (1) hydrochloric acid is unloaded to sodium hypochlorite tank with sodium hypochlorite inside; (2) sodium hypochlorite is unloaded to hydrochloric acid tank with hydrochloric acid inside; (3) ferric chloride is unloaded to sodium hypochlorite tank with sodium hypochlorite inside; or (4) sodium hypochlorite is unloaded to ferric chloride tank with ferric chloride inside; (5) sulphuric acid is unloaded to sodium hypochlorite tank with sodium hypochlorite inside; or (6) sodium hypochlorite is unloaded to sulphuric acid tank with sulphuric acid inside; (7) citric acid is unloaded to sodium hypochlorite tank with sodium hypochlorite inside; or (8) sodium hypochlorite is unloaded to citric acid tank with citric acid inside.

Since at this stage the detailed procedural steps, design and organisational factors are not confirmed, human error probability is modelled at a high task level using generic values as given by Hunns and Daniels 1980 [31].

Assuming:

(1) 9 road tanker deliveries per year for hydrochloric acid unloading operation;

(2) 243 road tanker deliveries per year for ferric chloride unloading operation;

(3) 4 road tanker deliveries per year for citric acid unloading operation; and

(4) 24 barge deliveries per year for sodium hypochlorite unloading operation.

The overall frequency of chlorine release due to accidental mixing of sodium hypochlorite with hydrochloric acid / ferric chloride / sulphuric acid / citric acid is calculated as 3.94E-08 per year. The event frequency for each scenario is summarized in Table 13.42. The details of frequency estimation analysis are presented in Annex I.

Table 13.42 Event Frequencies of Sodium Hypochlorite Hazardous Scenarios

Event Ref	Scenario no.	Component scenarios	Frequencies (per year)	Time periods during which event could occur
Accidental Mixing of NaOCl and Incompatible Chemicals due to Operational Error	-	Right product in wrong tank	0.00E-00	All except Night
	Scenario 1	Wrong product (HCl) in NaOCl tank	2.40E-09	All except Night
	Scenario 2	Wrong product (NaOCl) in HCl tank	9.00E-10	All except Night
	Scenario 3	Wrong product (FeCl3) in NaOCl tank	2.40E-09	All except Night
	Scenario 4	Wrong product (NaOCl) in FeCl3 tank	2.43E-08	All except Night
	Scenario 5	Wrong product (H2SO4) in NaOCl tank	2.40E-09	All except Night
	Scenario 6	Wrong product (NaOCl) in H2SO4 tank	4.20E-09	All except Night
	Scenario 7	Wrong product ($C_6H_8O_7$) in NaOCl tank	2.40E-09	All except Night
	Scenario 8	Wrong product (NaOCl) in $C_6H_8O_7$ tank	4.00E-10	All except Night
		Total	***3.94E-08***	

13.4.7 Consequence and Vulnerability Analysis

Source Term Modelling

Chlorine evolving rate in a decomposition process depends on the reaction of chemicals. The chlorine release rate was estimated according to the corresponding chemical formula and available quantity and concentration of sodium hypochlorite, hydrochloric acid (HCl), ferric chloride ($FeCl_3$) sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$). The quantity of chlorine that may be released due to accidental mixing of sodium hypochlorite with hydrochloric acid (HCl), ferric chloride ($FeCl_3$), sulphuric acid (H_2SO_4) or citric acid ($C_6H_8O_7$) solutions is estimated based on the following:

The reaction of sodium hypochlorite (NaOCl), hydrochloric acid (HCl), ferric chloride ($FeCl_3$) sulphuric acid (H_2SO_4) and citric acid ($C_6H_8O_7$) are shown below:

For Scenarios 1 to 4, reaction between NaOCl and HCl / $FeCl_3$ (contains HCl):

(1) $NaOCl + HCl \rightarrow NaOH + Cl_2$

For Scenario 5 and 6, reaction between NaOCl and H_2SO_4:

(2) $2NaOCl + H_2SO_4 \rightarrow Cl_2 + H_2O_2 + Na_2SO_4$

For Scenario 7 and 8, reaction between NaOCl and $C_6H_8O_7$:

(3) $3NaOCl + 3C_6H_8O_7 \rightarrow Cl_2 + H_2O_2 + 3C_6H_7O_7Na + HClO$

Scenario 1 (Event Ref: HCltoNaOCl)

The unloading rate of HCl or NaOCl solution into the tank is approximately 10 L/s. When HCl is unloaded to the sodium hypochlorite tank, a rapid reaction will occur leading to chlorine gas release.

The weight percentage of HCl in the HCl solution for the proposed Desalination Plant will be 10 wt.% and its density is 1kg/L. Therefore, the rate of pure HCl added to the NaOCl tank will be 10% × 10 L/s × 1kg/L = 1 kg HCl/s.

Based on the reaction and molecular weights of NaOCl, HCl and Cl_2, 36.45kg of HCl will react with 74.45kg of NaOCl to give 70.91kg of chlorine. 1 kg HCl/s is equivalent to about 1 kg HCl/s × 70.91 kg Cl_2/ 36.45 kg HCl = 1.95 kg Cl_2/s.

As a result, the release rate of Cl_2 is 1.95 kg/s for Scenario 1 and the duration of Cl_2 release is about 14.7 mins (by assuming 50% inventory in the NaOCl tank) which is a continuous release.

Scenario 2 (Event Ref: NaOCltoHCl)

Similarly, in case of NaOCl is added to the HCl tank, the concentration of NaOCl is 12 wt.% with density of 1.2kg/L. The rate of pure NaOCl added to HCl tank will be about 12% × 10 L/s × 1.2 kg/L = 1.44 kg NaOCl/s. Thus, 1.44 kg NaOCl/s is equivalent to about 1.44 kg NaOCl/s × 70.91 kg Cl_2/ 74.45 kg NaOCl = 1.4kg Cl_2/s.

The release rate of Cl_2 is 1.4 kg/s for Scenario 2 and the duration of Cl_2 release is about 40 mins (by assuming 50% inventory in the HCl tank) which is a continuous release.

Scenario 3 (Event Ref: $FeCl_3$toNaOCl)

The unloading rate of $FeCl_3$ solution into the NaOCl tank is approximately 10 L/s. When $FeCl_3$ is unloaded to the sodium hypochlorite tank, a rapid reaction, due to the presence of HCl in the ferric chloride solution, will occur leading to chlorine gas release.

The weight percentage of HCl in the ferric chloride solution for the proposed Desalination Plant is conservatively estimated as 5 wt.% and its density is 1.37 kg/L. Therefore, the rate of pure HCl added to the NaOCl Tank will be 5% × 10 L/s × 1.37kg/L = 0.69 kg HCl/s.

Based on the reaction and molecular weights of NaOCl, HCl and Cl_2, 36.45kg of HCl will react with 74.45kg of NaOCl to give 70.91kg of chlorine. 0.69 kg HCl/s is equivalent to about 0.69 kg HCl/s × 70.91 kg Cl_2/ 36.45 kg HCl = 1.33 kg Cl_2/s.

As a result, the release rate of Cl_2 is 1.33 kg/s for Scenario 3 and the duration of Cl_2 release is about 21.4 mins (by assuming 50% inventory in the NaOCl tank) which is a continuous release.

Scenario 4 (Event Ref: NaOClto$FeCl_3$)

Similarly, in case of NaOCl is added to the $FeCl_3$ tank, the concentration of NaOCl is 12 wt.% with density of 1.2kg/L. The rate of pure NaOCl added to $FeCl_3$ tank will be about 12% × 10 L/s

× 1.2 kg/L = 1.44 kg NaOCl/s. Thus, 1.44 kg NaOCl/s is equivalent to about 1.44 kg NaOCl/s × 70.91 kg Cl_2/ 74.45 kg NaOCl = 1.37kg Cl_2/s.

The release rate of Cl_2 is 1.37 kg/s for Scenario 4 and the duration of Cl_2 release is about 40mins (by assuming 50% inventory in the $FeCl_3$ tank) which is a continuous release.

Scenario 5 (EventRef: H_2SO_4toNaOCl)

The unloading rate of H_2SO_4 solution into the NaOCl tank is approximately 10 L/s. When H_2SO_4 is unloaded to the sodium hypochlorite tank, a rapid reaction will occur leading to chlorine gas release.

The weight percentage of H_2SO_4 in the H_2SO_4 solution for the proposed Desalination Plant will be 98 wt.% and its density is 1.84 kg/L. Therefore, the rate of pure H_2SO_4 added to the NaOCl tank will be 98% × 10 L/s × 1.84 kg/L = 18.03 kg H_2SO_4/s.

Based on the reaction and molecular weights of NaOCl, H_2SO_4 and Cl_2, 98.08 kg of H_2SO_4 will react with 148.9kg of NaOCl to give 70.91kg of chlorine. 1 kg H_2SO_4/s is equivalent to about 18.03 kg H_2SO_4 /s × 70.91 kg Cl_2/ 98.08 kg H_2SO_4 = 13.04 kg Cl_2/s.

As a result, the release rate of Cl_2 is 13.04 kg/s for Scenario 5 and the duration of Cl_2 release is about 1.1 mins (by assuming 50% inventory in the NaOCl tank) which is a continuous release.

Scenario 6 (Event Ref: NaOCltoH$_2$SO$_4$)

Similarly, in case of NaOCl is added to the H_2SO_4 tank, the concentration of NaOCl is 12 wt.% with density of 1.2kg/L. The rate of pure NaOCl added to H_2SO_4 tank will be about 12% × 10 L/s × 1.2 kg/L = 1.44 kg NaOCl/s. Thus, based on the reaction and molecular weights of the corresponding chemicals, 1.44 kg NaOCl/s is equivalent to about 1.44 kg NaOCl/s × 70.91 kg Cl_2/ 148.9 kg NaOCl = 0.69 kg Cl_2/s.

The release rate of Cl_2 is 0.69 kg/s for Scenario 6 and the duration of Cl_2 release is about 40 mins (by assuming 50% inventory in the H_2SO_4 tank) which is a continuous release.

Scenario 7 (EventRef: $C_6H_8O_7$toNaOCl)

The unloading rate of $C_6H_8O_7$ solution into the NaOCl tank is approximately 10 L/s. When $C_6H_8O_7$ is unloaded to the sodium hypochlorite tank, a slow reaction will occur leading to chlorine gas release.

The weight percentage of $C_6H_8O_7$ in the H_2SO_4 solution for the proposed Desalination Plant will be 50 wt.% and its density is 1.241 kg/L. Therefore, the rate of pure $C_6H_8O_7$ added to the NaOCl tank will be 50% × 10 L/s × 1.241 kg/L = 6.21 kg $C_6H_8O_7$/s.

However, compared with HCl and H_2SO_4, citric acid is a weak acid (acid dissociation constant, Ka = 7.45E-4), thus the reaction efficiency is estimated as < 1%. Conservatively take 1% citric acid in the reaction , i.e. the rate of $C_6H_8O_7$ to be reacted will be 6.21 kg $C_6H_8O_7$/s × 0.01 = 0.062 kg $C_6H_8O_7$/s.

Based on the reaction and molecular weights of NaOCl, $C_6H_8O_7$ and Cl_2, 576.39 kg of $C_6H_8O_7$ will react with 223.35 kg of NaOCl to give 70.91kg of chlorine. 1 kg $C_6H_8O_7$/s is equivalent to about 0.062 kg $C_6H_8O_7$/s × 70.91 kg Cl_2/ 576.39kg $C_6H_8O_7$ = 0.01 kg Cl_2/s.

As a result, the release rate of Cl_2 is 0.01 kg/s for Scenario 7 and the duration of Cl_2 release is about 116.67 mins (by assuming 50% inventory in the NaOCl tank) which is a continuous release.

As discussed in Note 4 of Table 13.20, continuous release rate of Cl_2 less than 0.56kg/s will have no impact to the off-site populated area (i.e. TKO 137 Area), as such, this scenario is not further considered in the study.

Scenario 8 (Event Ref: NaOClto $C_6H_8O_7$)

Similarly, in case of NaOCl is added to the $C_6H_8O_7$ tank, the concentration of NaOCl is 12 wt.% with density of 1.2kg/L. The rate of pure NaOCl added to $C_6H_8O_7$ tank will be about 12% × 10 L/s × 1.2 kg/L = 1.44 kg NaOCl/s. Thus, based on the reaction and molecular weights of the corresponding chemicals, 1.44 kg NaOCl/s is equivalent to about 1.44 kg NaOCl/s × 70.91 kg Cl_2/ 223.35 kg NaOCl = 0.46 kg Cl_2/s.

The release quantity of Cl_2 is 3 kg for Scenario 8 and the duration of Cl_2 release is about 7 s (by assuming 50% inventory in the $C_6H_8O_7$ tank) which is an instantaneous release.

Based on the relationships_derived from the PHAST modelling and CFD modelling for the chlorine release quantity versus hazard range, the hazard distance for 3 kg instantaneous chlorine release is less than 60 m. As the closest distance between the Chemical Building and the west site boundary is more than 100m, this scenario will have no impact to the off-site populated area (i.e. TKO 137 Area). As such, this scenario is not further considered in the study.

Dispersion Modelling

The same approach in Dispersion Modelling of Section 13.2.8 of 'PHI QRA' ("Methodology") has been adopted for sodium hypochlorite risk assessment. Dispersion modelling by Computational Fluid Dynamics (CFD) has been carried out on chlorine release and hazard distances to various fatality levels were presented in Section 13.2.8 ("Dispersion of Chlorine in the Atmosphere").

For Scenario 1 (1.95 kg/s continuous chlorine release), a scaling factor of 1.2 is obtained based on Figure 1.1 of the Annex A. The scaling factor of Scenario 2 (1.37 kg/s continuous chlorine release) is taken as 1 because the release rate is the same as the CFD result of '1.4 kg/s continuous' release case.

Similarly, a scaling factor of 1.0, 1.0, 2.7 and 0.7 are obtained for Scenario 3 (1.33 kg/s continuous chlorine release), Scenario 4 (1.37 kg/s continuous chlorine release), Scenario 5 (13.04 kg/s continuous chlorine release) and Scenario 6 (0.69 kg/s continuous chlorine release), respectively.

Details on how to get the scale factors are presented in Annex C of this study.

Toxic Impact Analysis

The same approach adopted in Toxic Impact Analysis of Section 13.2.8 of 'PHI QRA' has been applied for sodium hypochlorite risk assessment.

13.4.8 Risk Summation

The individual risk, societal risk in terms of FN curve and Potential Loss of Life (PLL) have been evaluated in the risk summation process for all possible hazardous events (Scenario 1 to 6) and then summed to determine the risk associated with sodium hypochlorite operation at the proposed Desalination Plant. The results were compared to Annex 4 of the EIAO TM Criteria.

Figure 13.23 presents the individual risks obtained for sodium hypochlorite. The individual risk contour is mainly contributed by the Scenario 4 (NaOCltoFeCl_3) due to its comparably high frequency (2.43E-8 per year). However, the risk is low and nowhere outside the proposed Desalination Plant site boundary does the individual risk exceed 1E-5 per year.

The FN curve for the sodium hypochlorite assessment (Year 2036) is presented in Figure 13.24. The maximum N numbers derived from the figure is around 3 for F > 1×10^{-9} per year. Table 13.43presents the overall PLL values, together with a breakdown of the PLL by release scenarios and affected population. The breakdown of the PLL by population group is presented in Table 13.44. As can be seen in Figure 13.24, the F-N curve for risk due to sodium hypochlorite operation at the proposed Desalination Plant lies within the “Acceptable” region.

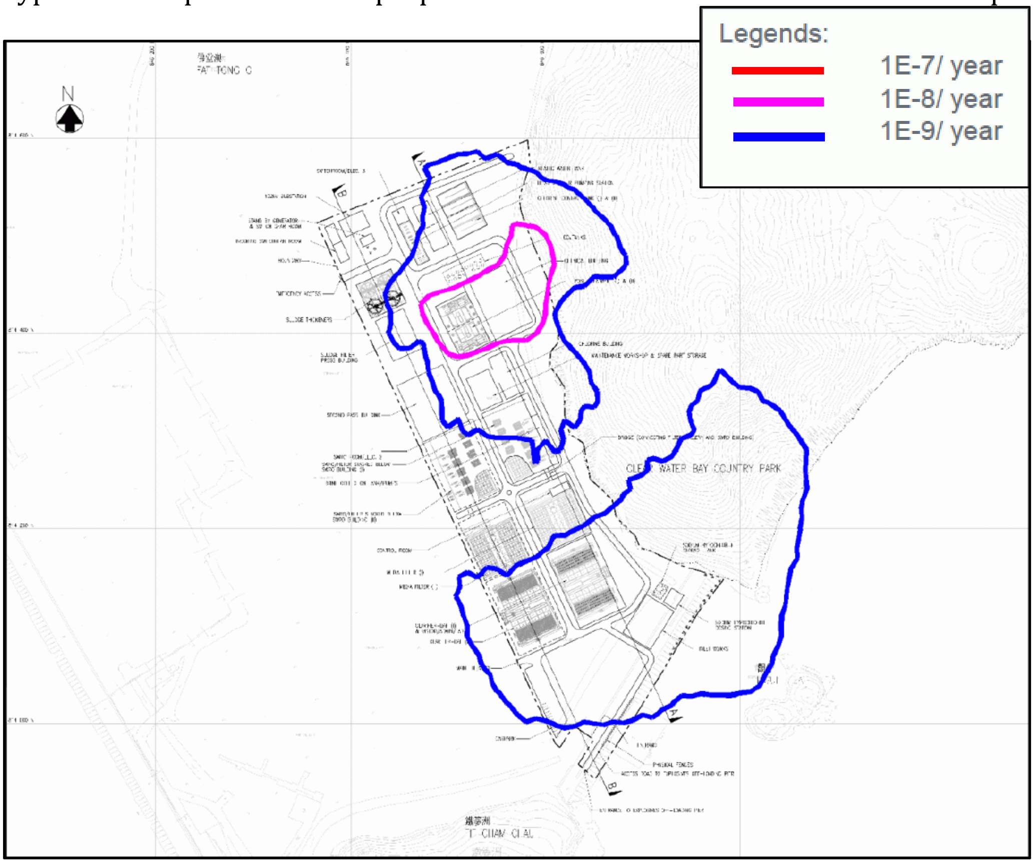


Figure 13.23 Individual Risk Contours for Sodium Hypochlorite Assessment

Table 13.43 Breakdown of PLL by Release Scenario for Sodium Hypochlorite Assessment

Event Ref	Operational Phase	
	Per Year	%
Scenario 1 - HCltoNaOCl	1.37E-10	2.7
Scenario 2 - NaOCltoHCl	1.63E-12	0.0
Scenario 3 – $FeCl_3$toNaOCl	3.16E-11	0.6
Scenario 4 - NaOClto $FeCl_3$	4.39E-11	0.9
Scenario 5 – H_2SO_4toNaOCl	4.89E-09	95.8
Scenario 6 - NaOClto H_2SO_4	0.00E-00	0.0
Total	**5.11E-09**	**100.0%**

Table 13.44 Breakdown of PLL by Population for Sodium Hypochlorite Assessment

Location Ref (Note 1)	Operational Phase	
	Per Year	%
04 TKO Area 137 Pier	4.07E-10	8.0
05 SENT Landfill Extension	1.57E-11	0.3
06 TKO Area 137	4.62E-09	90.4
07 Tathong Channel	6.84E-11	1.3
Total	**5.11E-09**	**100.0**

Note 1: For descriptions and locations of population units, refer to Table 13.6 and Figure 13.9.

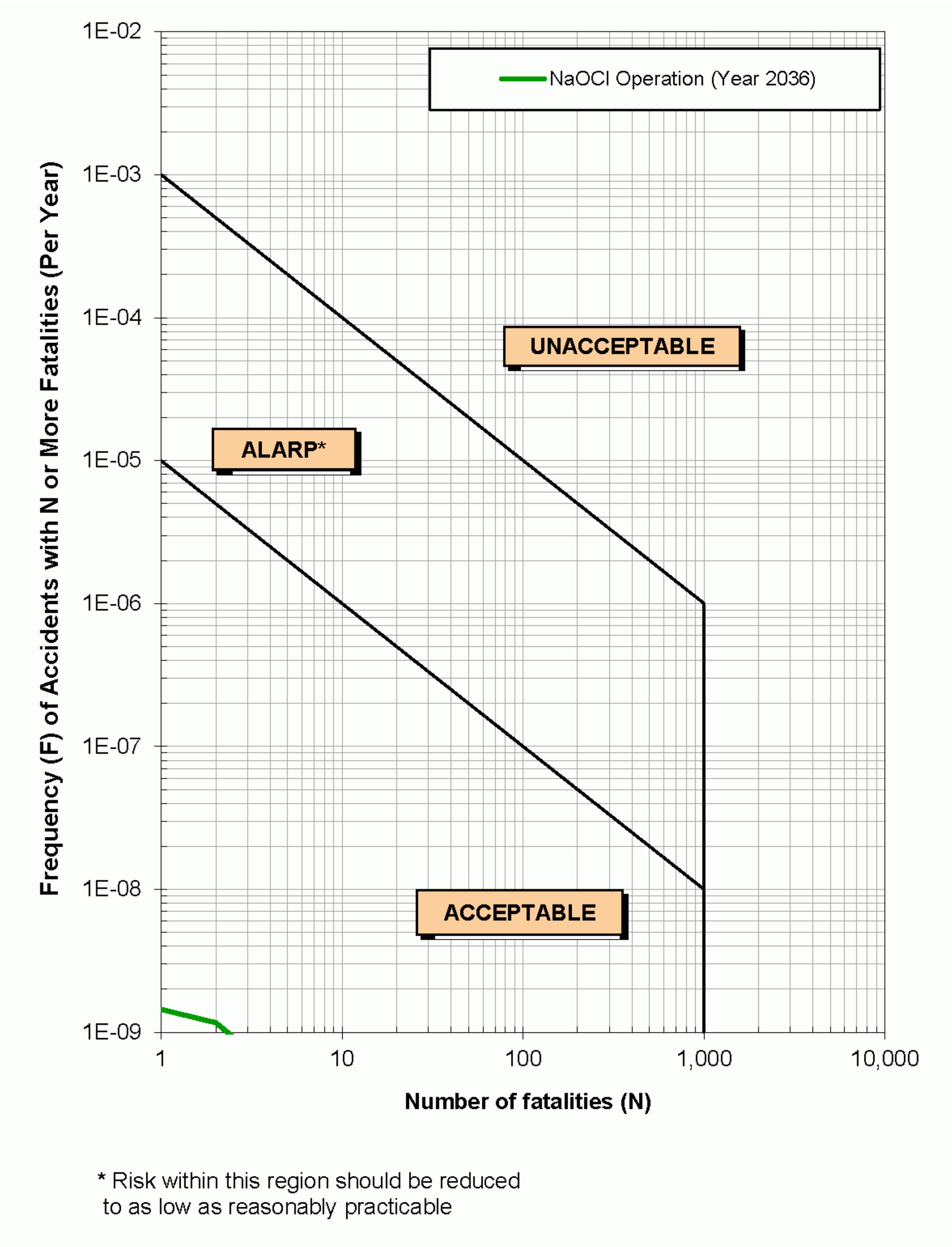


Figure 13.24 FN Curve of Operational Phase of the Desalination Plant for Sodium Hypochlorite Assessment

13.4.9 Result Summary

A Hazard Assessment of the risks associated with the storage, use and transport of sodium hypochlorite at the proposed Desalination Plant at TKO Area 137 has been conducted in this section.

The methodology adopted in this section hazard assessment is consistent with previous studies having similar issues, i.e. Harbour Area Treatment Scheme (HATS) Stage 2A Environmental Impact Assessment [29] and Construction of an International Theme Park [30].

The results show that individual risk and societal risk associated with the storage, use and transport of sodium hypochlorite at the Desalination Plant at TKO Area 137 are acceptable and the overall risk (in terms of individual risk and societal risk) lies within the acceptable level. The risk associated with sodium hypochlorite operation is negligible when compared with that from on-site chlorine operation at the Desalination Plant.

13.5 Transport (On-site and off-site), Storage, Handling of Cryogenic and Pressurised Liquid Carbon Dioxide

13.5.1 Scope of Liquid Carbon Dioxide Risk Assessment

The technical scope of the liquid carbon dioxide (CO2) assessment is defined as follows:

- The assessment is concerned only with the hazards posed by the on-site and off-site transport, storage and handling of CO2 (representing the most significant risk from the desalination plant to the population off-site).
- The assessment is concerned with the desalination plant operated at its ultimate design capacity (representing the highest CO2 storage and handling activities in the desalination plant).
- The assessment is concerned with off-site risk to the general public near the desalination plant. Risk posed to on-site population such as operating staff of desalination plant is excluded.
- The assessment considers the risk to the future population at operation stage in 2036. CO2 storage and handling are not anticipated during the construction stage of the desalination plant.

13.5.2 Approach to the Study

The Hazard to Life Assessment for liquid carbon dioxide has been conducted following the generic assessment steps listed below:

- Hazard identification, scenario definition;
- Consequence assessment;
- Frequency assessment;
- Risk summation; and
- Risk mitigation (as applicable).

Operations involving liquid carbon dioxide and relevant plant facilities have been reviewed and described in the assessment report. Population data and meteorological data in Section 13.2.5 and 13.2.6 of On-site Chlorine PHI QRA section of this study have been adopted for liquid carbon dioxide risk assessment for consistency.

13.5.3 Description of Liquid Carbon Dioxide Operation

Carbon dioxide (CO_2) will be used for pH adjustment and remineralisation in the post treatment process. Liquid carbon dioxide will be delivered to the Desalination Plant by road tankers. Carbon dioxide will be stored in liquid form in total number of 16 units of 100-tonne cryogenic pressurized tanks at outdoors. The tank size is about 3m in diameter and 14m in height. The location of CO2 Storage tanks is indicated in Figure 13.5. The total storage quantity is 1,600 tonnes which is based on the ultimate plant throughput and 90 days of consumption. The 90-day storage capacity meets WSD's chemical storage requirement for the operation of water treatment facilities. According to the daily consumption of 18 tonnes per day, the number of 20-tonne road tanker deliveries is estimated as (18 * 365)/20 = 329 deliveries per year. Storage temperature and pressure are -23^{o}C and 17 barg respectively for both storage tanks and road tankers.

Since there is no planned public road network within TKO Area 137 at this stage, the distance for offsite road transport within TKO Area 137 is estimated by extending the south end of Wan Po Road to the Desalination Plant which is approximately 1 km.

Gaseous or liquid carbon dioxide will be drawn from the storage tanks. External ambient type vaporisers, which consist of radiators without electrical or mechanical parts, will be installed to provide an adequate supply of carbon dioxide vapour and maintaining the pressure in the storage tanks within its design limitations. A trip is used on the gas outlet or on the heating unit to safeguard the installation against liquid carry over which may weaken the installation due to extreme low temperature.

13.5.4 Hazard Identification

Hazards of Carbon Dioxide

Carbon dioxide is not considered to be particularly toxic. However, it causes oxygen depletion effects. The effects of oxygen depletion are described by the British Cryogenics Council as the four stages of asphyxiation and are shown in the Table 13.45.

Table 13.45 The Four Stages of Asphyxiation

Asphyxiation stage	Oxygen concentration (% v/v) / effects
1st	21 to 14% Reducing: Increased pulse and breathing rate with disturbed muscular coordination
2nd	14 to 10%: Faulty judgement, rapid fatigue and insensitivity to pain
3rd	10 to 6%: Nausea and vomiting, collapse and permanent brain damage
4th	Less than 6%: Convulsion, breathing stopped and death

Without adequate venting or pressure-relief devices on the containers, enormous pressures can build up. The pressure can cause an explosion called a "boiling liquid expanding vapour explosion" (BLEVE). Unusual or accidental conditions such as an external fire, or a break in the vacuum which provides thermal insulation, may cause a very rapid pressure rise. The pressure relief valve may not be able to handle this increased pressure. Therefore, the containers must also have more than single device such as a bursting disc [58], plate pressure relief device or second pressure relief valve working in parallel.

Cryogenic liquids and their associated cold vapours and gases can produce effects on the skin similar to a thermal burn. Brief exposures that would not affect skin on the face or hands can damage delicate tissues such as the eyes. Prolonged exposure of the skin or contact with cold surfaces can cause frostbite. However, the cryogenic effect is caused by direct contact. Moreover, the cold vapours can be seen and avoided by people surrounding the release source.

Review of Historical Incidents

A survey of worldwide incidents involving storage of CO2 and transport by road tanker is conducted by referring to the following reference sources:

- MHIDAS Database (MHIDAS is a Major Hazard Incident Data Service developed by the Safety and Reliability Directorate of the UK Atomic Energy Authority. MHIDAS contains incidents from over 95 countries particularly the UK, USA, Canada, Germany, France and India. The database allows access to many other important sources of accident data, such as the Loss Prevention Bulletin, and is continuously updated)

- Energy Institute
- Global Congress on Process Safety 2013

Table 13.46 Historical Incidents Involving Liquid Carbon Dioxide

Incident Description	Potential Causes
Texas, United States, 19 September 2002 In September 2002 a worker from the Reliant Processing Group in Muleshoe, Texas, was killed while the vessel he was insulating (which contained carbon dioxide) exploded. Reports indicate that the vessel suffered from brittle fracture having been exposed to extremely low temperatures and a build-up of pressure finally caused the tank to explode. The Occupational Safety and Health Administration of the U.S. Department of Labor (OSHA) investigated the incident and found that Reliant had "failed to maintain the pressure vessels and follow safety standards to prevent hazardous conditions". There were 1 killed and 6 injured in the incident.	Human error during operation/ maintenance; Maybe caused by overheating (the vessel was undertaking maintenance on insulation)
Lothian, UK, 6 May 1997 Carbon dioxide used as a refrigerant in the chilling process leaked from a pipe in the roof of a chicken processing factory. Workers only noticed the leak when asthma sufferer had difficulty breathing. Staff were evacuated with 35 injuries.	Pipeline failure
Norfolk, UK, 14 September 1996 18te carbon dioxide used in food manufacturing process released from factory. Only security staff on site at early morning incident & no one was hurt. No damage reported.	Unknown
Worms, Germany, 21 November 1988 This is one of the most catastrophic incidents involving a CO2 tank explosion. The detailed description of Clayton and Griffin is summarized in [54]. The liquid CO2 was stored in a 30 tons capacity tank at 20bar and -20°C. The vessel was shattered into a number of pieces in the explosion. Most of the tank was propelled into the Rhein River about 300 meters away from the epicenter. Only 20% of the tank was recovered originally. The Worms's investigation concluded that the vessel failed catastrophically, most likely due to overpressure from overheating with a frozen relief valve. The failure pressure was estimated to be between 31 and 51 bara. It was speculated that the failure caused a CO2 BLEVE. There were 3 killed and 10 injured.	Overheating;; Pressure relief valve failure
Fukushima, Japan, 1 March 1969 A CO2 storage tank in a steel mill exploded [55][56][57]. A slate-roofed factory within a 50 m radius was completely destroyed, and only its pillars remained. Windows of houses located within a 500 m radius were damaged. Before the explosion, the main safety valves were closed during repairs. Liquid remained in the tank (50% filling level) and the heat source of the external evaporator was left on. The vapor phase temperature and pressure in the tank kept rising, and eventually the tank exploded when the pressure exceeded the burst pressure of the tank. Based on heating element power, CO2 usage, and heating time, it is estimated that almost all liquid CO2 was turned into vapor before the explosion. Thus, this incident is determined to be a PV release. There were 3 killed and 38 injured.	Overheating; Human error; Pressure relief valve failure

Incident Description	Potential Causes
Repcelak, Hungary, 2 January 1969 Two vessels containing liquid CO2 (15 bar, -30°C) in a CO2 production and filling plant exploded in rapid succession. The explosion completely destroyed the tank yard consisting of four liquid CO2 storage vessels and the equipment of the technological laboratory. Large fragments were scattered in a circle of approximately 400 m radius. A 2800 kg shell landed at a distance of 150 m and a fragment weighing 1000 kg landed 250 m away. During filling, the first vessel exploded. Some minutes later, another close-by vessel exploded. The second vessel probably failed as a result of impact from a fragment from the first vessel. The explosions tore the two vessels into pieces, and tore the third vessel off its foundation bolts. The third vessel was shot into the process laboratory like a rocket due to liquid CO2 rapid expansion through a hole on the bottom. The probable cause of the accident was overfilling the first tank due to a level indicator failure. The explosion of the second vessel was speculated to be caused by a CO2 BLEVE. There were 9 killed and 15 injured.	Overfilling; Knock-on effect
Illinois, USA, 32 August 2004 Carbon dioxide gas was vented to the atmosphere after a road tanker ran off the road into a ditch. It was through that venting would be the best emergency response, as it would reduce the risk of explosion.	Traffic accident (no failure)

Hazard Identification Workshop

A hazard identification workshop was conducted to identify initiating events leading to potential CO2 release and types of release. Details on the findings of the workshop in the form of HAZID worksheet together with relevant drawings refer to Annex J2. Hazards were studied for sub-systems including transportation, transfer, storage, draw-off & dosage and gas dispersion. Types of release are grouped into liquid release, gaseous release and BLEVE. Potential causes of hazards in each sub-system are summarized as follows,

Transportation

- Fire events (*)
- Road accidents (*)
- Spontaneous failure (*)

Transfer

- Transfer hose connection and spontaneous failures
- Fire events
- Inlet valves operation
- Vehicle impact
- Dry ice formation

Storage

- Spontaneous failure (*)

- Overfilling of storage tank during transfer operation (*)
- Corrosion and erosion of materials
- Object or vehicle impact
- Fire event
- Natural hazards including lightning, extreme weather conditions, flooding, subsidence, landslide, earthquake
- Aircraft crash (*)
- Construction activities
- Electromagnetic interference
- Failure of vacuum insulation (*)
- Failure of pressure building system (*)
- Escalation from road tanker incident (*)
- Sabotage

Draw-off & Dosage

- Pipework failure
- Regulation valve failure
- Formation of ice on vaporizers

Gas Dispersion

- Pipework failure

Amongst these initiating events, many of them have contribution from human error. According to the layout of the Desalination Plant and operation environment, causes potentially leading to BLEVE are indicated with (*) in the above listing. The rest of causes would lead to liquid or gaseous release in the worst case.

<u>Filling Operation</u>

According to the findings of the HAZID workshop, major causes of storage tank BLEVE are considered (1) loss of vacuum leading to overheating / over-pressurization initiated by spontaneous failure of the inner or the outer vessel; (2) over-pressurization due to overfilling of storage tank. Spontaneous failure of the inner or the outer vessel is contributed by construction material of the storage vessel. Overfilling can be caused by human error and / or monitoring equipment failure. The overfilling scenario is described in details by covering filling operation, human error and monitoring equipment failure in the following sections.

Filling operation is summarized in the following bullet points,

- Connect vapour return line to the road tanker and flexible hose to the road tanker delivery line.
- Turn on gas valve on road tanker to purge the flexible hose by allowing low CO2 gas flow.
- Open the Trycock valve on the storage tank to allow monitoring of liquid level.

- Connect flexible hose to the filling line and open the inlet valve. There is no hiss sound coming from the connection between the flexible hose and the filling line when the connection is set up properly.
- Turn off gas valve, turn on liquid valve for liquid transfer and start the transfer pump.
- Terminate the transfer by stopping the transfer pump when liquid begins to flow out of the Trycock valve and noise from the Trycock valve changes from small hiss to high pitch noise. The outflow of liquid and noise from the Trycock, which provide visual and audible alerts to operator, are normal during the operation of the Trycock.
- Close the inlet valve and liquid valve; disconnect.

Human error in filling operation

The operator may completely forget using the Trycock throughout the filling operation. If the operator opens the Trycock valve but fails to observe the liquid level and the noise generated by the Trycock valve, overfilling will occur.

Excessive liquid will circulate between the storage tank and the road tanker through the flexible hose and vapour return line. Over-pressurization will only be resulted if the operator fails to connect the vapour return line and overfills the storage tank.

Monitoring equipment failure

Although there are other monitoring equipment including contents gauge and high level alarm, Trycock provides the most direct indication to the operator for a full tank as the operator should monitor the Trycock by facing it throughout the filling operation. High level alarm can alert staff at the control room for overfilling. The operator does not know if the liquid level reaches the proper fill level when the Trycock fails and the high level alarm fails or staff at the control room ignores the high level alarm.

<u>Safety Measures</u>

Safety devices and operation procedures are in place to protect road tankers and storage vessels from operating outside the design conditions.

Road Tankers

- Vehicle fire extinguisher is available on road tankers for drivers to put out small fire.
- The storage vessel is screened with fire resisting shield from fuel tank fire.
- Drivers are not allowed to park on road tankers on streets during delivery or overnight.
- Inner vessel is made of resilient steel to resist low temperature and corrosion while the outer vessel protects the inner vessel from external impact. The outer vessel also provides secondary containment in case of leakage.
- 2 pairs of pressure relief valves (PRV) are installed on inner vessel. A change-over valve is used for switching between the 2 pairs of PRV. Pressure relief device is installed on outer vessel.
- Emergency release valves are installed for manual venting to prevent pressure build-up in the inner vessel.
- Crash protection is installed at both sides of the road tanker apart from front and rear crash protection.

- Trycock provides visual and audible alert for overfilling protection. Moreover, pressure gauge and content gauge are available on road tanker for monitoring of content level during refilling.
- Pre-trip inspection includes tank pressure, content level, weight check using weighbridge before departure.
- Dedicated access and unloading bay will be provided in the Desalination Plant for delivery and transfer operation. The unloading bay will be fenced off with bollards.
- Reversing or manoeuvring into unloading bay will be watched out by at least one operator of the Desalination Plant.
- Emergency shutoff switch on road tanker allows immediate stop of transfer operation.
- Length of flexible hose is restricted to maximum 3m to avoid handling difficulties. Also, hose-to-hose connection is not allowed to avoid disconnection between 2 hoses. Anti-whip cable fixes the hose to the inlet to restrict the hose movement in case of breakoff of joints at both ends of the hose.
- Prior to the liquid filling, gas valve on road tanker is turned on to purge the hose using very low gas flow. The hose is connected to the storage tank inlet while CO2 gas is discharged from the road tanker. High pitch noise indicates improper hose connection. The driver can remediate connection problem during the purging process. Liquid valve is turned on after the hose is properly connected.
- Pressure relief valves are installed on delivery hose and delivery line to prevent from over-pressurization.
- Wheel chocks are used to prevent the road tanker from moving in case of brake failure.
- Interlock system, via a hydraulic switch on the cabinet door, is installed to prevent brakes from being releases while transfer operation is undergoing.
- Speed control will be imposed within the Desalination Plant to prevent from serious traffic accident or serious vehicular impact.
- Road tanker is turned off during unloading. Transfer pump is operated from connecting to the external power source.

Storage vessel

- Trycock is installed to monitor the tank liquid level during filling operation. The Trycock valve is a physically fixed device set at the proper fill level. Trycock is the only acceptable indicator for a full tank although contents gauge provides an alternative way to monitor the tank liquid level.
- High level alarm. Signal from the tank contents gauge / level indicator is routed to the control room to alert operation staff for overfilling. Control room staff can use mobile telecommunication device to inform the staff, who accompanies with the road tanker driver (filling operator), to stop the filling operation.
- Safety relief devices are installed on the inner and outer vessels. 2 pairs of pressure relief valves (PRV) are installed on inner vessel. A change-over valve is used for switching between the 2 pairs of PRV. Plate pressure relief device is installed on outer vessel.
- Pressure gauges are used for monitoring storage and operating conditions. However, temperature gauges may be installed to enhance the monitoring capability.

- Inner vessel is made of resilient steel to resist low temperature and corrosion while the outer vessel protects the inner vessel from external impact. The outer vessel also provides secondary containment in case of leakage.
- Chain link fence installed surrounding storage area provides a distinct demarcation from the rest of facilities to avoid accidents such as vehicle crash into the storage area.
- Inlet filter is installed to remove foreign material to reduce the occurrence of corrosion.
- Lightning protection is installed within the Desalination Plant such that lightning protection zone covers the storage area.

Maintenance

Based on local experience, some CO2 tanks have already operated for approximately 40 years. Under normal and designed operating environment, the service life of the storage tank is minimum 30 years. According to the general DG license requirement, annual inspection should be carried out for the CO2 storage facility. The inspection covers pressure test for pipeline and pressure relief valves, calibration of pressure and contents gauges. To enhance the safety operation of the facility, the inspection frequency is increased to twice per year by following the practice of some existing commercial facilities.

In case of service of the storage tank such as hot work pipework directly connecting to the storage tank, CO2 content within the tank will be emptied to ensure the safety. Moreover, permit-to-work and hot work permit systems are recommended for carrying out hot work or other maintenance work within the CO2 storage area. Therefore, release through pipelines would be the potential worst case incident during maintenance of facilities at downstream of the storage tank.

Hazardous Scenarios

On-site CO2 facilities include storage tanks, pipeline and vaporizers. For off-site and on-site transport, road tankers are used for delivery of CO2 to the desalination plant. According to the historical accidents, CO2 release came from storage tank failure and pipeline leakage. Although no severe incident involving road tanker is identified from historical incidents, findings from the HAZID workshop concluded that potential hazards from road tanker transportation exist. It is anticipated that release scenarios would be similar to storage vessel. Major representative hazardous scenarios are listed as follows:

- Storage tank rupture failure - Rupture (100 tonnes)
- Road tanker rupture failure – Rupture (20 tonnes)
- Pipeline failure / storage tank / road tanker leak failure – Leak (50 mm / 25 mm)

Hazardous Outcomes

Based on historical incidents and hazard identification, outcomes from CO2 releases include,

- Toxic (Asphyxiation)
- Explosion
  - Overpressure
  - Flying fragment

13.5.5 Frequency Analysis

Primary Effects

BLEVE

According to DNV (2013) [45], CO2 Boiling Liquid Expanding Vapour Explosion (BLEVE) would occur when the initial conditions of containment failure are within the BLEVE envelope. The operating temperature and pressure of the CO2 tanks and road tankers are -23^{o}C and 17 barg, which are outside the BLEVE envelope, under normal operation. Off design conditions might be caused by initiating events by referring to the hazard identification section above,

- Spontaneous failure
- Road accidents
- Overfilling
- Fire
- Aircraft crash
- Failure of vacuum insulation
- Failure of pressure building system
- Escalation from road tanker incident

Under normal operating conditions, rupture or leak failures of containment would not result in vigorous phase change but just gas release to atmosphere. Therefore, it is considered damages to storage tanks in earthquakes or tsunamis would lead to CO2 release instead of BLEVE. Moreover, safety measures have already built into the design of the modern cryogenic storage system and road transport system to prevent BLEVE by referring to Figure 3 and Figure 4 in Annex J1. BLEVE occurs when safety devices and emergency responses fail at the same time. Safety measures have been described in the Hazard Identification above. Major safety devices for consideration in the frequency analysis include

- Vacuum insulated, double containment
- Pressure relief valves on inner containment
- Plate pressure relief device on outer containment (considered on storage tanks only)
- Trycock for overfilling alarm and warning

Pressure protection for the inner vessel is provided by 2 sets (1 duty and 1 stand-by) of pressure protection devices. Each set of pressure protection device is composed of 2 independent pressure relief valves. The pressure relief valves system will be designed to avoid the common mode failure such that the risk of common mode failure is negligible. Therefore, the risk of common mode failure is considered negligible for the operation of the 2 pressure protection devices. The pressure protection device on the outer vessel is a plate relief device. The plate relief device is a standard installation in accordance with industrial standards (EN 13458 Part 2 Annex 1). The plate relief device provides pressure protection of the inner vessel from external pressure, arising from pressure in the outer vessel. It also protects the outer vessel from possible gas or liquid leakage into the vacuum space.

Emergency responses and human intervention including use of fire extinguishers and fire services are taken into account in the analysis. However, manual venting in road tanker events is considered not effective, i.e. probability of failure 1, by adopting a conservative approach.

There is no storage of combustible materials surrounding the storage tanks. Although the storage tanks are adjacent to the Chemical Building, the Chemical Building containing DG stores is built in concrete with at least 2 hour fire rated construction. Fencing is provided surrounding the CO2 facilities to prevent car crash. Moreover, speed restriction will be imposed within the desalination plant. Therefore, external fire and car crash are not credible initiating events. Aircraft crash can lead to explosion of storage tanks. However, the frequency of aircraft crash to the Desalination Plant is very low by referring to frequency analysis for on-site chlorine PHI QRA.

Fault tree analysis, as shown in Figure 5 in Annex J1, is used to estimate the explosion (BLEVE) event frequency for storage tanks. Base failure rates for fault tree analysis are made reference to generic failure data from published data sources such as OGP (2010) [46] and tabulated in Table 13.47. The frequency of BLEVE is estimated as 3.13E-10 per year.

For on-site and off-site transport, loss of vacuum insulation due to spontaneous failure of or rollover damage to inner / outer and vehicle fire would be the major causes of road tanker BLEVE. In order to develop into a BLEVE event in a vehicle fire, time is required to heat up the CO2 content and cause failure of both inner and outer vessels. Considering the transport route from Linde HKO Ltd. at TKO Industrial Estate to the desalination plant, fire services from Tai Chik Sai Fire Station should be able to arrive at the fire scene within 6 minutes according to the performance pledge of FSD. BLEVE would occur if the following failures also occur at the same time,

- pressure relief valves on the road tanker fail to open (1.00E-03 per demand);
- the driver cannot rectify the problem by failing to control road tanker fire using vehicle fire extinguisher (0.5 per demand);
- fire services cannot control the fire (0.5 per demand).

The failure of the vacuum insulation system due to spontaneous failure of vessel on road tanker also leads to overheating. This overheating factor is also considered in the fault tree analysis. Referring to the cumulative risk assessment section, a zone of 1 km is sufficient cover the hazard range of PHI QRA. Since there is no layout plan available for TKO Area 137, the length of the road segment for the risk assessment is taken as 1 km from the Desalination Plant to the edge of the hazard zone according to the distance between the south end of Wan Po Road and the Desalination Plant. Fault trees for CO2 road tanker BLEVE during off-site and on-site transport are shown in Figure 6 and Figure 7 respectively in Annex J1 to derive the road tanker BLEVE frequencies. Off-site and on-site transport risks are 9.72E-12 per year and 3.07E-12 per year.

Rupture and Leak Failures

Referring to the HAZID worksheet as shown in Annex J2, leakage from a road tanker could be caused by traffic accidents or spontaneous failures. Although CO2 release would occur in fire events, the vehicle fire would take time to develop. It is considered that evacuation is possible prior to triggering the gas release. Depending on the severity of damage in a traffic accident or the size of a failure, the failure can be represented by rupture, large leak and small leak scenarios. The fault tree analyses in Figure 8 – Figure 10 of Annex J1 take into account probability of various degrees of damages to both inner and outer vessels in different initiating events. The failure frequencies for offsite transport of road tankers are summarized as follows,

- Road tanker rupture failure – 8.25E-07 per year;
- Road tanker large leak failure – 7.77E-07 per year ;

- Road tanker small leak failure – 2.91E-05 per year.

According to modeling results for onsite storage, use and transport of CO_2 in the consequence analysis section, gas dispersion of CO_2 due to neither storage tank failure nor road tanker failure would cause offsite impact. Further elaboration using frequency analysis is not necessary.

Table 13.47 Base Failure Rates

Parameter	Failure Rate	Unit	Reference
Rupture failure of double containment refrigerated tank	1.25E-07	/ tank year	OGP [46]
Leak failure of double containment refrigerated tank	1.00E-05	/ tank year	OGP [46]
Plate pressure relief device failure to open	1.00E-04	per demand	[48]
Failure of relief valve	1.00E-03	per demand	[48]
frequency of control valve failure	3.00E-05	per hour	[47]
Probability of aircraft crash	5.52E-17	per year	Refer to Chlorine PHI QRA.
Frequency of spontaneous truck fire	4.00E-09	per truck-km	Refer to Chlorine PHI QRA.
Truck rollover frequency	1.90E-07	per truck-km	Refer to Chlorine PHI QRA.
Truck impact frequency	4.00E-07	per truck-km	Refer to Chlorine PHI QRA.
Conditional probability of vessel rupture in traffic accident	4.25E-03	-	[5]; Also refer to "QRA of transport of LPG and Naphtha, Methodology report, DNV, 1996"
Conditional probability of large leak on vessel in traffic accident	4.00E-03	-	[5]; Also refer to "QRA of transport of LPG and Naphtha, Methodology report, DNV, 1996"
Conditional probability of small leak (all sizes including pipe, valve etc) in traffic accident	0.15	-	[5]; Also refer to "QRA of transport of LPG and Naphtha, Methodology report, DNV, 1996"
Driver fails to put out the fire with vehicle fire extinguisher	0.5	per demand	Refer to engulfment fire (aboveground tank) and jet fire on road tanker in [47] - Fire services fail to prevent BLEVE
Fire services fail to control fire	0.5	per demand	Refer to engulfment fire (aboveground tank) and jet fire on road tanker in [47] - Fire services fail to prevent BLEVE
Probability operator fail to turn on Trycock	8.00E-02	-	Derive from (Errors of omission where dependence is placed on situation cues and memory. Complex, unfamiliar task with little feedback and some distractions, 0.01) x (No obvious means of reversing an unintended action, 8); Refer to OGP 434-05 Table 2.7 & 2.8
Probability operator ignore alarm of Trycock	1.00E-02	-	Derive from (Errors of commission such as operating the wrong button or reading the wrong display. More complex task, less time available, some cues necessary, 0.001) x (A low signal-noise ratio, 10); Refer to OGP 434-05 Table 2.7 & 2.8

Parameter	Failure Rate	Unit	Reference
Probability of failure for high level alarm operation	4.20E-02	-	Lees [16]; taken into account (1) operator failed to take action; (2) breakdown of high level alarm system.

Secondary Effects

Referring to the consequence analysis section, BLEVE of CO2 storage tanks and road tankers within the Desalination Plant could be an initiating event for other onsite hazardous sources. The frequency of occurrence is equal to (3.13E-10 + 3.07E-12) = 3.16E-10 per year. Given the occurrence of a BLEVE, the escalation effect does not necessary take place as the following probability should also be taken into account,

- probability of explosives detonation
- probability of chlorine drum being damaged leading to leakage
- probability of chemicals mixing
- probability of being hit by flying fragments

Having accounting for the probability, the frequency of escalation would be even lower than 3.16E-10 per year. The frequency of escalation is far below contributing events to individual hazardous source in the order of at least 3 orders of magnitude. Therefore, contribution of CO2 BLEVE is considered insignificant and will not be further considered in the QRA for individual hazardous source.

13.5.6 Consequence Analysis

According to the frequency analysis above, BLEVE, overpressure and flying fragments effects and secondary impacts to other hazardous sources are well below the risk guidelines and have insignificant contribution to the overall risk. Consequence analysis in this section focuses on the remaining asphyxiation impact and are assessed using Phast Risk 6.7. Representative release scenarios are rupture, large leak (50mm) and small leak (25mm) to cover full range of release sizes. Escape factor is not included by adopting a conservative approach.

Asphyxiation Impact

The following probit equation [44] is used to estimate the likelihood of fatality due to the asphyxiation effect of CO2:

$$Pr = -90.8 + 1.01(\ln C^8 t)$$

where

Pr = probit value
C = CO2 concentration (ppm)
t = exposure time (minutes)

Downwind distances for representative hazardous scenarios under various weather classes are tabulated in Table 13.48. The maximum downwind distance from the release source at 1% fatality probability is 39m under weather class D4.5 for the 100-tonne rupture event. Therefore, there is no off-site toxic impact as the distance between CO2 storage area and the northern boundary, where off-site population exists, is approximately 100m. Lethality footprints from the Phast Risk model for representative hazardous events are plotted in Figure 1 in Annex J1.

Table 13.48 Downwind Distances for CO2 Toxic Impact under Various Weather Classes

Hazardous Event	Downwind Distance [(1)] from Release Source (m)			
	B3	D2	D4.5	F1.5
Rupture (100 tonnes)	36	36	39	36
Rupture (20 tonnes)	21	20	22	20
Large Leak (100 tonnes - 50mm)	33	33	33	33
Large Leak (20 tonnes - 50mm)	27	27	27	27
Small Leak (20 tonnes - 25mm)	14	15	14	15

Notes
(1) downwind distance at fatality probability 1%

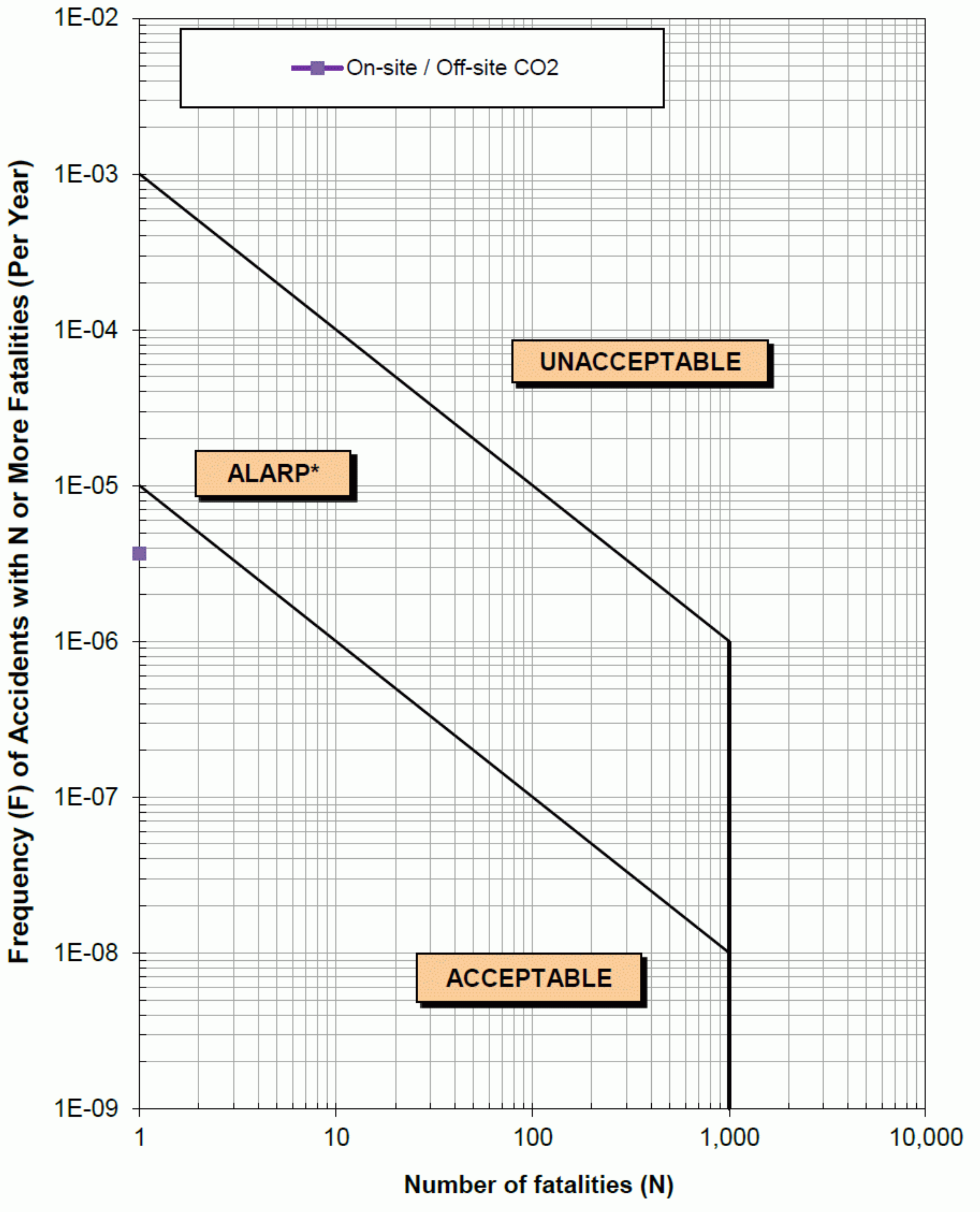
In road tanker failure (20-tonne cargo), hazard distances for an instantaneous release and continuous (50mm / 25mm leak) release are 22m and 27m / 15m respectively. The corresponding half cloud widths are 19m and 1m for instantaneous release and continuous release respectively.

13.5.7 Risk Summation

Hazardous events with off-site impact are included in the risk model using the software Phast Risk. Population stated and wind conditions in PHI QRA section are adopted in the model. Toxic (asphyxiation) effect is only included in the risk summation process.

The overpressure and flying fragments which are the consequences of BLEVE are not furthered considered due to the low frequencies of BLEVE. Referring to the frequency analysis, probability of fatality and distribution to the 1km road segment, the individual risk of CO2 offsite transport is in the order of 10^{-6} per year as plotted in Figure 13.26. The risk is below the 10^{-5} per year criteria and is considered acceptable. Since there is no gazetted road or layout plan currently available for TKO Area 137, the individual risk for CO2 as shown in Figure 13.26 is presented for a hypothetical road alignment in the individual risk plot.

Societal risk in terms of FN curve is presented in Figure 13.25. The risk of offsite CO2 transport is well within the ACCEPTABLE region of the risk guidelines. Since the onsite CO2 risk is insignificant by referring to the frequency and consequence analyses, Figure 13.25 also represents overall CO2 risk which is at acceptable level. Potential Loss of Life (PLL) breakdown from the risk model output shows that rupture event is the dominating event 3.39E-06 per year, accounting for 92% total PLL. PLL for large leak event is 2.871E-07 per year, account for 8% of PLL. Impact of small leak is insignificant. Also, the PLL is 100% contributing from the population of TKO Area 137.



* Risk within this region should be reduced
to as low as reasonably practicable

Figure 13.25 FN Curve for Liquid Carbon Dioxide Assessment

Figure 13.26 Individual Risk Contours for Liquid Carbon Dioxide Assessment

13.5.8 Risk Mitigation Measures

Since the risk associated with CO2 is acceptable, further risk mitigation measure is not required. However, the following safeguard measures are recommended for the safety operation of the CO2 facilities,

- Design of turning angle for access road within the desalination plant should cater for 40 feet container trailer to avoid reverse manoeuvring or impact to buildings / structures in cornering.
- Telemetry monitoring system should be installed to alert the content level in the control room for additional safety.
- The storage area should be divided into a number of compartments to protect storage tanks from fire or pipeline / valve failure.
- When leakage of an inner / outer tank occurs, a transfer pump should be used to remove CO2 content to other storage tanks as soon as possible. In case of emergency, venting should be carried out to ensure integrity of the storage tank.

- CO2 / O2 sensor should be installed for indoor environment with CO2 facilities or pipelines.
- Mechanical ventilation should be provided for indoor environment with CO2 facilities.
- Venting should be undertaken outdoor.
- To enhance the safety operation of the facility, the inspection frequency of CO2 storage tanks should be twice per year.

13.6 Other Risk Issues Associated with the Proposed Desalination Plant

13.6.1 Storage, Use and Transport of Other Dangerous Goods

Hazard assessment for chlorine, sodium hypochlorite and liquid carbon dioxide have been presented in previous sections. The EIA study brief requires risk assessment of storage, use and transport of other dangerous goods (DGs) associated with the proposed Desalination Plant. The DGs together with other chemicals will be stored in the Chemical Building. The list of those chemicals and their corresponding storage quantities are summarized in Table 13.49.

Storage and transport of DGs in the Desalination Plant are regulated by Dangerous Goods Ordinance and shall meet the relevant license conditions to ensure the safety storage and delivery of those chemicals.

Chemicals as shown in Table 13.49, such as caustic soda, hydrochloric and sulphuric acid, may cause local injuries upon accidental release/spillage for personnel in close vicinity of the release point during handling/transport process. The following sections assess impacts of these DGs quantitatively and give justification on their insignificant risk impact. The justification is based on either physical/chemical properties or Dangerous Toxic Load (DTL) for Specified Level of Toxicity (SLOT) [41]. For justification based on DTL, exposure conditions in terms of concentration and time of exposure as well as escape factor are considered.

Table 13.49 Storage Quantities of Chemicals in the Chemical Building

Substance	Maximum Storage Quantity [1]	Containment Type	DG Classification
Ferric Chloride	1520 m^3	Atmospheric tank	Category 3
Sulphuric Acid	248 m^3	Atmospheric tank	Category 3
Caustic Soda (Sodium Hydroxide)	1944 m^3	Atmospheric tank	Category 3
Polyelectrolyte	23 m^3	Atmospheric tank	Non DG
Hydrated Lime	1345 tonnes	Bags (solid form)	Non DG
Sodium Metabisulphite	182 m^3	Bags (solid form)	Non DG
Anti-scalant	24 m^3	Atmospheric tank	Non DG
Citric Acid	8 m^3	Atmospheric tank	Category 3
Sodium Silicofluoride	24 tonnes	Bags (solid form)	Category 4
Hydrochloric Acid	80 m^3	Atmospheric tank	Category 3

Notes:
[1] For ultimate water treatment capacity

13.6.2 Evaluation of Impacts

<u>Hydrochloric Acid</u>

Hydrochloric acid (10% wt) will be used for chemical cleaning of RO membranes. The cleaning process will be carried out 3 times per year.

Hydrochloric acid (10% wt) is a solution of hydrogen chloride in water. It is corrosive and considered toxic. It has high boiling at 109^{o}C for 30% solution. Different from fuming hydrochloric acid with concentration >25%, it does not release to the atmosphere in gaseous phase like hydrogen chloride. Except in direct contact, hydrochloric acid in a release may affect surrounding population via inhalation through evaporation.

Adopting a conservative approach, DTL for SLOT of hydrogen chloride (2.37E+04 ppm.min) is adopted in the hazard evaluation. Considering a puddle of 20% wt hydrochloric acid due to loss of total containment from a typical 24m^3 road tanker along the transport route, the puddle diameter is conservatively assumed 78m which is the largest allowable puddle size by the ALOHA model according to the prescribed volume. The actual puddle diameter should be smaller than the assumed figure because of road curb and drainage along the road. The concentration at the edge of the puddle is below 50 ppm which is obtained from ALOHA under wind conditions for urban area (wind speed 2 ms^{-1} and stability class D). At this concentration, it takes 474 minutes to cause incapacitation by reaching the DTL. The calculation indicates spillage of hydrochloric acid would not lead to fatality as there is plenty of time escaping to a safe place.

Since hydrochloric acid is stored at the chemical building, spillage of hydrochloric acid would be contained within the boundary of the Desalination Plant. Based on the calculation for road transport scenario, it is not anticipated that a person surrounding the Desalination Plant would be affected by the spill exceeding the DTL for SLOT. Therefore, the impact of hydrochloric acid to off-site population is not significant and is not further assessed.

<u>Sulphuric Acid</u>

Sulphuric acid (98% wt) will used be for pH adjustment in the pre-treatment process. Daily consumption is approximately 2.8 m^3.

Sulphuric acid is colorless to dark-brown, oily, odorless liquid. It is corrosive and considered toxic. It has high boiling point at 270^{o}C. The hazard comes from mist or vapour in a release to the atmosphere. In contrast with fuming sulphuric acid (oleum), the vapour pressure of 98% wt sulphuric acid is very low, <1 mmHg at 40^{o}C and 1 mmHg at 146^{o}C. Sulfuric acid is not volatile enough to cause toxic hazard through air dispersion. That is, under normal conditions, it cannot enter the atmosphere fast enough to reach concentrations hazardous to people within a large area. Therefore, the impact of sulphuric acid is not further assessed.

<u>Caustic Soda</u>

Caustic soda (sodium hydroxide) will be used for neutralizing chemical waste water which is generated in the chemical cleaning process of RO membranes. Apart from solid form, sodium hydroxide is commonly available in 50% wt solution. The chemical will be stored either in liquid or solid form under ambient conditions and delivered to the Desalination Plant by trucks.

The corrosive, irritant and permeator properties of caustic soda make the chemical hazardous in case of skin contact, eye contact and ingestion. It is not anticipated that the chemical has inhalation hazard unless it becomes airborne dust or mist. Moreover, the vapour pressure of sodium hydroxide solution is very low, 1.5 mmHg at 20^{o}C. Under the normal transport, storage and use conditions, dust or mist will not form. Caustic soda reacts with acids and produces water and the corresponding salts. The chemical reaction does not generate toxic gas but releases heat. Therefore, caustic soda will not lead to a hazard to life issue.

Ferric Chloride

Ferric chloride will be used in the pre-treatment, coagulation, process. Through coagulation, solid particles can remove from water for further treatment.

The skin irritant nature of ferric chloride may cause harm to human when it comes to skin, eyes or oral contact. The vapour pressure of ferric chloride solution is very low, <0.75 mmHg at 20°C. It is not expected that the chemical has inhalation hazard unless it becomes airborne dust or mist. Under the normal transport, storage and use conditions, dust or mist will not form. Therefore, ferric chloride will not lead to a hazard to life issue.

Polyelectrolyte

Polyelectrolyte will be used in the pre-treatment, flocculation, process in which causes colloids and other suspended particles in liquids to aggregate by forming a floc.

Polyelectrolyte is polymer whose repeating unit bears an electrolyte group. Since the repeating unit and electrolyte group of each polyelectrolyte vary, the potential risk associated with each polyelectrolyte can be different. In general, skin and eye contact may result in irritation. Inhalation and ingestion may also irritate the respiratory and digestive tracts. Under the normal transport, storage and use conditions, polyelectrolyte will not lead to a hazard to life issue.

Hydrated Lime

Hydrated lime will be used in the post-treatment process for pH adjustment and remineralisation. Adjustment of pH is needed to protect downstream pipelines and storages and prevent corrosion of concrete-lined surfaces. Remineralisation is needed to replace minerals removed from the water by desalination.

Hydrated lime (calcium hydroxide) is a medium strength base which is corrosive and irritant. Direct contact with calcium hydroxide may cause serious skin, respiratory irritations and eye damge. Under the normal transport, storage and use conditions, dust or mist will not form. It is anticipated that there is no inhalation hazard. Therefore, calcium hydroxide will not lead to a hazard to life issue.

Sodium Metabisulphite

Sodium metabisulphite will be used in the pre-treatment, dechlorination, process. The dechlorination process ensures chemicals in the water do not attack the sensitive membrane systems.

Sodium metabisulphite is in solid form. When it dissolves in water, the solution may release sulphur dioxide gas and may cause eye, dermal, gastric and respiratory irritations. Since sodium metabisulphite is in solid form, it does not have accidental mixing issue with other chemicals solutions or acids during unloading operation. With suitable precautionary measures implemented under normal transport, storage and use conditions, sodium metabisulphite will not lead to a hazard to life issue.

Anti-scalant

Anti-scalant will be applied to RO membranes for scaling control by increasing the solubility of sparingly soluble salts.

Anti-scalant is irritating to the skin. Eye contact may cause pain and severe inflammation of the conjunctiva. Inhalation of the mist or dust may irritate the respiratory tract and lung. Under the normal transport, storage and use conditions it is anticipated that there is no hazard to life issue.

Citric Acid

Citric acid will be used for chemical cleaning of RO membranes together with other chemicals.

Hazardous in case of eye contact (irritant), of inhalation (lung irritant). Slightly hazardous in case of skin contact (irritant, sensitizer), of ingestion. The amount of tissue damage depends on length of contact. Eye contact can result in corneal damage. Skin contact can produce inflammation and blistering. Severe over-exposure can produce lung damage. Under normal transport, storage and use conditions, no hazard to life issue is expected.

Sodium Silicofluoride

Sodium silicofluoride will be used in the post-treatment, fluoridation, process. Similar to existing water treatment works, addition of fluoride to a public water supply helps to reduce tooth decay for teeth protection.

Sodium silicofluoride (also called sodium flurosilicate) is irritating to respiratory tract, lungs, eyes and skin. Chronic exposure to it may have risk of cardiac and nervous disorders, and bone fluorosis. Under normal use conditions, no hazard to life issue is anticipated.

13.6.3 Summary of Impacts

Transport, storage and use of other dangerous goods would not lead to hazard to life issue by considering their concentrations in the atmosphere due to accidental spillage and the escape factor of the surrounding population. Therefore, off-site impacts of other DGs are considered insignificant and are not further assessed.

13.7 Cumulative Risk Assessment

This section addresses requirements of Section 3.2.1 (ix) of the Study Brief related to cumulative impacts of the project. These are presented as combined Individual Risk contours following the same approach as the approved EIA for the Kai Tak Development project [15] and In-situ Reprovisioning of Sha Tin Water Treatment Works [3].

The cumulative risks from hazardous installations was calculated by summing the risks from the proposed Desalination Plant on-site chlorine facilities, off-site chlorine transport, on-site/ off-site sodium hypochlorite facilities, on-site / off-site carbon dioxide facilities, on-site / off-site for other dangerous goods and risks in the vicinity of the proposed Desalination Plant.

The risks from the proposed Desalination Plant have been discussed in the above sections. The risks in the vicinity of the proposed Desalination Plant, based on the overlapping impact zone (i.e. Lethal Dose (LD) 03 contour of chlorine dispersion, 1% fatality contour of CO2 dispersion and explosives detonation) which is approximately 1 km centred at the proposed Desalination Plant, are presented below.

Explosive Transport in TKO Area 137

An explosive magazine site is currently set up within the boundary of the Desalination Plant site to temporally store explosives for existing projects including Shatin to Central Link (SCL) [2], Hong Kong Section of Guangzhou - Shenzhen - Hong Kong Express Rail Link (XRL) [8] and Kwun Tong Line Extension (KTE) [10]. Contractors for the construction of those projects using their explosive trucks deliver explosives from the magazine site to the corresponding work sites for tunnel blasting work. Since the temporary explosive magazine will be removed prior to any construction works for the Desalination Plant, the needs on explosive transport to and from the explosive magazine will no longer exist. Therefore, explosive transport arising from concurrent projects is not applicable to the operational phase of the Desalination Plant. Thus, there is no contribution to the cumulative risk from explosive transport in TKO Area 137.

Explosive Unloading at TKO Area 137 Pier

Risks from the unloading operation of explosives at TKO area 137 Pier has been conducted by ERM [14]. Risk to construction workers of desalination plant have been discussed in the study. During the explosive offloading period, no occupant is expected at the open area adjacent to the explosive off-loading pier (outdoor area for landscaping purpose). The 1% fatality cutoff for outdoor population only extends to the perimeter fence, which is located at the south of the outdoor landscaping area. Therefore, the construction workers are not anticipated to be affected by the accident explosives detonation of explosives off-loading operation during the delivery.

According to the Working Paper No. 5, it is concluded that the risk associated with the explosives off-loading operation at TKO Area 137 pier is Acceptable in terms of Individual Risk and Societal Risk.

Details are provided in Working Paper No. 5 – Feasibility of Coexistence of Explosives Off-loading Facilities of CEDD [14] conducted by ERM under this Desalination Plant feasibility study as well as hazard assessments of SCL EIA [2] and KTE EIA [10].

Overall Cumulative Risk

Cumulative risks in terms of individual risk contours and FN curves are shown in Figure 13.27 and Figure 13.28. Individual risk contours show that there is no off-site risk larger than 1×10^{-5}/year. Also, the FN curve for cumulative risk is within the “Acceptable” region. Therefore, the cumulative risk level is acceptable.

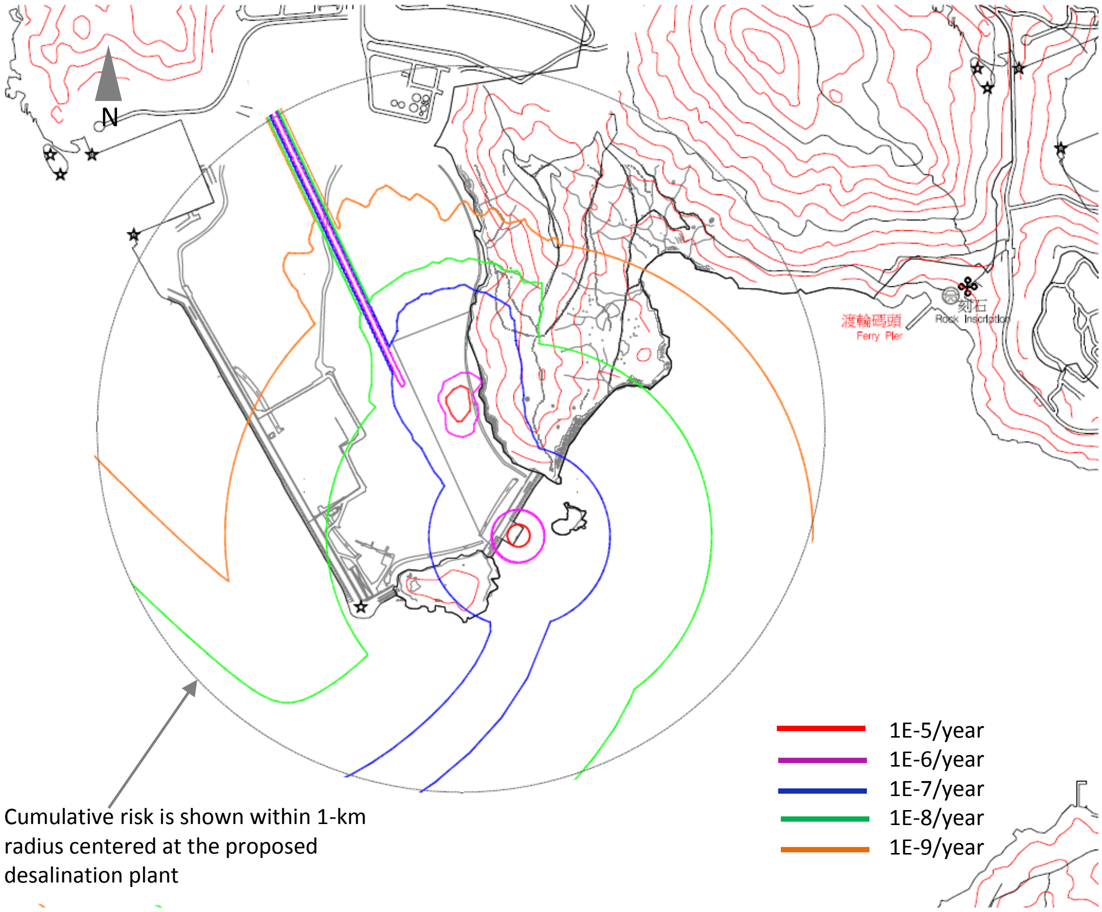


Figure 13.27 Cumulative Risk - Individual Risk Contours for Explosive Offloading Operation, On-site and Off-site Chlorine as well as CO2 Risks

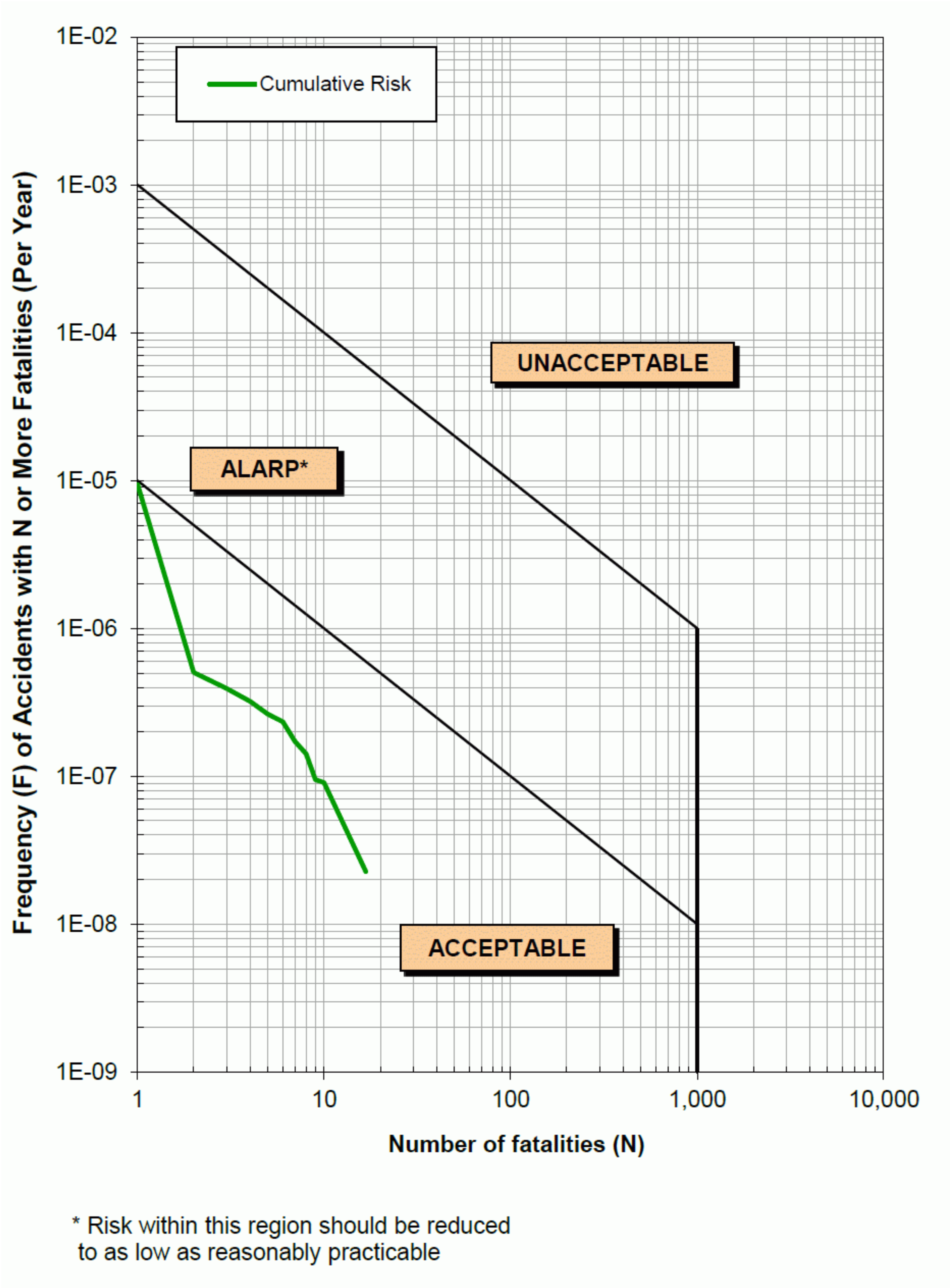


Figure 13.28 Cumulative Risk – FN Curves

13.8 Uncertainty Analysis

13.8.1 Chlorine and sodium hypochlorite assessment

This section assesses the level of uncertainty in the estimates of individual risk and societal risk by carrying out sensitivity studies on the key parameters and modelling assumptions, in association with the proposed desalination plant operation. The purpose of this is to gauge the level of confidence in the risk results.

The overall approach to this study has been to move away from the pessimistic assumptions of past studies to provide a more realistic assessment of the risks posed by the delivery, storage and handling of chlorine at the proposed Desalination Plant. This has involved extensive reviews of all aspects of the assessment methodology. The overall approach which has been adopted may be described as 'cautious best estimate'.

Annex K of 8 WTWs Reassessment Study [1] lists the key parameters and assumptions in the QRA, then identifies the level of uncertainty in the parameter (or assumption) and, finally, assesses the overall level of uncertainty in the risk results. The focus of this analysis is on key parameters (or assumptions) which may either significantly underestimate or overestimate the risk. The results of the uncertainty analysis are summarised in Table 13.50 below and details are presented in Annex K of this report.

One of the major differences in methodology between this study and that of 8 WTWs Reassessment Study [1] is the use of PHAST dispersion modelling instead of DRIFT for flat terrain dispersion modelling and abundant of wind tunnel modelling. It has been discussed in the Annex K of 8 WTWs Reassessment Study that the uncertainty related to DRIFT should be negligible and the same argument applies to PHAST dispersion modelling. Nevertheless, the uncertainty due to extent of dispersion modelling was still conservatively considered in this analysis.

Given that the weather data, chlorine dispersion model and Probit equation adopted in sodium hypochlorite assessment are the same as those in chlorine assessment, the parameters 1, 2 and 3 listed in Table 13.50 applies to sodium hypochlorite assessment.

For parameters 4 and 5 in Table 13.50, given that:

- The event frequencies for both chlorine assessment and sodium hypochlorite assessment are estimated by fault tree analysis; and
- The base event frequencies and conditional probabilities adopted in on-site chlorine assessment and sodium hypochlorite assessment are cited from other references / study reports which were estimated and derived from historical records.

Due to the above reasons, it is deemed appropriate to adopt the uncertainty factors from chlorine assessment to sodium hypochlorite assessment, i.e. parameters 4 and 5 listed in Table 13.50 applies to sodium hypochlorite assessment.

The above discussion is also applicable to off-site chlorine assessment although ALOHA is used for dispersion modelling except parameters 1 and 2 in Table 13.50 by referring to Annex K.

Table 13.50 Summary of Uncertainty Analysis

Parameter		Uncertainty in Risk Results	
		Magnitude	Affects frequency (F) or number of fatalities (N)?
1.	Influence of atmospheric stability on impacted area of chlorine cloud in building and terrain	± a factor of 2	F or N
2.	Extent of isopleths predicted by dispersion models	± a factor of 2	N
3.	Chlorine toxicity relationship	overprediction by a factor of 5 - 15	N
4.	Base event frequency data	± a factor of 10	F
5.	Conditional probabilities	± a factor of 3	F

Societal Risk

From Table 13.50, it is apparent that there are significant sources of uncertainty in the QRA. These are associated, in particular, with:

- the chlorine toxicity relationship, which may overpredict the number of fatalities (or, for an individual, the probability of fatality) by a factor of 5-15 when compared to actual fatalities in past incidents of major chlorine releases in urban environments; and
- estimation of the frequency of chlorine releases, for which the range of uncertainty is ± one order of magnitude (typical of the uncertainty in this aspect of QRA studies).

Considering the uncertainty magnitude shown in Table 13.50, an uncertainty band of factor of ±30 conservatively applied on the frequency (F) scale to account for the uncertainties in parameters 4 and 5 above. For consequence scale (N), if the N would be reduced by a factor of 10 (parameter 3 has an overestimation of 5-15) then the FN curve will be shifted to the left, with an uncertainty band of factor ±8 (= 2×2×10/5 for parameters 1, 2 and 3). From the uncertainty analysis summarised in Table 13.50, it can be noted that the net effect of the uncertainties is a shift in the FN curve further towards the left of the FN diagram, with the above range of the FN curves lying in the ACCEPTABLE region. Thus, the overall approach which has been adopted may be described as 'cautious best estimate'.

In addition, the maximum chlorine drum storage in the chlorination house will be limited to 37 tonnes, Hence, chlorine drums of 37 tonnes at the Desalination Plant representing the maximum storage capacity is considered as the reasonably worst case for modeling in the QRA. Therefore, the overall approach which has been adopted may be described as 'cautious best estimate', and it shall be noted that the risk analysis are on conservative side, with the off-set of uncertainties by using maximum inventory.

Similar to the on-site hazard, an uncertainty band of factor of ±30 conservatively applied on the frequency (F) scale to account for the uncertainties in parameters 4 and 5 above for the off-site hazard. For consequence scale (N), if the N would be reduced by a factor of 10 (parameter 3 has an overestimation of 5-15) then the FN curve will be shifted to the left, with an uncertainty band of factor ±2 (=10/5 for parameter 3).

Individual Risk

Similar considerations apply to the calculated individual risk levels. Individual risk is proportional to the frequency and number of fatalities summed for all incidents. In this case the combination of uncertainty in the parameters listed in Table 13.50, above may mean that the individual risk is underestimated by a factor of $2\times2\times(1/5)\times10\times3 \approx 24$.

Similar to the on-site hazard above, the individual risk is underestimated by a factor of $(1/5)\times10\times3 \approx 6$ for the off-site hazard by considering applicable parameters 3, 4 and 5.

This is not a significant factor, as when occupancy is taken into account, risks to actual individuals will still be below the criteria in the Hong Kong Risk Guidelines. Taking maximum cumulative risk of chlorine explosives as example, IR of 10^{-6}/year was found located in the vicinity of TKO Area 137 Pier, worker exposure related to worker occupancy in the vicinity is evaluated by assuming the individual risk could be up to 10^{-5} per year (after taking into account the uncertainties) then the risk to the most exposed individual (a worker spending 100% of his time outdoors) is as follows:

IR (most exposed individual of TKO Area 137 workers, refer to Population Ref No. 04 TKO Area 137 Pier in Table 13.6, assuming 1 hour per day and 6 days per week)

$= 10^{-5} \times$ fraction of (outdoor) working days each year

$= 10^{-5} \times 1 \times 6 \times 52/ (365 \times 24) = 3.56\times10^{-7}$ per year.

Note: Workers is assumed 100% of his time outdoors on conservative approach only, in fact the workers will not stay 100% of his time outdoors.

13.8.2 Carbon Dioxide assessment

Although the risk of carbon dioxide is low, the major contributor comes from the asphyxiation effect of gas dispersion while other effects have very low event frequencies. Event frequencies are derived from fault trees which are based on base failure rates and conditional probabilities by adopting conservative assumptions. The worst case scenario is already considered. The frequency (F) adopted in the assessment represents the upper bound. The effect of uncertainties on consequence (N) is considered not significant although probability of escape is not included.

Since the upper bound is adopted for the frequency data, the individual risk obtained from the assessment represents the worst scenario and underestimation in individual risk is not anticipated.

13.8.3 Explosives off-loading assessment

Uncertainty in risk due to explosives off-loading at TKO Area 137 Pier in Working Paper no. 5 has also been discussed below.

The maximum allowable load of explosives to be handled in TKO Area 137 pier is 5,000 TNT equivalence kg (TNT eqv.). Based on the available information provided by CEDD, the maximum quantities of explosives to be delivered by Mines Division of CEDD during the period from 2015 to 2018 are about 2,500 TNT eqv. kg. Nevertheless, this study conservatively assumes the maximum of 5,000 TNT eqv. kg for the off-loading operation at TKO Area 137 considering uncertainty of future requirements.

In the previous DNV study [53], the types of explosives off-loaded may include cartridges emulsion, boosters, detonating cords, detonators, fireworks, ammunition and pyrotechnics, and mixed types of explosives could be transported on the same vessel. Under latest Mines Division's practice, non-blasting explosives like fireworks, ammunition and pyrotechnics should not be stored with blasting explosives like cartridges emulsion, boosters and detonating cords in the same Cargo Hold of the explosives vessel and transshipped together and detonator should be stored in a separate Cargo Hold in explosives vessel. Fireworks, ammunition and pyrotechnics, which are far more sensitive to accidental initiation than commercial explosives, are currently not off-loaded at TKO Area 137 pier. Nevertheless, this study conservatively assumes a mixed load of explosives.

Currently Mines Division of CEDD has adopted Eversafe vessels for explosives transport and off-loading at TKO Area 137 pier, which is safer than the commercial vessels/barges/ships in the previous DNV study [53]. Nevertheless, this study conservatively assumes the local vessel in the previous DNV study [53] is used in the explosives transport and off-loading operation. This makes the frequency analysis at the conservative side.

In the consequence analysis, the mass for explosives dropped from crane and hand are conservatively taken as the maximum load per crane/manual lift provided by CEDD, i.e. 600 kg and 32 kg respectively, throughout the study as a simplification.

In conclusion, after taking into account the uncertainty in the hazard assessment by adopting conservative assumptions and parameters, this gives confidence that the risk level in the assessment is at the conservative side (high risk side of the uncertainty range).

13.9 Conclusions and Recommendations

A Hazard Assessment of the risks associated with the use, storage and transport of chlorine and DGs at the proposed Desalination Plant has been conducted for the operational phase (Year 2036) of the Project. The cumulative risk of the Project, through interaction or in combination with other existing, committed and planned developments involving DGs in the vicinity of the Project has also been assessed.

The assessment methodology and assumptions were based on previous assessments having similar issues, namely Shatin to Central Link [2], In-situ Reprovisioning of Sha Tin Water Treatment Works [3], Harbour Area Treatment Scheme (HATS) Stage 2A Environmental Impact Assessment [29] and Construction of an International Theme Park [30]. The list of major assumptions refers to Annex L.

In all cases, the Individual Risk complies with the Hong Kong Risk Guidelines and the Societal Risk lies in the acceptable region. The societal risk expressed in the form of FN curves, lies in the acceptable region of the HKRG for the use, transport and storage of chlorine at the Desalination Plant.

Therefore, the operation of the Desalination Plant is acceptable in terms of both individual risk and societal risk as stipulated in Annex 4 of the TM. Safeguard measures are recommended to ensure the risk associated with the use, storage, and transport of chlorine and DGs at the proposed Desalination Plant complies with the Hong Kong Risk Guidelines and stays in "Acceptable" region.

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