Projectile Risk Assessment

Introduction

The Linde HKO facility is located at Dai Shing Street, and is approximately 280 m to the south-west of the TPSTW. The facility consists of an oxygen production plant, storage tanks for liquefied gases, and a cylinder storage shed. A cylinder truck loading bay is provided in front of the cylinder storage shed, and transport of cylinders is made by cylinder wagons.

The cylinder shed is provided with open walls and natural ventilation. A wide range of chemicals are stored in the shed, including compressed oxygen, nitrogen, acetylene (dissolved), carbon dioxide, hydrogen, etc. Of these chemicals, hydrogen and acetylene (dissolved) cylinders are the major Dangerous Goods (DG) material stored in a dedicated area of the shed. In addition, liquefied gases, such as oxygen and nitrogen, are also stored onsite in vacuum insulated tanks.

Hazard Identification

Both hydrogen and dissolved acetylene are under Category 2 of DG (Compressed Gases) of the DG regulations (Cap295A) [31], which prescribes the required safety precautions and quality of cylinders. Hydrogen is under Class 1, which is highly flammable with a flash point below ambient temperature, and dissolved acetylene is under Class 3, which is combustible with flash points above ambient temperature.

Hydrogen is extremely flammable, and has the highest rating of 4 on the NFPA flammability [32] scale due to its wide range of flammable concertation in air. The flammable limits in terms of LFL and UFL is 4% and 94% (vol) respectively. When released to air, hydrogen is odorless, colorless, and tasteless, which make it difficult to detect. Nevertheless, hydrogen is buoyant, with tendency to rise and disperse quickly in air, so it would not accumulate near ground level if the release is in an open area.

Acetylene gas is mixed in liquid acetone for safe storage and usage. Acetone in acetylene cylinders helps stabilize the gas making it non-reactive within the cylinder. However, acetylene vapours are extremely flammable and unstable, and can also spread from leak creating an explosion hazard. Acetylene also has a very wide flammable range that the LFL and UFL concentration is 2.5% and 100%, respectively.

Other gases handled and stored on site is non-flammable, so there is no flammable hazard except for oxygen which can lead to oxygen enriched atmosphere. The reactivity of oxygen significantly increases the risk of ignition and fire. Materials that may not burn in normal air may burn vigorously in an oxygen-rich environment. For liquefied gases, including oxygen, vacuum storage tanks are provided for storage in cryogenic condition

A summary of the operational data for the concerned DG storage is provided in the table below.

Table 8.10.1 Hazardous Substance stored in Linde HKO Site

Substance	Storage Conditions
Dissolved Acetylene	Typical 7 kg each cylinder, at about 25 bar
Hydrogen (H_2)	Typical 9 m^3 each cylinder, at about 200 bar
Liquefied gases	Vacuum insulated tanks ranging from 30,000 to 250,000kg capacity

The fire and projectile hazard, a damaged cylinder could also act as missile as it being propelled by its own escaping gas. Such a runway cylinder event [10][34] typically involves opening or removal of valve or regulator due to operation error. For example, during cylinder lifting and loading to the wagon, an accidently dropped cylinder can lead to such a valve or regulator damage. The high velocity, runaway cylinder could then collide with the nearby facilities.

Cylinder Explosion

The cylinder explosion frequency model considers the number of fragments, initial fragment velocity (m/s), fragment range (m) and probability of building hit by fragment. Liquified gases storage is not pressurized to high pressure and therefore the projectile risk is not significant.

Number of Fragments

For ductile failures, Baum (1988) has reported that less than five projectiles will be produced [48]. Holden and Reeves (1985) report that there is an 80% chance that a rupture will produce fragments and there will be 2 to 4 fragments for each failure [49]. Most scenarios involve the valve being ejected so that there are 2 fragments (the valve and the cylinder). Assume that 90% of incidents produce 2 fragments, 10% of incidents produce 5 fragments and only 80% of incidents produce any fragments, the average number of fragments may be estimated as 0.8× (0.9×2 + 0.1×5) = 2.

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

Fragment Range

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

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

$$k = 1 - \left[\frac{p_0}{p_1}\right]^{\left(\gamma - \frac{1}{\gamma}\right)} + (\gamma - 1)\frac{p_0}{p_1}\left[1 - \left(\frac{p_0}{p_1}\right)^{\frac{-1}{\gamma}}\right]$$

$$E_k = \frac{k p_1 V}{\gamma - 1}$$

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

where:
v_i = initial fragment velocity (m/s)
E_k = kinetic energy (J)
M = total mass of the empty cylinder (kg)
k = fraction of internal energy converted to fragment kinetic energy
p_1 = absolute pressure in cylinder (Pa)

p_o = ambient pressure (Pa)
V = volume of the vessel (m3)
γ = ratio of specific heats of the gas

Summary of assumptions used in the model:

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

Cylinder design pressure for dissolved acetylene, carbon dioxide and hydrogen are 2.5 MPa, 7 MPa and 20 MPa respectively.

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

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

Empty cylinder mass is 30 kg for the 15 kg capacity cylinders [54]

Initial fragment velocity of chemical

Based on information of cylinders, the table below shows the calculation result of initial fragment velocity of various cylinders. The results show that the highest initial fragment velocity is 268 m/s for hydrogen.

Table 8.10.1 Initial Fragment Velocity of Chemical

Chemical	Initial fragment velocity (m/s)
Dissolved Acetylene	103
Carbon Dioxide	179
Hydrogen	268

Summary of fragment velocity and range

The table below shows the calculation result of each representative cylinders. End cap, valve and split represent three components of cylinder. The calculation result shows the maximum range is 468 m.

Table 8.10.2 Summary of Fragment Velocity and Range

Chemical type	Cylinder size	Fragment case	Surface Area of Fragment (m^2)	Initial velocity	Range
Dissolved Acetylene	End Cap	2.05	0.087	103	183
Dissolved Acetylene	Valve	0.5	0.012	103	288
Dissolved Acetylene	Split	5	0.370	103	124
Carbon Dioxide	End Cap	2.05	0.087	179	245
Carbon Dioxide	Valve	0.5	0.012	179	375
Carbon Dioxide	Split	5	0.370	179	159
Hydrogen	End Cap	2.05	0.087	268	287
Hydrogen	Valve	0.5	0.012	268	468

Chemical type	Cylinder size	Fragment case	Surface Area of Fragment (m^2)	Initial velocity	Range
Hydrogen	Split	5	0.370	268	171

Probability of hitting in each zone

Many past incidents and experiments have been documented in the literature. Baker et al. reported 20 events that he classified into 6 event groups [52]. The most relevant data is for cylindrical vessels containing 512 kg of propane gas, for which 98% of the fragments had a range of less than 500 m. The study of Baker et al. also provides information on the fragment range distribution, rather than simply the maximum fragment range [52]. From the previous calculations, it can be seen that the maximum range of debris was found to be 500m, which is consistent with the data reported by Baker et al. Therefore, it is reasonable to apply the distribution by Baker et al, as summarized in the table below. Since the maximum distance covered in this study is 468m, the probability of 300-468m is combined as 6% in each incident.

Table 8.10.3 Probability of Hitting in Each Zone

Range	Probability
0-100m	54%
100-200m	30%
200-300m	10%
300-400m	4%
400-500m	2%

Probability of projectile hitting each equipment

The probability of a projectile striking any equipment can thus be calculated by the following equation:

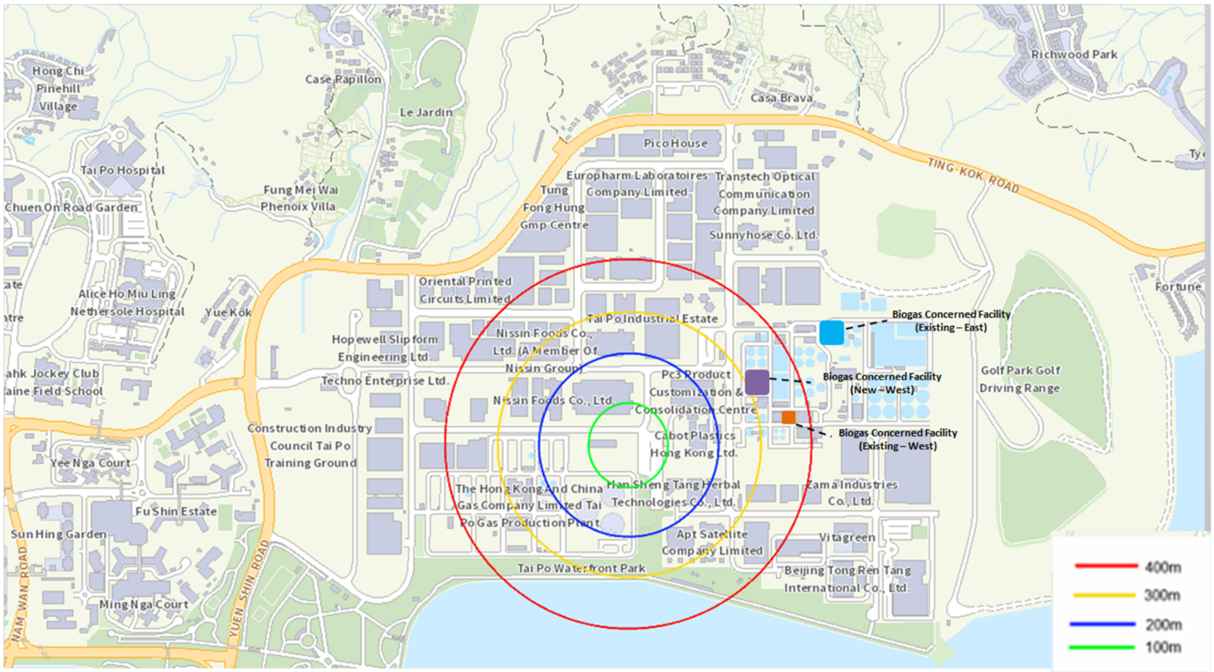
$$p(x) = \frac{FBH}{Z}$$

where F is the frequency of cylinder rupture per year; B is the area of the target equipment; H is the probability of a zone being hit; and Z is the total area of a zone where the equipment located.

The frequency of cylinder rupture per year was assumed to be 1.00E-06 per cylinder-year. Each rupture was estimated to produce 2 fragments on average, but 50% of these will be trapped within cylinder stacks based on a previous LPG cylinder projectile QRA study.

The figure below shows the location of Biogas Holders and range of projectile.

Exhibit 8.10.1 Concerned facility in Biogas



Based on this target area, the new biogas holder and the existing biogas holder in west plant (i.e. New – West and Existing – West) are located within the projectile range of 301-468m. The hit frequency was calculated to be 9.5E-08 per year per biogas holder. The existing biogas holder in east plant (i.e. Existing – East) is outside the projectile impact range. The knock-on effects, which are basically flammable biogas loss of containment with subsequent fires, and their associated risk have been incorporated in the biogas QRA. Note that there are total of 3,000 cylinders stored onsite which is provided by Linde [30].