Original Article

Consequence Modelling of a Potential Major Hazard Accident of Chlorine Gas Leakage in Water Treatment Plant

Mohamed Haffis Bin Mohossain Molla,[a,*] Hamdan b. Mohamed Yusoff[a]

[a] *Department of Chemical and Environmental Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

*Corresponding author: haffis@yahoo.com

ABSTRACT: A loss-of-containment scenario in the chemical industry can be devastating, for both property and human life. Over the past, there have been many chlorine-related accidents reported in Malaysia. Chlorine is one of the most commonly used water disinfectants in water treatment plants and this toxic chemical can cause adverse impacts to human health and the environment. In this research, DNV PHAST 8.11 (Process Hazard Analysis Software Tool) a consequence modelling software was used to describe the consequence of a chlorine leak at water treatment facilities. The worst-case scenarios of chlorine storage listed in the Hazard Register will be analyses by using the mentioned software. A catastrophic rupture with a 5mm leak was chosen for the simulation. The results rectify that potential hazard could exist under an average weather condition. This study corroborates that an estimated of 7,677 lives within a radius of 3.2 km distance could be affected by a 10 ppm of chlorine exposure during day time. By taking into account on the individual risk contours (IRC) claiming on workers' continuous expose to chlorine leak up to a year, the findings have shown that the probability of fatality rate is 1.2 in a million. A buffer zone should be allocated beyond the accepted individual risk contour. It is recommended that the emergency response and execution team should be coordinated to the Plant Emergency Controller in ensuring all personnel are well-informed of emergency alarms on all sites and to perform a safe and orderly evacuation. A comprehensive Emergency Response Plan (ERP) for all sites should be developed in collaboration with government agencies such as Local Authorities, Fire and Rescue Department and Police Department.

Keywords: *Chlorine, Consequences Analysis, Major Hazard, PHAST, Water Treatment Plant*

1.0 INTRODUCTION

A loss-of-containment scenario in the chemical industry can be devastating, for both property and human life. In the past, the world has witnessed numbers of Major Hazard disaster that cause thousands of lives perish (Khudbiddin et al., 2018; Drogaris, 1993; Christou, 1999). When toxic gas is released from the containment, it creates a cloud of gas that is heavier than air, and when it remains in contact with the ground as it dissipates, the condition will threaten people in its path. Chlorine gas is heavier than air when compressed and it can be extremely harmful to humans. Table 1 shows chlorine exposure thresholds and reported responses in humans (Oxychem, 2013)(White & Martin, 2010). The only chemical that are contributed A loss-of-containment scenario to industrial accident as well as used as chemical weapon is chlorine (Agency France-Presse, 2018; Dina Esfandiary, 2018) as shown in Fig. 2 below. There had been a few accidents of chlorine gas leak occurred in the industry which cause some damaged to property and human life (Law et al, 2018; Jimmy Goh, 2017; Iyuke et al, 2004).

Table 1 Chlorine Exposure Thresholds and Reported Responses in Human

Exposure level (ppm)	Effect
0.2 – 0.4	Threshold of odour perception with considerable variation among subjects
1 - 3	mild mucus membrane irritation
5 -15	moderate mucus membrane irritation
30	Immediate chest pain, vomiting, dyspnoea, and cough
430	Lethal over 30 minutes
1000	Fatal with a few minutes

In the context of Malaysia, several incidents of chlorine leaks have occurred in the past 2 years. On September 18, 2016, a chlorine concentration of up to 3 ppm was detected in chlorine gas leaked at the Bukit Merah Industrial Park from a Chlor-alkali plant, which triggered by a breakdown and collapse of a ferric acid reservoir. All workers of the plant were evacuated immediately. Two workers were hospitalized and one of them was diagnosed with pneumonia and was treated in the intensive care unit. One fireman suffered breathing difficulty, dizziness and red eyes during the rescue mission while some of the residents around the plant suffered irritation to eyes, nose and throat (Law et al, 2018).

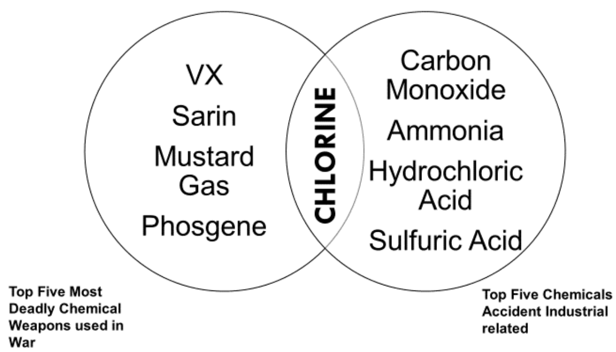

Figure 1 Similarity of Hazardous Chemical Use in War and Industry

On July 21, 2017, a chlorine leakage incident reported at the Water Treatment Plant in Kota Belud, Sabah. As discovered the ruptures in one of the valves connected to the chlorine drum was a leak and it has caused a small amount of chlorine to escape. The personnel from the plant has stopped the leaks by securing the valve instantly. No injured were recorded in this incident (Jimmy Goh, 2017). In another incident happened on September 28, 2017, involved illegal dumping of chlorine drums close to the residential area at Kampung Tambak Paya, Melaka. The situation has caused fifty residents hospitalized, including four firemen. The dispersion of the chlorine cloud was within 1 km in radius from the disposed of the drum. Most of them suffered from breathlessness (Koh, 2017). On another incident that occurred at the Kg Tudang Water Treatment Plant, Kuala Kerai, Kelantan at around 11:35 a.m. on July 4, 1997, a case whereby chlorine gas leaked from one of the cylinders inside the chlorine room. The leak was caused by 1–2 mm hole at the bottom of 68 kg chlorine cylinder cause more than 79 people were examined at the local hospital for respiratory distress caused by chlorine exposure and 20 of them were admitted for further treatment (Iyuke et al, 2004).

It is significant that the recent incident of chlorine leaks has caused a severe impact on both the plant workers and nearby residents. It can also be being observed from these incidents that the chemical processing industry is prone to accidents because many chemicals are used in the operation process. These scenarios often exposing oneself to process hazards and lead to higher risks. As an apropos remark on the research study on Water Treatment Plant (WTP), the growing of water demand in an area tends to lead to an increase of chlorine used in the plant. The plant began in 1982 with the capacity to produce clean water for approximately 545 million litres of water per day (MWA, 2016). The plant currently produces 600 mld –caters for a higher demand for clean water. Higher output means more chlorine being used daily. In order to balance and sustain the supply and demand needs, huge numbers of chlorine need to be stored on-site to ensure indestructible supply to support the process. As an estimate quantity of 60 – 80 tonnes of chlorine are kept at the Water

Treatment Plant storage area. According to a desk study, the plant is situated near to the government administration building and residential area in Putrajaya.

The consequences analysis model is important to be inferred as to ensure corrective measures can be applied to prevent such a major hazard accident occurring. DNV, GL PHAST, software is used to perform consequences modelling. This kind of application makes things easy, it helps safety professionals to calculate and analyze the effects of these scenarios and subsequently develop the right prevention or containment protocols (DNV, 2018). Thence, DNV PHAST 8.11 is put to use in this study to evaluate the consequences of a chlorine leak at Water Treatment Facilities.

2.0 METHOD

2.1 Research Framework

The framework of this study has been established based on the background of the study. The objective of the research study, literature review and issues are identified accordingly. The framework and the flow of the study shown in Fig. 2. will be used as a guideline.

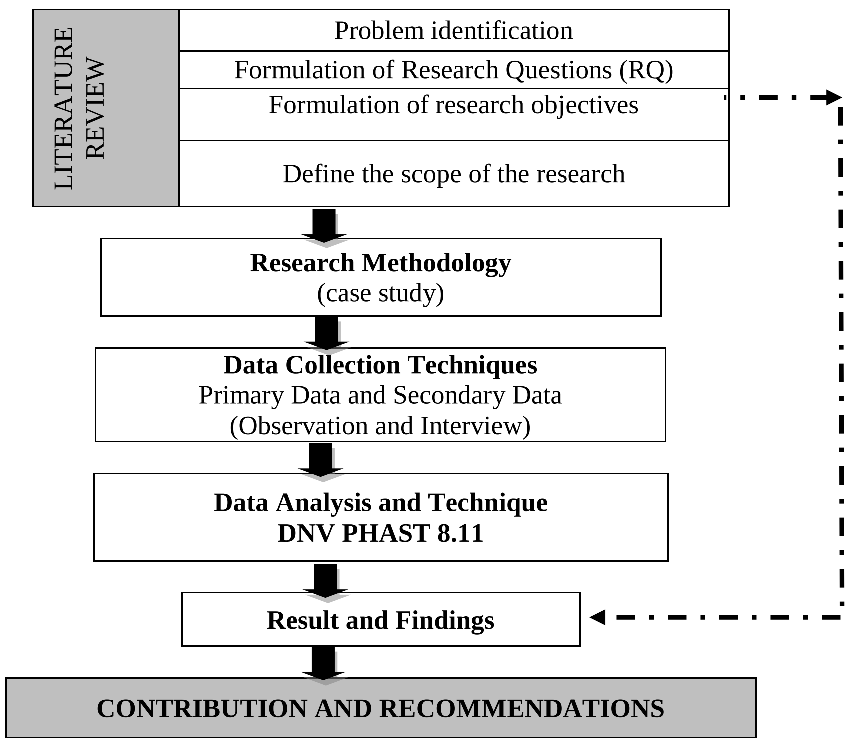

Figure 2 Research Framework

2.2 Data Collection

The data collected in this study can be divided into two categories which is the primary data and the secondary data. Primary data refers to data obtained from observation and interviews. These observations and interviews are used to identify potential risks that may arise when chlorine is stored in a water treatment plant. In adjunction, the secondary data is a general description of the processing path such as standard operating procedure (SOP), number of workers, the volume of hazardous materials used and stored, chlorine process flow and control system and certainly the emergency detection that has been installed on the site. Secondary data will be used in the consequences analysis.

Hazard identification and assessment are performed to foreshadow catastrophic failure on hazards and risks that could potentially triggered by chlorine leakage. The process of chlorination is dependent on properties and parameters such as pressure, temperature, and phase change. It is essential to understand the chlorine release phases in order to prioritize the loss of containment condition by projecting the most severe and more likely to occur scenarios. A risk assessment matrix could be used to support in determining the risk level. The matrix provides a quick view of both the likelihood and the severity of consequences. For each risk and hazard, control measure can be formulated or at least to reduce it. There are five stages in control measures: elimination, substitution, engineering controls, administrative controls, and the use of personal protective equipment. Once the scope of the study is defined, an Event Tree Analysis (ETA) will be established to determine the probability of hazard occurrence by referring to the frequency of the accident that has been recorded from the literature, incident statistics of the manufacturing plant, experiences of employees and historical data of incidents occur from various sources which internationally recognized. ETA is used in this study to identify and evaluate each of the sequences of events in predicting the potential accident scenario through screening at the occurrence of an initiating event.

2.3 Consequences Modelling Analysis

Based on the hazardous substance criterion, source modelling, the effect of chemical release and consequences event are predetermined. Three scenarios were chosen for the studies, vapor phase release, liquid phase release and catastrophic rupture on containers. The phenomenon is described by a hypothetical case of chlorine release from the Water Treatment Plant located in Putrajaya. The accidental release was due to leakage in a chlorine drum with approximately 930kg of chlorine was directly released into the atmosphere from the drum through a circular hole with a diameter of 5mm catastrophic rupture. The diameter of the cylindrical drum is measured at 0.78 m and with a total length of 2.08 m. The air temperature is 30°C, and the wind is travelling with a speed of 2 meters per second. After the direction and the mean of the studies are defined, the Event Tree Analysis (ETA) is applied to reckon the scenarios taking into account all possible failure modes. ETA is used in this study to determine the pathway to creating the biggest probability and frequency of failure for the specific system. Risk identification is the first process in determining risks that pertaining to multiple resources such as literature reviews, statistic reports from manufacturing plants, employee's knowledge and experiences, historical data of incidents recorded from international publications, etc. ETA is used in identifying and evaluating the sequence of events in causing a potential accident by focusing on the occurrences and severity of an initiating event. Record for speed of the wind is retrieved from the Malaysian Meteorological Department whereby the nearest meteorological station from the site would be KLIA Sepang. The study phase considers two different wind blow and its direction has been perceived as the major concerns. As observed, the highest percentage of wind blow is orientated from the northern and the second-highest wind blow was orientated from the northeast as it illustrated in Fig.3. The information and data were then analyzed by using the mathematical model or refer as QRA software. PHAST 8.11 is also applied to this research study. As for pasquill stability classification, Class B is referring to stability at day time while class F is referring to night time. Two different stabilities were chosen because the population at surrounding area are different in comparing to day time and night as the numbers of risk varies according to time changes. Both the stabilizer was selected in concert with the weather at a specific location to support the studies.

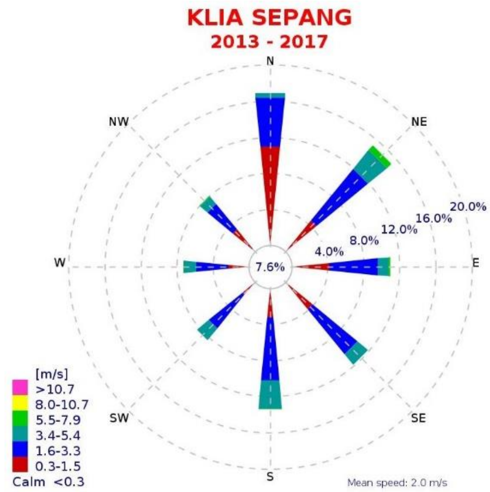

Figure 3 Windrose for KLIA Sepang Station from 2013-2017

3.0 RESULTS

3.1 Hazard Register

The potential danger is dependent on the combination of hazardous material and the complexity of the process that counts in different sizes of equipment used in the processing unit. The total amount of hazardous material used as well as the danger processes or activities in the chlorine storage area are defined and simplified in Fig. 4. The hazard register is a record where all chlorine-related operational hazards are listed as a point of reference.

3.2 Toxic Release Consequences Modelling

The result computed by PHAST 8.11 is summarized and tabulated in Table 2 below. The findings reflect on the worst outcome of a chlorine leak at a concentration of 10 ppm. Chlorine released in water treatment plants has led to a total rupture. The results indicated that the chlorine cloud dispersion could extend up to 3.2 km from F source under atmospheric conditions. Meanwhile for atmospheric condition class B in the same scenario, the chlorine concentration of 10ppm could reach as far as 545m. For 5mm liquid leak, at 10 ppm of concentration, the chlorine disperses as far as 3 km from the source for atmosphere stability class F but as for class B, under a similar criterion with 10 ppm chlorine concentration, the dispersion could have gone as far as 467.1 m. As for the 5mm vapour leak, the consequences are less compared to catastrophic rupture and liquid phase leak. The distance for 10 ppm of concentration for stability F is 914m while for stability B the distance is 144.6m.

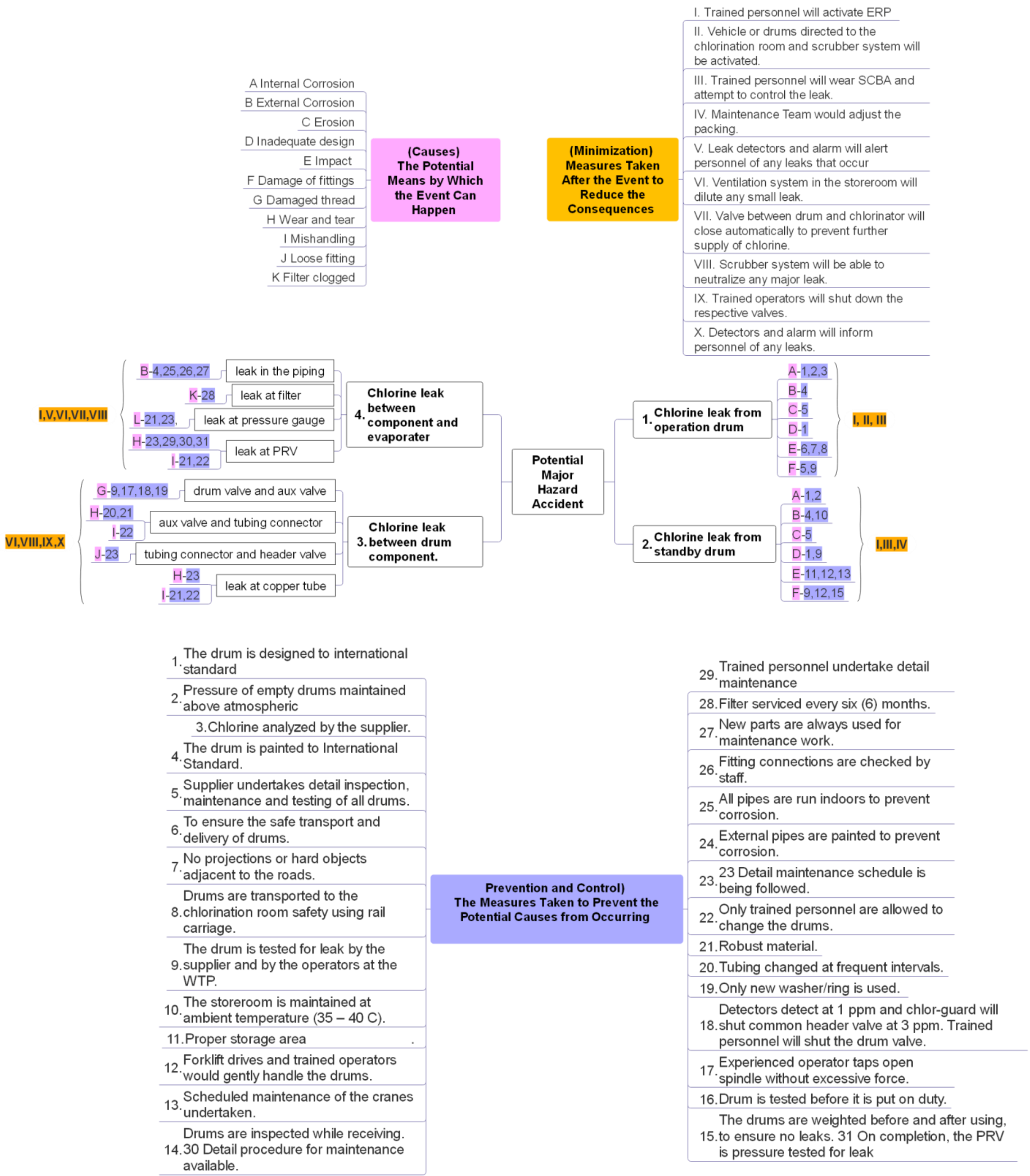

Figure 4 Simplify Hazard Register

Table 2 Downwind Distance for Different Level of Concentration

Scenario 1: Vapour phase release Release Rate = 0.06 Kg/s					
Level of Concern (LOC)	10 ppm	50ppm	100ppm	500ppm	1000ppm
Distance from source at stability class B(m)	144.6	64.7	47.0	26.9	17.4
Distance from source at stability class F(m)	914.97	289.1	157.7	27.2	16.3
Scenario 2: Liquid phase release Release Rate = 0.6Kg/s					
Level of Concern (LOC)	10 ppm	50ppm	100ppm	500ppm	1000ppm
Distance from source at stability class B(m)	467.1	195.6	136.3	68.3	56.6
Distance from source at stability class F(m)	3007.7	1008.2	593.5	146.0	85.4
Scenario 3: Catastrophic Rupture Release Rate = Sudden release					
Level of Concern (LOC)	10 ppm	50ppm	100ppm	500ppm	1000ppm
Distance from source at stability class B(m)	545.0	228.8	160.3	82.4	68.9
Distance from source at stability class F(m)	3220.0	1132.0	672.2	170.1	101.5

3.3 Effect on People On-Site and Off-Site

By accepting the meteorological circumstance, the most wind direction throughout the year 2013 to 2017 originates from the north (0°) and northeast (45°) of the plant as shown in Fig. 3 above. Thus, the south and southwest section, which is located downwind of the prevailing wind of the plant will be severely affected in the event of a chlorine release. However, by referring to the consequences modelling results for similar scenarios, the chlorine release distance for different wind speeds at different concentrations could extend beyond the water treatment plant boundary. The impact on the surrounding population as shown in Table 3.

Table 3 Residential Population Distribution Along the Downwind Path

Distance (m)	Direction	Label	Estimated population	
			Day	Night
<10	Source	1 - WTP	125	11
500	South	2 - EQP	150	50
1000	South west	3- MIB	60	120
1200	South	4 -IWK	35	6
1300	South west	5- CC	8700	650
1400	South West	6- RQ1*	373	2115
1500	South west	7 -SR	1732	2

1600	South west	8- SM	714	2
1700	South West	9- CON	100	20
1900	South West	10- RQ2*	548	3408

(source = From telephone conversation from respective personnel except for *)
Key: WTP = Water Treatment Plant, EQP= Equestrian Park, MIB= Medan Ikan Bakar, CC = Convention Center, IWK = Indah Water Konsortium, RQ1= Residential Quarters 1, SR = Sekolah Rendah, SM = Sekolah Menengah, CON = Construction Area and RQ2 = Residential Quarters2
**based on estimation from Bahagian Pengurusan Hartanah (JPM)*

It should be highlighted as that the tabulated results are referring to the worst-case scenario in consequence modelling. It should be noted that the tabulated results are referring to the worst-case scenario in consequence modelling. Table 4 illustrates the affected areas, the corresponding people that exposed to the 2m/s wind speeds for both the north and northeast direction and high concentration risk exposure.

Table 4 Areas and Population Affected at Different Wind Speeds for Worst-Case Release

Event	Effect Level & distance	Downwind Distance	Wind direction	Affected Area	Affected Population	
					Day	Night
Chlorine Toxic Cloud Release from drum catastrophic Rupture	500ppm	170.1m	From North (0°)	WTP	125	11
	100ppm	672.2m		WTP & EQP	275	66
	50 ppm	1132.0m		WTP, EQP	275	66
	10 ppm	3220.0		WTP, EQP & IWK	310	72
	500ppm	170.1m	From North east (45°)	WTP	25	11
	100ppm	672.2m		WTP & EQP	275	66
	50 ppm	1132.0m		WTP, EQP & MIB	335	186
	10 ppm	3220.0		WTP, EQP MIB, SM, SR, 50% CC, 50%CON, 50%RQ1 & 50%RQ2	7677	3288

4.0 DISCUSSION

4.1 Toxic Gas Dispersion

Based on the results in Table 2, it is estimated that 930 kg of saturated liquid chlorine was released into the atmosphere at a flow rate of 0.6 kg / s within 26.9 minutes for the release of the liquid phase scenario, while chlorine gas takes a long time to escape under the vapor phase scenario, the discharge rate is at 0.06 kg / s. PHAST software estimates the escape of 198.7 kg of chlorine vapors is within an hour. As for the initial release stage, the drum is full and the internal pressure is 8 bar, but as the chlorine level drops, the internal pressure will then approach the ambient pressure causing the flow to stop from the upper side hole of the drum. As for the vapor phase scenario, emptying the entire drum volume takes about 9.8 hours long. The release of chlorine into the atmosphere over a long period of time is also the same as the continued release that can lead to plume (Iyuke et al, 2004). For liquid phase release, the discharge rate takes less than 30 minutes to empty the entire chlorine drum and, in the process, some portion of the chlorine released will either become aerosol or fall to the ground as liquid, while 930 kg of chlorine in a drum was assume to be released within a time frame of fewer than 5 minutes in a catastrophic release case. No mitigation function was activated at the time of the release. All liquid chlorine was spilled on the ground. The situation is similar to sudden or instantaneous release in a catastrophic and liquid release scenario where the condition can lead to puff (Paul & Mondal, 2014).

The dispersion of a pollutant gas depends on wind velocity (Safakar et al., 2016) (Paul & Mondal, 2014). In the presence of turbulent wind speeds which is class B stability, the plume being buoyant will disperse more in the vertical direction compared to the downwind direction. As the concentration of the chlorine is constant over the duration of the continuous release, the dilution will be more intense and aggressive at a higher wind speed (Iyuke et al., 2004). Dense chlorine gas is released in the ventilated area of the building containing the chlorine drum, promoting the mixing with the air and moisture in the air squarely to the B atmospheric stability level during its descent to a lower level. This indicates that complete dilution of chlorine occurs immediately upon release from the building and maintained at the height prior to a complete dispersion. For stability F, the wind is more stable (Crowl & Louvar, 2002) therefore the dilution of chlorine would be less accord. It will be impossible for the developed vapor to quickly mix in the atmosphere after the released as it will be continuously transported by the wind. Moreover, in comparing the class F stability to class B stability, class F stability has an enormous toxic cloud coverage over distance. According to Soman, A. R (2015), Naimeh Setareshenas (2014) the atmosphere stability makes a lot of different in the dispersion of the toxic downwind. The class F stability gave the longest distance to toxic gas dispersion in all leak scenarios.

The worst-consequences scenario of chlorine leakage with a chlorine concentration of 10 ppm for a total rupture scenario, the studies has shown that the chlorine cloud reaches up to 3.2 kilometers from the source under class F atmospheric conditions. The area coverage is up to 1.06 km².

4.2 Effect on People On-Site and Off-Site

Referring to Fig. 5 below, for 45° of wind direction and 10 ppm concentration of chlorine the downwind distance is 3.2 km, the toxic cloud did not reach the CC (label 5), RQ1 (label 6), CON (label 9) and RQ2 (label 8) but the plume cloud slightly encroached into this area. Presuming half of this area and its population was exposed to SR (label 7), and part of the school area was covered by the toxic cloud of 10 ppm, the overall population surrounded the school area is affirmed to be affected. It has been extrapolated the total number of 7677 people were affected at 10 ppm of concentration in the daytime and 3288 people were affected at night time.

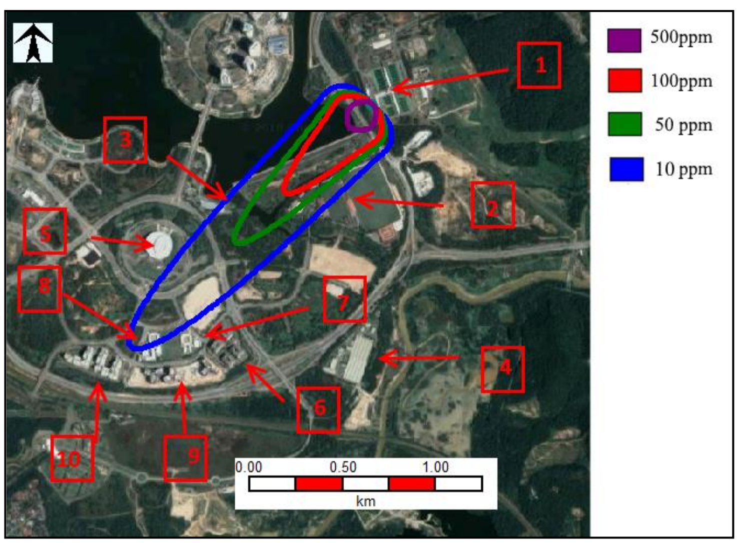

Figure 5 Affected Area From 45° Wind Direction for Worst Scenario

For a 50 ppm chlorine concentration, 335 people were affected at the day time and 186 people were affected at night time. At this distance, it should be alarming as that the toxic cloud has reached the public area and the public are exposed to the toxin. Relatively as for100 ppm chlorine concentration, 275 people are affected at the daytime and 66 people are affected at night time. Within the plotted area, the affected population is mostly workers or visitors at EQ (label 2) and personnel at the WTP (label 1). For 500 ppm level of concentration in wind direction of 45°, affected area are at the WTP plant and the surrounding area at a distance of 170m. The highest concentration of the toxic cloud covered the main road in front of the WTP. 125 people of the population are affected at daytime and 11 personnel that work at night time.

Fig. 6 below shows the affected area for the wind direction from 0° (north). For the 10pmm chlorine concentration at a downwind distance of 3.2km, 310 people are affected at daytime and 72 people at night time. The population mainly resides at WTP (label 1), EQ (Label 2) and IWK (label 9). For 50 ppm chlorine concentration, 275 people are affected in the daytime and 66 people at night time. The total number of the population affected is the same as for 100 ppm concentration because there are found no buildings neither population exists. Yet, there is the main road across the path of the toxic cloud in the downwind direction. As for 1000 ppm concentration, 125 people are affected at the daytime and 11 personnel who work at the night time. This quantity is the same as the affected population in the 0° wind direction. Based on this study, it can be concluded that most of the population exposed to toxic clouds is caused by the northeast wind blowing from the source compared to the north direction. There are a number of new and ongoing developments in the southwest of the WTP. It is necessary to focus on the results obtained from the consequence analysis to reduce the potential risk and danger in the water the treatment plant, which stored more than 60 MT of chlorine to disinfect water and support on municipal water supplies to the community.

5.0 CONCLUSION

The conclusion can be drawn from this research study by applying the Consequence Modelling to Potential Major Hazard Accident of Chlorine Gas Leakage in the Water Treatment Plant. The loss of containment of chlorine at the Water Treatment Plant has been investigated and simulate using consequence analysis package software PHAST 8.11. The release of toxic gases into the surrounding environment could cause a hazard and severe damages.

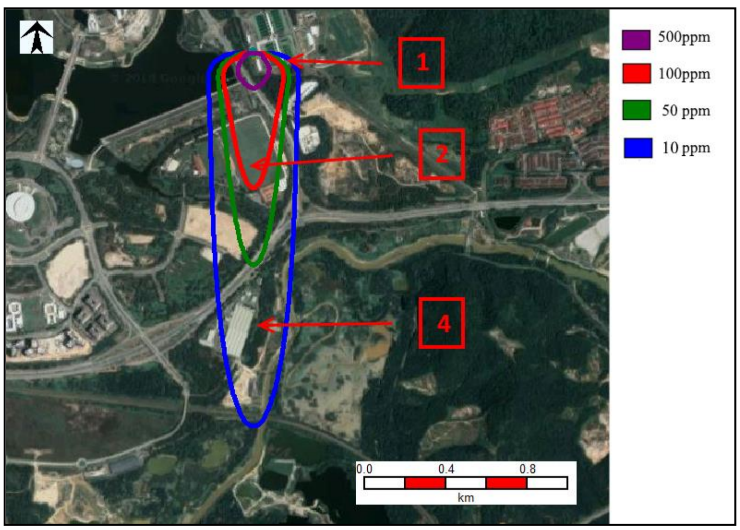

Figure 6 Affected Area From 0° Wind Direction for Worst Scenario

Based on the study it has been identified that the worst-case scenario is the catastrophic event of chlorine drum rupture, which can cause instantaneous release 930kg of liquid chlorine at the chlorine storage room. In general, the concentration of chlorine in the downwind path deem to cause fatality. However, anyone who has not been exposed to an attention level that could affect their health should proceed to escape in a safe area. The assembly point of the water treatment plant should be located in a safe area. It is assumed that people can survive and escape when exposed to toxic concentrations below 1000 ppm and yet fatality is assumed to be exposed to a higher concentration value.

Based on the PHAST modelling, it is proven with the evidence that higher emission rates cause the expansion of toxic cloud coverage. This can be observed by comparing the size and location of the ruptures with a similar chlorine mass of 930 kg, an operating pressure of 8 bar, and a wind speed of 2m/s. By referring to the findings, the catastrophic fracture at the atmospheric, stability F shows the longest downwind distance when the IDHL value is at 10 ppm, the distance of 3.2 km, which may affect 7677 people corresponding to the wind direction of the northeast (45°).

As a conclusion, it would be an ideal approach to perform consequence modelling using PHAST software as a method to indicate potential Major Hazard Accident of chlorine gas and evaluate the distribution of chlorine gas at off-site to detect over various leak scenarios. A gas detection system is an important safety system which can interface with several other safety systems and it is able to address leaks before they become a disaster.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my parents for their constant prayers for my success, my wife for her understanding and sacrifice, my three children who inspired me and a special thanks to my supervisor Dr. Hamdan for his guidance and encouragement in completing this paper and thesis.

REFERENCES

Christou M. Analysis and control of major accidents from the intermediate temporary storage of dangerous substances in marshalling yards and port areas. Journal of Loss Prevention in the Process Industries 1999;12:109–119.

Department of Occupational Safety and Health Malaysia (2018) Slide presentation of Major Hazard to Singapore delegate.

DNV, 2018. https://www.dnvgl.com/services/process-hazard-analysis-software-phast-1675?utm_campaign=plant_phast_safeti&utm_source=google&utm_medium=cpc&gclid=Cj0KCQiAi57gBRDqARIsABhDSMp9EL_4b2WYQ4MruSDfKD25yODOFdKQk7V5iXYYRIPwLO8F_UXH7gaAuVEEALw_wcB

Drogaris G. Learning from major accidents involving dangerous substances. Safety Science 993;16:89–113.

Iyuke, S. E., Fakhru'l-Razi, A., Liew, A. G., & Nasir, M. K. (2004). Offsite consequence analysis of liquefied chlorine gas spill at a water treatment plant in Malaysia. International Journal of Environmental Studies, 61(3), 293–305. https://doi.org/10.1080/0020723032000203286

Jimmy Goh. (2017). Gas leak at KB Water Dept | Daily Express Online, Sabah, Malaysia. Retrieved December 14, 2018, from http://www.dailyexpress.com.my/news.cfm?NewsID=118977

Law, W. P., Erain, N., Ramli, N. I., & Gimbun, J. (2019). Assessment of chlorine leak dispersion around Gebeng industrial area and potential evacuation route. Atmospheric Research, 216(April 2018), 117–129. https://doi.org/10.1016/j.atmosres.2018.10.003

MWA. (2016). Sungai Semenyih Water Treatment Plant. Water Malaysia, (31), 25.

Oxychem, Material Safety Data Sheet, Oxychem, Dallas, Texas, USA, 2003.

Paul, R., & Mondal, A. (2014). Dispersion Modeling of Accidental Release of Chlorine Gas, (December), 29–30.

Safakar, M., Syafiie, S., & Yunus, R. (2016). CFD analysis of indoor chlorine gas dispersion storage: Temperatures, wind velocities and ventilation effects studies. ASEAN Journal of Chemical Engineering, 16(1), 1219–1222.

White, C. W., & Martin, J. G. (2010). Chlorine gas inhalation: human clinical evidence of toxicity and experience in animal models. Proceedings of the American Thoracic Society, 7(4), 257–63. https://doi.org/10.1513/pats.201001-008SM