Risk Assessment and Management for CO_2 Transportation Pipelines

by

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Dissertation submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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Approved by,

(Dr. Risza bt. Rusli)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
July 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and the work contained herein have not been undertaken or done by specified sources or persons.

NGUYEN KIM CHI

ABSTRACT

Carbon Capture and Storage (CCS) technologies are still in its initial stage in Malaysia so the existence of CO_2 pipeline network relatively small which leads to the unadequate understanding of risk associated with CO_2 release. In this project, risk-based approaches are used to evaluate the possible risks may occur when carbon dioxide (CO_2) is transported in pipelines from its source to desired destinations. There are two case studies are presented. The first one is the risk analysis of CO_2 pipeline network onshore and the second one is about the comparison study of risk between the CO_2 and natural gas pipeline in order to raise awareness of the order of magnitude of CO_2 risk.

It is found that CO_2 pipeline may represent significant risks once a large amount of CO_2 is released close to dense population. This project also proposes some mitigation methods of the relevant risks regarding the current practices.

ACKNOWLEDGEMENT

I would like to express my gratitude to all those who gave us the possibility to complete this report. Especially, I would like to send my sincerest appreciation to my supervisor, Dr. Risza bt Rusli for giving to me a chance to do this interesting topic, for her whole-hearted guidance, encouragement, cooperation and constructive criticism throughout the duration of the project.

I also take this opportunity to thank all the lecturers who have directly or indirectly involved in this project. I pay my respects and love to my family for their love and encouragement throughout my studying. Last but not the least I express my thanks to my friends for their cooperation and support.

Hopefully, the knowledge and findings gained from this project will be essential for us in the future.

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ABBREVIATIONS AND NOMENCLATURES

CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
DGC	Dakota Gasification Company
DNV	Det Norske Veritas
DTL	Dangerous Toxic Load
EOR	Enhanced Oil Recovery
GCCSI	Global Carbon Capture and Storage Institute
GHG	Greenhouse Gases
IEA	International Energy Agency
OPS	Office of Pipeline Safety
PSR	Pipeline Safety Regulation
IPCC	Intergovernmental Panel on Climate Change
UDM	Unified Dispersion Model
QRA	Quantitative Risk Analysis
LOPA	Layer of Protection Analysis
MAH	Major Accident Hazard
MAOP	Maximum Allowable Operating Pressure

CHAPTER 1

INTRODUCTION

1.1. Background

Greenhouse gases have been one of the main sources caused global warming in which carbon dioxide (CO_2) is the most critical component so there is an urgent demand to reduce CO_2 emission to the atmosphere. Currently Carbon dioxide Capture and Storage (CCS) technology is considered as the most effective method to reduce CO_2 exhaust. Carbon capture technologies can potentially remove 80 – 95% of CO_2 emitted from an electrical power plant or other industrial sources. CCS consists of three parts which are capture, transportation and sequestration in geological formations as in **Figure 1.1**.

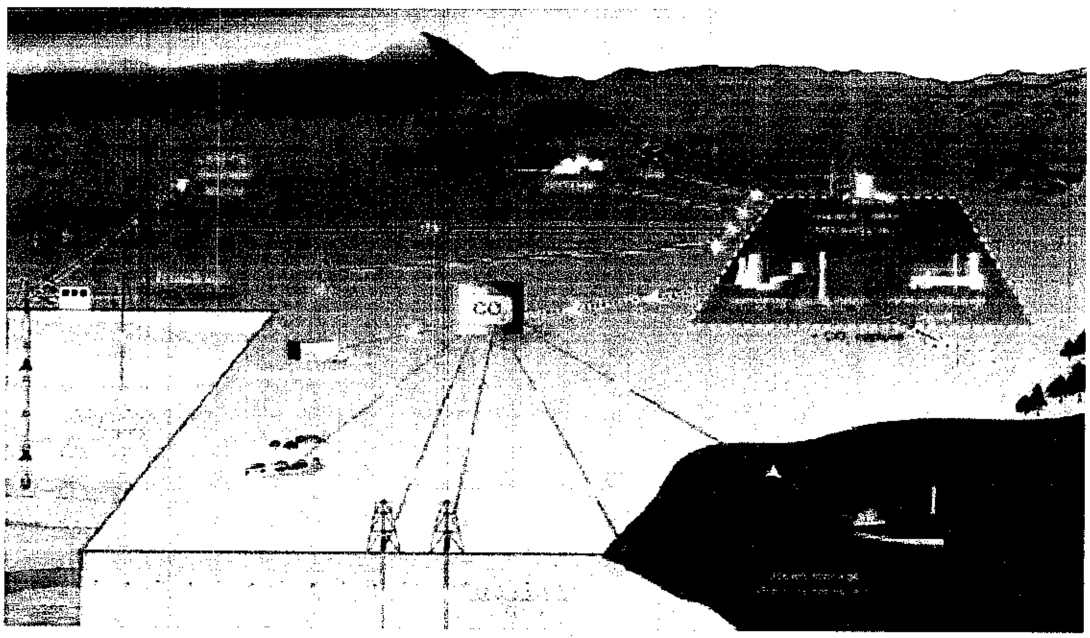

Figure 1.1: *Schematic diagram of possible CCS systems (Courtesy of CO_2CRC)*

Due to its effectiveness, CCS attracts attention of many countries all over the world and becomes the target research. Below is the list of four largest projects are in operation which are considered as samples for other CCS-related activities. Please refer **Appendix A** for more details about these projects.

Table 1.1: *The largest scale CCS projects worldwide (2009)*

Project	Location	Capacity (Mt CO_2/year)	Starting year
The Sleipner CCS project	Norway	1	1996
The IEA GHG Weyburn-Midale CO_2 monitoring and storage Weyburn project	Canada	1.6	2000
The In Salah CCS project	Algeria	0.8	2004
The SnØhvit CCS project	Norway	0.7	2008

Nevertheless, the research programs are mainly focus on the capture technologies, on how to remove CO_2 efficiently and economically which results in unintentionally leaving out the vital component, CO_2 transportation since many oil and gas fields are in remote regions which is required certain carrier network to bring CO_2 to target destinations.

The goal of this project is to investigate any potential risk related to CO_2 transportation pipeline on land from the source to the desired destination for CCS purpose.

1.2. Problem Statement

Parfomak and Folge (2007) states the incidents were caused by CO_2 are relatively small in comparison with by natural gas. It was proven by the historical data recorded by Office of Pipeline Safety (OPS), in the United States, records that there were 12 leaks from CO_2 pipelines reported from 1986 through 2006 — none resulting in injuries to people. In contrast, there were 5,610 accidents causing 107 fatalities and 520 injuries related to natural gas and hazardous liquids (excluding CO_2) pipelines during the same period.

However, it cannot be concluded that the risk of CO_2 is insignificant and can be negligible since the CO_2 pipelines possess less than 1% of total natural gas and hazardous liquid pipelines (5,000km CO_2 pipeline in comparison with 490,850km natural gas pipeline in United State only). And one reason carbon dioxide pipeline accidents are rare is because we do not really have that many CO_2 pipelines in use. Accidents related to CO_2 will likely increase once the number of pipelines grows. Moreover, the CO_2 pipelines currently travel through remote areas only.

In fact, exposure to CO_2 gas, as for other asphyxiates, may cause rapid circulatory insufficiency, coma, and death. History verified CO_2 fatal side by catastrophe occurred in 1986 in Cameroon, when a cloud of naturally-occurring CO_2 spontaneously released from Lake Nyos killed 1,700 people and 3,500 livestock in nearby villages.

Undoubtedly, once the CCS is widely implemented, the number of CO_2 pipelines will increase dramatically and get closer to the population which implies the evident risk of CO_2 incidents to environment as well as residence.

In Malaysia, the CCS technology is still in its budding stage whereby in the year 1999, the first commercial plant at 200 tCO2/day recovery from a flue gas has been in operation for urea production (equivalent to the emission from a 10MWt coal-fired power plant).

In 2009, Malaysia officially joined the global CCS Institute (GCCSI), Australia with the hopes of promoting the CCS technology in Malaysia to mitigate its carbon footprint. Apart from environmental protection, CCS is also a green economic driver and has the potential to nurture a whole new industry in green technology and contribute to Malaysia's economic growth. New job opportunities will also be created in Malaysia through CCS.

1.3. Objectives and Scope of Study

- To evaluate the risks associated with CO_2 pipelines release;
- To raise awareness to industrial and community by comparing the degree of risk between CO_2 and natural gas;
- To recommend suitable mitigation methods to reduce/eliminate its potential risks;

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1. Review of incidents (accidents/deaths) caused by carbon dioxide

According to National Response Center's database, a total of 13 accidents related to CO_2 pipelines occurred in the US between 1986 and 2008. Of these 13 accidents, none had reported human injuries or fatalities, compared to the more than 5,000 accidents and 107 fatalities in the same period caused by natural gas and hazardous liquid pipelines (Parfomak and Folger 2007). Below is the detail of 13 CO_2-accidents:

Table 2.1: *Detailed report on CO2 pipeline accidents between 1986 and 2008 (URS, 2009)*

Date of Incident	Description	Cause	Location	Suspected Responsible Party	Medium Affected
02/27/1994	Hazardous Liquid Pipeline/Gasket Failure	1	Texas	Inron Liquids Pipeline Co.	Air
04/15/1994	8in. Pipeline/External Corrosion	1	Oklahoma	Arco Permian	Air
06/15/1998	12in. CO_2 pipeline/DOT Regulated/semi-truck ran into a structure	2	Oklahoma	Transpectco	Air
11/19/2000	Strong odor reported from private citizen and confirmed release from pipeline 12in. below ground	1	North Dakota	Dakota Gasification Co.	Air
01/13/2001	8in. transportation line discovered leaking into the atmosphere due to an unknown	3	North Dakota	Dakota Gasification Co.	Air

	cause				
02/25/2001	14in. distribution line leaked CO_2 and H_2S into the atmosphere	1	Texas	Borger CO_2 Pipeline LLC	Air
03/07/2002	Third-party company contracted a backhoe and hit a carbon dioxide underground pipeline during digging.	2	Oklahoma		Air
02/25/2003	8in. transmission pipeline failed due to corrosion and caused material to release	1	Texas	Chaparral Energy	Air
11/14/2003	Release of CO_2 due to valve failure	1	Mississippi	Denbury Resources	Air
10/14/2004	A leak was found on the CRC pipeline releasing CO_2	4	Texas	Kinder Morgan CO2 Co.	Air
09/22/2006	A magnetic flux leakage (MFL) pig was struck in a pipeline and when efforts were made to remove the object, the line developed a crack and discharged CO_2 in to the air.	1	North Dakota	Dakota Gasification Co.	Air
01/09/2007	CO_2 was released to the atmosphere from a 20in. underground pipeline.	3	Mississippi	Denbury Onshore LLC	Air
03/15/2007	An ice mound formed on a line used for liquid CO_2 injection from Texas to Oklahoma due to a pinhole leak.	1	Texas	Chaparral Energy	Other

1. Equipment failure 2. Operator error 3. Unknown 4. Under investigation

Based on the very little CO_2 incidents reported, Duncan et al. (2009) has declared that the CO_2 transportation and injection associated with enhanced oil recovery (CO_2-EOR) has an excellent safety record. However, those historical data will not applicable anymore when the number of CO_2 pipeline increases once the CCS is widely employed. Those historical numbers also implicate that the current practices involved CO_2 is very limited. As a result, Connolly (2007) has stated that *"There is relatively little experience worldwide in managing risks associated with CO_2, compared with oil and gas"*.

2.2. Literature review

The risk related to CO_2 becomes an evident concern as the CCS activities are increasing rapidly and plays an important role in climate change reduction. This concern has been studied and mentioned by many group of scientists worldwide. Most of them agreed that the potential risk of CO_2 cannot be neglected and overlooked, careful and detail study should be carried out to estimate any potential risk.

Barrie et al. (2004) suggest that before doing a quantitative analysis comparing the risks associated with CO_2 injection and transportation with natural gas, it is desirable to get an improved understanding of CO_2-EOR industries safety record.

At the present, almost CO_2 is transported through remote areas so that its impacts are not clearly noticeable. With the deployment of CCS projects in some regions as Northwest Europe, a huge CO_2 pipeline networks will be closer to dense population. It will result in the potential for leakage from a pipeline in close proximity to residential areas to cause a Major Accident Hazard (MAH) due to the toxicity and asphyxiant of CO_2 (Connolly, 2007), which incidentally, is currently not defined as a dangerous fluid under PSR.

Moonis and Wilday (2008) recommended further investigation into the possibility of including CO_2 as a dangerous fluid under Pipeline Safety Regulation (PSR) since CO_2 is not currently regulated as a dangerous fluid. This work suggested that in terms of hazard range and hazard footprint area, CO_2 should be categorized as a dangerous substance but further analysis would be required in terms of risk. McGillivray and Wilday (2009) continued Moonis and Wilday's work and concluded that CO_2 used for

CCS has sufficient toxicity to be regulated as a dangerous fluid under the Pipeline Safety Regulation.

In case a substantial amount of CO_2 could be released and the concentrations of CO_2 in the air were to surpass 8%, the effects would be lethal to anybody nearby. Although the regulation for the structural integrity of CO_2 pipeline is about 30 - 36 times (capacity of 365 MPa) that of operational pressure, 9.6 MPa, there are still risks associated with transporting huge amounts of CO2 (Balat, 2009).

According to IPCC Special Report on Carbon Dioxide Capture and Storage from Cambridge University, a sudden and large release of CO_2 which has concentration greater than 7–10% by volume in air would pose immediate dangers to human life and health. In such manner, this certain report suggests that pipeline transport of CO_2 through populated areas requires attention to route selection, overpressure protection, leak detection and other design factors.

2.3. Risk assessment techniques

Risk assessment comprises of incident identification and consequence analysis. Incident identification describes how an incident occurs. It frequently includes an analysis of the probabilities. Consequence estimation is to determine the potential for damage and injury from identified incidents.

In order to determine the actual risk of a chemical process or plant, some methods are employed such as qualitative risk analysis, quantitative risk analysis (QRA) or layer of protection analysis (LOPA), where the QRA and LOPA are the most common techniques.

In this project, QRA is chosen due to its advantage as following:

- QRA can be applied at any stage in the life of a facility. Maximum benefits result when QRA is applied at the beginning (conceptual and design stages) of a project and maintained throughout its life.
- QRA provides a quantitative method to evaluate risk and to identify areas for cost-effective risk reduction.

- QRA is used to help evaluate potential risks where qualitative methods cannot provide adequate understanding of the risks and more information is needed for risk management. It can also be used to evaluate alternative risk reduction strategies.

2.4. Quantitative risk assessment (QRA)

2.4.1. QRA procedure

QRA component techniques are flexible and can be applied selectively, in various orders. The general procedure is outlined in **Figure 2.1** below; it has been designed in such a way to shorten the time and effort needed to achieve the desired results.

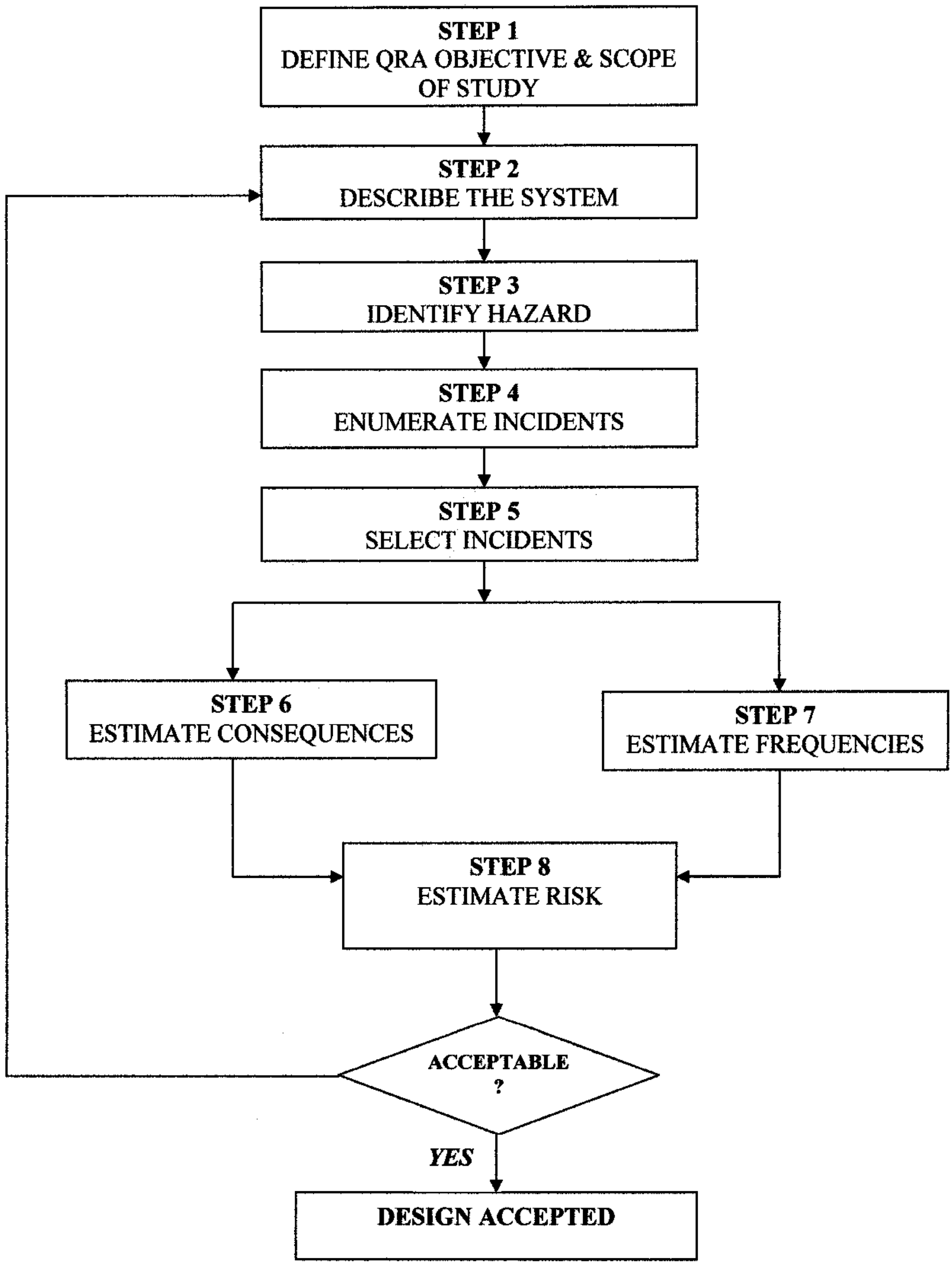

Figure 2.1: *The QRA procedure*

2.4.2. QRA database

List of recommended input data for a successful QRA is shown in **Figure 2.2**.

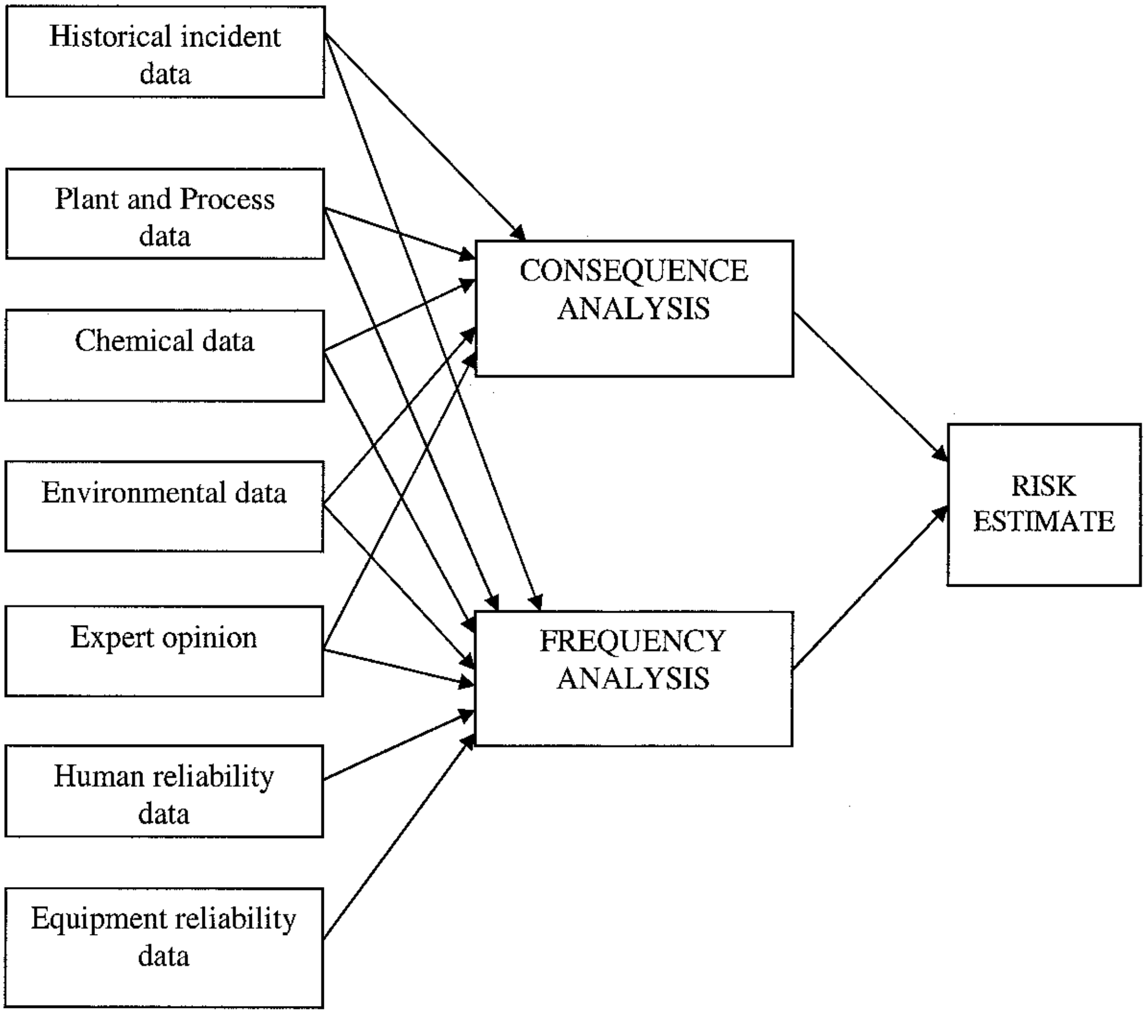

Figure 2.2: *QRA database (CPQRA, 2000)*

Chapter 3

METHODOLOGY/PROJECT WORK

3.1. CO_2 characteristics

3.1.1. CO_2 is non-flammable

Based on the physical properties below, carbon dioxide is not classified as a flammable substance so that in QRA the fire and explosion probabilities will be eliminated.

Appearance: colourless odourless gas	Vapour density: 1.53 (air = 1)
Boiling point: -78°C (sublimes)	Density (g cm^{-3}): 1.101 at -37°C
Critical temperature: 31.6°C	Critical pressure: 73.8 atm.
Flash point: none	Explosion limits: none
Auto-ignition temperature: none	Water solubility: slight

3.1.2. CO_2 is an asphyxiant

Gas encyclopedia states that workers briefly exposed to very high concentrations showed damage to the retina, sensitivity to light (photophobia), abnormal eye movements, constriction of visual fields, and enlargement of blind spots. Several deaths have been attributed to exposure to concentrations greater than 20%. Effects of CO_2 can become more pronounced upon physical exertion, such as heavy work. Please refer **Appendix C** for more information about effect of CO_2 to human health.

Due to this fact, in the proposed QRA, the toxicity of CO_2 will be evaluated with the worst setup scenarios in order to estimate how it affects the community.

3.1.3. CO_2 is heavier than air

Since the vapor density of CO_2 is much heavier than of air, the normal dispersion model such as Gaussian dispersion models do not accurately stimulate dense gas as CO_2 discharges. Hence, we may use dense mathematical models such as Computational

Fluid Dynamics (CFD) or dimensional analysis as Britter and Quaid (1988) model for a sophisticated estimation.

3.1.4. CO_2 is corrosive

CO_2 corrosion results from the attack of carbonic acid gases, which dissolve in water on the pipe walls and other equipment. The resulting corrosion reaction is as follows:

$$H_2CO_3 + Fe \rightarrow Fe^{2+} + CO_3^{2-} + H_2$$

The above corrosion reaction can result in the formation of stable corrosion product films ($FeCO_3$, Fe_2O_3, Fe_3O_4) which may reduce corrosion rates over time. The formation and stabilization of the corrosion product films are temperature and flow rate dependent.

3.2. Dense gas dispersion

When a gas whose density is greater than the density of the ambient air is released, it initially behaves completely different from a neutrally buoyant gas. The heavy gas will first slump or sink, because it is heavier than the surrounding air. As the gas cloud moves downwind, gravity makes it spread; this can cause some of the vapor to travel upwind of its release point as **Figure 3.1**. Farther downwind, as the cloud becomes more diluted and its density approaches that of air, it begins behaving like a neutrally buoyant gas. This takes place when the concentration of heavy gas in the surrounding air drops below about 1 percent (10,000 parts per million). For many small releases, this will occur in the first few meters. For large releases, this may happen much further downwind.

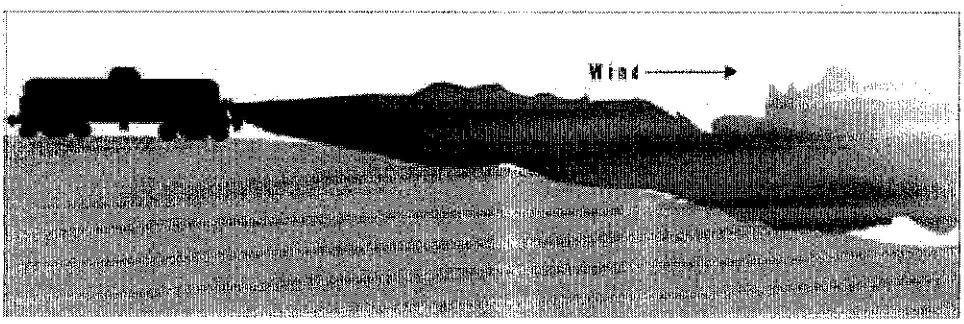

Figure 3.1: *Heavy gas dispersion*

There are different methods to predict the dense gas dispersion behavior, in this project; a modeling approach, PHAST Risk version 6.53, is used due to its capability of heavy gas calculation and its availability in Simulation lab of UTP's Chemical department. The principles of PHAST Risk version 6.53 was described in the following section.

3.2.1. Heavy-gas Entrainment

Dense gas and aerosol clouds are known to suppress dispersion below that obtained by ambient turbulence (passive dispersion) in the surrounding atmosphere. This phenomenon is described in the UDM (Unified Dispersion Model) by making the dominant (top) entrainment velocity depend on the layer Richardson number, an indicator of cloud buoyancy.

3.2.2. Heavy-gas entrainment for instantaneous plume

For an instantaneous release the heavy gas entrainment rate E_{hvy} (kg/s) is given by:

$$E_{hvy} = \left[\frac{W_{gnd}}{R_y}\right] \left\{u_{side} A_{side} + u_{top} A_{top}\right\} \rho_a \qquad (1)$$

where u_{side} is the horizontal air-entrainment velocity through the plume side-area A_{side}, u_{top} is the vertical air-entrainment velocity through the plume top-area A_{top}. The side area A_{side} and the top area A_{top} correspond to an instantaneous plume of cylindrical shape with height $H_{eff}(1+h_d)$ and radius W_{eff}:

$$A_{side} = 2\pi W_{eff} H_{eff} (1 + h_d) , \qquad A_{top} = \pi W_{eff}^2 \qquad (2)$$

Note that the term $[W_{gnd}/R_y]$ in equation above ensures that the heavy-gas entrainment is not applied for an elevated plume, is phased in during touching down and phased out during lifting-off.

3.2.3. Heavy-gas entrainment for continuous plume

For a continuous cloud the heavy gas entrainment rate E_{hvy} (kg per second per unit of downwind length of the plume) at a given downwind distance is given by:

$$E_{hvy} = \left[\frac{W_{gnd}}{R_y}\right]\left\{u_{side}H_{eff}(1+h_d) + u_{top}(2W_{eff})\right\}\rho_a \qquad (3)$$

where the cloud width and height are chosen to correspond to the effective cloud width $2W_{eff}$ and the effective cloud height $H_{eff}(1+h_d)$.

3.2.4. Side Entrainment Velocity

The side surface entrainment velocity is taken to be proportional to the spread rate or

$$u_{side} = \gamma\frac{dW_{eff}}{dt} \qquad (4)$$

where γ is an edge-entrainment coefficient. For a continuous release the side entrainment is ignored [γ =0].

3.2.5. Top entrainment velocity

The top surface entrainment generally dominates over the side entrainment except very near the source. The top surface entrainment velocity u_{top} is formulated to have the same functionality as the vertical dispersion coefficient, K_z. That is, for a vertical wind profile in a power law form:

$$u_a(z) = u_a(z_{ref})\left(\frac{z}{z_{ref}}\right)^p \qquad (5)$$

K_z satisfies the two-dimensional dispersion relationship:

$$u_a(z)\frac{\partial c}{\partial x}=\frac{\partial}{\partial z}\left(K_z\frac{\partial c}{\partial z}\right) \quad (6)$$

with a functional form given by:

$$K_z=\frac{\kappa u_* z}{\Phi(Ri_*)} \quad (7)$$

where κ =0.4 is the Von Karman constant, and Φ the entrainment function of the Richardson number Ri_*.

To retain this form, the top-entrainment velocity u_{top} is defined by:

$$u_{top}=\frac{\kappa u_*}{\Phi(Ri_*)} \quad (8)$$

3.2.6. Richardson number, entrainment function

The layer Richardson Number is defined by:

$$Ri_*=\frac{g\left[\rho_{cld}-\rho_a(z=z_{cld})\right]H_{eff}(1+h_d)}{\rho_a u_*^2} \quad (9)$$

where z_{cld} is the centre-line height.

The entrainment function $\Phi(Ri_*)$ represents the phenomenon that heavy gases ($Ri_*>0$) tend to suppress turbulent mixing within a cloud below that of ambient turbulence. On the other hand, positively buoyant clouds ($Ri_*<0$) lifting off are known to have enhanced turbulence. The entrainment function is given as follows:

$$\Phi(Ri_*) = \frac{1}{1+0.65\,|Ri_*|^{0.6}} \quad Ri_* < 0$$
$$= 1 \quad 0 < Ri_* < 2.3625$$
$$= (1+0.8\,Ri_*)^{1/2}/1.7 \quad 2.3635 < Ri_* < 14.72$$
$$= Ri_*/7 \quad Ri_* > 14.72 \qquad (10)$$

For Ri* < 0, the above formula is taken from the correlation adopted by Havens and Spicer for the model DEGADIS.

For Ri* > 0, the formulation adopted by Witlox (1989) is adopted. The latter formulation is based on an entrainment function proposed by Britter (1988). It is close to those adopted by DEGADIS and the HGSYSTEM model AEROPLUME. In addition the above function does accurately fit experimental data for a wide range of Richardson numbers.

3.3. Risk determination

3.3.1. Rate of Death

This is the expected number of fatalities on an annual basis, calculated as follows:

$$R_d = \sum_{All\ edfs} \sum_{o} F_{edf,o} N_{edf|o} \qquad (11)$$

where $F_{edf,o}$ is the frequency of a given outcome for a given Model, and $N_{edf,o}$ is the number of fatalities associated with that outcome.

3.3.2. Risk Integral (based on Aversion Integral = 1.2)

$$RI_{ai} = \sum_{All\ edfs} \sum_{o} F_{edf,o} N^{ai}_{edf|o} \qquad (12)$$

where $F_{edf,o}$ is the frequency of a given outcome for a given Model, $N_{edf,o}$ is the number of fatalities associated with that outcome, and *ai* is an aversion index, set to 1.2 for this calculation.

3.3.3. Risk Integral (Land Use)

$$RI_{LUP} = \sum_{All\ edfs} \sum_{o} F_{edf,o} (N_{edf|o} + N^2_{edf|o}) / 2 \qquad (13)$$

where $F_{edf,o}$ is the frequency of a given outcome for a given Model, and $N_{edf,o}$ is the number of fatalities associated with that outcome.

3.3.4. Potential Loss of Life (Individual Risk Based)

$$PLL_I = \sum_{All\ x,y} N_{x,y} IR_{Tot,x,y} \qquad (14)$$

where $N_{x,y}$ is the population in a given cell in the grid used for the risk calculations, and $IR_{Tot,x,y}$ is the level of individual risk calculated for the centre of that cell.

3.3.5. Potential Loss of Life (Societal Risk Based)

This is based on the FN Curve Data as follows:

$$PLL_S = \sum_{N=1}^{\infty} N \times F(N) \qquad (15)$$

where N is the lower limit of one of the ranges of fatalities used in the table of FN Curve Data and $F(N)$ is the frequency of fatalities in that range.

The value for this measure will be lower than the value for the **Rate of Death** since the **Rate of Death** is calculated with the exact number of fatalities for each outcome, whereas this measure is calculated with the lower limit for the range.

3.4. Specific CO_2-QRA

Figure 3.2 below shows the QRA model which is specific for CO_2 pipelines only.

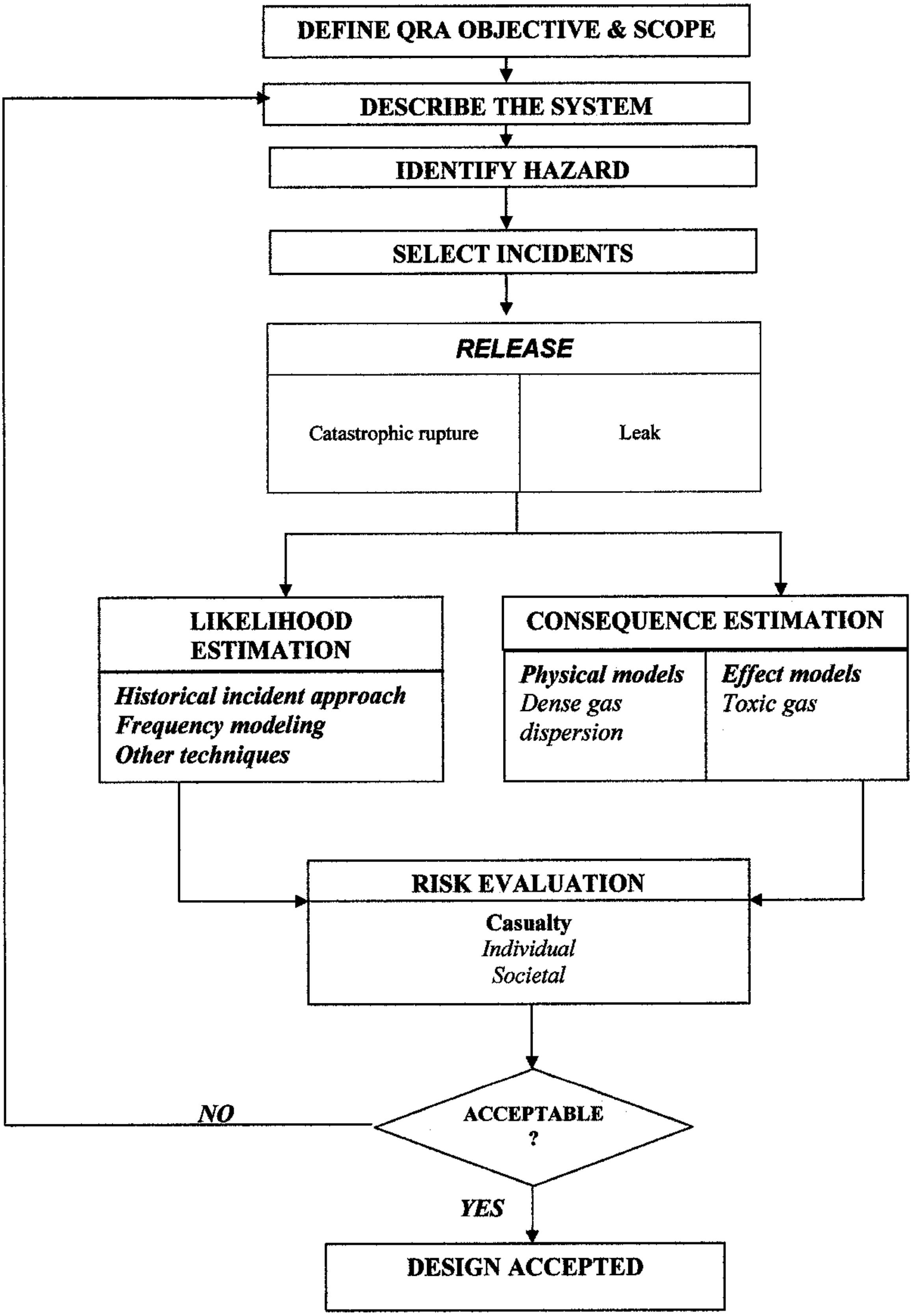

Figure 3.2: *Specific CO_2 QRA*

3.5. Software used

There are two proposed software to do the dispersion and risk stimulation for CO_2 release.

- **PHAST Risk 6.53** (Software for the Assessment of Flammable, Explosive and Toxic Impact): commercial consequence modeling software developed by DNV (Det Norske Veritas). It is designed to perform all the analytical, data processing and results presentation elements of a QRA within a structured framework. Phast Risk analyses complex consequences from accident scenarios, taking account of local population and weather conditions, to quantify the risks associated with the release of hazardous chemicals.
- **Excel**

3.6. Software validation

In this work, Phast risk version 6.53 was used to evaluate the release consequences altogether with risks. Unfortunately, in Phast risk v6.53 database, CO_2 is considered as inert material as in **Figure 3.3** which means there is no risk associated with this particular chemical.

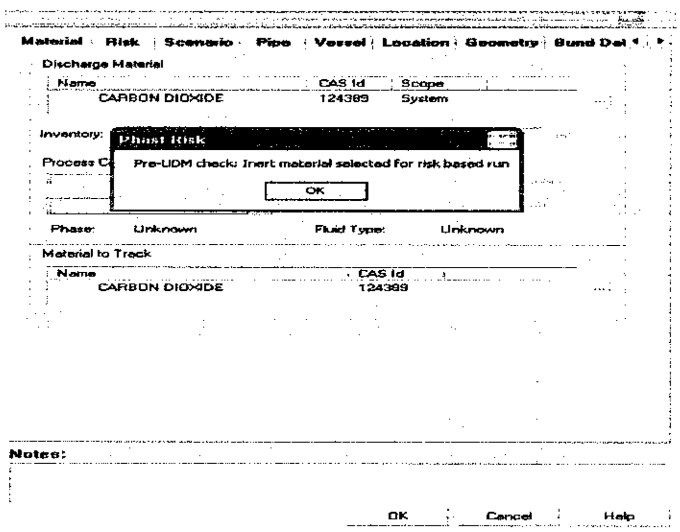

Figure 3.3: *CO_2 is an inert chemical in Phast risk database*

In order to overcome this problem, the intensive literature review was carried out. After doing the comparison with other toxic chemical in Phast risk and McGillivray & J.Wilday (2009), some default settings were changed as in **Table 4.5**.

Table 3.1: *Changes made in PHAST risk*

	Default value	Changed value
Droplet evaporation	0.001	1E-6
Droplet thermodynamic model	Rainout & Non equilibrium	Rainout & Equilibrium
Toxic paramaters	x-direction: 25m y-direction: 2.5m	x-direction: 1m y-direction: 0.1m height for calculation of effect: 1m

The comparison on consequences with other available works was done to make sure the changed parameters is really work for CO_2 case.

The chosen one is carried out by J. Koornneef et al. In their work, two commercial software packages developed by TNO: EFFECTS and RISKCURVES are used.

Table 3.2: *Consequences comparison between Phast risk v6.53 and J. Koornneef et al.*

Release type	Consequences	Phast risk v6.53	J. Koornneef et al.	Remark
Instantaneous	Maximum conc. (ppm)	255,300	1,040,000	Catastrophic rupture
	Distance downwind (m)	20-25	104	
Horizontal	Maximum conc. (ppm)	50,090	50,000	Leak
	Distance downwind (m)	15-22	105	

From **Table 3.2**, there was a huge deviation between the Phast risk and J. Koornneef et al. for instantaneous release but for the horizontal release case these both models gave almost the same value.

These two models give different results which do not indicate that one model or methodology is necessarily better than any other but that these models are formulated differently. Even when two models have the same basic mathematical formulation, different results may produced since different sets of data may have been used to calibrate them. One problem is that it is not practical to run experiments under all combinations of different chemicals, different release rates, different wind speeds, different surface roughness conditions, different atmospheric stabilities, and look at different concentration averaging times. What is done is to develop empirical expressions or algorithms from a limited data set and assume that the relationships hold true for conditions not tested.

However, in terms of risk, both Phast risk v6.53 and J. Koornneef et al. have risk contour from $1x10^{-5}$ to $1x10^{-9}$/average year. Moreover, Phast risk produced higher consequences for weather stability class F (2m/s) than class B (2m/s). This point is proven by McGillivray & J. Wilday (2009) and J. Koornneef, et al. (2010).

Due to those facts, it could be concluded that Phast risk v6.53 after changing certain default data can work well for CO_2 release especially leak scenarios.

CHAPTER 4

CASE STUDY 1: CO_2 RISK ANALYSIS

4.1. The Great Plains Synfuels Plant, Dakota, USA

Dakota Gasification Company (DGC) is a wholly owned subsidiary of Basin Electric Power Cooperative and a North Dakota corporation, owns and operates the Great Plains Synfuels Plant, which is located near Beulah, North Dakota.

DGC sells the compressed carbon dioxide to two companies in Saskatchewan: EnCana Oil & Gas Partnership and Apache Canada, Ltd., which use this carbon dioxide for enhanced oil recovery (EOR) at their Weyburn oil field and Midale oil field, respectively. The first CO_2 was sent to Canada in October 2000.

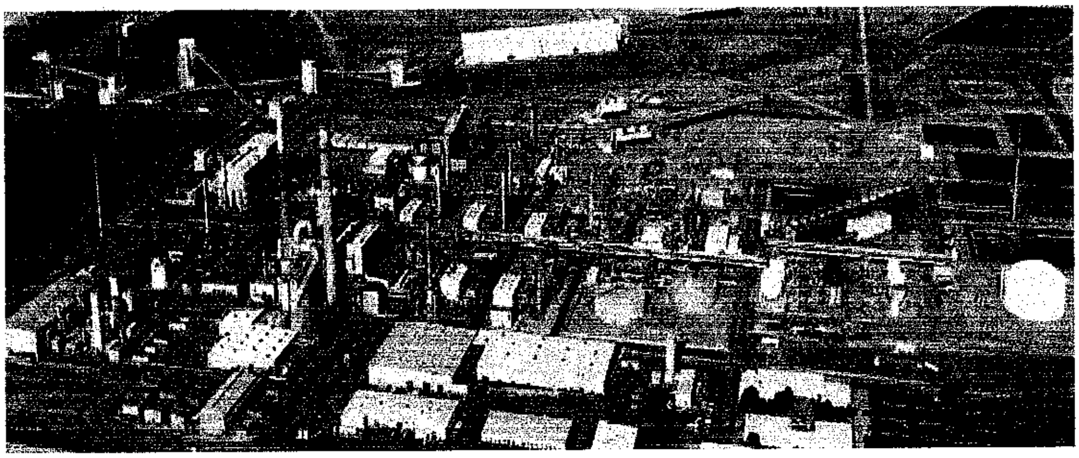

Figure 4.1: *The Great Plains Synfuels Plant*

Today, Dakota Gas exports about 152 million cubic feet per day of CO_2 to Canada – about 50 percent of the CO_2 produced when running at full rates. As of Dec. 31, 2009, Dakota Gas has captured more than 17.4 million metric tons of carbon dioxide.

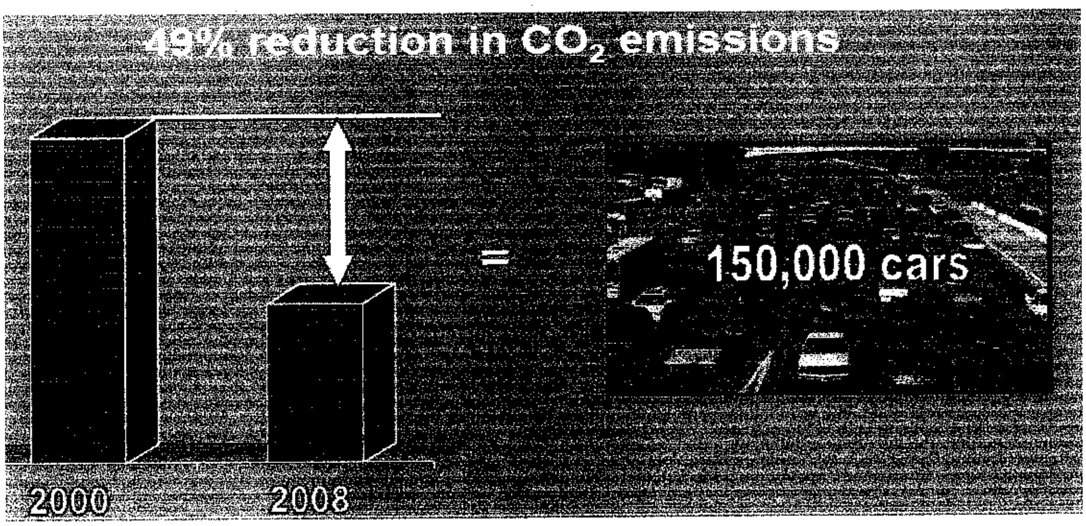

Figure 4.2: *CO_2 emission reduction at DGC's Synfuel Plant*

The Synfuels Plant's unique gasification operations and CO_2 capture and transport continue to draw worldwide attention. Visitors from Germany, China, Italy, Korea, Great Britain and Japan, the United States and other nations have toured their facilities. National media from 60 Minutes, The History Channel, and Fox News, and television reporters from London, Tokyo, and Montreal have produced reports and special programs about the plant.

The Synfuels plant is a coal gasification plant that uses a Lurgi coal gasification process to gasify lignite coal into gases and liquids. The plant consumes approximately 17,000 tons of lignite per day. When production is dedicated to synthetic gas production, the plant produces approximately 160 million standard cubic feet per day of synthetic natural gas. As byproducts, the plant produces a combination of krypton/xenon gas, liquid nitrogen, cresylic acid, phenol, ammonium sulfate and carbon dioxide. As a co-product, the plant is capable of producing up to 1,200 tons of anhydrous ammonia per day.

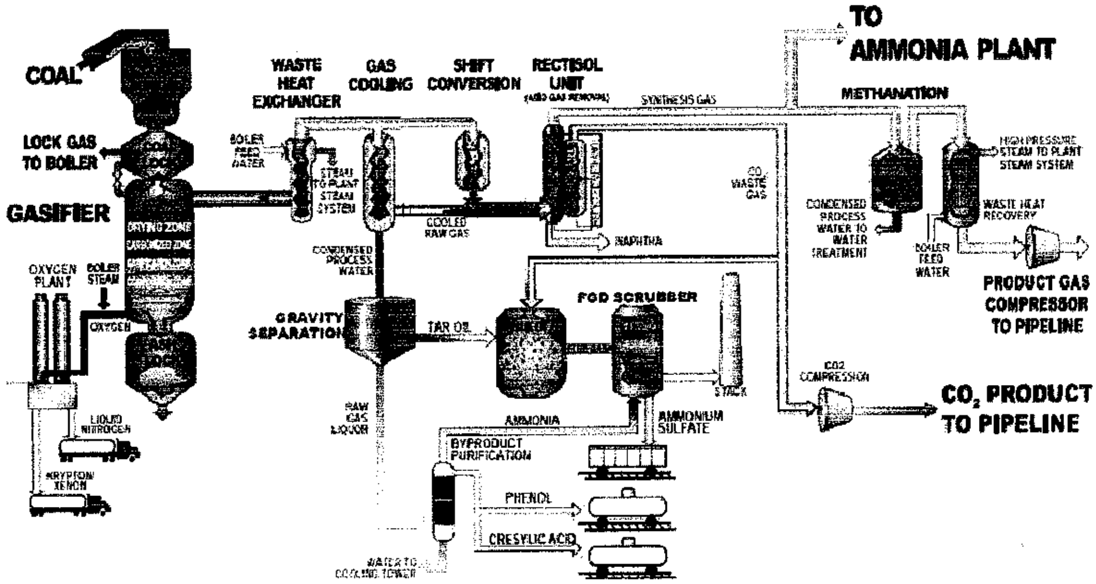

Figure 4.3: *Great Plains Synfuels Plant process flow diagram*

CO_2 pipeline routine is 204.8 miles length from the Great Plains Synfuels Plant near Beulah, North Dakota, USA to the GoodWater Unit, this is part of Cenovus Energy's Weyburn oil field in Saskatchewan, Canada. Please refer **Appendix F** for further details about Weyburn oil field.

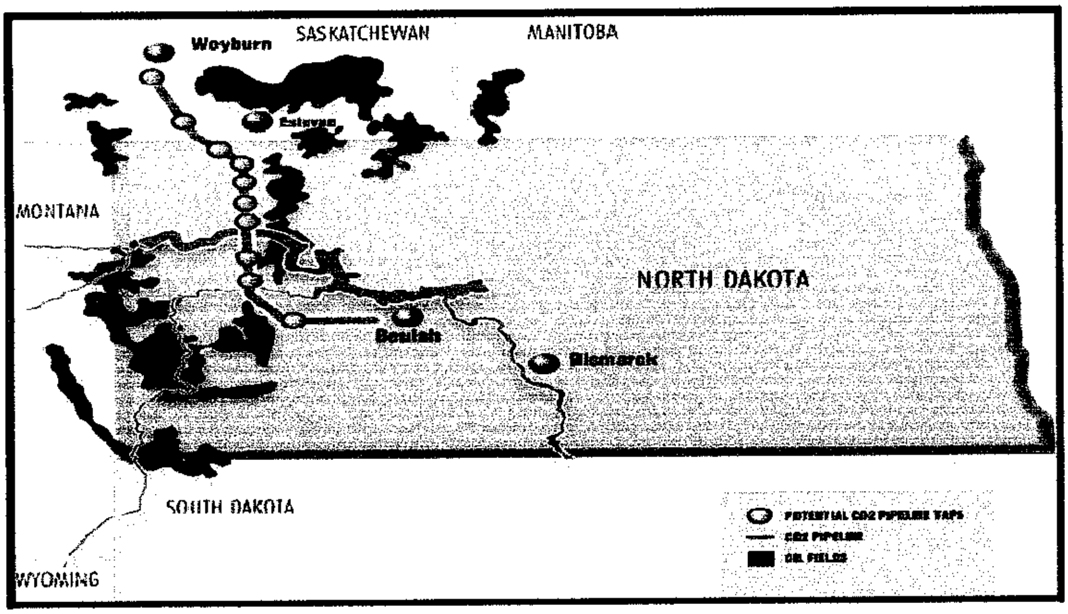

Figure 4.4: *Pipeline routine from Great Plains Synfuel Plant, Dakota to Weyburn*

Table 4.1: *Pipeline operating conditions*

Line size	Grade	MAOP (psig)	Hydro test pressure (psig)	Designed capacity (MMSCFD)
14"	X70	2700	3375	240
12.75"	X70	2964	3705	

CO_2 from other power plants is very wet and diluted with nitrogen and oxygen and requires further processing, but Dakota Gas' process results in a CO_2 stream that is very dry and 96 percent pure, so no additional processing is needed.

Table 4.2: *Composition of product CO_2*

Component	Volume Percent
Carbon Dioxide	96.8
Hydrogen Sulfide	1.1
Ethane	1.0
Methane	0.3
Other	0.8
Total	**100.00**

4.1.1. Hazards identification

When supercritical gaseous CO_2 is transported in the pipeline, there are many risks associated such as following:

- ✓ Choke: CO_2 velocity may increase along the pipeline and result in building up to a very high pressure or choking condition at a certain distance.
- ✓ Corrosion: As in **section 3.1** stated that CO_2 is a corrosive chemical so if there is a significant amount of water exist in the pipeline it may increase the corrosion rate which leads to higher failure frequencies.
- ✓ Failure due to puncture, fullbore rupture or third party (corrosion, material defects, operator errors, etc.)
- ✓ Two phase flow

- ✓ Reverse flow
- ✓ Pressure reduction failure leads to no or low flow.
- ✓ Blockage due to valve closure or solidification.

4.1.2. Select incidents

Since the historical data in **Table 2.1** shows that majority of CO_2 pipeline incidents was caused by equipments failure, corrosion and operator errors, in this project, the risk related to equipment failures was investigated through two major types of failure:

- ➢ Catastrophic rupture
- ➢ Leak

The information in **Table 2.1** on CO_2 pipeline incidents will be used to estimate the failure rate as displayed in **Table 4.3**.

Table 4.3: *Failure rates for CO_2 pipelines*

Failure Mode	Total Number of Accident Between 1986 and 2008	Percentage	Historical Failure Rate per Mile of Carbon Dioxide Pipeline per year
Equipment Failure	6	46	7.77E-05
Corrosion	2	15.5	2.70E-05
Operation Error	2	15.5	2.70E-05
Unknown	3	23	3.89E-05
Total	13	**100**	**1.69E-04**

A sensitivity analysis was performed to study the effect of operating conditions on the CO_2 releases. The details of this are shown in **Table 4.4** below.

Table 4.4: *Setup scenarios*

Scenario	**Volume (m^3)**	**Pressure (psi)**	**Temperature (°C)**	**Weather condition**	**Type**
1	1900	2700	40	F	Catastrophic rupture
2	1900	2700	40	D	

3	1900	2700	40	F	Leak (20mm)
4	1900	2700	40	D	
5	1900	5000	40	F	Catastrophic rupture
6	1900	5000	40	D	
7	1900	5000	40	F	Leak (20mm)
8	1900	5000	40	D	
9	5000	2700	40	F	Catastrophic rupture
10	5000	2700	40	D	
11	5000	2700	40	F	Leak (20mm)
12	5000	2700	40	D	

4.1.3. Determination of consequences

Since the tool for consequence and risk estimation was proven can do its work properly, the project proceeded with analyzing case study.

Table 4.5: *Consequence results*

Scenario	Max. conc. (ppm)	Area (m^2)	Distance downwind (m)	Probability of fatality (at m downwind)
1	100,500	28824.5	-75 to 75	1 (-55 to 75)
2	29,750	73,676.4	-120 to 180	1 (-60 to 70)
3	52,060	32.33	13.5 to 33	1 (0 to 15)
4	57,570	4.54	15.5 to 22.5	1 (0 to 14)
5	119,100	29053.8	-80 to 100	1 (-62 to 83)
6	33,700	73842.5	-120 to 180	1 (-62 to 78)
7	53,660	47.8961	14 to 37	1 (0 to 17)

8	52,350	33.2082	14 to 34	1 (0 to 17)
9	**100,500**	**55786.7**	**-90 to 135**	**1 (-76 to 104)**
10	**26,020**	**160244**	**-200 to 250**	**1 (-95 to 100)**
11	52,060	32.33	13.5 to 22.5	1 (0 to 14.5)
12	57,570	4.53	15.5 to 22.4	1 (0 to 14)

4.1.4. Determination of risk

Table 4.6: *Risk results*

Scenario	**Individual risk**		**Societal risk**		
	Per avg year	**Per outcome**	**Max. fatalities/100**	**Avg outcome**	**Risk integral**
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	-	-	-	-	-
6	-	-	-	-	-
7	-	-	-	-	-
8	-	-	-	-	-
9	2.05E-5	1.32E-1	79	1.00E+1	1.56E-4
10	2.13E-6	5.03E-2	62	3.44E+0	2.14E-4
11	-	-	-	-	-
12	-	-	-	-	-

4.1.5. Human injury

The sensitivity study with total of 12 scenarios setup were carried out, only Scenario 9 and 10 produce unacceptable risk to residence nearby so the risk of CO_2 release in pipeline is strongly influenced by the amount of release. But this result is applicable for average time of 600 seconds and duration up to 3600 seconds only. In case of long-term health effects, majority of 12 cases (except Scenario 2, 6 and 10) will cause some certain effects to any human nearby. In Canada's Occupational Health and Safety state if the any worker is exposed to the concentration in the range of 10,000ppm to 15,000 for duration of 42 – 44 days will result in e a reversible acid-base imbalance in the blood and an increased volume of air inhaled per minute. Please refer **Appendix D** for more information about toxicity of CO_2 published by Canada.

There is no risk for all leak case with diameter of 20mm so the sensitivity study of hole diameter was performed to estimate which hole diameter can expose significant risk. For the Scenario 3 and 4 there is unacceptable risk if the hole diameter is more than 100mm for 14 inches (355.6mm). And for the Scenario 7 and 8 in which the operating pressure is almost doubled, there is no unacceptable risk if the hole diameter is less than 85mm for same pipeline size. The same situation goes for Scenario 11 and 12.

For CO_2, if it does not expose any risk, it will be very safe but once the incident occurs the damage is expected high. Like in Scenario 9 and 10, the percentage of fatality can reach up to 79% of the population.

4.2. Malaysian F-N curve

The F-N curve is a common measure of societal risk. The numerical limits which cross the x and y axes and the slopes for the F-N line differ from countries to countries

Table 4.7: *Annual frequency of wind direction and speed at Kuala Terengganu (1985 – 2007)*

Speed (m/s)	Direction									
	N	NE	E	SE	S	SW	W	NW	CALM	TOTAL

<0.3	-	-	-	-	-	-	-	-	11.0	11.0
0.3 - 1.5	0.8	1.5	3.1	1.6	11.1	12.6	2.8	0.8	-	34.3
1.6 - 3.3	2.2	6.8	8.5	1.7	5.8	6.0	1.3	0.6	-	32.9
3.4 – 5.4	2.2	7.4	5.1	0.8	0.4	0.4	0.2	0.3	-	16.8
5.5 – 7.9	0.4	2.0	0.6	0.2	0.0	0.0	0.0	0.1	-	3.3
8.0 – 10.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-	0.1
>10.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0
TOTAL	5.6	17.8	17.3	4.3	17.3	19.0	4.3	1.8	11.0	98.4

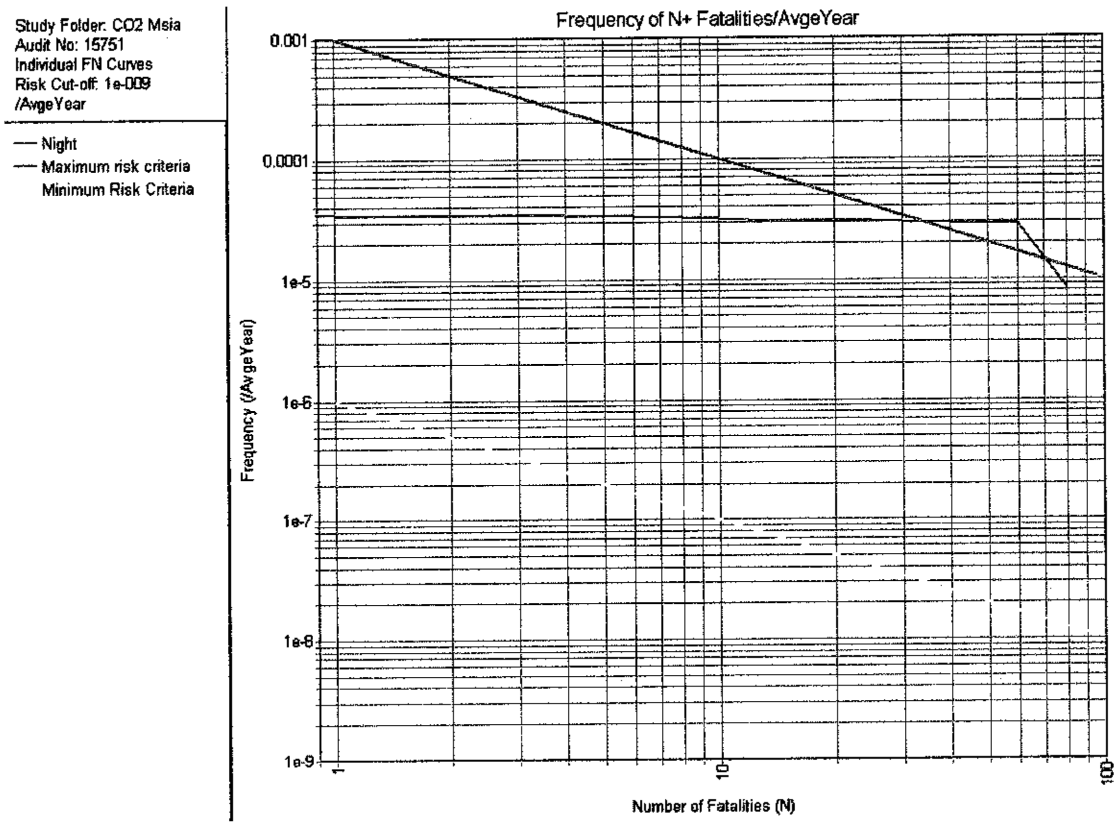

Figure 4.5: *Malaysian F-N curve for* CO_2

Based on the F-N curve above, there is still intolerable risk.

CHAPTER 5

CASE STUDY 2: COMPARISON STUDY OF RISK BETWEEN CO_2 AND NATURAL GAS PIPELINES

5.1. Natural gas pipelines

Natural gas is a mixture of various hydrocarbon gases such as methane, ethane, propane and butane, etc. Over 70% of natural gas is formed by ethane. So it is reasonable to do risk analysis for natural gas via methane, the major component.

Table 5.1: *Physical properties of methane*

Molecular weight	16.043 g/mol
Critical temperature	-82.7 °C
Critical pressure	45.96 bar
Heat capacity at constant pressure (Cp)	0.035 kJ/(mol.K)
Heat capacity at constant volume (Cv)	0.027 kJ/(mol.K)
Gas density at boiling point	1.819 kg/m^3
Gas density at 15 °C	0.68 kg/m^3
Autoignition temperature	595 °C

5.2. Result & discussion

Table 5.2: *Comparison result between CO_2 and natural gas*

	Max. conc. (ppm)	**Cloud area (m^2)**	**Individual risk potential**	**Societal risk potential**
1,900m^3, 40°C, 2700psig, Night weather				
CO_2 (toxic)	100,500	28824.5	-	-
Natural gas (flammable)	1.65E+5	10636.1	1.08E-3/avg year	1.09E-3/avg year

1,900m³, 40°C, 2700psig, Day weather				
CO_2 (toxic)	29,750	73,676.4	-	-
Natural gas (flammable)	1.65E+5	10245	6.28E-4	6.42E-4
5,000m³, 40°C, 2700psig, Night weather				
CO_2 (toxic)	100,500	55786.7	2.25E-3	1.98E-3
Natural gas (flammable)	1.65E+5	20515.1	1.69E-3	1.61E-3
5,000m³, 40°C, 2700psig, Day weather				
CO_2 (toxic)	26,020	160244	9.34E-4	8.71E-4
Natural gas (flammable)	1.65E+5	19668	6.28E-4	6.42E-4

As shown in **Table 5.2** above, in case of huge release, the degree of risk of CO_2 is relatively comparable to of natural gas pipelines.

CHAPTER 6

CONCLUSION and RECOMMENDATION

5.1. Conclusion

The conclusions are:

- The CO_2 may cause serious problem to residence if huge amount of CO_2 is released and its impacts are relatively comparative to which caused by natural gas.
- Operating pressure is the most critical parameter which can make great change in CO_2 concentration in comparison with volume and temperature.
- The night weather (class F) accumulates higher concentration than the day weather (class D) for the same amount of released CO_2 as well as operating conditions.

Nevertheless, there are still some limitations due to:

- Incomplete or inadequate enumeration of incidents;
- Improper selection of incidents;
- Unavailability of required data such as frequencies;
- Consequence or frequency model assumption.

5.2. Recommendation

Since the outcome of this project verified that the carbon dioxide may make certain impacts on community and especially environment if any failure is occurred. Knowing the potential risk of CO_2 transportation pipeline, many countries such as United States, Netherland, United Kingdom, Norway, etc. have been developing a national regulation for CCS to promote the safe CO_2 transportation and handle. In case of Malaysia, at present, there is no legislation or regulation regarding CO_2 capture, transportation & storage. So it is highly recommended that Malaysia should create standard or framework to support the application of CCS widely.

5.2.1. A national regulatory framework

The most important single conclusion to be drawn from this research is the need for industry to classify CO_2 as hazardous material and develop a regulatory framework to allow the appropriate approach for all CO_2 projects or locations in terms of technologies and environmental concerns.

Before any project related to CO_2 is approved to implement, a risk assessment must be conducted to determine what the significant effects would be from the project to residence as well as environment and propose the potential mitigation measures. For example in United State, they have so called Electronic Code Federal Regulations for the transportation of hazardous liquids and carbon dioxide by pipeline. In this regulation, a detail guideline about annual report, design requirement, construction, operation and maintenance, etc. is provided to guarantee the safe transportation.

5.2.2. Standard industrial practices

In order to prevent and control any potential accidental carbon dioxide releases, the industry has developed standard mean to maintain the reliability and safe operation of pipelines in addition to design, construct, operate and maintain the carbon dioxide pipeline in accordance with applicable laws, ordinances, regulations, and standards.

Based on the current practice of some typical companies, the following factors are considered in defining control and mitigation measures for pipeline safety:

- To reduce exposure to a failure mechanism;
- To increase the resistance to a failure mechanism;
- To mitigate the effect of a failure;
- To limit the impact of a failure on environment.

Pipeline construction requirement

- Pipeline design pressure and temperature must be designed in the manner to minimize the potential of CO_2 release.
- Burial of pipeline should be employed to limit the release of CO_2.
- Pipe material selection

- External internal-corrosion control
- Block valves: block valves will be installed on the carbon dioxide pipeline to block-in the pipeline whenever unlikely event of a loss of integrity.
- Eleven tap points were installed on the pipeline. These taps would allow take-off of carbon from the pipeline for a potential customer or customers without forcing a shutdown of the pipeline.
- The pipe size: 0.5 inch wall bevel end 14 inches API 5L Gr. X65 seamless pipe. All pipe and field joints will be coated with fusion bonded epoxy (16mils), and abrasion resistant epoxy (44 mils) and a two-inch concrete jacket weight coating. Field welds will be 100% radio-graphed. The pipeline will be hydrostatically tested in accordance with applicable regulation to establish the maximum allowable operating pressure. Testing will be conducted for a minimum of eight hour and will include a leak test.
- The pipeline should be studied to determine the effectiveness of pipeline safety systems including leak/rupture detection & automatic block valve closure at approximately 14 locations along the pipeline route. Safety systems are designed to mitigate the potential effects of releases from the pipeline by limiting the amount of pipeline product that can be released into the atmosphere in the event of an accidental release.
- A telemetry (SCADA) system provides 24-hour monitoring of the pipeline and compressor operations, including pressures, temperatures and flow rates. This telemetry system enhances immediate response capability to any potential problems. The pipeline is also designed to accommodate an instrumented internal inspection device to detect and record the type and location of corrosion or other defects for long-term monitoring of the pipeline integrity.

Pipeline sitting

- Pipeline routing should be design in less dense population to prevent the severe impact on community.

Pipeline inspection

- Pipeline control: will provide reliable and responsive controls to detect potential leaks. Real-time monitoring of key parameters, including pressure, temperature, and flow rate, enables timely intervention in the event of a release.
- Right-of-way inspections: (interval of inspection schedule)
- Emergency Response Plan addresses an accidental release of the operating pipeline and outlines pre-emergency planning and education, operational safety precautions, emergency response procedures and associated agency coordination.

5.2.3. Carbon dioxide tax

Since the most factor caused climate change is greenhouse gases in which carbon dioxide is the main component, it is suggested to impose a carbon tax on oil and gas production. In such manner, the industrial producers will consider their carbon dioxide emission as well as look into the CCS technologies to make a clean and green discharge.

Based on what we learnt from the case study, the Dakota gasification, the implementation of CO_2 capture for conventional power plants is highly recommended in order to promote a cleaner technology and proceed to green production.

5.2.4. Malaysia CCS

The IPCC Special Report projects that "by 2050, around 20-40% of global fuel CO_2 emissions could be technically suitable for capture, including 30-60% of power generation". We can use the case study 1 – Dakota Gasification as our sample for CO_2 capture from electrical power plant in Malaysia.

Table 5.1: *List of coal-fired plant in Malaysia*

Plant	State	MW	Type	Owner/operator
Jimah power	Lukut, Negri	1,400	Thermal	Jimah Engergy

station	Sembilan			Ventures Sdn Bhd
Manjung power station	Manjung, Perak	2,295	Thermal	TNB Janamajung Sdn Bhd
PPLS Power Generation plant	Kuching, Sarawak	110	Thermal	PPLS Power Generation
Sejingkat Power Corporation plant	Kuching, Sarawak	100	Thermal	Sejingkat Power Corporation Sdn Bhd
Sultan Sahahuddin Abdul Aziz Shah power station	Kapar, Selangor	2,420	Thermal, open cycle, natural gas and coal with oil backup	Kapar Energy Ventures Sdn Bhd
Tanjung Bin power station	Pontian, Johor	2,100	Thermal	Tanjong Bin power Sdn Bhd

Once this technology is widely employed in Malaysia the number of CO_2 pipeline network will increase rapidly so there is a need to develop a national & technical framework for CO_2 pipeline in a proper manner in order to minimize any potential hazards.

5.3. Suggestion for future work

The case study chosen for this project whose composition do not have any water but in practice other CO_2 pipeline operators transport CO_2 with large amount of water presence up to 257ppm wt (see **Appendix K**). The presence of water in CO_2 pipeline will introduce hydrate and corrosion formation.

Moreover, the impurities in CO_2 pipelines such as CH_4, H_2S or N_2 will raise a concern about how these impurities will affect the release of CO_2 in case any failure may occur.

Currently CO_2 is mainly used for CCS technologies which means CO_2 pipelines will travel offshore and through the seabed so it is desirable to know the potential influence of CO_2 release to the marine life.

Following are some suggestion for future work:

- Effect of water presence;
- Effect of impurities;
- Subsea pipelines.

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CCOHS: Canada's National Centre for Occupational Health and Safety information <http://www.ccohs.ca/oshanswers/chemicals/chem_profiles/carbon_dioxide/health_cd.htm>

APPENDIX A

Current CCS Projects

The Sleipner CCS project, Norway

The first commercial CCS project in the world was implemented in Sleipner, one of the largest gas field in North Sea, 230km off the coast of Norway. The amount of CO_2 produced was nearly 3% of Norway's total emissions in 1990.

The annualized CAPEX-related costs (at a 10% discount rate) were USD 9.6 millions, while OPEX is about USD 16 per tonne of CO_2 injected.

The IEA GHG Weyburn-Midale CO_2 monitoring and storage Weyburn project, Canada

The Weyburn EOR project currently injects 6,500 tonnes per day of CO_2, along with approximately 3,000 tonnes per day of recycled CO_2. The CO_2 is purchased from a coal gasification plant in North Dakota, United States, and transported through a 320km pipeline to Weyburn.

Weyburn is also the host site of an international research project on CO_2 storage.

The In Salah CCS Project, Algeria

It was designed to test the commercial viability of CO_2 storage as a CO_2 mitigation option. The first phase of the project began in 2004, and involves the injection of up to 4,000 tonnes a day of CO_2. Gas from the Reg and Tiggentour fields is dehydrated on-site, transported via pipeline over 100km and then mixed with gas produced from Kerchba field.

The SnØhvit CCS project, Norway

The Norwegian SnØhvit CCS project in the Barents Sea is similar in a number of ways to the Sleipner project. Natural gas containing CO_2 is transported via a 145km multiphase pipeline to the receiving liquefaction plant onshore near the city of Hammerfest, where it is separated into gas and condensates. CO_2 is removed from gas prior to its liquefaction, using an amine process at high pressure. Another 145 km pipeline has been built to transport this CO_2 offshore back to SnØhvit field where it is injected into a 45 – 75km thick formation called Tubasen lying 2,500m below the seabed. The cost of the pipeline and injection is estimated at EUR 125 millions.

(Source: International Energy Agency, 2008, *CO2 Capture and Storage – A Key Carbon Abatement Option*, Organization for Economic Co-Operation and Development (OECD), France)

APPENDIX B

Lake Nyos

Lake Nyos is a crater lake in the Northwest Province of Cameroon, located about Northwest of Yaoundé. Nyos is a deep lake high on the flank of an inactive volcano in the Oku volcanic plain along the Cameroon line of volcanic activity. A natural dam of volcanic rock hems in the lake water.

A pocket of magma lies beneath the lake and leaks carbon dioxide into the water, changing it into carbonic acid. Nyos is one of the only three lakes to be saturated with carbon dioxide in this way, the others being Lake Monoun, at a distance of SSE and Lake Kivu in Rwanda.

On August 21, 1986, possibly triggered by a landslide, the lake suddenly emitted a large cloud of carbon dioxide (1.6 million tones of CO_2), which suffocated 1,700 people and 3,500 livestock in nearby villages. Though not completely unprecedented, it was the first known large-scale asphyxiation caused by a natural event.

(Source: *http://www.absoluteastronomy.com/topics/Lake_Nyos*)

APPENDIX C

Carbon Dioxide Safety Information

Carbon dioxide is a compound of carbon and oxygen in proportions by weight of about 27% carbon to 73% oxygen. It is a gas at normal atmospheric temperatures and pressures. CO_2 is colorless, odorless, and about 1.5 times as heavy as air. It is a slightly acid gas which is felt by some persons to have a slight pungent odor and biting taste.

Carbon dioxide is relatively non-reactive and nontoxic. It will not burn, and it will not support combustion or life. When dissolved in water, carbonic acid is formed. Solid carbon dioxide ("dry ice") is used quite extensively to refrigerate dairy products, meat products, frozen foods, and other perishable foods while in transit. Gaseous carbon dioxide is used to carbonate soft drinks, for pH control in water treatment, in chemical processing, as a food preservative, metal welding and as a growth stimulant for plant life. Liquid carbon dioxide is used as an expendable refrigerant for freezing and chilling food products, for stimulation of oil and gas wells, etc.

Acute and chronic health effects

Carbon dioxide is normally present in the atmosphere at about 0.035% by volume. It is also a normal end product of human and animal metabolism. The exhaled breath contains up to 5.6% carbon dioxide. The greatest physiological effect of carbon dioxide is to stimulate the respiratory center, thereby controlling the volume and rate of respiration. It is able to cause dilation and constriction of the blood vessels and helps to control the pH of the blood. Carbon dioxide acts as a stimulant and a depressant on the central nervous system.

Increases in heart rate and blood pressure have been noted at a carbon dioxide concentration of 7%. Prolonged exposure at this concentration may cause labored breathing, headache, dizziness, and sweating. Concentrations of 10% and above will cause unconsciousness in one minute or less. Impairment in coordination has been noted during prolonged exposure to concentrations of 3% carbon dioxide even while the oxygen concentration was 21 percent.

Inhalation of gaseous carbon dioxide can adversely affect body function. Gaseous carbon dioxide is an asphyxiant. Concentrations of 10% or more can produce unconsciousness or death. Lower concentrations may cause headache, sweating, and rapid breathing, and increased heartbeat, shortness of breath, dizziness, mental depression, visual disturbances, and shaking. The seriousness of these symptoms is dependent on concentration and length of time the individual is exposed. Carbon dioxide when inhaled in elevated concentrations may act to produce mild narcotic effects, stimulation of the respiratory center, and asphyxiation depending on the concentration present and the duration of exposure. Chronic effects of CO2 have received little attention and there is very little information available on long term health effects from chronic exposure. Skin, eye, or mouth contact with dry ice or compressed carbon dioxide can cause tissue damage or burns.

The acute effects of carbon dioxide and causal concentrations are listed below:

0.5% or 5,000 ppm	OSHA PEL-8hr workshift
2% or 20,000 ppm	May cause deepened breathing
4% or 40,000 ppm	May cause marked increase in breathing rate
4.5-5% or 45,000 to 50,000 ppm	Breathing becomes labored and distressing to some individuals
10% or 100,000 ppm	May cause visual disturbances, tremors, perspiration, increased blood pressure, and loss of consciousness
25% or 250,000 ppm	Results in CNS depression, convulsions, coma, and death

Permissible exposure limit: The OSHA PEL-TWA for carbon dioxide is 5,000.

Warning properties: Carbon dioxide is an odorless gas. Since carbon dioxide has no odor, and since no quantitative information is available relating its irritant effects of to air concentrations, this product has been treated as a material with poor warning properties.

Respirators: Personnel, including rescue workers should not enter areas in which the carbon dioxide content exceeds 3% by measurement unless wearing self-contained breathing apparatus or air-line respirators.

First aid care

First aid for inhalation:

- if a person has inhaled large amounts of carbon dioxide and is exhibiting adverse effects, move the exposed individual to fresh air at once
- if breathing has stopped, perform artificial respiration
- keep the person warm and at rest
- seek medical attention at once
- fresh air and assisted breathing are appropriate for all cases of overexposure to gaseous carbon dioxide

First aid for skin contact:

- if solid carbon dioxide (dry ice) or compressed CO2 gas comes in contact with the body, stop the exposure at once
- if frostbite has occurred, seek medical attention

First aid for eye contact:

- if the eyes are involved, obtain prompt medical attention

http://www.dakotagas.com/Products/Product_Safety/Carbon_dioxide_safet.html

APPENDIX D

TOXICITY OF CARBON DIOXIDE

	Concentration, %	Exposure duration (time)	Effect
Atmos-phere	0.035%		No harm
Experiment	Below 2%	Short term	No harm
	3.3% – 5.4%	15 minutes	Increase depth of breathing
	7.5%	15 minutes	Inability of breath (dyspnea), increased pulse rate, headache, dizziness, sweating, restlessness, disorientation and visual distortion developed
	6.5% - 7.5%	20 minutes	Decreased mental performance
	6.5%	70 minutes	Irritability and discomfort
	6%	Several minutes	Affects the heart by altered electrocardiograms
	30%	20 – 30 seconds	
Working environment	1% - 1.5%	42-44 days	Cause a reversible acid-base imbalance in the blood and an increased volume of air inhaled per minute (minute volume)
	3%	Over 15 hours for 6 days	Decreased night vision and colour sensitivity
	10%	1.5 minutes	Cause eyes flickering, excitation and increased muscle activity and twitching
	Over 10%	1.5 minutes	Difficulty in breathing, impaired hearing, nausea, vomiting, a strangling sensation, sweating, stupor within several minutes and loss of consciousness for 15 minutes
	To 30%	1.5 minutes	Quickly unconsciousness and convulsions

(Source: CCOHS: *Canada's National Centre for Occupational Health and Safety information*)

APPENDIX E

UNITED STATE CO_2 TRANSPORTATION REGULATION

PART 195—TRANSPORTATION OF HAZARDOUS LIQUIDS BY PIPELINE

§ 195.1 Which pipelines are covered by this part?

(a) *Covered.* Except for the pipelines listed in paragraph (b) of this section, this part applies to pipeline facilities and the transportation of hazardous liquids or carbon dioxide associated with those facilities in or affecting interstate or foreign commerce, including pipeline facilities on the Outer Continental Shelf (OCS). This includes:

(1) Any pipeline that transports a highly volatile liquid (HVL);

(2) Transportation through any pipeline, other than a gathering line, that has a maximum operating pressure (MOP) greater than 20-percent of the specified minimum yield strength;

(3) Any pipeline segment that crosses a waterway currently used for commercial navigation;

(4) Transportation of petroleum in any of the following onshore gathering lines:

(i) A pipeline located in a non-rural area;

(ii) To the extent provided in §195.11, a regulated rural gathering line defined in §195.11; or

(iii) To the extent provided in §195.413, a pipeline located in an inlet of the Gulf of Mexico.

(5) Transportation of a hazardous liquid or carbon dioxide through a low-stress pipeline or segment of pipeline that:

(i) Is in a non-rural area; or

(ii) Meets the criteria defined in §195.12(a).

(6) For purposes of the reporting requirements in subpart B, a rural low-stress pipeline of any diameter.

(b) *Excepted.* This part does not apply to any of the following:

(1) Transportation of a hazardous liquid transported in a gaseous state;

(2) Transportation of a hazardous liquid through a pipeline by gravity;

(3) A pipeline subject to safety regulations of the U.S. Coast Guard;

(4) A low-stress pipeline that serves refining, manufacturing, or truck, rail, or vessel terminal facilities, if the pipeline is less than one mile long (measured outside facility grounds) and does not cross an offshore area or a waterway currently used for commercial navigation;

(5) Transportation of hazardous liquid or carbon dioxide in an offshore pipeline in State waters where the pipeline is located upstream from the outlet flange of the following farthest downstream facility: The facility where hydrocarbons or carbon dioxide are produced or the facility where produced hydrocarbons or carbon dioxide are first separated, dehydrated, or otherwise processed;

(6) Transportation of hazardous liquid or carbon dioxide in a pipeline on the OCS where the pipeline is located upstream of the point at which operating responsibility transfers from a producing operator to a transporting operator;

(7) A pipeline segment upstream (generally seaward) of the last valve on the last production facility on the OCS where a pipeline on the OCS is producer-operated and crosses into State waters without first connecting to a transporting operator's facility on the OCS. Safety equipment protecting PHMSA-regulated pipeline segments is not excluded. A producing operator of a segment falling within this exception may petition the Administrator, under §190.9 of this chapter, for approval to operate under PHMSA regulations governing pipeline design, construction, operation, and maintenance;

(8) Transportation of a hazardous liquid or carbon dioxide through onshore production (including flow lines), refining, or manufacturing facilities or storage or in-plant piping systems associated with such facilities;

(9) Transportation of a hazardous liquid or carbon dioxide:

(i) By vessel, aircraft, tank truck, tank car, or other non-pipeline mode of transportation; or

(ii) Through facilities located on the grounds of a materials transportation terminal if the facilities are used exclusively to transfer hazardous liquid or carbon dioxide between non-pipeline modes of transportation or between a non-pipeline mode and a pipeline. These facilities do not include any device and associated piping that are necessary to control pressure in the pipeline under §195.406(b); or

(10) Transportation of carbon dioxide downstream from the applicable following point:

(i) The inlet of a compressor used in the injection of carbon dioxide for oil recovery operations, or the point where recycled carbon dioxide enters the injection system, whichever is farther upstream; or

(ii) The connection of the first branch pipeline in the production field where the pipeline transports carbon dioxide to an injection well or to a header or manifold from which a pipeline branches to an injection well.

(c) *Breakout tanks.* Breakout tanks subject to this part must comply with requirements that apply specifically to breakout tanks and, to the extent applicable, with requirements that apply to pipeline systems and pipeline facilities. If a conflict exists between a requirement that applies specifically to breakout tanks and a requirement that applies to pipeline systems or pipeline facilities, the requirement that applies specifically to breakout tanks prevails. Anhydrous ammonia breakout tanks need not comply with §§195.132(b), 195.205(b), 195.242 (c) and (d), 195.264(b) and (e), 195.307, 195.428(c) and (d), and 195.432(b) and (c).

[73 FR 31644, June 3, 2008]

(Source: Electronic Code of Federal Regulations http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=439274fadcf66108c147eccdb99c197d;rgn=div5;view=text;node=49%3A3.1.1.1.7;idno=49;cc=ecfr#49:3.1.1.1.7.1.21.2

APPENDIX F

WEYBURN OIL FIELD

The Weyburn oilfield lies on the northwestern rim of Williston Basin, 16km south east of Weyburn. The oilfield began operation in 1954 and currently there are about 650 production and water injection wells in operation. Average daily crude oil is 2,900m^3/day (about 18,200barrels/day). The Weyburn field produces about 10% of EnCana's total oil production. Over its lifetime the field has produced some 55 millions m^3 of oil from primary and water flood production. The field is in production decline, having produced more than 25% of the estimated. In order to keep the field viable, CO_2 injection began in 2000.

Figure F1: *Weyburn unit*

In late 2000, CO_2 injection was initiated at an initial injection rate of 2.69 million m^3/day into 19 patterns. By 2002, the rate of CO_2 injection increased to 3.39 million m^3/day including 0.71 million m^3/day of CO_2 recycled from oil production. The CO_2-EOR has contributed over 788m^3/day (5000 barrels/day) to a total daily production of 3240m^3/day (20,560 barrels/day) for the entire Weyburn unit.

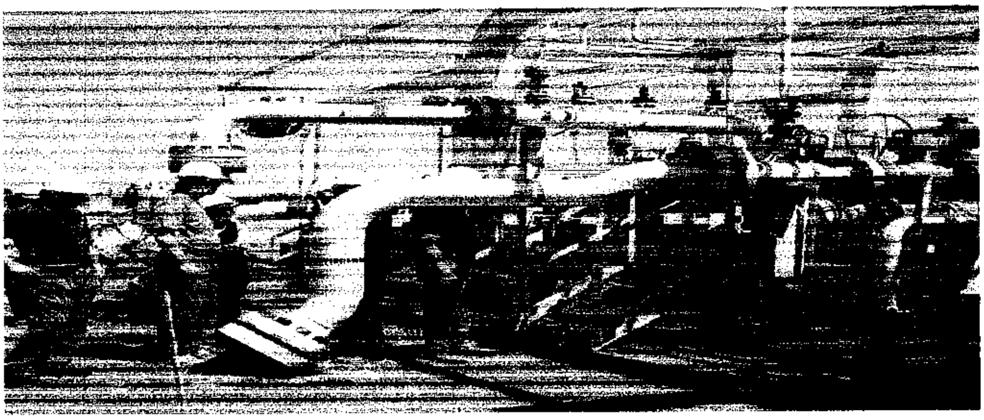


Figure F2: *The Weyburn facilities where the main CO_2 pipeline comes from Beulah, North Dakota (Image courtesy of PTRC)*

CO_2-EOR is projected to help the oilfield remain viable for another 20 years and will produce an additional 130 million barrels of oil.

APPENDIX G

VALIDATION OF PHAST RISK v6.53 FOR CO_2

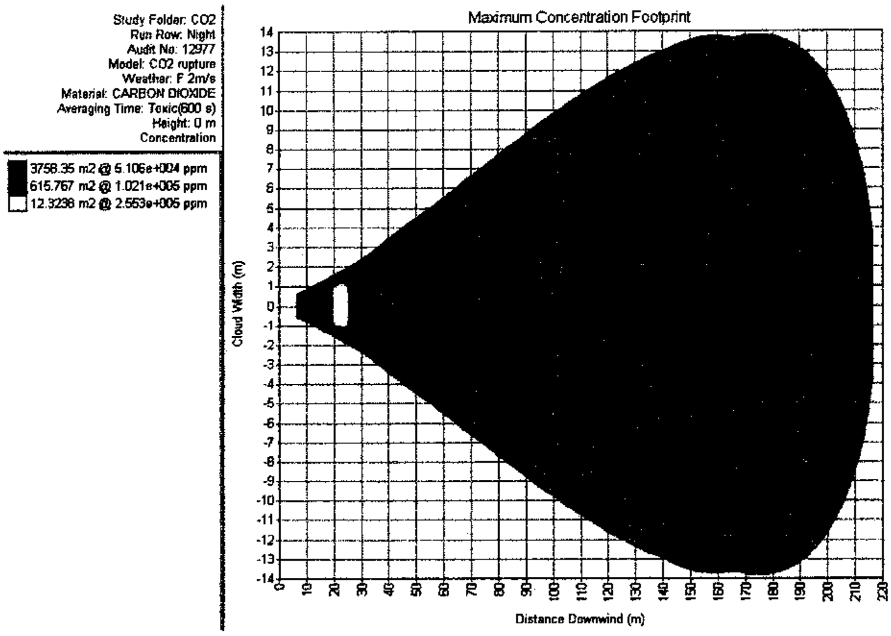


Figure G1: *Maximum concentration for instantaneous release*

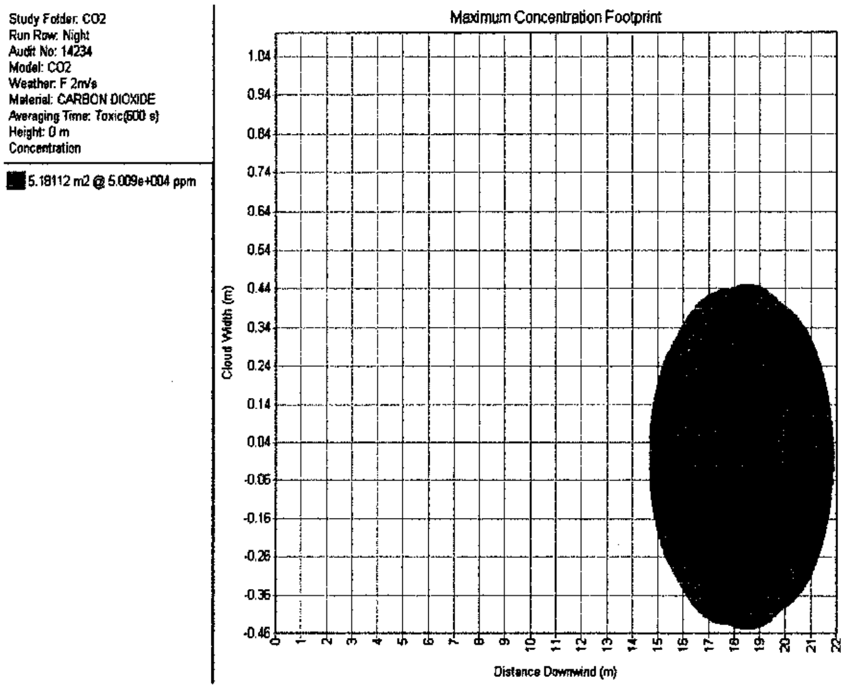


Figure G2: *Maximum concentration for leak release*

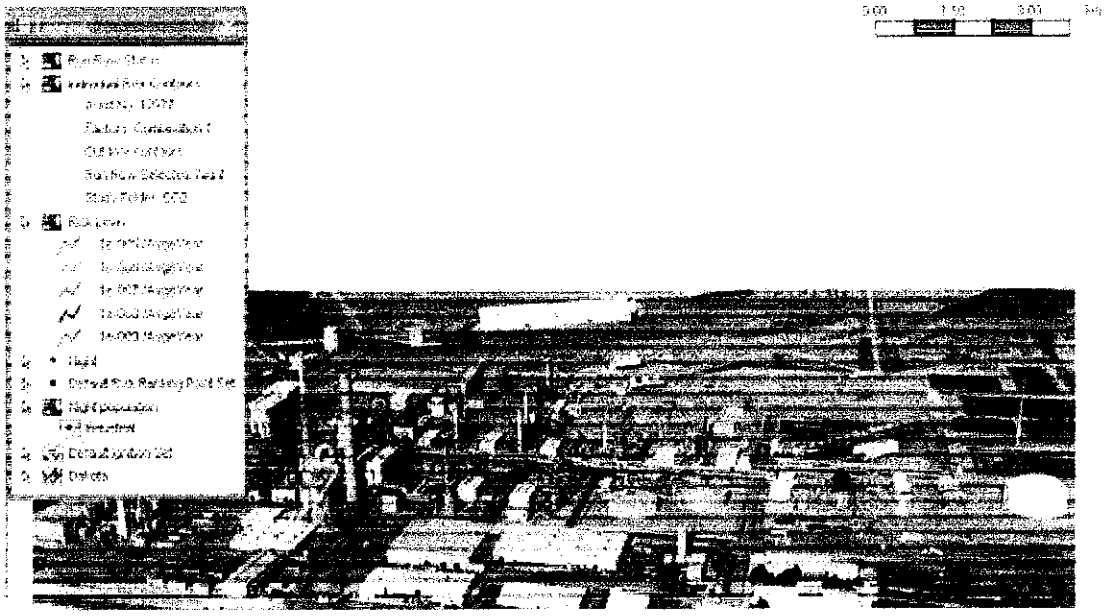


Figure G3: *Risk contour for leak release*

APPENDIX H

CASE STUDY 1 RESULTS

SCENARIO 9

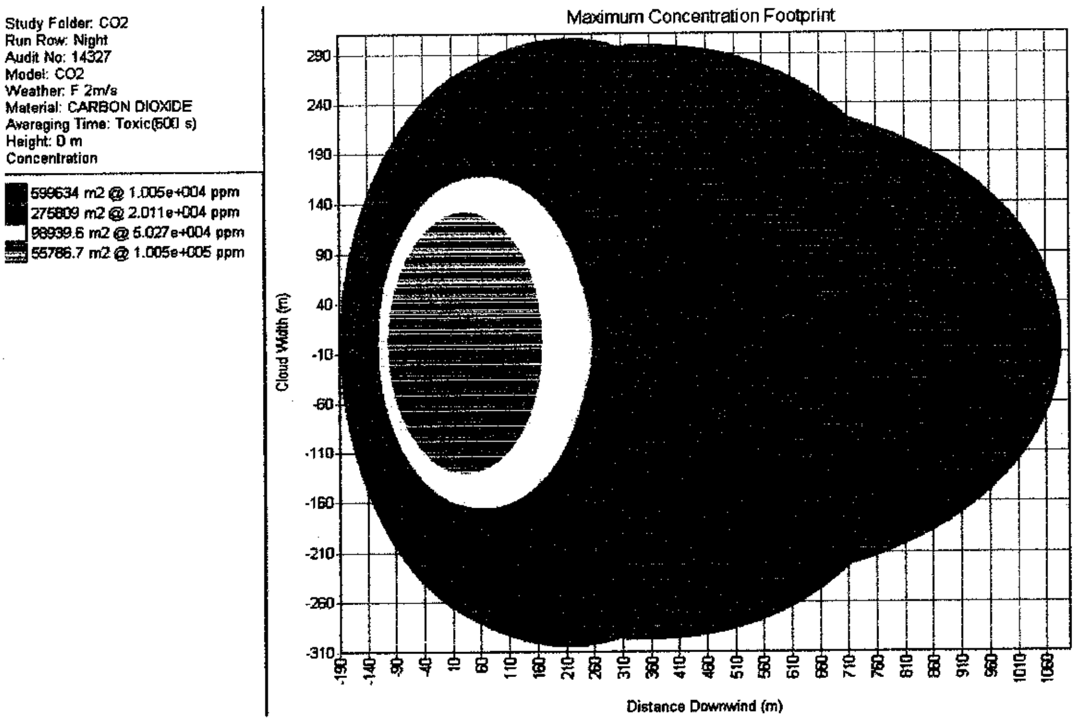


Figure H1: *Maximum concentration*

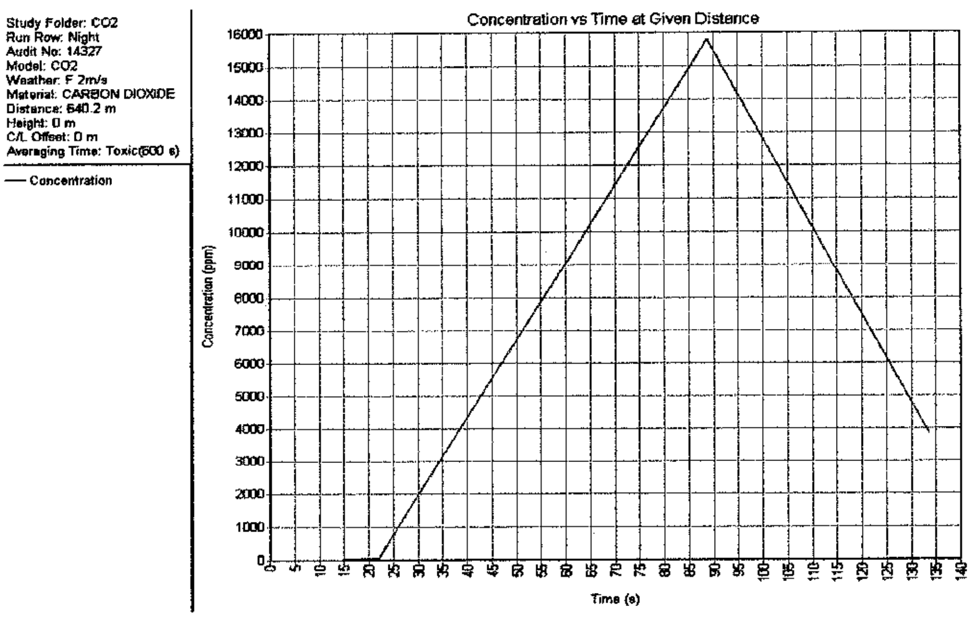


Figure H2: *Concentration vs. time*

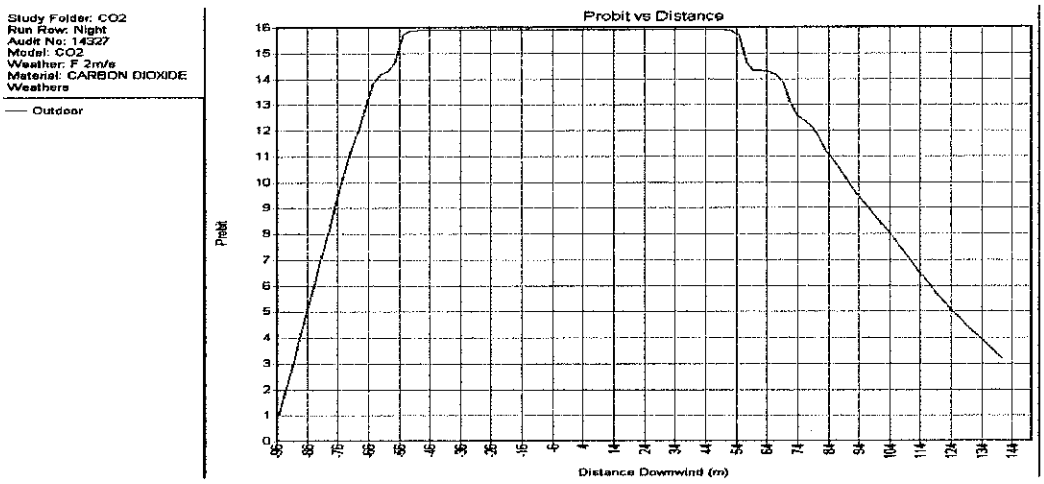


Figure H3: *Probit vs. distance*

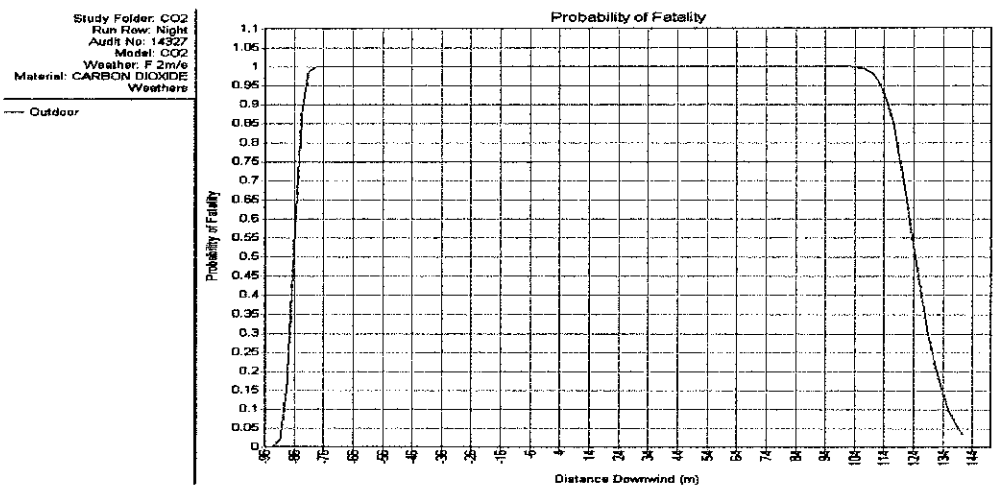


Figure H4: *Probability of fatality*

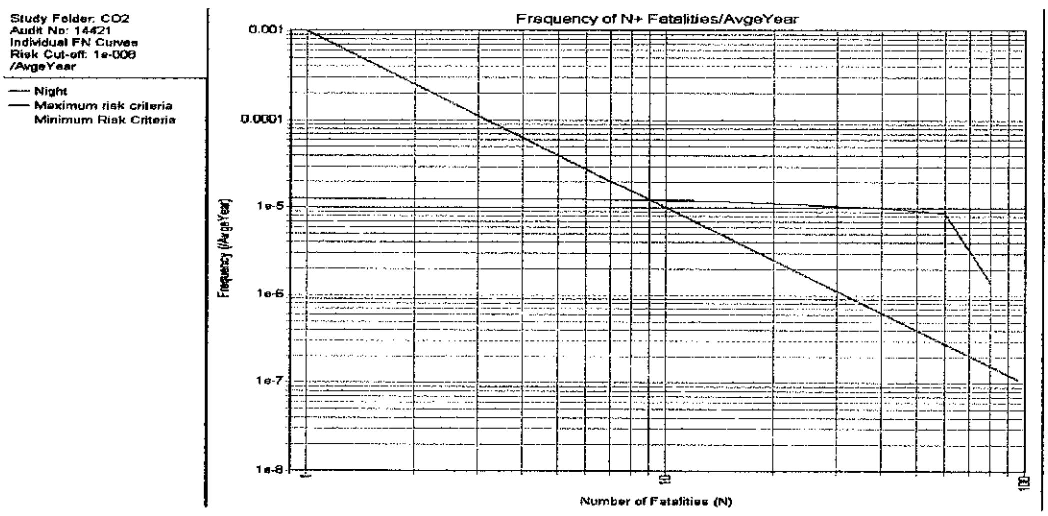


Figure H5: *FN curve*

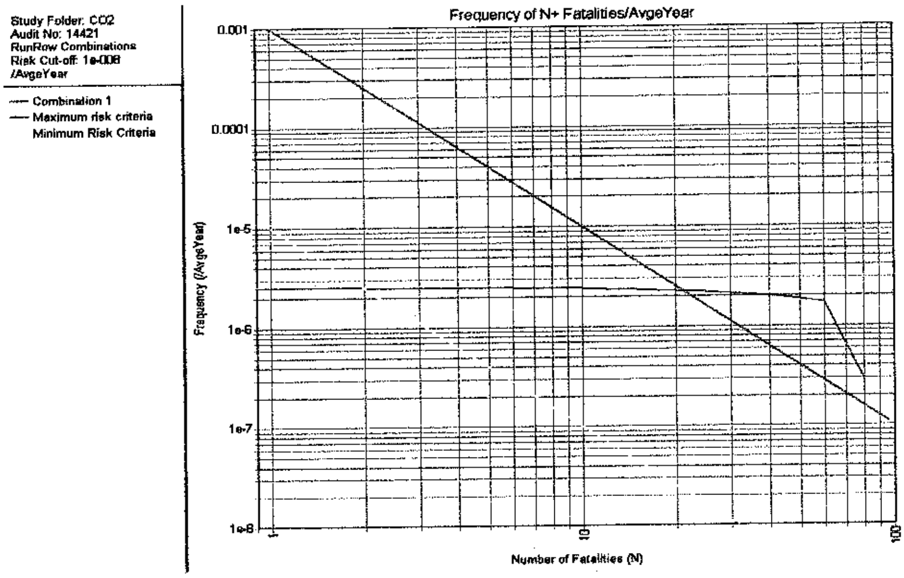


Figure H6: *Combined F-N curve*

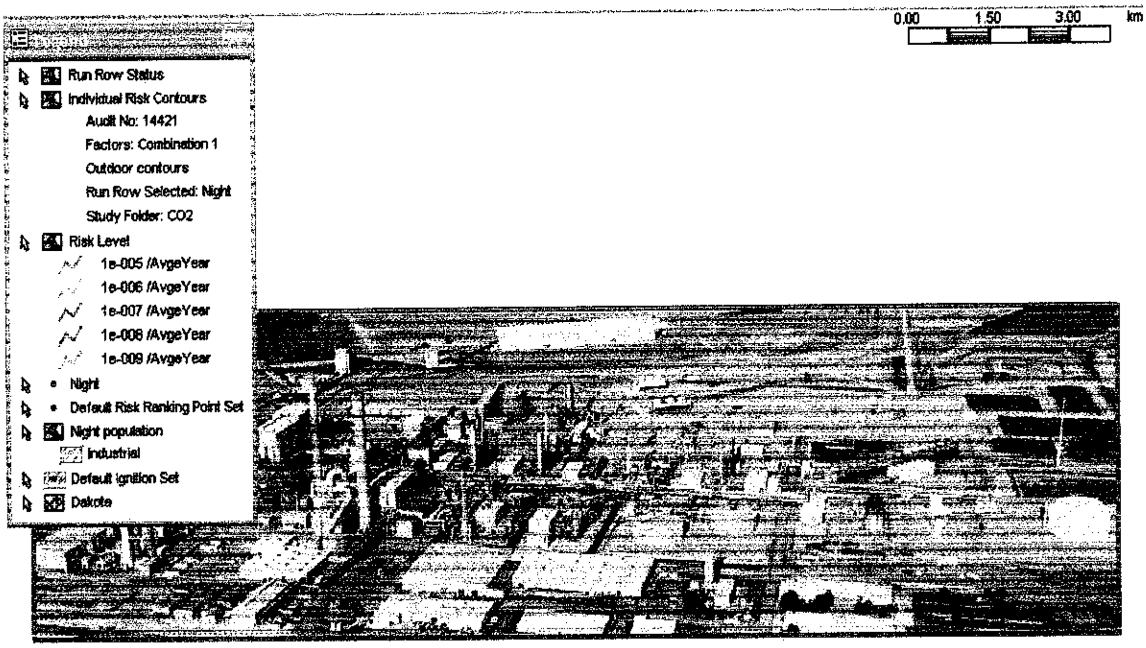


Figure H7: *Risk contour*

SCENARIO 10

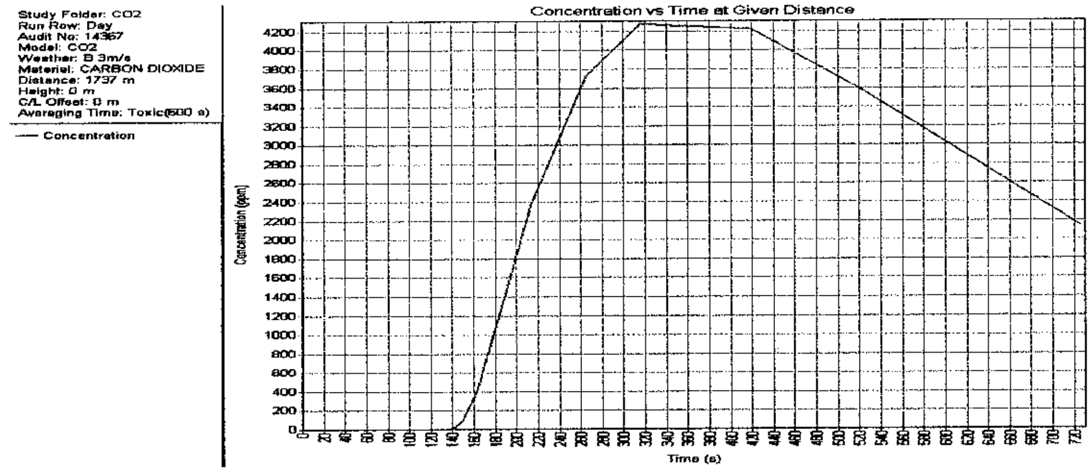


Figure H8: *Concentration vs. time*

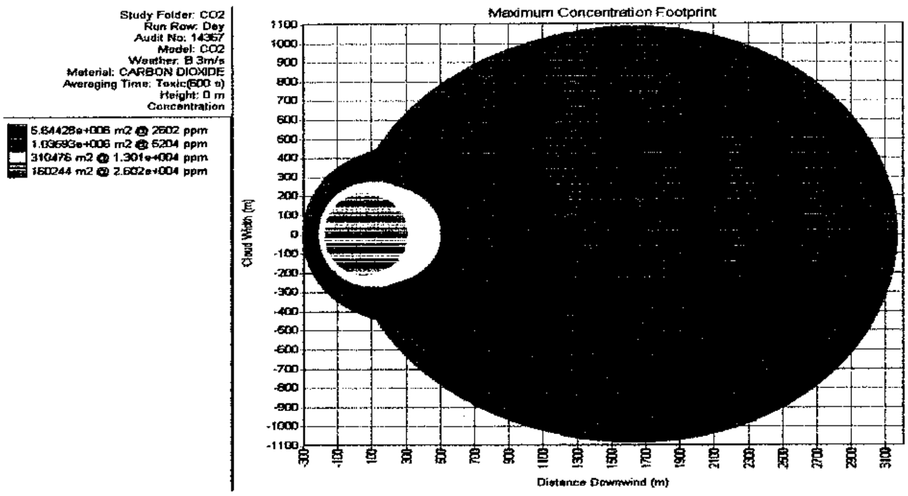


Figure H9: *Maximum concentration*

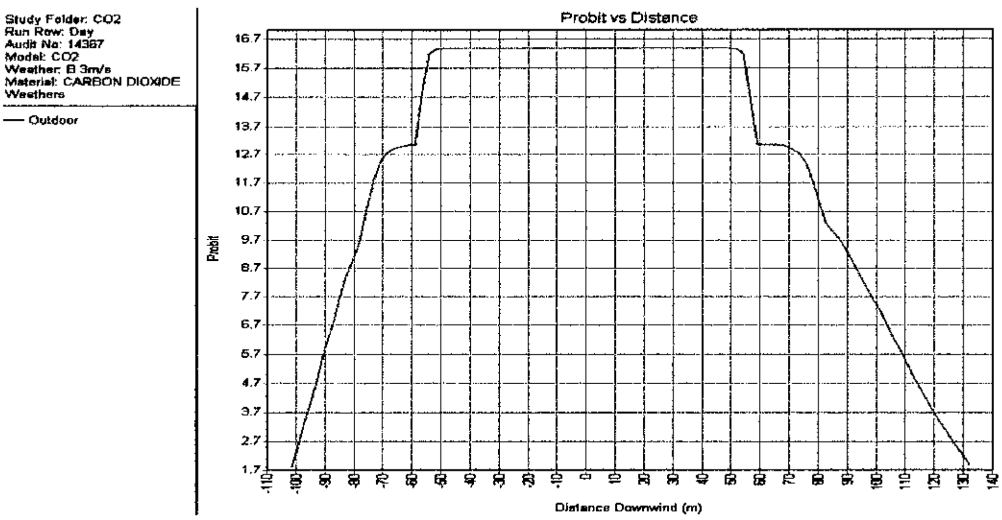


Figure H10: *Probit vs. distance*

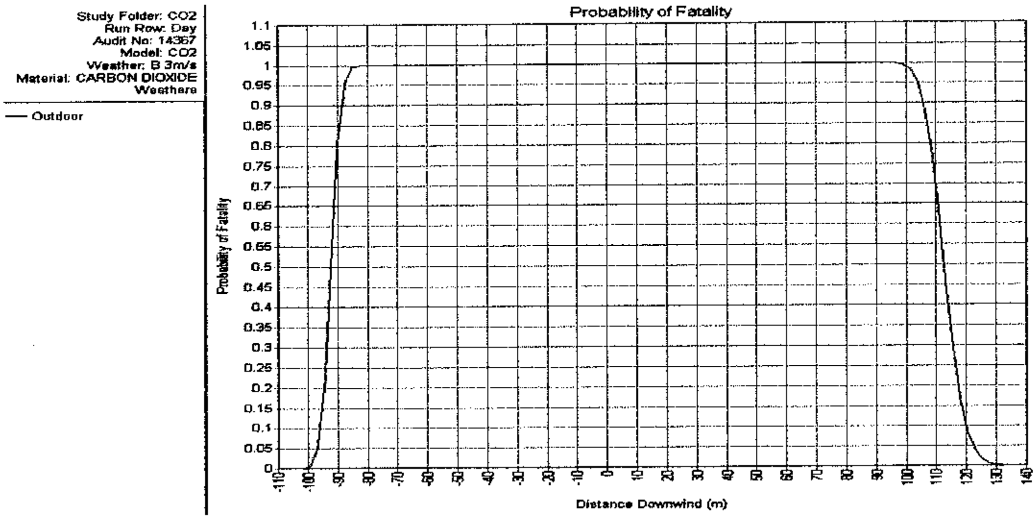


Figure H11: *Probability of fatality*

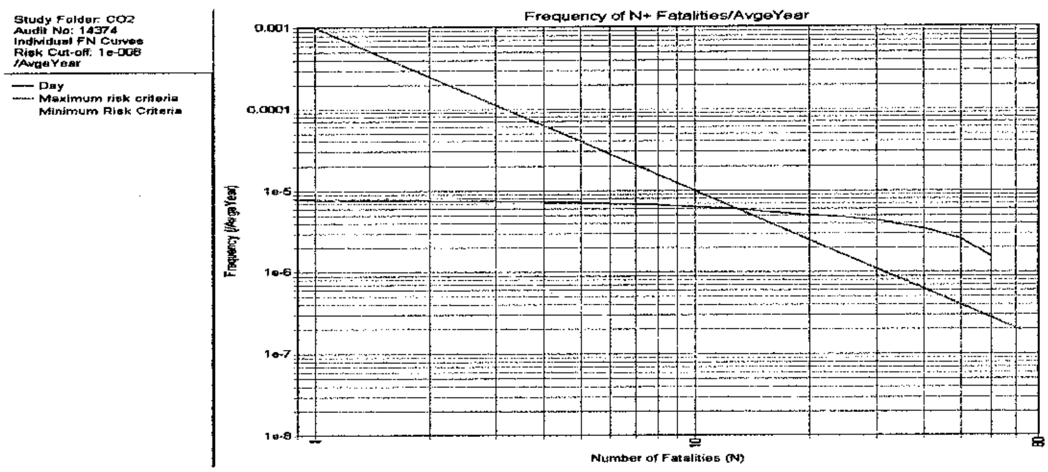


Figure H12: *F-N curve*

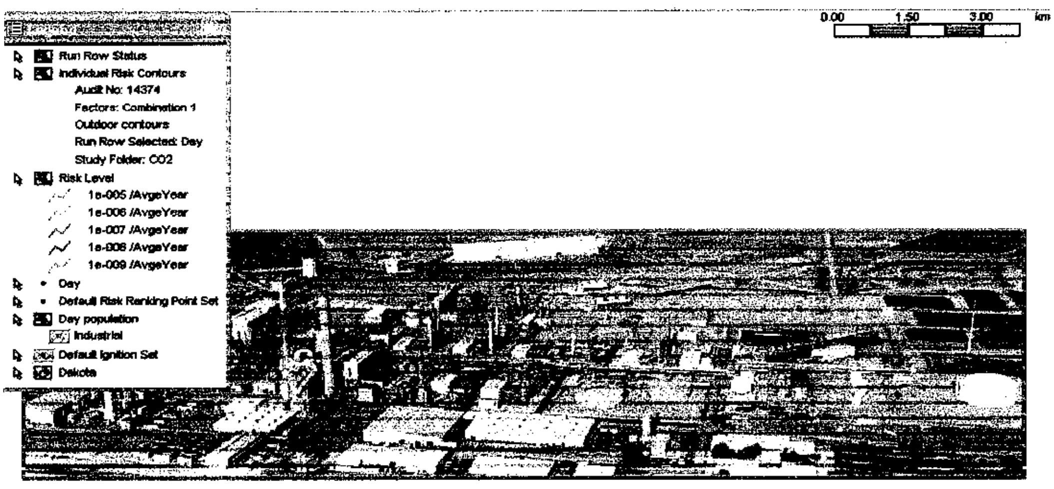


Figure H13: *Risk contour*

APPENDIX I

CASE STUDY 2 RESULTS

Scenario 1

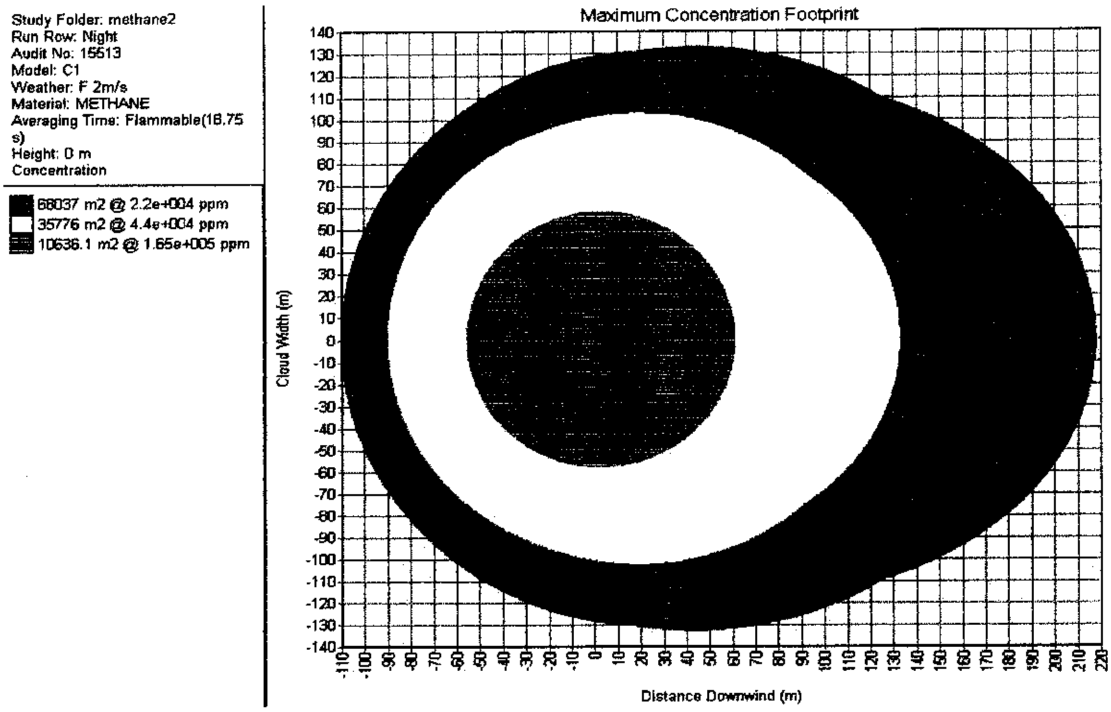


Figure I1: *Maximum concentration footprint*

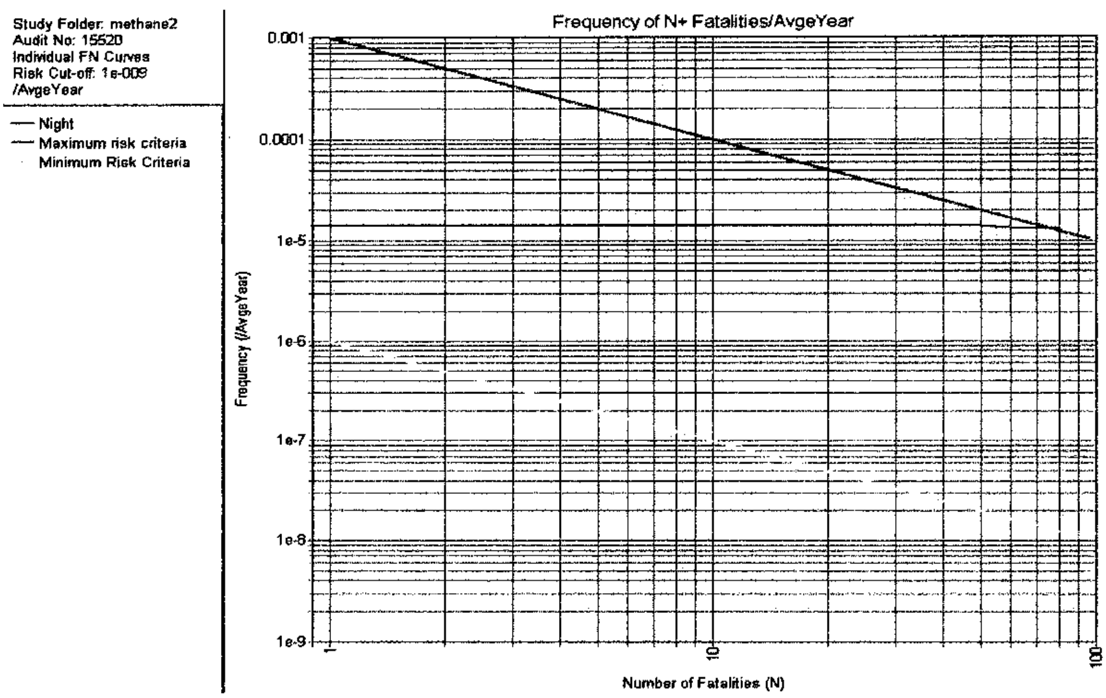


Figure I2: *FN curve*

Scenario 2

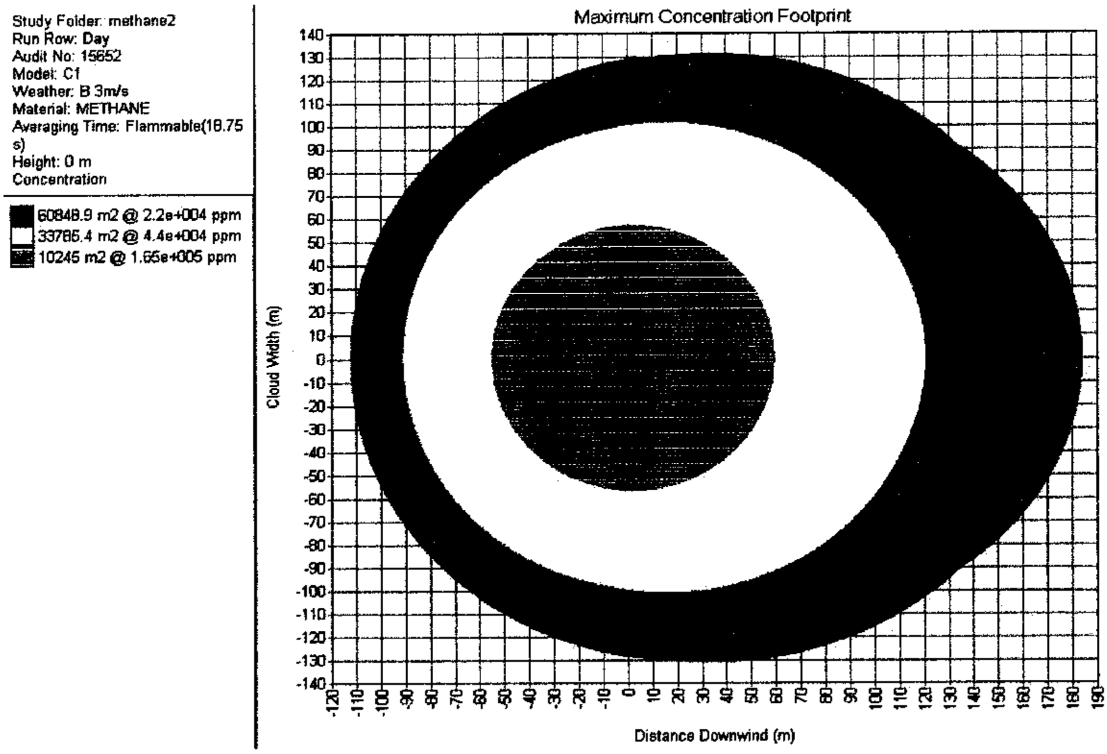


Figure I3: *Maximum concentration footprint*

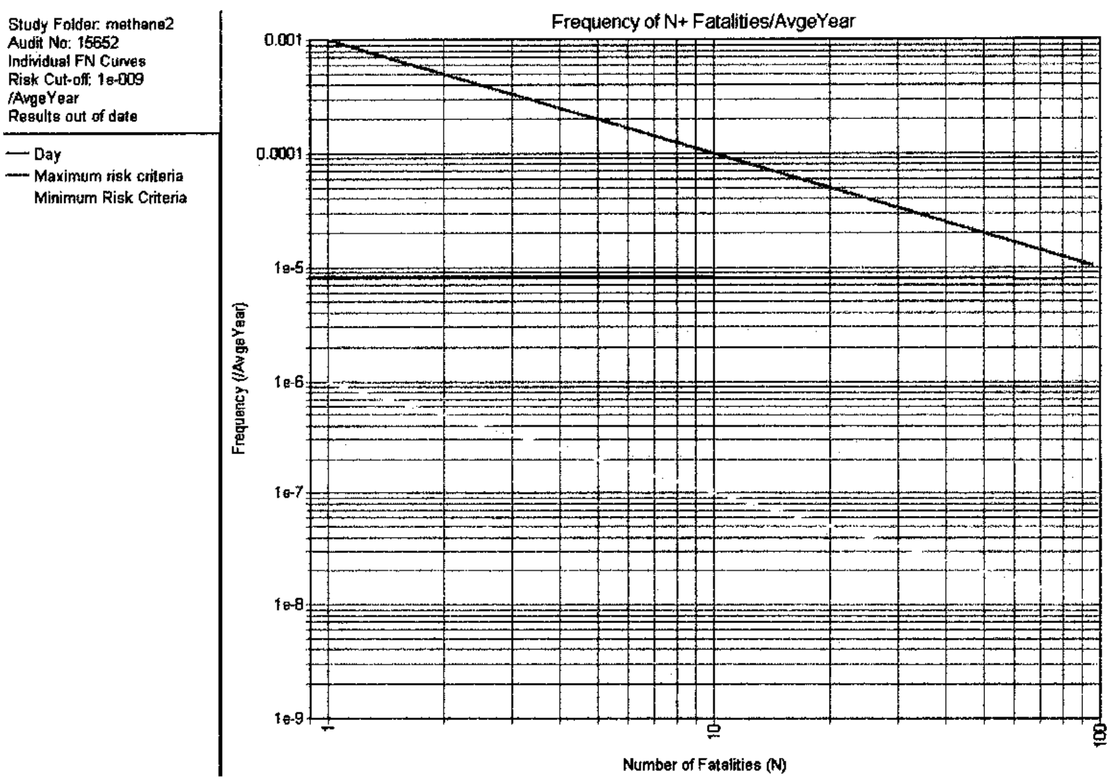


Figure I4: *FN curve*

Scenario 9

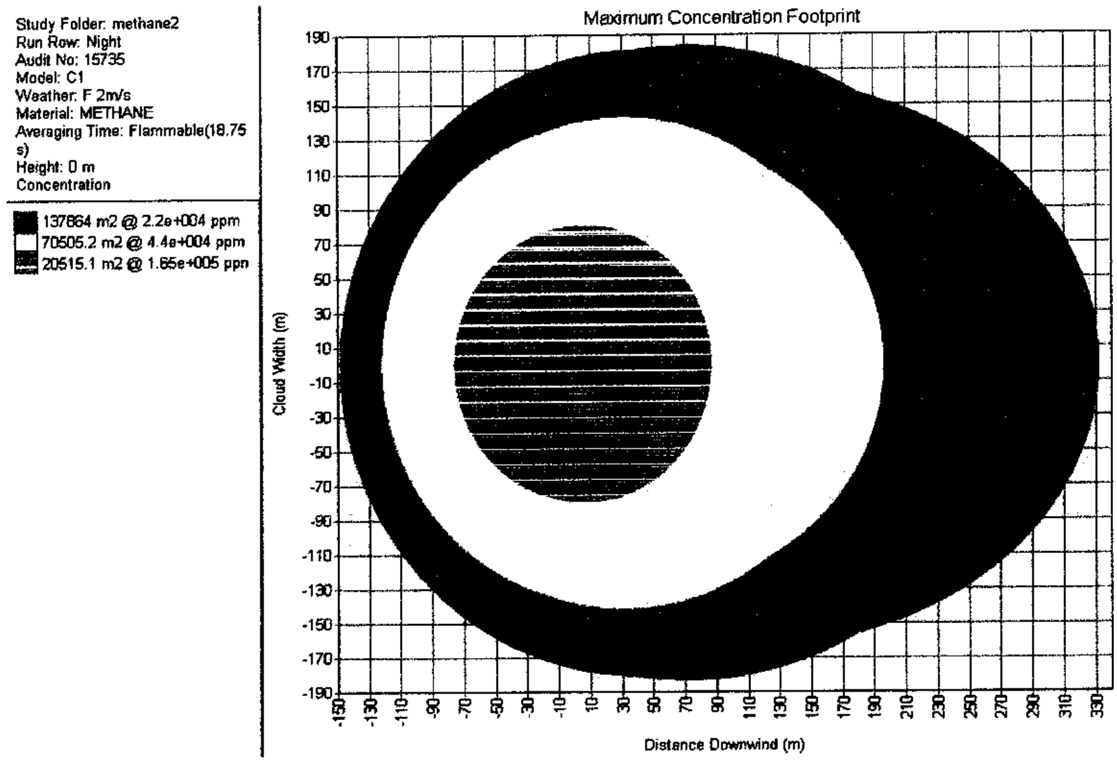


Figure I5: *Maximum concentration footprint*

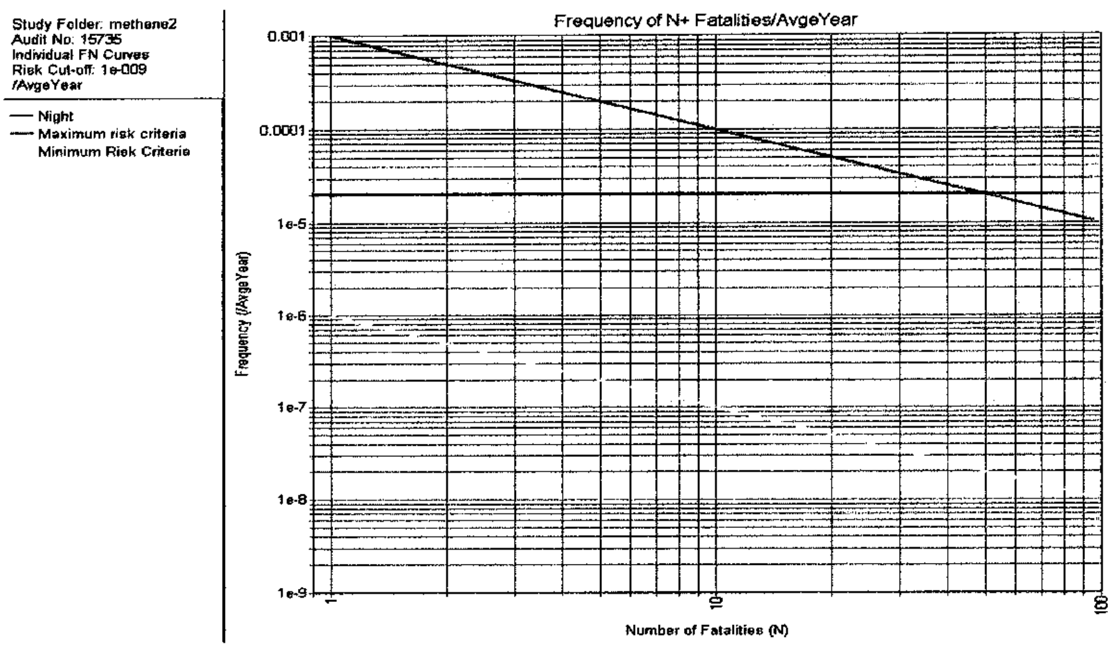


Figure I6: *FN curve*

Scenario 10

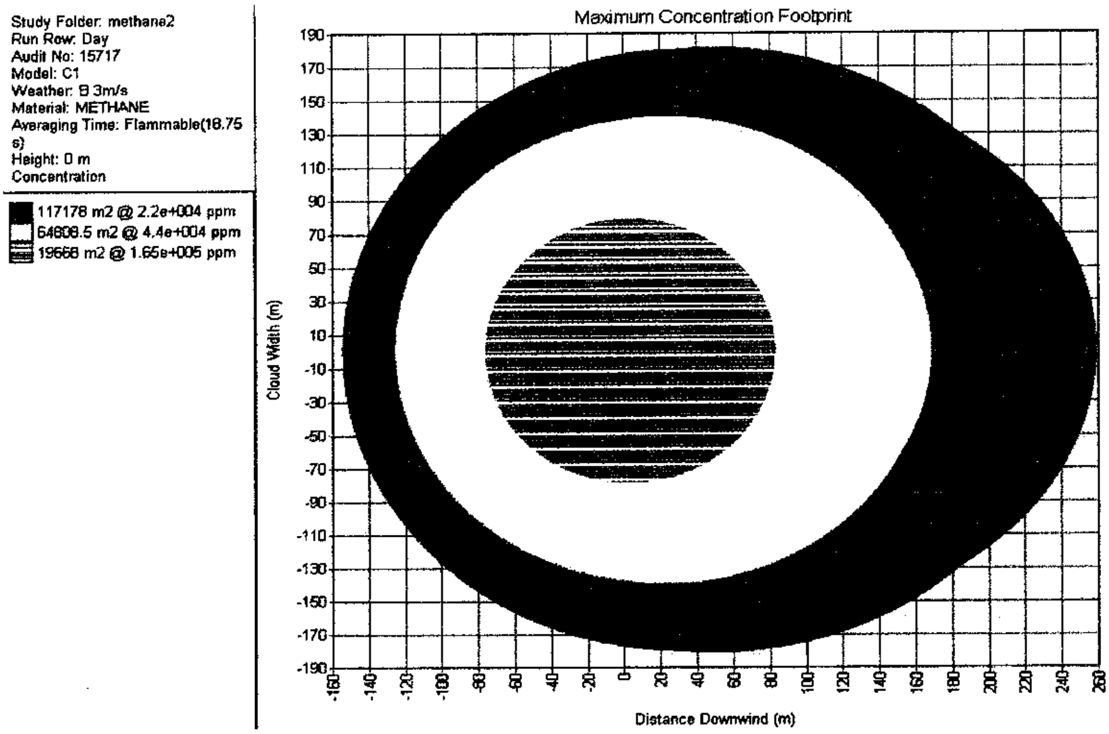


Figure I7: *Maximum concentration footprint*

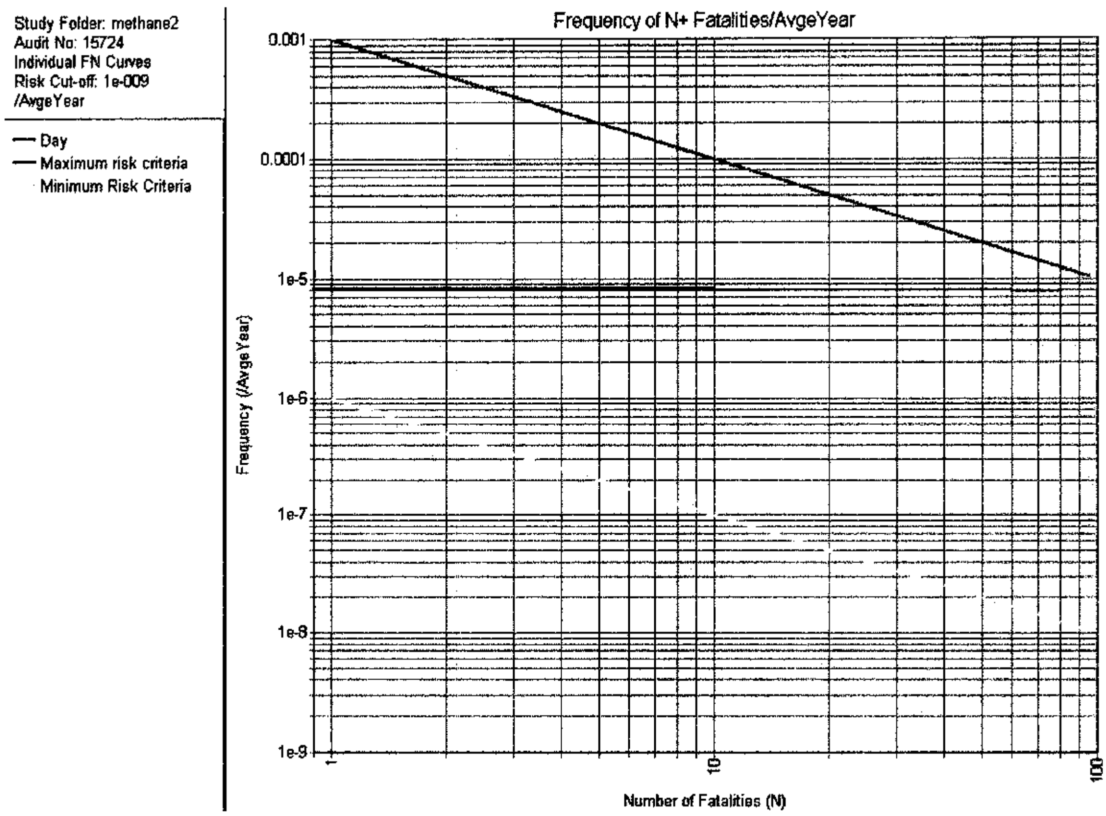
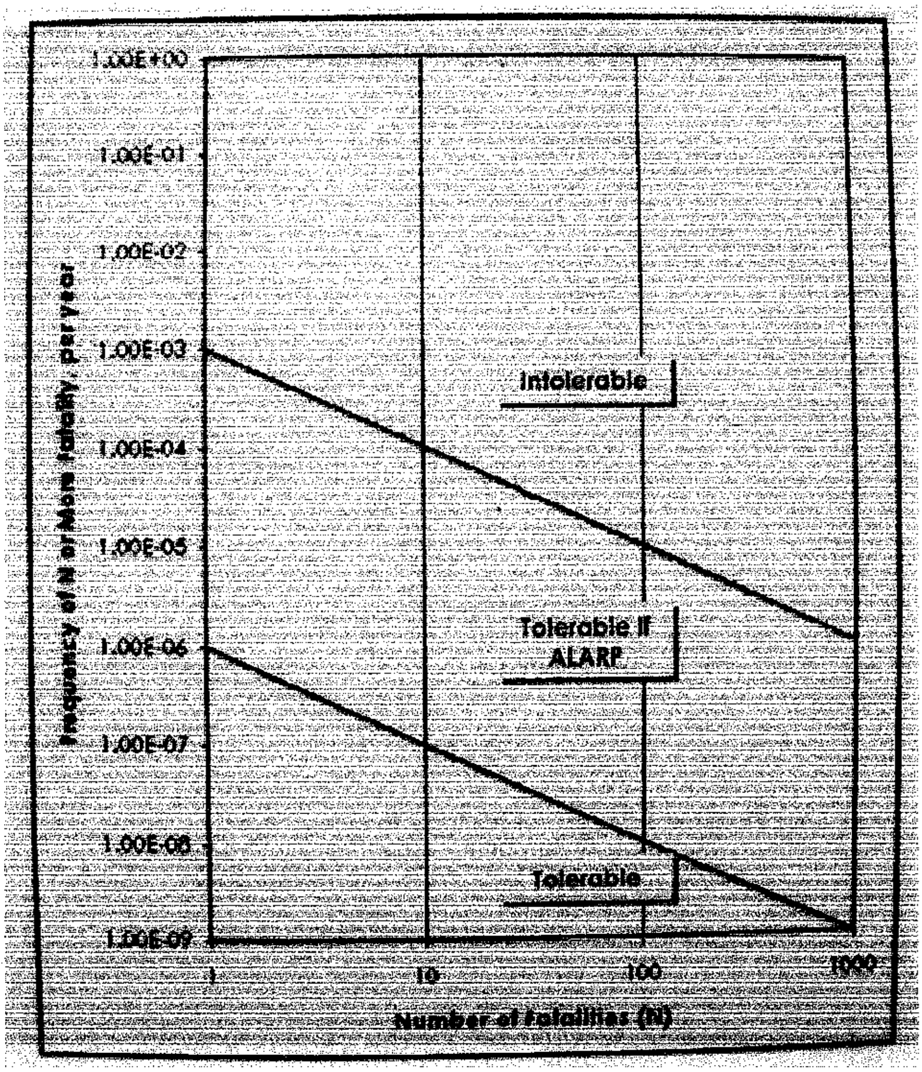


Figure I8: *FN curve*

APPENDIX J

MALAYSIAN F-N CURVE



APPENDIX K

GAS COMPOSITION IN CURRENT CO_2 PIPELINE

	Canyon reef carriers	Central basin pipeline	Sheep mountain	Bravo dome source	Cortez pipeline	Weyburn	Jackson dome, NEJD
CO_2	85-98	98.5	96.8-97.4	99.7	95	96	98.7-99.4
CH_4	2-15	0.2	1.7	-	1-5	0.7	Trace
N_2	<0.5	1.3	0.6-0.9	0.3	4	<300ppm	Trace
H_2S	<200ppm	<20ppm	-	-	0.002	0.9	Trace
H_2O	50ppm wt	257ppm wt	129ppm wt	-	257ppm wt	20ppm vol	-
C_2+		-	0.3-0.6	-	Trace	2.3	-
CO	-	-	-	-	-	0.1	-
NOx	-	-	-	-	-		-
SOx	-	-	-	-	-		-
H_2	-	-	-	-	-	Trace?	-
Ar	-	-	-	-	-		-