DEVELOPMENT OF A NATIONAL RISK ACCEPTANCE CRITERIA FOR MANAGING MAJOR INDUSTRIAL HAZARDS

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DECLARATION BY CANDIDATE AND SUPERVISOR

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DEDICATION

“Dedicated to my Father and late Mother”

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ABSTRACT

This work attempts to address the issue of managing risk to the safety of the public posed by Major Accident Hazards (MAH) from the Chemical Process Industry (CPI) in Sri Lanka. The research essentially focuses on the establishment of a suitable risk acceptance criteria as well as an appropriate framework that can be used in determining the level of safety offered by a particular MAH installation in Sri Lanka. The “level of safety” of an installation is then compared against the risk acceptance criteria to determine its acceptability in the Sri Lankan context.

The history of process safety management as is understood at present was investigated and the different risk regulation regimes currently in practice globally were identified. The role of risk assessment in each risk regulatory regime was investigated and the need for risk informed decision making was firmly established. The thesis then focuses on the prevalent categories of approaches in risk assessment. The different risk assessment approaches are investigated further. Out of those approaches, the consequence assessment and probabilistic risk assessment approaches or methods were chosen for the development of the risk assessment framework. The different risk metrics used to express the risk for each approach and the respective risk acceptance criteria were identified. Then appropriate risk acceptance criteria were developed for the two approaches. The establishment of a safety distance corresponding to 1% fatality of the public was adopted for the consequence based assessment method whereas a FN criteria line with an anchor point of (10, 10^{-4}) and slope -1 was chosen for the probabilistic risk assessment method.

The applicability of the different risk acceptance criteria in the Sri Lankan context is carried out for the case of propane storage tank. Data gaps and constraints are identified. Both methods adopt a conservative decision making approach. A significant constraint is the lack of a nationally verified and validated set of failure rate data for process equipment and ignition probability data; these are essential for establishing conditional probabilities when calculating accident frequencies. The usage of generic data for failure rates is not recommended due to the wide variability in different data sources. Further, allowing room for choosing an arbitrary set of failure rate data could create an opportunity for biasing the risk acceptance decision.

In this work, a framework is presented for applying the risk acceptance criteria developed. An FN curve based on upper bound data for the probabilistic risk assessment method and modified consequence assessment method are developed. The probabilistic risk assessment method is modified to accommodate the variability in generic failure rate data. The decision of acceptability is made by defining an FN curve using upper bound values of the FN curve and comparing it with the criterion line. A safety distance proportionate with the overall level of risk based on a relative risk reduction factor (RRRF) is introduced.

Keywords: Major Accident Hazard, Risk Acceptance, Criterion Line, Consequence analysis, Quantitative Risk Assessment, Failure rate

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
CPI	Chemical Process Industry
AEGL	Acute exposure guideline level
ALARP	As low as reasonbly practicable
ALOHA	Areal location of hazardous areas
API	American Petroleum Institute
API RP	American Petroleum Institute Recommended Practice
ASME	American Society of Mechanical Engineers
BLEVE	Boiling liquid expanding vapor explosion
CA	Consequence Assessment
CAAA	Clean Air Act Amendment
CCPA	Canadian Chemical Producers Association
CCPS	Center for Chemical Process Safety
CFR	Code of Federal Regulations
CIMAH	Control of Industrial Major Accident Hazards
COMAH	Control of Major Accident Hazards
CRED	Center for Research on the Epidemiology of Disasters
DEGDIS	Dense gas dispersion
DMC - SL	Disaster Management Center - Sri Lanka
DTL	Dangerous toxic load
EIA	Environment Impact Assessment
EPA	Environment Protection Agency
ERD	Emergency Response Division
ERPG	Emergency Response Planning Guideline
ETA	Event Tree Analysis
EU	European Union
FF	Failure frequency
FMEA	Failure modes and effects analysis
FRED	Failure rate and event data
FTA	Fault Tree Analysis
HAZID	Hazard identification
HAZOP	Hazard and Operability
HEGADIS	Heavy gas dispersion from Area Sources
HI	Hydrocarbon Industry
IDLH	Immediately dangerous to life and health
IP	Institute of Petroleum
IPL	Independent Protection Layer

IR	Individual Risk
IRPA	Individual Risk per annum
KPI	Key Performance Index
LEL	Lower explosive limit
LFL	lower flammability limit
LOC	Loss of containment
LOPA	Layers of Protection Analysis
LPG	Liquefied Petroleum Gas
LUP	Land use planning
MAH	Major Accident Hazard
MIC	Methyl Iso Cyanate
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
OGP	International Association of Oil & Gas Producers
OSHA	Occupational Safety and Health Administration
PFD	Probability of failure on demand
PSM	Process Safety Management
QRA	Quantitative Risk Assessment
RBI	Risk based insepction
RIVM	Netherlands National Institute for Public Health
RMP	Risk Management Plan
RRRF	Relative risk reduction frequency
SLOD	Significant likelihood of death
SLOT	Specified level of toxicity
SR	Societal Risk
TCDD	Tetrachlorodibenzoparadioxin
TNO	Netherlands organization for applied scientific research
UK	United Kigndom
UK HSE	United Kigndom Health and Safety Executive
UN	United Nations
VCE	Vapor Cloud Explosion

CHAPTER 1

1.0 INTRODUCTION

1.1 BACKGROUND

The development of the Sri Lankan Chemical Process Industry (CPI) and the Hydrocarbon Industry in particular is an essential requirement towards the development of the country's economy. However, the development of the CPI leads to an increase in the scale and complexity of the installations as well as the associated operations. This aspect brings into focus significant challenges which need to be addressed in order to benefit from the available opportunities.

A significant challenge related to the CPI is the risk posed by a category of hazards related to industrial activity, generally referred to as Major Accident Hazards (MAH). At present, a clear definition for the term MAH installation with reference to Sri Lanka is not available in literature. Therefore, in this thesis the following definitions are considered for the purpose of major accident hazards and installations with major accident potential,

1. Major Accident –An uncontrolled occurrence due to the release of a chemical substance or petroleum product resulting in either a toxic effect, fire or explosion causing fatalities of 10 or more (Ball & Floyd, 1998)
2. Major Accident Hazard - The intrinsic property of a dangerous substance or physical situation, with a potential for creating damage to human health or the environment (Health & Safety Executive UK [UK HSE], 2015)
3. Installation - A technical unit within a location under the control of an operator in which dangerous substances are produced, used, handled or stored; it includes all the equipment, structures, pipe work, machinery, tools, private railway sidings, docks, unloading quays serving the installation, jetties, warehouses or similar structures necessary for the operation of that installation (UK HSE, 2015).

The types of industries in Sri Lanka coming within the aforementioned definition are selected in conformance within the existing regulatory framework of the country. At present large scale development projects or projects in environmentally sensitive areas in Sri Lanka are subjected to an Environmental Impact Assessment (EIA) process. The amendment to the National Environmental Protection Act No.47 of 1980 named as Act No.56 of 1988, introduced the EIA process to Sri Lanka. However, the EIA process became fully operative with the publication of the required orders and regulations in 1993 in the Government Extraordinary Gazette No.772/22 of 1993. The Gazette No.772/22 of 1993 specifically provides a list of "prescribed projects" which are to be subjected to an EIA process. This thesis considers the following subset of categories of industries stated in the aforementioned Gazette No.772/22 of 1993,

1. Basic Industrial Chemicals
2. Pesticides and Fertilizers
3. Petroleum and Petrochemicals

The scope of this definition considers only installations sited onshore.

MAH leads to catastrophic events leading to multiple fatalities and significant asset damage within the plant as well as in the surrounding neighborhoods of the respective CPI installation. Such events although rare (low probability) can lead to significantly adverse impacts on the public perception leading to potentially damaging litigation and regulatory outcomes for that particular industry and the industrial sector as a whole. Hence, it is imperative that risks from MAH are identified, estimated, assessed, reduced to an acceptable level, monitored and managed.

The Sri Lankan CPI has so far been spared from a Major Accident, possibly due to the comparatively low scale and complexity of industrial operations in the country. However, this is not a guarantee that such an accident will not occur in the future. When the necessary conditions are fulfilled for a MAH to be realized, a major accident is most likely to occur. Hence, it is necessary for Sri Lanka to be equipped with a suitable mechanism to estimate and assess such risks as well as a robust decision making framework for evaluating and selecting CPI installations.

A critical aspect of the risk assessment process is the “level of risk” deemed safe or acceptable to a particular society or regulator; or in other words – “How safe is safe enough?” The acceptable “level of risk” leads to the determination of the “risk acceptance criteria”. The risk acceptance criteria should be supported by a robust decision making framework.

This research proposes societal risk acceptance criteria for establishing safe distances and a decision making framework for risk assessment using frequency of occurrence of an accident and number of fatality.

1.2 PROBLEM STATEMENT

The evaluation of major CPI projects in Sri Lanka at present is limited to the Environment Impact Assessment (EIA) process as described in section 1.1. The risk posed by MAH and the catastrophic nature of its consequences are not considered in a consistent manner. There is no nationally recognized “Risk Acceptance Criteria” and/or methodology at present for determining the safe risk level for society with respect to MAH installations in Sri Lanka. Furthermore, safety aspects such as vulnerability of humans, potential of damage to the public and extent of physical damage depend on the nature of the MAH involved. These aspects need to be captured in the existing EIA process of the country or in any other appropriate assessment instrument.

Hence, a significant gap exists with respect to the assessment and management of MAH in the Sri Lankan context. A risk assessment and management method cannot be developed for Sri Lanka without establishing a suitable risk acceptance criteria and framework for risk assessment. Any such criteria must be transparent in its development as well as in its application.

Hence, for consistent decisions when assessing major CPI projects with MAH potential, a suitable and sufficient risk assessment mechanism ably supported by a regulatory framework is required for Sri Lanka. This research addresses the development of a risk informed decision making process and focuses specifically on developing a suitable “risk acceptance criteria” for the CPI in the Sri Lankan context and a risk assessment framework.

The risk acceptance criteria and risk assessment decision making framework developed in this research considers only onshore fixed installations with MAH potential in the CPI. Facilities such as offshore installations, marine and overland transportation (marine & overland) and pipelines (cross country and subsea) are excluded from the scope.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to develop and propose suitable risk acceptance criteria for deciding on the acceptability of MAH installations in Sri Lanka and to develop a decision making framework with respect to the risk faced by the public or the society.

The following sub objectives are included in this research,

1. To identify and establish Risk Evaluation Data
2. To apply in a case study in the Chemical Process Industry (CPI)

1.4 ORGANIZATION OF THE THESIS

The thesis is organized as follows. Chapter 1 is an introductory chapter outlining the background leading to this research, the research problem, the research objectives and structure of this thesis. Chapter 2 provides a literature review of the historical development of risk management in the CPI, with emphasis on how major accidents in the world have led to the development of different regulatory approaches and the shift towards risk based decision making. Chapter 2 also consists of a detailed review of the different risk acceptance criteria and risk assessment frameworks in practice globally with respect to MAH. In Chapter 3 risk acceptance criteria are derived for two different risk assessment approaches; the consequence based assessment and probabilistic risk assessment methods. Viable risk assessment approaches appropriate for Sri Lanka are chosen and “risk acceptance criteria” are developed based on Sri Lankan accident data applicable for MAH analysis. In Chapter 4, the different risk assessment criteria are applied in a case study of a propane storage tank in the hydrocarbon industry to assess or test their applicability. Chapter 5 consists of a comparison of the different criteria assessed in Chapter 4. Further it proposes a framework for selecting an appropriate risk assessment criteria and risk assessment methodology for the decision making process. Chapter 6 demonstrates the applicability of the risk acceptance criteria and the methodology developed in chapter 5, which is a probabilistic risk based method, using a case study of a propane storage tank. This application is done to demonstrate the applicability of the selected methodology to Sri Lanka and availability of data. The availability of data with respect to failure frequencies and conditional probabilities are considered in detail. Shortcomings in data availability and applicability with respect to the selected “risk acceptance criteria” are then identified. Chapter 6 provides the rationale for the selection of the appropriate “risk acceptance criteria” and the applicable decision making framework. Chapter 7 provides conclusions and recommendations for future works for the application and further development of the “risk acceptance criteria”.

CHAPTER 2

2. LITERATURE REVIEW

This chapter reviews the historical development of risk assessment criteria within the context of different risk regulatory regimes, risk assessment methods, risk metrics and risk criteria. The development of legal instruments related to control of risks posed by MAH installations, risk assessment methods and associated risk assessment criteria are reviewed in the order it has evolved. A study of risk assessment criteria would be incomplete without considering the historical factors leading to the development of risk assessment as practiced at present.

2.1 INTRODUCTION

Modern process safety management and initiatives to manage MAH in the CPI has its roots in a series of events occurring between years 1970 to 2000 (Mannan, Chowdhury & Reyes, 2012). The scale of these industrial accidents had a profound impact on the public perception resulting in both industries and governments across the world rethinking about the safety of technology and management systems in industries.

2.2 SEMINAL EVENTS

The Flixborough disaster in 1974 launched the effort which culminated in modern Process Safety Management (PSM). The fire and explosion at the Flixborough Plant at Nypro Ltd (UK), producing caprolactum, resulted in 28 fatalities, complete destruction of the industrial site and domino effect on other industrial activity in the area (Wettig, Porter & Kirchsteiger, 1999). This accident was followed by the following major chemical accidents,

- Icmesa Chemical Company,Seveso, Italy (1976) – Toxic release of dioxin (TCDD)
- Bhopal, India (1984) – Toxic release of methyl isocyanate (MIC);Considered as the world’s worst industrial disaster thus far

- Piper Alpha, UK, North Sea (1988) – Explosion and fire on the Piper Alpha Offshore platform causing 167 deaths and the total destruction of the facility

While there were other major accidents during the period under consideration (Mexico – 1984, Philips – 1989), the aforementioned events led to major changes in the way MAH was managed in the CPI. Some of the changes were in fact paradigm shifts in how risk was perceived and managed within the CPI. Hence, a study of modern PSM in MAH would be incomplete without a detailed look at these seminal events and the resulting regulatory and legislative outcomes.

2.2.1 THE REGULATORY RESPONSE TO FLIXBOROUGH, UK – 1974

This major disaster resulted in the formation of the Advisory Committee on Major Accident Hazards (ACMH) in the UK and the Health and Safety at Work Act (Wettig et al., 1999). While the response was essentially regional, it formed the cornerstone for the introduction of consequence modeling and risk assessment in the CPI which led to the subsequent risk based approach.

2.2.2 THE REGULATORY RESPONSE TO SEVESO, ITALY – 1976

The Seveso Directive was passed by the European Community in 1982 as a consequence of the public outcry over the release of tetrachlorodibenzoparadioxin (TCDD) in Seveso, Italyin 1976 (Wettig et al., 1999). The UK passed the Control of Industrial Major Accident Hazards (CIMAH) regulation in 1984 (The UK updated CIMAH to “Control of Major Accident Hazards – COMAH” as a result of Seveso II in 1999.). The Seveso Directive was updated again in 1999 and amended in 2005 as the Seveso II Directive forming the backbone of almost all regulatory approaches for the management of MAH in the EU member countries until 2012. The Seveso II directive is now superseded by the Seveso III directive which was adopted in 2012 by the EU . Seveso III places emphasis on classification of chemicals and rights of citizens to access information and justice.

2.2.3 BHOPAL AND ITS REGULATORY AFTERMATH - BHOPAL, INDIA IN 1984

The most severe chemical accident ever, Bhopal can be considered as a “wake up call” to the CPI (Mannan, West, Krishna, Aldeeb, Keren, Saraf, Liu & Gentile, 2005). The regulatory response took place on a global scale.

In the USA, the US Congress passed the Clean Air Act Amendment (CAAA) in 1990. The legislation contained three major provisions. OSHA came up with the PSM standard more formally known as the “Process Safety Management of Highly Hazardous Chemicals (29 CFR 1910.119)”. The EPA created the RMP or Risk Management Plan Rule (40 CFR 68). The PSM standard and the RMP Rule address different needs of the CPI as given below,

- PSM Standard – Process Safety
- RMP Rule – Protection of Personal and Surrounding Communities from hazards associated with an accidental release

The EU responded by amending the Seveso I regulations. Canada responded with the Responsible Care® program which was developed by the Canadian Chemical Producers Association (CCPA).

2.2.4 PIPER ALPHA DISASTER, NORTH SEA, UK – 1988

The total destruction of the offshore platform “Piper Alpha” with a majority of the crew (165 fatalities) in the North Sea in 1988 (Dahle, Dybvig, Ersdal, Guldbransen, Harrison, Tharaldsen & Wiig, 2012) was a defining event which changed the way in which risk assessment was conducted. The public reaction and inquiry resulted in Lord Cullen’s Report which introduced the Safety Case Regulations in 1992. This resulted in a dramatic change in the manner safety is managed in the Offshore Oil & Gas Industry worldwide.

2.3 SUBSEQUENT DEVELOPMENTS

The aforementioned regulations and initiatives contributed towards wider awareness on MAH in the CPI and safer installations. However, Major Accident Hazards did continue to happen worldwide. Incidents such as the Explosion at Toulouse, France in 2001 (30 Fatalities), Texas City – USA in 2005 (15 fatalities), the much publicised Macondo Well Blowout in the Gulf of Mexico, USA in 2010 (11 fatalities) and the explosion and fire in the port city of Tianjin, China in 2015 highlighted the gaps in the structure as well as the implementation of existing systems. However, it should be emphasized that most installations are safer today due to regulations stemming from the lessons learnt.

The EU brought changes in the Seveso II Directive as a response to the incident in Toulouse, France while France made drastic changes in the way risk assessment is applied to Land Use Planning (LUP) (Taveau, 2010). The outcome to the Texas City incident resulted in the Baker Report in 2007. The Buncefield incident in the UK resulted in far reaching recommendations for Tank Farm Management and Siting.

The regulations in effect and the management approach currently in place globally for controlling the MAH in the CPI are shaped by these historical developments. Regulations have been essentially shaped as a consequence of specific major accidents, the subsequent societal response as well as the lessons learnt. However, the management systems and risk assessment criteria have been largely defined by how society perceives risk resulting from demographic variations. Societal aversion to risk has largely been determined by regional and cultural differences resulting in a marked variation in the regulatory and legislative systems developed for the management of MAH. This fact has been reflected in the difference between the US and EU regulations. The EU regulations are biased towards performance based regulations, whereas the USA follows a mix of performance based as well as prescriptive standards (Pitblado, 2011).

2.4 COMPARISON OF MAJOR RISK REGULATORY REGIMES FOR MAJOR ACCIDENT HAZARDS

The two main demographic regions with well developed Major Accident Hazard (MAH) regulations are the European Union (EU) and the United States of America (USA). The development of MAH regulations in both regions have been stimulated by specific major accidents (Wetig, Porter & Kirchsteiger, 1999). However, the MAH regulations of the two regions vary significantly in many aspects (Hopkins, 2011). The EU follows a "performance based regulatory system" with heavy emphasis on risk assessment whereas the USA has adopted a combination of both "performance based and prescriptive regulations" with more emphasis on process safety management systems.

The regulations currently in effect over the world are either,

1. Performance based
2. Prescriptive
3. Combination of Performance and Prescriptive based (i.e. Hybrid)

The ability of the respective regulatory regimes to effectively control MAH is still a much debated topic. Prescriptive or rule compliance is considered as the traditional approach, whereas performance based regulation is considered to be a more modern approach (Taveau, 2010). The shift towards performance based regulation/ goal setting regulation from prescriptive regulation started in the early 1970's with the recommendation of Lord Robens requiring employers in the UK to ensure the safety of workers by lowering risk to "as low as reasonably practicable (ALARP)". Both approaches have a certain level of risk assessment and commitment to an overall risk management framework. The proponents of rule compliance too support an overall risk management approach (Vesluis, Van Asselt, Fox & Hommels, 2010). However, the depth of risk analysis may differ between the two approaches stated above. In a regulatory regime where risk assessment forms the core of the decisions making process, risks are considered to be calculable, controllable and reducible (Christou, Amendola & Smeder, 1999).

2.5 INVESTIGATION OF RISK ASSESSMENT APPROACHES IN THE CPI WITH RESPECT TO MAJOR ACCIDENT HAZARDS

2.5.1 INTRODUCTION

Different regulatory regimes for the management of Major Accident Hazards (MAH) prevail in different regions of the world due to demographic and cultural differences as stated in section 2.4. However, all regulatory regimes have at their core, the process of risk assessment. A wide variation in risk assessment approaches can be seen based on historical, cultural and demographic characteristics of the region in which a particular approach and acceptance criteria has developed. Different countries have differing approaches with respect to risk management culture and philosophy based on their own experience and degree of risk aversion perceived by society.

2.5.2 DEFINITION OF RISK

The notion of “risk” has different meanings in different disciplines (financial risk, political risk, security risk, technological risk). A generally accepted definition of the term “risk” is difficult to find. The definition offered by (Kaplan & Garrick, 1981) is adopted in this work as it provides a comprehensive means of defining accident scenarios. Their definition tries to answer the three fundamental questions given below.

1. WHAT can go wrong?
2. HOW LIKELY is it that this (i.e. event) will happen?
3. IF IT DOES, what are the CONSEQUENCES?

This approach provides the analyst with a mechanism for defining different “scenarios” (question 1) and then deriving a quantitative risk measure (questions 2 &3). Kirchsteiger elaborates this concept further (Kirchsteiger, 1999). Kirchsteiger states that risk analysis for a system fundamentally is a response to the three questions given above and combining the individual responses to one statement for the purpose of decision – making. According to Kirchsteiger, risk analysis means reconstructing reality by means of the above three questions in an either qualitative or quantitative way, resulting in statements or numbers. He summarizes the response to the three questions as follows,

- What can go wrong? – Response to this question relies entirely on qualitative type of analysis, resulting in the identification and qualitative ranking of all possible failure events and event sequences.
- How likely and what are the consequences? – The response to the 2nd and 3rd questions can be through either a qualitative or quantitative analysis. For this purpose deterministic or probabilistic modeling approaches can be used.

The outcome of this approach yields the following information shown in Table 2.1 for a particular MAH installation (Kaplan and Garrick, 1981). This paper bases its definition of "Risk" fundamentally on the above definition.

Table 2.1 – Listing of Accident Scenarios

SCENARIO (S_i)	LIKELIHOOD (f_i)	CONSEQUENCE (n_i)
S_1	f_1	n_1
S_2	f_2	n_2
.	.	.
S_m	f_m	n_m

Source: Kaplan and Garrick, 1981

Where,

i – ith accident scenario where the total number of accident scenarios is m, S_i – Description of identity of the ith Accident Scenario, f_i – Probability of the ith scenario, n_i– Consequence due to the ith scenario

2.5.3 RISK ASSESSMENT APPROACHES AND THEIR CATEGORIZATION

Risk assessment can be broadly defined as a structured procedure to evaluate qualitatively and/or quantitatively the level of risk imposed onsite and/or offsite by hazard sources identified within the installation (Cozzani, Bandini, Basta & Christou, 2006). However, the risk assessment approaches and methodologies with respect to major accident hazard installations vary widely as emphasized in paragraph 2.1. A number of researchers have attempted to categorize these different approaches as shown in Table 2.2. However, a review of the different approaches reveals that they can be assigned to the following broad classes with respect to the methodology of assessment,

- Consequence based
- Risk based

Table 2.2 – Comparison of Different Risk Assessment Approaches

	SOURCE	***CATEGORIES***	***BASIS***
1	(Christou et al., 1999)	Consequence based	Focuses on the assessment of consequences of a number conceivable event scenarios.
		Risk Based	Focuses on the assessment of both consequences and probabilities of occurrences of the possible event scenarios
		Generic "Safety" Distances	Focuses on the type of industrial activity rather than a detailed analysis of the specific site; derived from expert judgement, historical data, experience and/or environmental impact of the plant
2	(Cozzani et al.,2006)	Consequence based	Focuses on the assessment of consequences of a number conceivable event scenarios (Reference Scenarios)
		Risk Based	Focuses on the assessment of both consequences and occurrence frequencies of the possible event/accident scenarios
		Safety Distances	Focuses on a simplified approach based on expert judgement, historical data, experience and/or environmental impact of the plant
		Hybrid criterion	Consequence oriented approach followed by accounting of accident frequencies as a mitigation factor for the identified damage zones
3	(Christou et al., 2011)	Deterministic approach	Usage of pre – defined separation distances (deterministic) depending on the type of hazardous substances present
		Consequence based	Focuses on the assessment of consequences of a number conceivable event scenarios
		Risk based	Focuses on the assessment of both consequences and probabilities of occurrences of the possible event scenarios
		Semi - quantitative	Some parameters of risk are assessed in a quantitative way (e.g. likelihood analysis) while others are assessed qualitatively (e.g. consequence assessment).
4	(Christou et.al,2006)	Consequence based	Assessment of consequences of credible (or conceivable) accidents, without explicitly quantifying the likelihood of the accident
		Risk based	Evaluates the severity of the potential accident, and estimates the likelihood of their occurrence
		State of the Art	Objective of operation without imposing any "conceivable" risk to the population outside the fence of the installation (Zero Risk Principle); Implicit judgement of risk
		Hybrid Methods	Semi – Quantitative methods where a specific quantitative element (e.g. likelihood analysis) is accompanied by a qualitative one (e.g. the consequence assessment)

All other classifications are essentially either a subclass or a hybrid of the aforementioned methodologies. As per Table 2.2, the different risk assessment methodologies can be divided into the following categories,

1. Deterministic Approach/ Generic “Safety” Distances Approach
2. Consequence Based Approach
3. Risk Based/ Probabilistic Approach
4. Semi quantitative/ Hybrid Approach

The following discussion is based on the aforementioned categorization.

2.5.3.1 DETERMINISTIC OR GENERIC SAFETY DISTANCES APPROACH:

The concept of generic safety distances is based on the principal that uses of land which are not compatible with each other should be separated by separation distances (Cozzani et al., 2006). This is a straight – forward and simplistic approach; pre – defined (deterministic) separation distances are used. The focus is on the type of activity and the quantity of hazardous substance present in the installation. A detailed analysis of the specific site is not performed. The safety distances are derived from expert judgment based on,

- Historical data
- Experience from operating similar plants/installations
- Environmental Impact of the Installation

Christou et al., in their study of different types of risk assessment approaches (Christou et al., 1999), states that the concept of practically “zero risk” forms the basis of this approach. According to this principle, no residual risk is allowed to be present outside of the borders of the installation. These safety distances may be elaborated in national regulations which are prescriptive in nature or voluntary standards such as IP 15, API 500 and/or NFPA 30 etc.

A major disadvantage of this method is that, the design characteristics, safety measures and inherent characteristics of the installation under consideration is not accounted for. However, this approach of generic safety distances is useful when a formal risk assessment/ consequence assessment is not available.

This approach is mainly adopted in countries such as Germany and Sweden. The German approach breaks down the uses of the land into categories, where different categories have to be separated by appropriate safety distances. Furthermore, the installation should be established and operated so that no risk is imposed to man or environment. The Swedish approach though established on similar principles differs due to the fact that the safety distances are based on effects from normal plant process emissions (e.g. noise, smell and continuous emission of chemicals) and not on risk or consequence of major accidents (Cozzani et al.,2006).

2.5.3.2 CONSEQUENCE BASED APPROACH:

This approach explicitly considers the consequences of credible or conceivable accidents without quantifying their likelihood. According to some researchers this approach circumvents the quantification of frequencies of occurrence of the potential accidents and their related uncertainties (Kaplan & Garrick, 1981; Christou, 2011).

The fundamental principle behind this approach is based on the existence of one or more “worst credible scenario(s)” or reference scenarios (Markowsky & Mannan, 2010). It is assumed that if there are enough measures to protect the population from the worst conceivable accident, enough protection will be provided for any accident having a lesser impact than the worst. This approach is highly dependent on the selection of credible or conceivable scenarios. These scenarios are defined using the following,

- Expert judgment
- Historical data

- Qualitative information from Hazard Identification

Extremely unlikely scenarios may not be considered as “credible” or “conceivable” and may be excluded from further analysis. However, the consideration of likelihood albeit qualitatively is an implicit consideration of the probability of an event. Major criticism of this method stems from the difficulty in selecting the credible or conceivable scenarios; experience has shown that accidents initially believed to be “worst” resulted in less consequences than others considered to be less severe.

Consequence analysis requires the application of mathematical models to estimate the consequences of potentially hazardous events. The models may vary from simple mathematical models to software based solutions with large data bases inclusive of physical & chemical property data. The detail and complexity of the consequence analysis will depend on the type of hazards and facility specific conditions. More refined models require more detailed design information and more time for analysis. The selected model should be appropriate for the specific scenario(s) being analysed. The decision criterion for this method is the extent of the consequence from a credible/ conceivable scenario. The consequences of the accidents are taken into consideration quantitatively by estimating the distance in which the physical magnitude describing the consequences reaches a threshold value corresponding to the undesired effect (International Association of Oil & Gas Producers, 2010). The threshold values prevalently in use are (International Association of Oil & Gas Producers [OGP], 2010),

- Toxic releases – The IDLH(Immediately Dangerous to Life & Health), ERPG – 2 (Emergency Response Planning Guideline), LOC (Level of Concern), LC1% (Lethal Concentration corresponding to the first death)
- Thermal effects – Thermal radiation corresponding to 3rd degree burns (e.g. 5 kW/m^2)
- Explosions – Overpressure corresponding to eardrum rupture (e.g. 140 mbar)

In addition to the “lethal threshold” distance, the distance corresponding the beginning of “irreversible” effects is estimated if required. This “irreversible” distance is used for separation of areas with sensitive population (e.g. schools, hospitals) or very densely populated areas from the hazardous installation. Hence,- two distances or zones can be defined in this approach as follows,

- Internal zone – Beginning of lethal effects
- External zone – Beginning of irreversible effect

In the "Internal Zone – Z1", no urban development is allowed while no sensitive population or increased densities are allowed in the "External Zone – Z2" (Refer Fig 2.1).

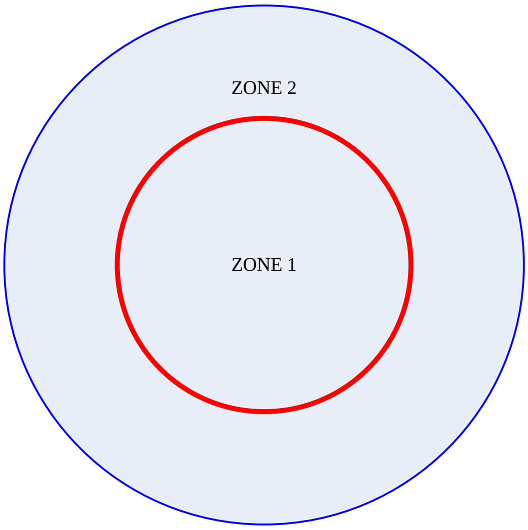


Figure 2.1 – Land Use Restriction Zones According to the Consequence Based Approach, Source: (Cozzani et al., 2006)

A similar approach was used in France until 2003 (Taveau, 2010). The approach followed in the USA for emergency planning and communication to the public is similar (Cozzani et al., 2006).

2.5.3.3 THE RISK BASED APPROACH:

The "Risk Based Approach" not only evaluates the severity of the potential accidents but also estimates the likelihood of their occurrence in quantitative terms. Hence this approach is often referred to as “Probabilistic Risk Assessment”. It is also known as Probabilistic Risk Analysis due to its emphasis on the quantification of the probability of occurrence of an event. The Probabilistic Risk Assessment process is shown in figure 2.2 below. The assessment methods are more sophisticated and can be considered as being more complete than the other methods discussed so far. However, they are proportionately more time consuming and expensive to conduct.

This approach defines the risk as a combination of the consequences derived from the range of possible accidents and the likelihood of the accidents. Four phases are identified in this approach (Cozzani et al., 2006),

- Identification of Hazards
- Estimation of the probability of occurrence of the potential accidents
- Estimation of the Consequences of these accidents
- Integration into overall risk indices

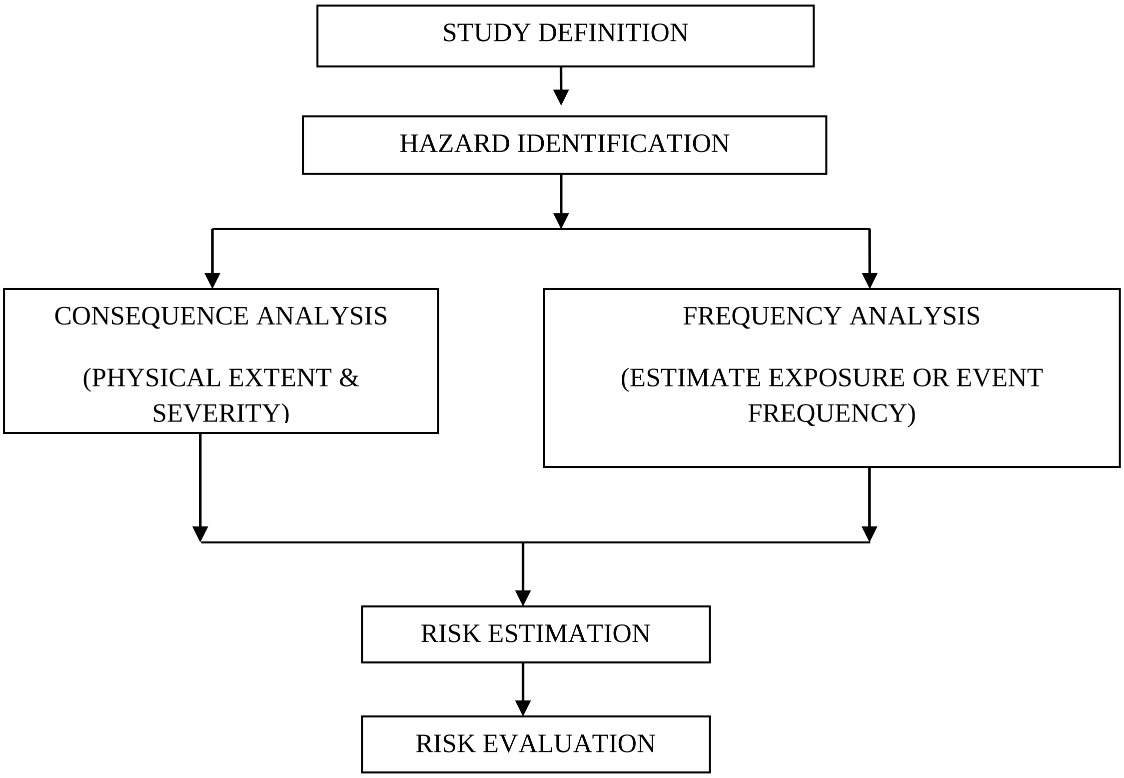


Fig 2.2 – Probabilistic Risk Assessment Process

The consequence analysis process would be almost identical to consequence analysis approach. However, the frequency analysis requires the estimation of frequency of occurrence for the identified accident scenarios. The following two approaches are commonly used,

- Event Tree Analysis (ETA)
- Failure database reference – Historical data

Other techniques, such as fault tree analysis (FTA) and Failure Modes and Effects Analysis (FMEA) are also used.

The “Risk Based Approach” defines two types of risk measures. Namely,

- Individual Risk
- Societal Risk

The Individual Risk (IR) is defined as the probability of reference damage (e.g. fatality/ receiving a dangerous dose) due to an accident in the installation for an individual located at a specific point in the vicinity of the installation. Whereas, Societal Risk (SR) is defined as the probability of the occurrence of any single accident resulting in reference damage (e.g. fatalities) greater than or equal to a specific figure. Individual Risk is presented by iso – risk curves, while societal risk is presented using the relationship between Cumulative Frequencies, F vs N number of or more fatalities; commonly known as FN curves.

The Individual Risk criterion is applied for the protection of each individual against a hazardous event; however it does not depend on the population around a plant. It expresses a pre – set level of risk, above which no individual is permitted to be exposed. The SR criterion primarily focuses on the protection of society as a group against the occurrence of large scale/ major accidents; it requires information on the population density around the plant as well as their temporal variation during the course of a day. The underlying philosophy in assigning these two criterions is that even when individual risk criterion is met, if a population center is located close to “safety distance” it is possible that a major accident can cause a large number of fatalities (Christou, Struckl & Biermann, 2006). The Netherlands, the UK, Australia, Switzerland and the Flemish region of Belgium follows the risk based approach (Christou, Amendola & Smeder, 1999).

2.5.2.4 HYBRID/ SEMI – QUANTITATIVE APPROACH:

Methods falling under this category are essentially a subcategory of the risk – based or the consequence approaches where a quantitative element is accompanied by a qualitative element (Christou, 2011).

The level of risk posed by an installation with MAH potential in the vicinity of sensitive receptors depends on the following,

- The potential scenarios that may lead to a MAH
- Their occurrence frequencies
- Their severity and extent
- Vulnerability of the receptors in the vicinity
- The size of the affected population

Each of the parameters given above can be assessed as follows,

- Quantitatively – Assessing the exact value together or not with the relevant uncertainty measure
- Semi quantitatively – Assessing the range of the parameter instead of giving the exact value
- Qualitatively – Giving a description of the magnitude of the parameter

Acceptability is then assessed by analysing the level of each element and applying certain combination rules (e.g. Risk Matrix). France and Italy follow a similar hybrid approach at present.

An example of a widely used hybrid approach is the Layers of Protection Analysis (LOPA) approach. LOPA is a simplified risk assessment method and has at its core the concept of Independent Protection Layers (IPLs). LOPA assumes that no protection layer is perfect; every layer has some probability of failure on demand

(PFD) and may not perform independently of other layers of protection (Markowsky & Mannan, 2010). The LOPA methodology provides an opportunity to assess the adequacy of existing safeguards (if any) and to decide any additional safeguards which may be needed.

2.6 RISK ASSESSMENT CRITERIA

The results from each risk assessment approach require interpretation. They should be assessed and interpreted based on acceptance criteria unique to each risk assessment approach. These criteria are primarily dependent on the concept of "Risk Aversion" and "Risk Perception" of the particular society in which the criteria was formulated; it is in essence a response to the question, "How safe is safe enough?". Hence, it will also need to consider not only the methodology adopted but ethical and philosophical considerations as well.

The ultimate purpose of risk analysis is to generate information in order to arrive at an informed decision. However, the level of information generated and depth of analysis is directly dependent on the manner in which the results are expressed in terms of one or more risk metrics (Johansen & Rausand, 2012). The risk metric is a quantitative benchmark. However a variety of risk metrics exist (Johansen & Rausand, 2012). The term risk can have different meaning to different stakeholders giving rise to the question which risk metric provides the most appropriate representation of the risk scenario. Hence, the selection of a single or multiple numbers of risk metrics is critical in representing a particular category of risk for decision making. Therefore, two critical questions have to be answered when selecting risk metrics to represent a particular decision making context,

1. Whether to choose a single risk metric or multiple risk metrics?
2. Which risk metric(s) to choose from

The answers to the aforementioned questions require a thorough review and analysis of the prevailing risk metrics with respect to their explicit and implicit content as well as their suitability for a particular context.

2.6.1 OVERVIEW OF RISK ASSESSMENT METRICS

Risk metrics are also referred to as risk measures and risk indicators. There are different categorizations of risk metrics. One such often cited categorization is given according to the consequences under consideration (Jonkman, Van Gelder & Vrijling, 2003). The categorization is given as follows,

1. Fatalities (Individual Risk, Societal Risk)
2. Economic Damage
3. Environmental Damage
4. Integrated risk measures (i.e. considering various risk measures)
5. Potential Damage

(Jonkman et al, 2003) identified a total of 29 risk metrics belonging to the aforementioned categories whereas Johansen identifies a total of 17 (Johansen & Rausand, 2012). The Center for Chemical Process Safety of the American Institution of Engineers identifies 13 risk measures (Center for Chemical Process Safety [CCPS], 1999).

Even though there is a wide variation in the different types of risk measures available for selection, the risk measures adopted in the context of Major Accident Hazards (MAH) considers risk to humans as an individual or as a group (Jonkman et al., 2006). Hence the risk measures in the context of MAH broadly fall into the following categories,

1. Individual Risk Metrics
2. Group/ Societal Risk Metrics

Individual risk is a measure of the probability that an individual at a particular location suffers a fatality whereas societal risk is a measure of the probability of a group of persons suffering from a multiple fatality accident (Trbojevic, 2010). The common risk measures identified in the context of MAH risk metrics is given in Table 2.3.

Table 2.3 – Common Risk Metrics for Major Accident Hazards

NAME		TYPE	CONSEQUENCE	DESCRIPTION
1	IRPA – Individual Risk per Annum (Jonkman et al., 2003)	Individual Risk	Loss of life	The probability a specific/ hypothetical individual will be killed due to exposure to the hazards or activities during a period of one year
2	LIRA – Localized individual risk (Jonkman et al., 2003)	Individual Risk	Loss of life	The probability that an average unprotected person, permanently present at a specified location is killed during a period of one year due to a hazardous event at an installation
3	IR_{HSE} - Individual Risk of Dangerous Dose (Jonkman, 1999; CCPS, 1999)	Individual Risk	Receiving a dangerous dose	The frequency of receiving a dangerous dose from a toxic chemical leading to severe distress, injury or fatality per 10^6 years
4	PLL - Potential Loss of Life (Jonkman, 1999; CCPS, 1999)	Group Risk	Loss of life	The expected number of fatalities within a specific population per year
5	FAR - Fatal Accident Rate (Jonkman et al., 2003)	Group Risk	Loss of life	The expected number of fatalities within a specific population per 100 million hours of exposure
6	FN Diagram – Cumulative Frequency Diagram (Jonkman, 1999; CCPS, 1999; Jonkman et al., 2006)	Societal Risk	Loss of life	Diagram displaying the relationship between severity and frequency of single accidents. Severity is indicated in terms of the number of fatalities
7	RI_{COMAH} – Weighted risk integral (Jonkman, 1999; CCPS, 1999)	Societal Risk	Loss of life	Expected number of fatalities corrected for risk aversion with respect to a high number of fatalities
8	SRI – Scaled risk integral (Jonkman, 1999; CCPS, 1999)	Group risk	Loss of life	Group risk per area per year
9	TR – Total Risk (Jonkman, 1999; CCPS, 1999)	Societal Risk	Loss of life	Expected number of fatalities corrected for risk aversion with respect to extreme events
10	PEF – Potential equivalent fatality	Group Risk	Injury and loss of life	Expected harm per year from both fatalities and injuries, where injuries are expressed as fractions of a fatality

Table 2.4 – Comparison of Risk Metrics for Major Accident Hazards

NAME		ADVANTAGES	DISADVANTAGES
1	IRPA – Individual Risk per Annum (Jonkman et al., 2003)	• Can be used to represent risk for the most exposed individual	• Possibility of being inaccurate if averaged across a diverse group of people or activities
2	LIRA – Localized individual risk (Jonkman et al., 2003)	• Can represent risk at the most exposed location • Can be graphically displayed by iso – risk contours	• Does not account for actual exposure or population
3	IR$_{HSE}$ - Individual Risk of Dangerous Dose (Jonkman, 1999; CCPS, 1999)	• Accounts for injuries and severe distress in addition to fatalities	• Sensitive to a dangerous dose resulting in variation across individuals
4	PLL - Potential Loss of Life (Jonkman, 1999; CCPS, 1999)	• Group risk is expressed in a single number	• Extreme outcomes are not reflected
5	FAR - Fatal Accident Rate (Jonkman et al., 2003)	• Suitable for comparison between different activities	• Extreme outcomes are not reflected
6	FN Diagram – Cumulative Frequency Diagram (Jonkman, 1999; CCPS, 1999;	• Distinguishes between high consequence/ low probability and low consequence/ high probability events	• Evaluations can be inconsistent
7	RI$_{COMAH}$ – Weighted risk integral (Jonkman, 1999; CCPS, 1999)	• Expresses group risk in a single number	• Implicit value judgement is required on the importance of major vs minor accidents
8	SRI – Scaled risk integral (Jonkman, 1999; CCPS, 1999)	• Important decision factors are included such as population, are and exposure	• Difficulty in interpreting
9	TR – Total Risk (Jonkman, 1999; CCPS, 1999)	• Both average and extreme outcomes are included	• Difficult to interpret the risk aversion factor
10	PEF – Potential equivalent fatality	• Provides a measure of the expected harm due to both injuries and fatalities	• The evaluation incorporates fixed weighting of expected number of minor and major injuries

However, some sources present the usage of impact criteria based on impact thresholds related to consequence effects alone (Institution of Oil and Gas Producers Association[OGP], 2010; Ham, Struckl, Heikkila, Krausmann, Mauro, Christou & Nordvik, 2006). Hence, impact thresholds from a particular consequence can also be used as an indicator of risk although the frequency of the event is not explicitly incorporated into the metric. Percentage damage (e.g. injury or fatality) due to exposure from Thermal Radiation, Overpressure and/or Toxic exposure is also used in addition to the two broad groups of risk metrics stated above.

Hence, there is a wide variation in the different types of risk metrics available when selecting appropriate risk metric(s). A comparison of the different risk metrics identified in Table 2.3 is given in Table 2.4.

2.6.2 INTERNATIONAL USAGE OF RISK METRICS AND RISK CRITERIA

It would be prudent to identify and evaluate the different risk metrics and criteria adopted in the word presently with respect to MAH prior to selecting any such metrics for a particular country. The risk metrics and criteria as applied in the EU, USA, Australia, Hong Kong and Brazil where risk assessment of Major Accident Hazards (MAH) is currently practiced are investigated and discussed in the following section.

2.6.2.1 UNITED KINGDOM (UK)

The UK mainly follows a probabilistic risk analysis approach as stipulated in the Seveso Directive. However, there is a difference in how risk criteria are set for decision making with respect to Land Use Planning (LUP) requirements and offshore requirements. The UK Health and Safety Executive (HSE) address both individual risk and societal risk consideration (CCPS, 1999) in LUP decision making. The risk is presented in following formats (Ham et al., 2006),

- Iso – risk contours on a map, for individual risk
- Societal risk graphs (FN Curves)
- Risk matrix or a frequency – hazard plot

The risk acceptance criteria are as follows,

- Individual risk for the public: 10^{-6} per year is broadly acceptable for the entire population
- Individual fatality risk to people off – site: 10^{-4} fatalities per year is the maximum tolerable level
- Individual risk to a worker: 10^{-3} per year is intolerable
- Societal risk/ Societal concern: 50 fatalities at 2 x 10-4 per year. This stems from the concept of ALARP (As Low As Reasonably Practicable) arising from Lord Roben's Recommendation in 1974
- For LUP purposes, three zones of occupation around major accident hazard installations are distinguished with respect to individual risk criteria for the outer boundary. The three zones are given in Table 2.5.

Table 2.5 – Risk Criteria for the Demarcation of Zones in LUP, UK

ZONE	TOXIC [RISK BASED]	THERMAL RADIATION [$kW/m^2)^{4/3}s$]	OVERPRESSURE [mbar]
Inner	IR = 10^{-5} per year	1800	600
Middle	IR = 10^{-6} per year	1000	140
Outer	IR = 3 x 10^{-7} per year	500	70

2.6.2.2 NETHERLANDS

The Netherlands too has developed a robust risk assessment process for MAH as per the Seveso Directives. Risk for MAH is presented as Location Specific Risk and Societal Risk.

Location Specific risk is expressed in frequency (yr^{-1}) and is presented in iso – risk contours over a topographical map of the surroundings of the establishment (Ham et al., 2006). Contours are presented for 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8} per year. No vulnerable installations are allowed within the 10^{-6} per year contour.

Societal Risk is presented as an FN Curve with criteria line with 10 fatalities with 10^{-5} per year and 100 fatalities with 10^{-7} per year. Netherlands has applied these criteria informally since 1990 and has regulatory status since October 2004.

2.6.2.3 BELGIUM/ FLANDERS

Flanders follows a probabilistic risk assessment approach and is based to a largely on the approach of the Netherlands. Two risk measures are used. Namely,

1. Location Specific Risk
2. Societal Risk

Location specific risk is expressed in frequency (fatalities per year) and is presented as an iso – risk contour of the topographical surroundings of the establishment. Contours are presented for location risk with a frequency per year 10^{-4}, 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8}, similar to the Netherlands.

The Societal Risk is presented as an FN Curve and is similar to the Netherlands.

However, the risk acceptance criteria differ from that of the Netherlands. Criteria for location specific risk is given in Table 2.6.

Table 2.6 – Criteria for External Human Risk in Flanders

CRITERION	EXISTING ENTERPRISE	NEW ENTERPRISE
Maximum location risk at enterprise boundary	10^{-5} per year	10^{-6} per year
Maximum location risk at boundary of industrial area	10^{-6} per year	10^{-7} per year
Maximum location risk at vulnerable object/ location	10^{-7} per year	10^{-8} per year

Source: (Ham et al., 2006)

For societal risk a FN linear curve for acceptability with a probability of 10 fatalities with a probability of 10^{-5} per year and 100 fatalities with a probability of 10^{-6} per year is given as the criterion. A group risk of 1000 deaths or more at any probability is not acceptable.

2.6.2.4 GERMANY

Germany, unlike other EU countries subject to the Seveso Directives does not follow a probabilistic risk assessment approach. Instead a deterministic approach is adopted. Every installation is required to meet state of the art requirements on safety technology and good management practice. A high level of technical and organisational measures are required by the operator of the installation and controlled by the competent authorities (Ham et al., 2006). Even though MAH scenarios are considered, risk assessment is essentially qualitative and quantitative analysis is not performed. Hence no quantitative risk metrics are used to present the risk. Quantitative risk acceptance criteria are not available. Licensing of MAH installations is subject to expert judgment.

2.6.2.5 FRANCE

France follows a hybrid approach to risk analysis inclusive of both qualitative and probabilistic aspects. The French approach requires the identification of all accident scenarios. The risk is defined as a function of gravity, probability and kinetics (Taveau, 2010). Gravity is a combination of the two parameters; intensity of the effects and number of people in each dangerous area outside the facility. Probability of an event is determined either qualitatively or quantitatively. Kinetics refers to the speed at which a dangerous phenomenon will develop.

Table 2.7 – Gravity Levels

Scale of Accident	5% Lethal Effects	1% Lethal Effects	Irreversible Effects
Disastrous	>10	>100	>1000
Catastrophic	1 - 10	10 - 100	100 - 1000
Major	1	1 – 10	10 – 100
Serious	0	1	1 – 10
Moderate	0	0	<1

Source: (Taveau, 2010)

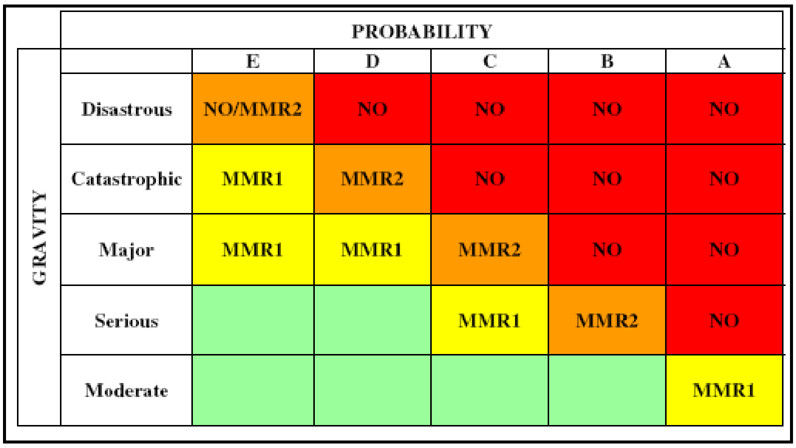
Table 2.8 – Probability Levels

E	D	C	B	A
Extremely unlikely scenario	Realistic but unlikely scenario	Improbable scenario	Probable scenario	Usual Scenario
Not impossible considering the current knowledge, but it hasn't happened anywhere in the world	Not impossible but it hasn't happened in a similar industry	Already happened in a similar industry in the world	Already happened (or supposed to have happened) during the lifetime of the facility	Already happened (possibly several times) during the lifetime of the facility
$<10^{-5}$/year	$>10^{-5}$/year	$>10^{-4}$/year	$>10^{-3}$/year	10^{-2}/year

Source: (Taveau, 2010)

Decision criteria for acceptance of risk are based on a matrix of acceptability of the risk for high – risk facilities. This is shown in Table 2.9. The matrix defines four zones (Red, orange, yellow and green).

Table 2.9 –Matrix of Acceptability of Risk for France



GRAVITY	PROBABILITY				
	E	D	C	B	A
Disastrous	NO/MMR2	NO	NO	NO	NO
Catastrophic	MMR1	MMR2	NO	NO	NO
Major	MMR1	MMR1	MMR2	NO	NO
Serious			MMR1	MMR2	NO
Moderate					MMR1

Source: (Taveau, 2010)

The red zone signifies unacceptable risk and no dangerous phenomenon are allowed. The orange zone does not allow more than five dangerous phenomenon. New facilities are only allowed if there is no dangerous phenomenon in the box

“NO/MMR” and the best available technologies are implemented (MMR implies risk reduction measures are required). The yellow zone signifies authorization for the facility provided the operator has taken all safety measures within a reasonable cost effectiveness ratio. The green zone signifies acceptability of risk and authorization of the facility.

2.6.2.6 SPAIN

Risk assessment is fundamentally deterministic with the risk presented for three zones for each scenario. However, these zones are used for emergency response planning and not for LUP (Ham, 2006). Risk quantification is not required but may be advised by the competent authority for LUP decisions. Catalonia alone follows a systematic QRA process for new establishments and extensions to existing establishments based the risk acceptance criteria of the Netherlands. No national risk acceptance criterion exists at present.

2.6.2.7 HONG KONG

Hong Kong has a formalized risk criteria added to the Hong Kong Planning Standards and Guidelines in 1993. Risk is presented as individual and societal risk. However, the individual risk is a “personal risk” and not a “location risk” (Ham et al., 2006) which implies that the duration of exposure is factored into the individual risk calculation. Risk criteria for Individual Risk is as follows,

- Maximum Tolerable Risk to the Public (Existing Situations and new situations) – 10^{-5} fatality per year

Hong Kong specifically identifies “Potentially Hazardous Installations (PH I)” and each PHI has surrounding control zone within which LUP is required[25]. Each PHI requires a QRA. The Societal Risk is presented as an FN Curve and the criteria for maximum tolerable risk is 10 fatalities per 10^4 years and public perception as being risk neutral (Gradient of the criteria line is set as -1). This is drawn from the anchor point initially set for UK by the Advisory Committee on Major Hazards (ACMH) in 1976 (Ball & Floyd, 1998). The curve for acceptable risk is set two orders of magnitude lower with both curves terminating at fatalities of 1000 irrespective of the cumulative frequency which implies that fatalities in excess of 1000 is neither acceptable or tolerable.

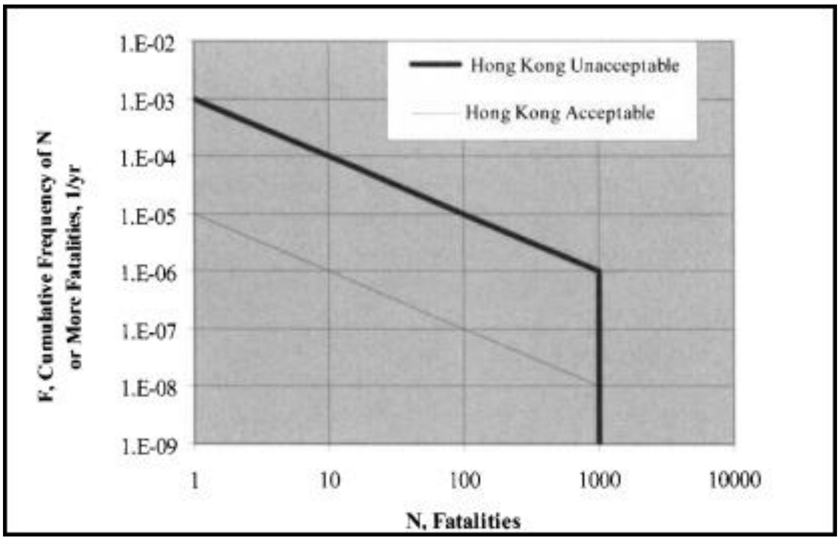


Figure 2.3 – Societal Risk Criteria for Hong Kong, Source: (CCPS, 1999)

2.6.2.8 SINGAPORE

Singapore requires a QRA for installations that store, transport or use hazardous substances (CCPS, 1999). Singapore has established individual risk criteria but no societal risk criteria.

Singapore has implemented a three tier criteria for individual risk for offsite populations. The maximum tolerable risk to the public for existing as well as new situations is as follows,

1. Industrial Developments– 5 x 10^{-5} fatality per year
2. Commercial Developments – 5 x 10^{-6} fatality per year
3. General Public – 10^{-6} fatality per year

Singapore requires a 1 km buffer zone between residences and installations such as oil refineries, petrochemical plants and toxic industrial waste treatment facilities.

Singapore's QRA guidelines require the following additional requirements,

1. 37.5 kW/m^2 thermal effect zone must not extend outside the site

2. 4 kW/m^2 thermal effect zone must not extend outside industrial areas or encroach into residential areas or housing areas for construction workers
3. Toxic effect zone corresponding to a 3% probability of fatality must not go outside industrial areas or encroach into residential areas or housing areas for construction workers
4. 5 psi (34.47 kPa) explosion overpressure zone must not go outside the site
5. 0.5 psi (3.45 kPa) explosion overpressure zone must not go outside industrial areas or encroach into residential areas or housing areas for construction workers

No guidance is provided on the nature of the individual risk; location risk or fractional time exposed is reflected in the risk parameter.

2.6.2.9 MALAYSIA

Malaysia requires Major Hazardous Industrial Installations to submit a risk assessment along with the EIA required by the Malaysian Environmental Quality Act (CCPS, 1999). Malaysia has established individual risk criteria as given below,

For residential areas, schools, hospitals and places of continuous occupancy – 10^{-6} fatality per year

For industrial developments – 10^{-5} fatality per year

In addition, a buffer zone is required between the boundary of the major hazardous installations and any other development. A buffer zone with a minimum of 500 meters or the safety distance to the 10^{-6} fatality per year risk contour for the general public, whichever is greater is required. The inclusion of the buffer zone ensures that any development is outside the 10^{-6} fatality per year risk contour for LUP purposes.

2.6.2.10 AUSTRALIA

Certain states in Australia have their own risk criteria and metrics. Western Australia, New South Wales, Queensland and Victoria have risk criteria while Tasmania, South Australia, Northern Territory and the Australian Capital Territory do not (CCPS, 1999).

Western Australia utilizes an Individual Risk Criteria defined for a spectrum of populations as per their sensitivity. The different individual risk criteria are given below,

- Sensitive Developments (Majority of the population are less able than the general population to protect themselves from risk) – 0.5 x 10^{-6} fatality per year
- Residential Areas – 1 x 10^{-6} fatality per year
- Commercial Developments – 5 x 10^{-6} fatality per year
- Open Areas and other non – industrial developments – 10 x 10^{-6} fatality per year
- Industrial Developments – 50 to 100 x 10^{-6} fatality per year

The individual risks are estimated as location risk.

New South Wales has published individual risk criteria for major hazard facilities as follows,

- Hospitals, schools, child care facilities, old age housing – less than or equal to 0.5 x 10^{-6} fatality per year
- Residential, hotels, motels, tourist resorts – less than or equal to 1 x 10^{-6} fatality per year
- Commercial developments including retail, offices and entertainment – less than or equal 5 x 10^{-6} fatality per year
- Sporting complexes and active open spaces – less than or equal 10 x 10^{-6} fatality per year
- Industrial – less than or equal 50 x 10^{-6} fatality per year

The individual risk criteria are identical to that of Western Australia. Societal risk criteria too have been included in the risk assessment process since 2007 (CCPS, 1999). Societal risk is presented as an FN Curve. Societal risk criteria are set as a maximum tolerable risk curve with the anchor point (10 fatalities per 10^4 years) from the ACMH report. However, the slope of the criteria line is set at -1.5. The FN Curve for negligible risk is set two orders of magnitude below the FN Curve for maximum tolerable risk. The societal risk criteria lines are given in figure 2.3.

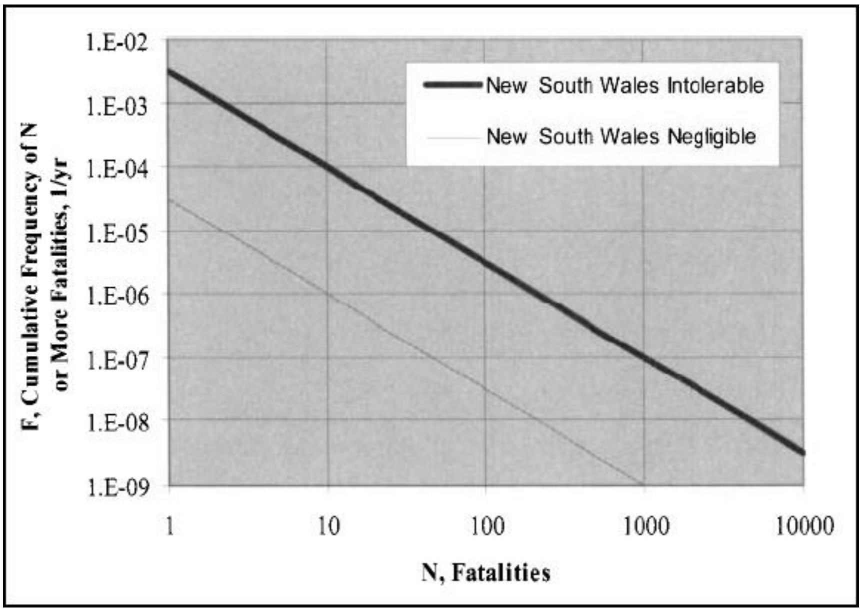


Figure 2.4 – Societal Risk Criteria for New South Wales, Source: (CCPS, 1999)

Queensland too has adopted the individual risk criteria adopted by New South Wales. Queensland does not specifically address Societal Risk but suggests that this concept should be addressed in the case of facilities that are close to significant population centers.

Victoria considers both individual and societal risk. Individual risk criteria for Victoria are as follows,

- Must not exceed 10 fatalities per 10^6 years at the boundary of the facility
- If risk exceeds 10 fatalities per 10^6 years at the boundary of an existing facility, risk reduction measures must be taken
- If offsite risk is between 0.1 and 10 fatalities per 10^6 years, all practicable risk reduction measures are to be taken, and residential developments are to be restricted
- Risk levels below 0.1 per million per year are broadly tolerable

The societal risk criteria are presented using the FN Curve. The Societal Risk Criteria line uses the same anchor point as New South Wales but has a slope of -2 which is identical with that adopted by the Netherlands. The curve for broadly acceptable risk is two orders of magnitude lower as given in Fig 2.4. This criterion does not have a legislative standing but is advisory in nature.

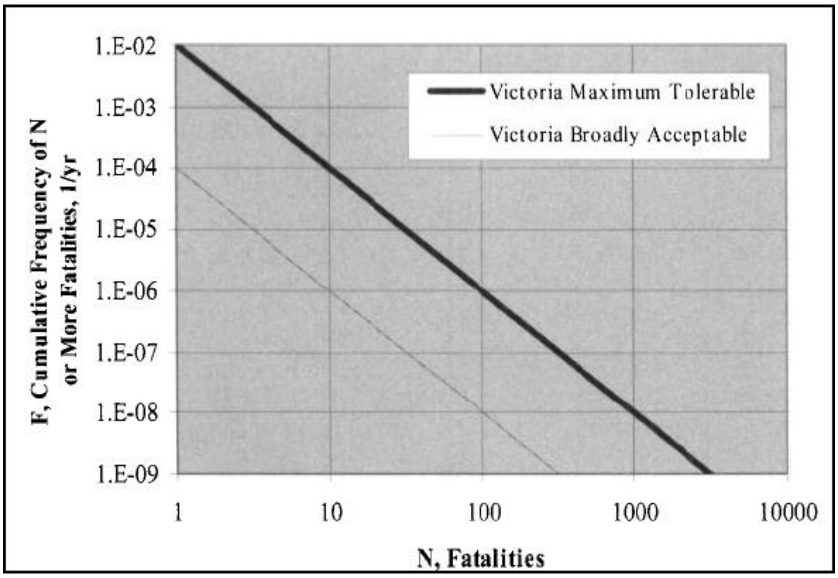


Fig 2.5 - Societal Risk Criteria for Victoria, Source: (CCPS, 1999)

2.6.2.11 BRAZIL

Risk criteria has been implemented in three states in Brazil. The states of Sao Paolo, Rio de Janeiro and Rio Grande do Sul have defined both individual and societal risk criteria.

Rio Grande do Sul and Sao Paulo have identical individual risk criteria. Criteria is set for “maximum tolerable risk to the public” for new situations and “broadly acceptable risk”. The criteria are as follows,

- Maximum Tolerable Risk (New Situations) – 10^{-5} fatality per year (Plants)
- Maximum Tolerable Risk (New Situations) – 10^{-4} fatality per year (Pipelines)
- Broadly acceptable risk – 10^{-6} fatality per year (Plants)
- Broadly acceptable risk – 10^{-5} fatality per year (Pipelines)

Rio de Janeiro has adopted the following individual risk criteria,

- Maximum Tolerable Risk (Existing Situations) – 10^{-5} fatality per year (Plants)
- Maximum Tolerable Risk (Existing Situations) – 10^{-5} fatality per year (Pipelines)
- Maximum Tolerable Risk (New Situations) – 10^{-6} fatality per year (Plants)
- Maximum Tolerable Risk (New Situations) – 10^{-6} fatality per year (Pipelines)

Societal risk criteria for the three Brazilian States are as shown in Fig 2.6.

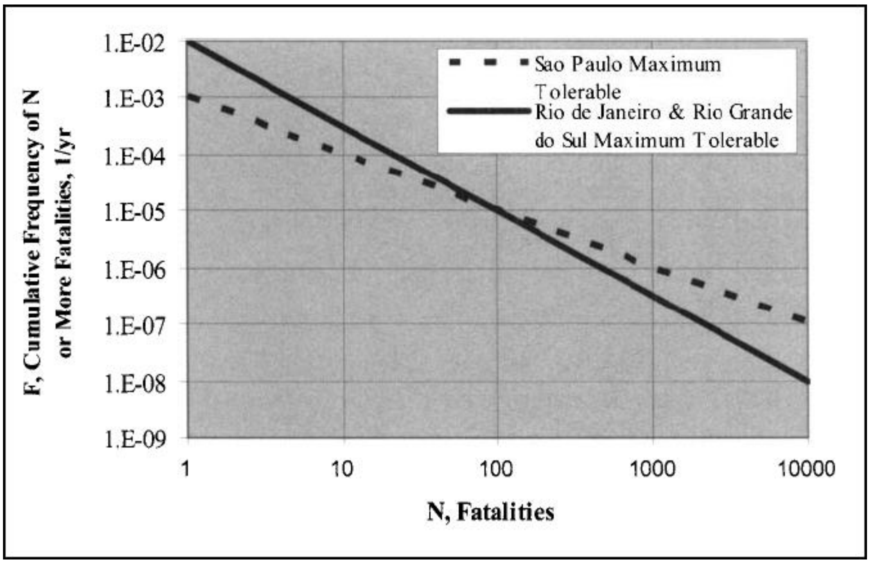


Fig 2.6 - Societal Risk Criteria for different states in Brazil, Source: (CCPS, 1999)

The aforementioned criteria are used for licensing purposes than land use planning decisions.

2.6.2.12 UNITED STATES OF AMERICA (USA)

The USA does not specifically prescribe probabilistic risk assessment for Major Accident Hazards throughout the country but certain federal government agencies do prescribe such assessments for selected industrial sectors.

The Nuclear Regulatory Commission (NRC) has in place a Probabilistic Risk Assessment (PRA) Implementation Plan (CCPS, 1999). Licensing of nuclear power plants is based on the PRA. Acceptance guidelines are clearly given. NRC's risk criteria is based on the following precept (CCPS, 1999),

"The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one – tenth of one percent (0.1 percent) of the sum of prompt fatality risks resulting from other accidents to which members of the US population are generally exposed"

This risk criterion only considers risk of public fatality. Furthermore, prompt fatality implies acute fatalities and not chronic fatalities. This criterion is interpreted as being 10^{-7} fatalities per year (CCPS, 1999).

In addition to the NRA other federal agencies such as the Department of Energy (DOE), Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) have their own risk acceptance criteria.

Santa Barbara County, California is one of the few federal counties having specific requirements for quantitative risk analysis (QRA) and risk criteria for decision making. QRAs are required by planning agencies within the county for siting or modifications of hazardous facilities or development in the vicinity of a hazardous facility or activity. Risk criteria supplements the decision making project. Risk criteria are applicable for public/ off – site risk only. Both individual and societal risk criteria are used. The individual risk criteria can take into consideration the duration of exposure. The individual risk criterion is used to trigger the need for a QRA using the following guidelines,

- The consequence assessment shows that a hazard zone extends to an off - site receptor

and

- A preliminary risk screening yields and individual risk of 10-6 fatalities per year or greater

Individual risk is not used as a criterion for risk tolerability. Risk tolerability is based on Societal Risk Criteria. This is presented in the form of an FN Curve. The risk criteria includes lower and upper bounding FN Curves defined by the anchor points (10, 10^{-5},-2) and (10,10^{-7},-2) respectively. Three risk zones are defined.

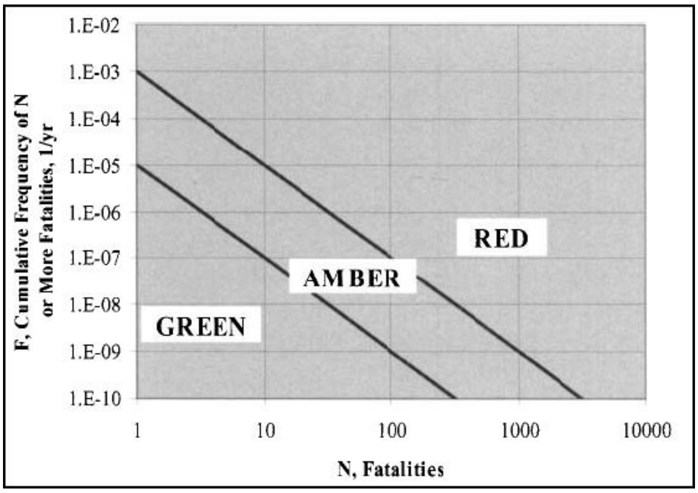


Fig 2.7 – Societal Risk Criteria for Santa Barbara County, USA, Source: (CCPS, 1999)

The following guidelines are used to make risk decisions (CCPS, 1999),

- For new developments any risk profile, after mitigation, extends into the red zone is judged to be an unacceptably high risk warranting denial of the proposed development
- For new developments involving highly sensitive land use (schools, hospitals, nursing homes) with a risk profile, after mitigation, extends into the amber zone is judged to be unacceptably high risk
- Any risk profile which falls into the green zone is deemed to have an insignificant impact on public safety requiring no mitigation
- For existing facilities, any modification that increases risk, causing the risk profile to enter the red zone and for highly sensitive land use, to enter the amber zone would be deemed an unacceptably high risk warranting denial of the proposed development

2.6.2.13 CANADA

The Major Industrial Accidents Council of Canada (MIACC) has published risk criteria for LUP decisions (CCPS, 1999). However, this criterion does not have any regulatory status and is only used for guidance. The risk parameter used is individual risk. The risk criterion is given in Table 2.10.

Table 2.10 – MIACC Risk Criteria for Land Use Planning

Range of Risk Values, fatality/year	Permitted Land Use
>100 x 10^{-6}	No land use other than the risk source itself (i.e. facility, pipeline).
10 x 10^{-6} to 100 x10^{-6}	Uses involving continuous access and low population density, evacuation could be easily effected (Manufacturing facilities, warehouses and open spaces).
1 x 10^{-6} to 10 x 10^{-6}	Uses involving continuous access and low population density, evacuation could be easily effected (Commercial use, offices, low – residential areas).
<1 x 10^{-6}	Development is not restricted in any way (includes institutional use and high density residential areas)

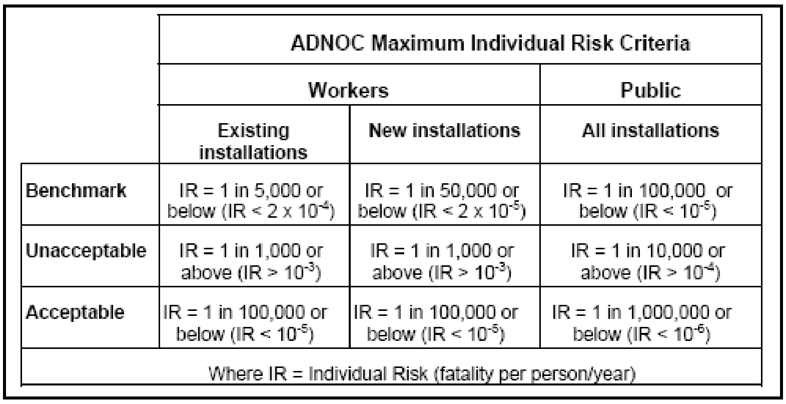
Source: (CCPS, 1999)

2.6.2.14 ABU DHABI

The Gas & Oil sector in Abu Dhabi is regulated by the Abu Dhabi National Oil Company (ADNOC). ADNOC specifies both an individual risk and societal risk criterion. Both IR and SR results are required by ADNOC for the approval (Pitblado, Bardy, Nalpanis, Crossthwaite, Molazemi, Bekaert & Raghunathan, 2012).

Societal risk is presented as FN Curves and is required to be evaluated for new developments as well as for existing facilities/ installation. However, ADNOC also requests the use of IRPA and PLL values. No societal risk is specified for offshore facilities. HSE UK guidelines are used as guidelines only.

Table 2.11 – ADNOCMaximum Individual Risk Criteria



	ADNOC Maximum Individual Risk Criteria		
	Workers		Public
	Existing installations	New installations	All installations
Benchmark	IR = 1 in 5,000 or below (IR < 2×10^{-4})	IR = 1 in 50,000 or below (IR < 2×10^{-5})	IR = 1 in 100,000 or below (IR < 10^{-5})
Unacceptable	IR = 1 in 1,000 or above (IR > 10^{-3})	IR = 1 in 1,000 or above (IR > 10^{-3})	IR = 1 in 10,000 or above (IR > 10^{-4})
Acceptable	IR = 1 in 100,000 or below (IR < 10^{-5})	IR = 1 in 100,000 or below (IR < 10^{-5})	IR = 1 in 1,000,000 or below (IR < 10^{-6})
Where IR = Individual Risk (fatality per person/year)			

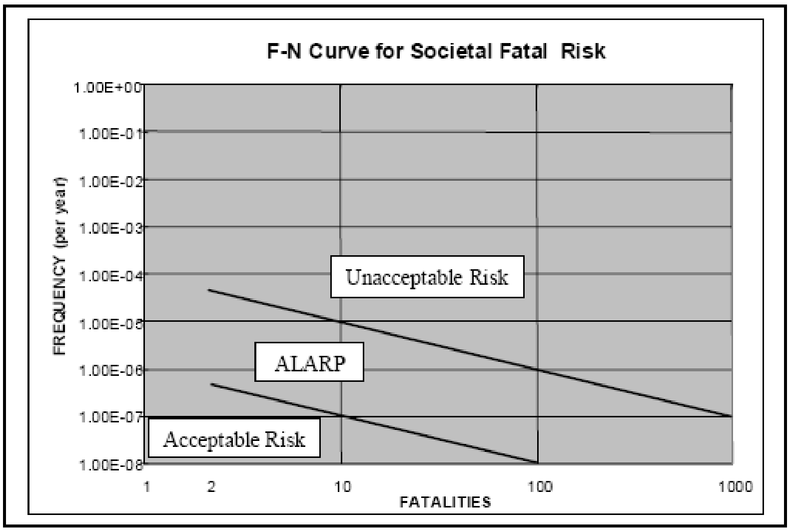


Fig 2.8 – Societal Risk Criteria for ADNOC Group, Abu Dhabi, UAE, Source: (Pitblado et al, 2012)

2.6.3 COMPARISON OF THE APPLICATION OF RISK METRICS AND RISK CRITERION

The previous discussion highlighted the different worldwide practices with respect to the application of risk metrics and respective risk criterion. Table 2.12 gives a comparison of the different risk metrics and risk criterion applied in different countries.

Table 2.12 – Comparison of World Wide Application of Risk Metrics and type of respective Risk Criterion

COUNTRY		RISK METRIC (S)	TYPE OF RISK CRITERION	COMMENTS
01	United Kingdom	1. Individual Risk 2. Societal Risk	1. Individual Risk 2. Societal Risk (presented as an FN Curve) 3. Risk Matrix	Risk Assessment is Probabilistic in nature. Offshore applications use a separate risk criteria than that for Land Use Planning (LUP)
02	Netherlands	1. Individual Risk (Location Specific) 2. Societal Risk	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Risk assessment is probabilistic in nature.
03	Belgium/ Flanders	1. Individual Risk (Location Specific) 2. Societal Risk	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Risk assessment is probabilistic in nature. Societal Risk Criterion is similar to that of the Netherlands.
04	Germany	None	None	The risk assessment is essentially qualitative
05	France	1. Gravity Levels 2. Probability Levels	1. Risk/ Decision Matrix	Includes both qualitative and probabilistic aspects.
06	Spain	No quantification	None	Risk assessment is essentially deterministic with emphasis on emergency response
07	Hong Kong	1. Individual Risk (Personal Risk not Location Risk) 2. Societal Risk	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Risk assessment is probabilistic in nature.
08	Singapore	1. Individual Risk (Does not differentiate between Location or Personal Risk)	1. Individual Risk (Additionally Buffer Zones and Guidelines for decision making)	Risk assessment is essentially probabilistic in nature
09	Malaysia	1. Individual Risk	1. Individual Risk (Additionally buffer zones are advised)	Risk assessment is probabilistic in nature. Focuses on land use planning (LUP)
10	Western Australia	1. Individual Risk (Location Risk)	1. Individual Risk	Risk assessment is probabilistic in nature
11	New South Wales	1. Individual Risk 2. Societal Risk	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Risk assessment is probabilistic in nature
12	Victoria	1. Individual Risk 2. Societal Risk	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Risk assessment is probabilistic in nature
13	Brazil	1. Individual Risk 2. Societal Risk	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Risk assessment is probabilistic in nature. Emphasis is on licensing.
14	USA	Individual Risk and Societal Risk are specified by certain counties and federal agencies	Societal Risk is presented as an FN Curve in New Jersey. The federal agencies such as the NRC specify individual risk criterion	Probabilistic risk assessment is not prescribed in all states or regulatory agencies
15	Canada	Individual Risk	Individual Risk	Specifically focuses on land use planning (LUP)
16	Abu Dhabi	1. Individual Risk 2. Societal Risk (In addition IRPA and PLL are recommended)	1. Individual Risk 2. Societal Risk (Presented as an FN Curve)	Probabilistic in nature. Limited to the Oil & Gas Industry regulated by ADNOC.

2.7 DISCUSSION

The review of the risk management regulations, risk assessment approaches and risk metric(s)/ respective risk criterion demonstrates that the manner in which risk based decisions are taken with respect to MAH differ widely across different countries in the world. Furthermore, it is clear that the selection of a particular set of risk metrics and respective risk criterion for a specific industry and country cannot be done without considering the respective risk management regulations and risk assessment approaches practiced.

The interpretation of a particular risk criterion is dependent on the nature of the legal systems in place in a particular country (Ale, 2005). A typical example is the interpretation of the terms “tolerable” and “acceptable” in the UK and Netherlands. Even though the Societal Risk criterion used in the UK and Netherlands seem similar, the judgment of the terms “tolerable” and “acceptable” differ between the two countries due to the different legal systems in place (Pasman, Jung, Prem, Rogers & Yang, 2009). Hence, it should be emphasized that risk criterion cannot be studied nor adopted in isolation from the legal system within which it is either embedded or proposed to be embedded.

It must also be emphasized that the risk assessment approaches too are closely related to the historical development of risk management in a particular country with due consideration for how the public perceives risk. This is an additional dimension to be considered along with the prevailing risk regulatory system in a country. Four main types of risk assessment approaches were identified in section 2.5.3. Each approach yields information at varying levels of depth and quality which are interpreted using respective risk metrics. Risk metrics obviously differ from one risk assessment approach to another. Furthermore, there is a clear separation of the different risk assessment approaches as either being prescriptive (rule compliance) or goal setting (risk based). Even though there is no conclusive evidence as to which system is better (Hopkins, 2011) there is a shift towards risk based decision making frameworks. The growth of the risk based approach is shown in Fig 2.8 (Indicative

Volume implies the number of risk assessments conducted). Even though four main types of risk assessment approaches were identified they can be classified into two main categories considering whether probabilistic aspects are specifically considered or not. The two categories are as follows,

- Purely Consequence based methods
- Probabilistic methods

The aforementioned two classes are considered further in this thesis. Some researchers such as Christian Kirchsteiger state that "there is neither a strictly deterministic nor a strictly probabilistic approach to risk analysis" (Kirchsteiger, 1999). Each approach has its advantages and disadvantages as given below in sections 2.7.1 and 2.7.2.

2.7.1 ADVANTAGES OF THE DIFFERENT RISK ASSESSMENT APPROACHES

The advantages from the consequence assessment and probabilistic risk assessment approaches are compared in table 2.13.

Table 2.13 – Comparison of Advantages between Consequence and Probabilistic Risk Assessment Approach

PURELY CONSEQUENCE BASED	PROABILISTIC APPROACH BASED
Analysis is relatively easy and fast	Complete analysis is possible
Decision process is simple (either "safe" or "unsafe")	Transparent as both likelihoods and severities of consequences are included
Results are easy to communicate to the public	Results for different types of facilities can be compared easily

2.7.2 DISADVANTAGES OF THE DIFFERENT RISK ASSESSMENT APPROACHES

The disadvantages from the consequence assessment and probabilistic risk assessment approaches are compared in table 2.14.

Table 2.14 – Comparison of Disadvantages between Consequence and Probabilistic Approach

PURELY CONSEQUENCE BASED	PROABILISTIC APPROACH BASED
Selection of scenarios is often tacit or implicit	Expensive and detailed analysis requiring expert knowledge
Use of “Worst Case” scenarios can often lead to conservative results	Difficulty in communicating the probabilistic elements to the public
Tendency to overlook less severe scenarios in risk control	Uncertainty in the estimation of the probabilistic elements

Furthermore, application of the different methodologies for several European LUP criteria lead to the following observations regarding consequence based and risk based methods (Cozzani et al., 2006),

- Consequence based methods seem to be more conservative than probabilistic methods
- Consequence based methods are less sensitive to mitigation actions oriented towards plant safety improvement and protection of vulnerable centers
- Probabilistic methods were found in general to be more sensitive and more suitable to evaluate the effects of risk reduction actions

Hence, the selection of the most appropriate method has to be done with the aforementioned factors in mind. Furthermore, different MAH scenarios may require different approaches to be adopted; however there may not be uniformity in the results for comparison purposes considering the different risk assessment criteria.

The review of the risk metrics show a broad spectrum of metrics from which to choose from (Table 2.3). However, only a few of them were found to be used widely in actual practice. A comparison of the different risk metrics used worldwide (Table 2.12) clearly show that Individual Risk (IR) and Societal Risk (SR) metrics prevail widely except for exceptions such as France. However, the manner in which these risk metrics (IR and SR) were used in the decision making process varied widely with simple pass/fail decisions, usage of ALARP zones, incorporation in decision matrices (i.e. approach adopted by France), usage of the IR as a trigger for SR and prescribing buffer zones in addition to the risk criterion.

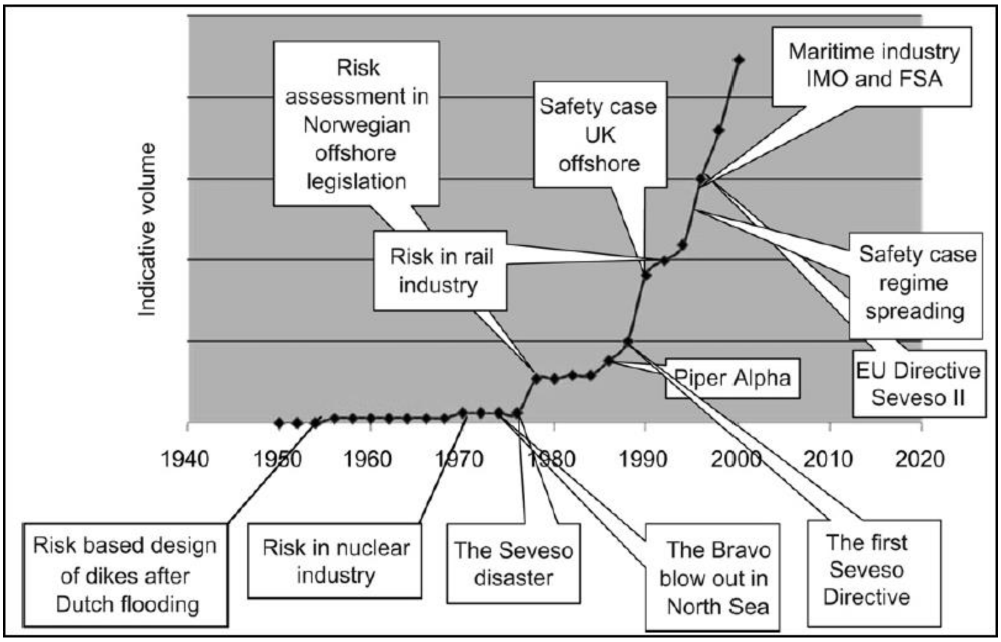


Fig 2.9 – Historical Development of the Risk Based Approach, Source: (Pasman, Jung, Prem, Rogers & Yang, 2009)

Hence, it must be emphasized that the risk metric alone is not sufficient but how it is incorporated into the decision making process as a risk criterion determines the quality of the decision and its impact on public policy. The IR and SR metrics when considered separately lead to different risk based decisions and it is difficult to arrive at a correlation between the two. Hence, the most suitable use of IR and SR as risk criterion is to either use one type of metric or to use both with the IR acting as a trigger to activate further analysis of Societal Risk criteria. Table 2.15 provides a comparison between IR and SR metrics.

Table 2.15 – Comparison of Individual and Societal Risk Metrics

	SOCIETAL RISK (SR)	INDIVIDUAL RISK (IR)
Advantages	1. Focuses on all the population exposed to risk 2. Explicit identification of major accident risks for both low and high probability events 3. Allows the incorporation of risk reducing measures as total risk exposure is calculated 4. Risk aversion for multi – fatality accident can be incorporated	1. Risk can be communicated as Iso – Risk contours
Disadvantages	1. Difficult to communicate to non – specialists 2. Does not provide a measure of the maximum risk to an individual	1. Does not show the maximum event possible 2. Difficult to incorporate risk reduction measures 3. Does not provide a measure of risk aversion

CHAPTER 3

3.0 DETERMINATION OF RISK ACCEPTANCE CRITERIA

3.1 INTRODUCTION

Different risk assessment approaches require different risk acceptance criteria which are rarely comparable. Hence, different risk assessment criteria have to be derived to correspond with the specific risk assessment approach chosen. Two main risk assessment approaches are evaluated for their suitability in the Sri Lankan context. Namely,

1. Consequence based risk assessment approach
2. Risk based or Probabilistic assessment approach

The following section derives respective risk assessment criteria for the aforementioned risk assessment approaches based on conditions in Sri Lanka.

3.2 DETERMINATION OF RISK ACCEPTANCE CRITERIA FOR CONSEQUENCE BASED RISK ASSESSMENT

The establishment of risk acceptance criteria for determining safety distances based on the consequence assessment approach for Sri Lankan conditions is discussed in this section.

The establishment of risk acceptance criteria for consequence effects requires the identification and selection of Human Vulnerability and/or Damage Effects. End Points are then selected for the respective effect. Safety Distances or Consequence Distances are then established based on the selected End Points. Human Vulnerability effects are categorize as Harm (i.e. Injury) or Fatality effects whereas Damage Effects consider Structural Damage to Buildings and structures.

Fire, explosions and toxic releases can be the resulting consequences from major accidents. Threshold levels or endpoints are selected for the aforementioned types of consequences. However, it should be emphasized that a single incident can give rise to any one or more of the consequences mentioned above. Hence, more than one of the harm or damage effects may contribute towards an Injury or Fatality.

End points can be categorized as,

1. Fixed Endpoints
2. Probit Endpoints

Fixed Endpoint implies a threshold specifying a specific level of harm for a single recipient. Probit endpoints consider a certain percentage of damage or harm in a number of recipients and take account of exposure time. Both types of these categories are investigated in this section.

3.2.1 SELECTION OF ENDPOINTS FOR FIRE CONSEQUENCES

Direct Harm to humans from fire consequences are due to exposure from "Thermal Radiation" and/or "Engulfment" (OGP, 2010). Indirect harm can occur due to failure of damaged structures and exposure to combustion products. However, only direct harm is considered in this study.

The "International Association of Oil & Gas Producers" has identified the relationship between fire type and human vulnerability as follows in Table 3.1,

Table 3.1: Relationships between Fires and Potential Vulnerabilities

FIRE TYPE		POTENTIAL VULNERABILITY		
		ENGULFMENT	THERMAL RADIATION	INSIDE BUILDING
1	Flash Fire	Yes	NO	Possibly
2	Jet Fire	Yes	Yes	Yes
3	Pool Fire	Yes	Yes	Yes
4	Fireball/ BLEVE	Yes	Yes	Possibly

Source: (OGP, 2010)

3.2.1.1 ENGULFMENT FROM FIRE

Establishing the area of engulfment is straight forward and consequence models for different types of fire provide the radius or the dimensions of the Fireball. A person fully or substantially engulfed by a fire can be considered to suffer fatality (OGP,2010). Hence we can consider 100% Lethality for humans engulfed in the types of fire mentioned in Table 3.1. However, fatality may extend outside the radius of the fireball due to thermal radiation, hence, the end point has to be determined based on the extent of fatalities from exposure to thermal radiation while considering 100% fatalities within the dimensions of the fireball itself.

However, for a Flash Fire the threat zone for a fatality cannot be established based solely on the Flame Dimensions. A Flash Fire may occur within any location where the mixture of flammable vapor/gas is within the limits of flammability if an ignition source is present. The area within which the mixture lies between the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL) should be considered as being vulnerable. Hence the end point for a Flash Fire scenario is considered as the LFL of the flammable gas/ vapor.

3.2.1.2 THERMAL RADIATION

Thermal radiation effects are a function of the following,

1. Thermal Radiation Flux
2. The Duration of Exposure
3. The type of clothing worn
4. The ease of sheltering
5. Nature of the individual exposed

In this analysis Pathological Effects of Thermal Radiation is considered. Pathological effects consider the development of burns to the skin due to exposure to thermal radiation. While it is relatively easy to quantify for exposed skin it is more complex for a clothed body (The Netherlands Organization of Applied Scientific Research [TNO], 1996). Pathological effects from “Thermal Radiation” can generally be expressed as,

1. Pain
2. 1st Degree Burns
3. 2nd Degree Burns
4. 3rd Degree Burns
5. Fatal Burns

3.2.1.2.1 FIXED END POINTS FOR THERMAL RADIATION

Fixed end points for Thermal Radiation are not used widely. Thermal Radiation end points expressed as threshold limits (Fixed Endpoints) were mostly derived from probit functions for Dose – Response relationships. However, US EPA's ALOHA modeling program uses the following Thermal Flux values.

The values given in Table 3.2 can be derived from the following sources,

1. Experimental Data
2. Recorded Data from Actual incidents
3. Existing Thermal Radiation Dose – Response Models

Table 3.2: Heat Flux Values used in ALOHA 5.4.1.2 Program

THERMAL RADIATION FLUX VALUE (kW/m^2)	EFFECT
10	Potential of death within 60 seconds
5	Second – degree burns within 60 seconds
2	Pain within 60 seconds

However, fixed end points suffer from the limitation in fixing a static exposure time in the calculation. This will limit their application in cases where the exposure time varies.

3.2.1.2.2 PROBIT ENDPOINTS FOR THERMAL RADIATION

The level or magnitude of the harm caused by the "Thermal Radiation" is expressed using Probit functions. The Probit approach considers the relationship between the Thermal Dose and Response of the exposed population (CCPS, 1999). The Thermal dose is an expression of both the Thermal Radiation Flux and the Exposure Time. It is expressed as,

$$C = t \times I^n \tag{1}$$

Where, t – Exposure Time (s), I – Heat Flux (Wm^{-2}), n – Exponent (n – is a constant), C – Thermal Dose

The Probit approach offers more flexibility in considering the duration of exposure than simply considering a fixed Thermal Radiation Flux. A probit function provides a measure of the probability on the range of susceptibility in a population to a harmful consequence. The measure is expressed as the percentage of a defined population which will suffer a defined level of harm when exposed to specified dangerous dose (Der Norsk Verita Technica, 2001 [DNV Technica]). The probit method is given in Appendix A.

A Probit function is generally expressed as,

$$Pr = a + b\ln(I^n * t) \tag{2}$$

Where,

a,b and n – Constants

Pr – Measure of Probability

Probits exist for 1st, 2nd, 3rd degree burns and Fatalities due to exposure to Thermal Radiation. However, the primary focus in this thesis will be mortality (Fatalities). Probit functions are derived using statistical data for a particular exposure effect (e.g. Mortality due to Thermal Radiation Effects). While it is convenient when expressing the percentage of a population subjected to a particular degree of an effect, it is constrained by the availability and accuracy of the data (Crowl & Louvar, 2013). The probit function is most often used in the evaluation of toxic effects as the data obtained from toxicological tests on animals can be extrapolated for humans [33]. However, thermal radiation effects on animals cannot be extrapolated for humans due to substantial variation in the character of animal and human skin. Most of the probit functions currently in use for Thermal Radiation rely on Historical Data.

Some of the most commonly used probit functions for thermal dose estimation are those developed by Eisenberg, Lees, Tsao & Perry and TNO (Health and Safety Executive UK [HSE UK], n.d.). Eisenberg used results published by White (1971) (Dlabka, Ova & Rehacek, 2011) on the effects on humans exposed to UV radiation in the atomic bomb explosions in Nagasaki and Hiroshima. Therefore the Eisenberg probit function includes effects of UV exposure (LaChance, Tchouvelev & Engebo, 2011). However, in an industrial fire both the infrared and UV spectrums can contribute towards the Radiation Flux. Tsao and Perry modified the Eisenberg probit function to include the influence of Infrared Spectrum and are based on measurements of both UV and IR heat fluxes from Hydrocarbon fluxes (LaChance at al., 2011). The combustion products from a Hydrocarbon Fire (H_2O & CO_2) emit radiation flux in the IR range. The “Green Book” (TNO, 1996) published by the TNO discusses at length on the effects of the Wave Spectrum on harm. The wavelengths due to Thermal Radiation from a nuclear explosion are mainly within the range of the “Visible and UV (<1 μm)” part of the radiation spectrum. However, for Hydrocarbon Fires, the radiation is within the IR range (>1μm). A higher wavelength will result in deeper penetration into the skin and warming up at a greater depth.The same level of harm can be caused by a lower dosage of thermal radiation from a Hydrocarbon, whereas a higher dosage will be required from a nuclear explosion (TNO, 1996).

However, both Eisenberg’s as well as Tsao& Perry’sprobit functions do not account for the effects of clothing. Probit function developed by Lee and TNO (TNO, 1996) do account for the effects of clothing. The Lees model was developed based on burn mortality data taking into account the age and burn area impacts (LaChance et al., 2011). Hence, it can be concluded that the Lee’s probit accounts for the degree of protection provided by clothing.

A degree of protection can be given by clothing provided it does not ignite due to auto ignition or sparks. However, the degree of protection provided by clothing with regard to “Thermal Radiation” exposure depends on a variety of factors,

1. Reflective Properties of Clothing
2. Heat conducting capability
3. Heat Capacity of the Textile
4. Thermal insulation effects due to air layers beneath the clothing
5. Humidity in the clothing
6. Level of clothing

The effects of clothing on Thermal Radiation exposure are deduced from burn injury data which is dependent on exposed areas of the human body. The exposed areas are estimated based on a “typical” level of clothing (UK HSE, 2000) but the term “typical” level of clothing is not elaborated. The most commonly used Thermal Dose probit functions for mortality are as given below in Table 3.3.

Table 3.3 : Thermal Dose Probit functions for Human Mortality

PROBIT EQUATION	SOURCE	VULNERABILITY	DESCRIPTION
Y = -38.48 + 2.56 ln(V)	Eisenberg (UK HSE, 2000)	Fatality	Based on the atomic bomb explosion exposure data from Hiroshima and Nagasaki (UV Radiation)
Y = -36.38 + 2.56 ln(V)	Tsao&Perry (UK HSE, 2000)	Fatality	Eisenberg model modified to account for infrared (IR) Radiation
Y - -37.23 + 2.56 ln(V)	TNO (TNO, 1996)	Fatality	Tsao and Perry Model modified to account for clothing
Y = -29.02 + 1.99 ln(FV)	Lees (Lees, 1996)	Fatality	Uses burn mortality information. Accounts for clothing based on pig skin experiments and Eisenberg Model

In table 3.3, the variable $V = I^{4/3}t$ while $F = 0.5$ for normally clothed population and 1.0 when clothing ignition occurs.The above probit functions are compared and the comparison of the Probit Functions is shown in the following table 3.4,

Table 3.4: Qualitative Comparison of Probit Functions for Thermal Radiation

PROBIT MODEL	WAVELENGTH OF EXPOSURE	CLOTHING	AGE
Eisenberg	UV	Not included	Not included
Tsao& Perry	UV & IR	Not included	Not included
TNO	UV & IR	Included	Not included
Lees	UV	Included	Included

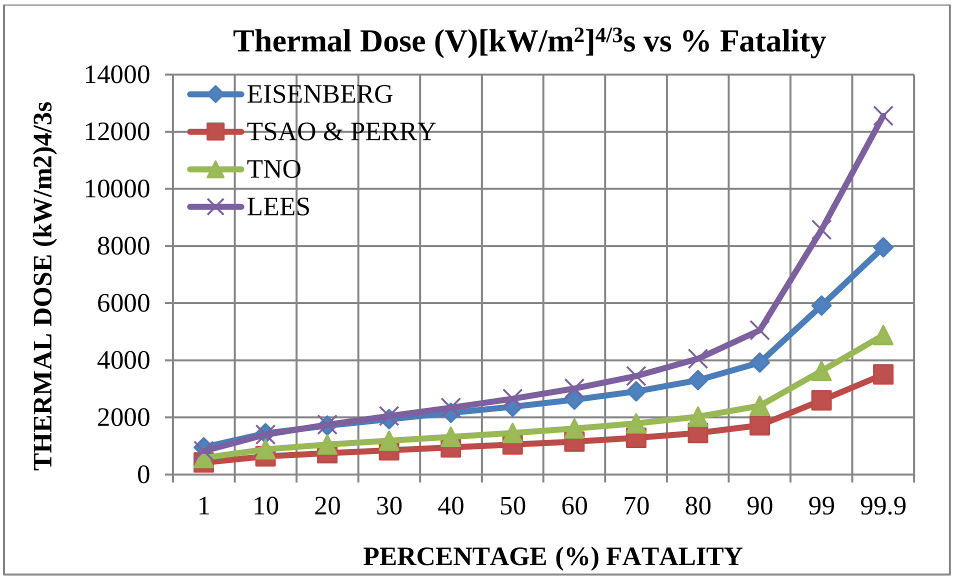


Figure 3.1 - Quantitative Comparison of Probit Functions for Thermal Radiation

3.2.1.2.3 Selection of an appropriate Probit for Dose – Response relationships under Sri Lankan Conditions

This analysis considers only probit functions for Mortality as fatalities are considered as the worst case outcome from exposure to thermal radiation. A Probit function from the four probit relationships discussed above are analysed in order to select a suitable probit function as given below.

It is considered that the majority of accidents giving rise to a Major Accident Hazard scenario in Sri Lanka will be from Hydrocarbon related industries or usage of fuel sources based on Hydrocarbons. Hence, the nature of the Thermal Radiation emitted by a fire or fireball shall essentially be in the IR spectrum as discussed in section 3.2.1.2. Hence, the most suitable probit to be considered would be either the Tsao & Perry or TNO Model.

Even though protective effects from clothing are considered in the TNO Model, it is not certain whether all aspects of the protective features of cloths have been captured in the probit. Furthermore, as the data is derived for European conditions, it is not known whether the data can be applied for conditions prevailing in Sri Lanka. Winter wear and clothes worn for cold climates would differ considerably from cloths worn in a country which is Hot and Humid throughout the year. The attire in Sri Lanka is mostly light clothing suitable for the hot climate in the country. Hence, it is assumed that clothing under Sri Lankan conditions would not offer significant protection from thermal radiation exposure from a major fire or fireball.

Considering the aforementioned conditions, the most applicable probit would be the Tsao & Perry model. Hence, the following probit by Tsao & Perry is adopted for determining suitable endpoints,

$$Y = -36.38 + 2.56 \ln(V) \tag{3}$$

3.2.2 SELECTION OF ENDPOINTS FOR EXPLOSION CONSEQUENCES

Explosion phenomena such as BLEVES and VCEs result in significant overpressures and projectiles that can lead to one of more of the following damaging effects (TNO, 1996),

1. Fatalities
2. Injuries
3. Structural Damage

3.2.2.1 PROBIT ENDPOINT SELECTION FOR BLAST OVERPRESSURE

Human vulnerability to overpressure effects can arise from both direct and indirect effects.

- Direct Effects: Pressure changes caused by an explosion or blast can result in injury to sensitive organs in humans. It is considered that an individual will directly experience and be subjected to the increase in pressure
- Indirect Effects: Indirect effects in turn can be considered as Secondary or Tertiary effects. Secondary effects result due to harm caused by projectiles (flying fragments at high velocity), whereas tertiary effects result from the whole body displacement of an individual resulting in a collision with stationary objects/ structures.

In this study only direct effects are considered.

3.2.2.2 DIRECT EFFECTS OF BLAST OVERPRESSURE

A blast overpressure results in rapid compression and decompression which will transmit the pressure wave through the tissues in a human being (UK HSE, 2010). Damage results at junctions between tissues of different densities (i.e. bone and muscle) or at interfaces between tissue and airspace.

It has been established that lung tissue and the gastrointestinal system are especially prone to injury due to effects of overpressure (UK HSE, 2010). The tissue disruptions can lead to severe hemorrhage or to air embolism resulting in fatal injuries. The eardrum is also susceptible to injury due to the aforementioned factors; however eardrum rupture is non – lethal.

While different types of injuries can result from direct exposure to blast overpressure, the end points established herein are derived for fatalities only as fatalities are considered as the worst case outcome. The commonly used probits are given in Table 3.5.They are used to express the percentage of fatalities resulting from a particular overpressure event and are directly correlated to the Peak Overpressure.

Table 3.5 – Commonly used Probit Equations used to predict Human Exposure Effects due to Overpressure

PROBIT EQUATION		SOURCE	DESCRIPTION
1	$Y = -77.1 + 6.91\ln(Ps)$	Eisenberg et al. (Lees, 1996)	Death due to lung hemorrhage
2	$Y = 1.47 + 1.371\ln(Ps)$	UK HSE (UK HSE, 2010)	Death due to lung hemorrhage

Note: Ps – Peak Overpressure is expressed in Pa

It must be stated that other probits for fatalities from overpressure do exist (e.g. TNO) but are not directly correlated to Peak Overpressure but require the determination of additional parameters such as the impulse of the shock wave, pulse duration and debris velocity (TNO, 1996). Probits which can be directly correlated with overpressure are chosen due to the added uncertainty arising from the calculation of the impulse, pulse duration and debris velocity.

3.2.2.3 COMPARISON OF PROBIT FUNCTIONS FOR OVERPRESSURE DUE TO EXPLOSIONS

The two probits functions, that of Eisenberg and UK HSE are compared as follows,

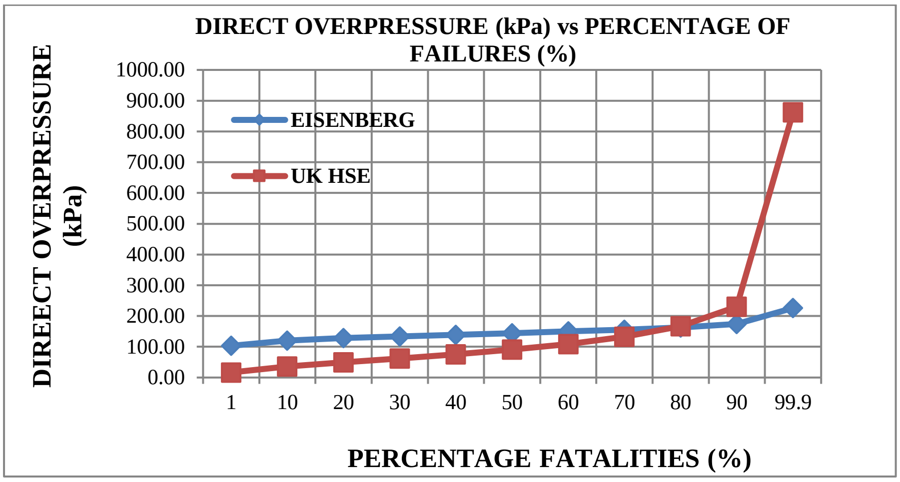


Figure 3.2 - Comparison of Probit Functions for Fatalities due to Overpressure

Figure 3.2 shows that the UK HSE Probit provides a more conservative estimate of fatalities compared to that of Eisenberg. However, a majority of fatalities do occur due to indirect effects such as death from impacting fragments, struck or crushed by collapsing buildings/ structures and collision of the human body with stationary objects due to whole body displacement. It is not known whether these aspects are included in the probits discussed above. In order to account for the uncertainties resulting from their exclusion, a conservative dose – response model is adopted (Goodstein, 2005). Hence, it is proposed that the more conservative probit function be used to establish the end points.

However, it must be emphasized that indirect effects can result in considerable fatality probabilities for a given overpressure (LaChance, 2011). The following probit for Total Damage from Structural Failure given by Eisenberg (Lees, 1996), shows that structural damage occurs at lower pressures than that causing fatalities. The probit yields the following values as given in Table 3.6.

$$Y = -23.8 + 2.92 \ln(Ps) \tag{4}$$

Table 3.6: Percentage Damage values for the Eisenberg Probit for Total Structural Damage

PROBIT VALUES FOR STRUCTURAL FAILURE (TOTAL DAMAGE)	
% Damage	**Eisenberg (kPa)**
1	8.62
10	12.41
20	14.41
30	16.06
40	17.65
50	19.17
60	20.89
70	22.96
80	25.58
90	29.79
99.9	55.30

As shown above 100% of the buildings in the affected zone will suffer total damage at a blast overpressure of 55.3 kPa. As per the more conservative of the fatality probit considered in Table 3.6, UK HSE, only 20 % – 30 % of the exposed population will suffer fatalities in the threat zone. However, it is highly likely that any person indoors at the time of the blast is prone to suffer fatality or will be subjected to fatal injuries if 100% structural collapse occurs. This creates a dilemma with regard to the selection of an appropriate probit equation.

Furthermore, this is compounded by the unavailability of a correlation between % Structural Damage and % Fatality as a result of Blast Overpressure even though it can be intuitively assumed that 100% Fatalities may occur due to 100% structural damage. Any such assumption without a proven basis will introduce more uncertainties with regard to the end points. Therefore the probit for total structural damage is not considered further in establishing end points. Hence, the more conservative of the fatality probit (i.e. probit proposed by UK HSE) is chosen in determining the fatality end point for blast overpressure effects.

3.2.3 SELECTION OF END POINTS FOR EXPOSURE TO TOXIC CHEMICALS

The study of human exposure to a varied number of harmful agents (Toxic Chemicals) is well developed and comprehensive. Different approaches exist with respect to estimating the level of fatality due to exposure to toxic chemicals resulting in a number of threshold limits.

This analysis considers only the lethal effects resulting from acute intoxication as it leads to fatalities. Furthermore, it is understood that potential receptors can be exposed through either one or more of the following pathways (Crowl & Louvar, 2013),

- Oral (via the alimentary canal)
- Skin (Dermal)
- Inhalation (Respiratory)

Mass acute exposure with lethal consequences usually results from inhalation; hence acute inhalation intoxication is considered to be the main pathway for fatalities. The probit approach is adopted due to the ability to correlate with varying percentages of fatalities for different dosages.

In addition to the probit approach, the following alternative approaches are used (Jonkman et al., 2006),

- IDLH – Immediately Dangerous to Life or Health
- AEGL – Acute Exposure Guidelines Levels
- SLOT – Specified level of Toxicity
- SLOD – Significant likelihood of death

The acronym IDLH is defined as the maximum exposure concentration for a given chemical in the workplace from which one could escape within 30 minutes without escape impairing symptoms or any irreversible health effects. The exposure levels as specified by the US National Institute for Occupational Health and Safety (NIOSH) and are expressed as airborne concentrations. Hence, it can be considered as an exposure limit beyond which impairment may occur hindering escape.

AEGL or Acute Exposure Guideline Levels specify exposure concentrations for time periods ranging from 10 minutes to 8 hours that would prevent three levels of harm; discomfort, disability and death. These limits are for accidental short term exposures.

Specified level of Toxicity or SLOT is proposed by UK HSE (UK HSE, 2010). The SLOT levels are derived from toxicity data extrapolated to human exposure from animal experiments. The limit is specified as SLOT Dangerous Toxic Load (SLOT DTL). It is defined as the dose that results in highly susceptible people being killed, a substantial portion of the exposed population requiring medical attention and severe distress to the remainder exposed. It represents the dose resulting in the onset of fatality (can be considered as 1% Fatality) for an exposed population. SLOT DTL is considered as being equivalent to the Lethal Concentration (LC_{1-5}) derived from animal experiments.

Significant Likelihood of death (SLOD) is also proposed by UK HSE (UK HSE, 2010). It is defined as the dose typically resulting in 50% fatality (LD_{50}) of an exposed population. Similar to SLOT, data for SLOD is extrapolated from animal data.

However, the aforementioned approaches essentially consider only a specific cut off for the end point (e.g.1% Fatality or 50% Fatality). Such end points are useful when setting exposure limits at workplaces. However, they do not provide a means of estimating the overall effect of exposure on a vulnerable population. Hence, they are of limited value when considering major accident risk assessment where public exposure is concerned, even though they can be used as limits for evacuation, where emergency response is considered.

The probit approach albeit an approximate methodology, allows the means of quantifying the percentage damage due to a specified level of exposure. Hence, the probit method is selected for determining the end points for toxic chemical exposure.

It must be emphasized that probit equations related to toxicity from chemicals are derived from data obtained from experiments conducted on animals (Crowl & Louvar, 2013) which are then scaled up or extrapolated to human dose – response relationships. Different scaling relationships and interspecies variation in the extrapolation of animal data to humans result in uncertainties when applying the probit functions (Schubach, 1995). Hence, to account for uncertainties, a conservative estimate is made when setting endpoints for toxic exposure (Goodstein, 2005).

The harmful chemicals considered in this study are toxic gases liable to cause mass exposure of the public in Sri Lanka due to loss of containment (The major focus is on the Hydrocarbon Industry). The scope does not include pesticides or synthetic fertilizers as mass exposure of the public has not been reported (Refer Appendix C). The probits selected are for fatality levels resulting from exposure to the selected toxic gases. The toxic gases were selected based on toxic gas emission incidents which occurred in Sri Lanka with potential for major public exposure during the years from 2005 to 2013). The list of the accidents is given in Appendix C.

From the above list the following toxic gases are considered for the selection of probits,

- Hydrogen Sulphide (H_2S)
- Ammonia (NH_3)
- Chlorine (Cl_2)

3.2.3.1 SELECTION OF PROBITS FOR H_2S EXPOSURE

H_2S is a highly lethal and toxic gas encountered both in the upstream and downstream sectors of the petroleum hydrocarbon industry. It is a toxic gas which causes systemic effects resulting in fatalities even at low concentrations and exposure duration. The effects encountered by its exposure as described in literature are given below in Table 3.7,

Table 3.7: Effects of Exposure to Hydrogen Sulphide

CONCENTRATION (ppm)	EFFECT
20 – 30	Conjunctivitis
50	Objection to light after 4 hrs exposure. Lacrimation
150 – 200	Objection to light, irritation of mucous membranes, headache
200 – 400	Slight symptoms of poisoning after several hours
250 – 600	Pulmonary edema and bronchial pneumonia after prolonged exposure
500 – 1000	Painful eye irritation, vomiting
1000	Immediate acute poisoning
1000 – 2000	Lethal after 30 to 40 minutes
>2000	Rapidly lethal

Source: (OGP, 2010)

Exposure levels as expressed above are suitable as guidelines but are not useful when quantifying dose response relationships. Hence, suitable probits are selected as it gives a continuous dose response relationship. There is a variation between the different probits in use. This study considers the most commonly used probits at present and are given in Table 3.8,

Table 3.8: Probits for lethal effects from H_2S

PROBIT EQUATION	SOURCE
$Y = -31.42+3.008\ln(C^{1.43}t)$→CCPS	CCPS [6]
$Y = -30.08+1.16\ln(C^{4}t)$→OGP	OGP [11]
$Y = -32.92+3.01\ln(C^{1.43}t)$→TNO1	TNO [12]
$Y = -42.6+2.36\ln(C^{2.17}t)$→ TNO2	
$Y = -44.7+2.9\ln(C^{2}t)$→ TNO3	

CCPS – Center of Chemical Process Safety

OGP – International Association of Oil & Gas

TNO – The Netherlands Organization of Applied Scientific Research

The probit equations as named in column 1of Table 3.8 (CCPS, OGP, TNO1,TNO2 & TNO3) are compared for different fatalities from 1% to 99.9%as shown in Figure 3.3. The calculation has been done based on a hypothetical exposure time of 10 minutes for deriving the comparison.

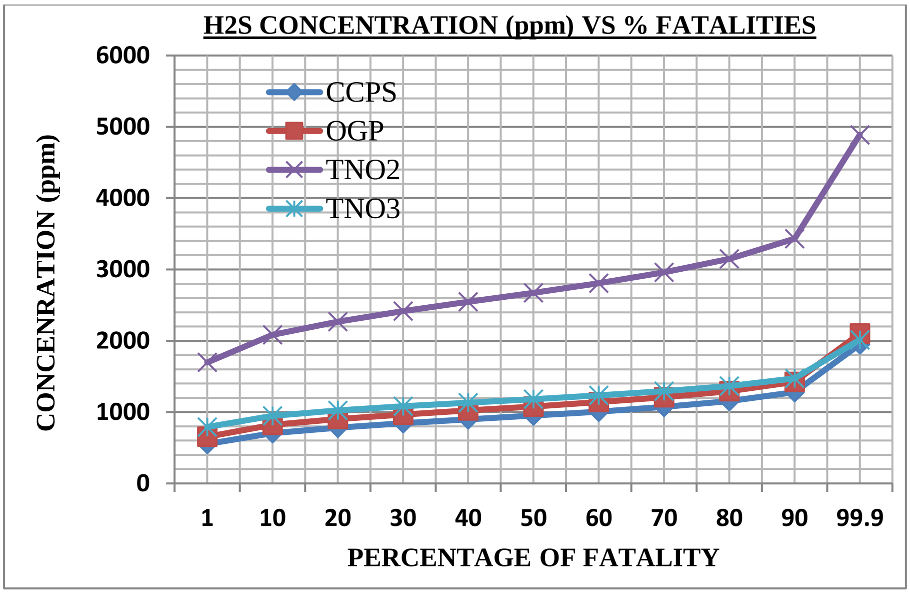


Figure3.3 - Comparison of Dose – Response relationships for Lethal Effects from H_2S

The most conservative of the probits are CCPS (CCPS,1999) and TNO1 (TNO, 1996). It is likely that both organizations refer to the same probit relationship. The probit relationship used by CCPS is adopted because it is the most conservative of the probit relationships and models a worst case response to H_2S.

3.2.3.2 SELECTION OF PROBITS FOR NH_3 EXPOSURE

NH_3 is an irritant and is not systemic. However, exposure to high dosages can lead to fatalities. The following probit relationships given in Table 3.9 are used in the probit selection analysis of NH_3.

Table 3.9: Widely used Probit Equations for lethality from NH_3 Exposure

PROBIT EQUATION	SOURCE OF REFERENCE
$Y = -35.9+1.85\ln(C^2t)$→LEES	(Lees, 1996)
$Y = -28.33+2.27\ln(C1.36^t)$→Perry & Articola	

In Table 3.9, concentration C is given in ppm by Volume and Exposure time t in minutes.

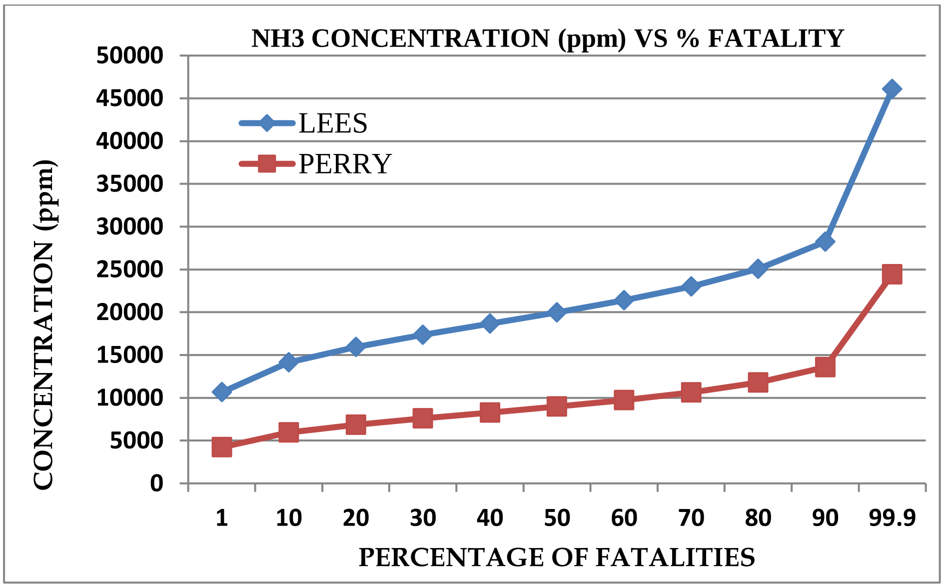


Figure 3.4 - Comparison of Dose – Response relationships for Lethal Effects from NH_3

The probit proposed by Perry & Articola (Lees, 1996) is the most conservative of the two and is selected for establishing the endpoints for lethality from NH_3 exposure.

3.2.3.3 SELECTION OF PROBITS FOR Cl_2 EXPOSURE

Chlorine is an irritant and not systemic. The respiratory tract and/or the eyes are usually affected by Cl_2. However, acute exposure to high dosages of Cl_2 can result in death due to pulmonary edema. For the Cl_2 the widely used probits are shown in Table 3.10.

Table 3.10: Widely used probit equations for lethality from Cl_2exposure

PROBIT EQUATION	SOURCE OF REFERENCE
$Y = -8.29+0.92\ln(C^2t)$ → LEES	(Lees, 1996)
$Y = -5.3+0.5\ln(C^{2.75}t)$ → CCPS	(CCPS, 1996)

Concentration C is given in ppm by volume and exposure time t in minutes. The aforementioned probits are compared in Figure 3.5 using a hypothetical exposure time of 10 minutes. The probit relationships proposed by Lees (Lees, 1996) are more conservative compared to that of CCPS (CCPS, 1996). Hence, the relationship given by Lees is selected based on a worst case exposure scenario.

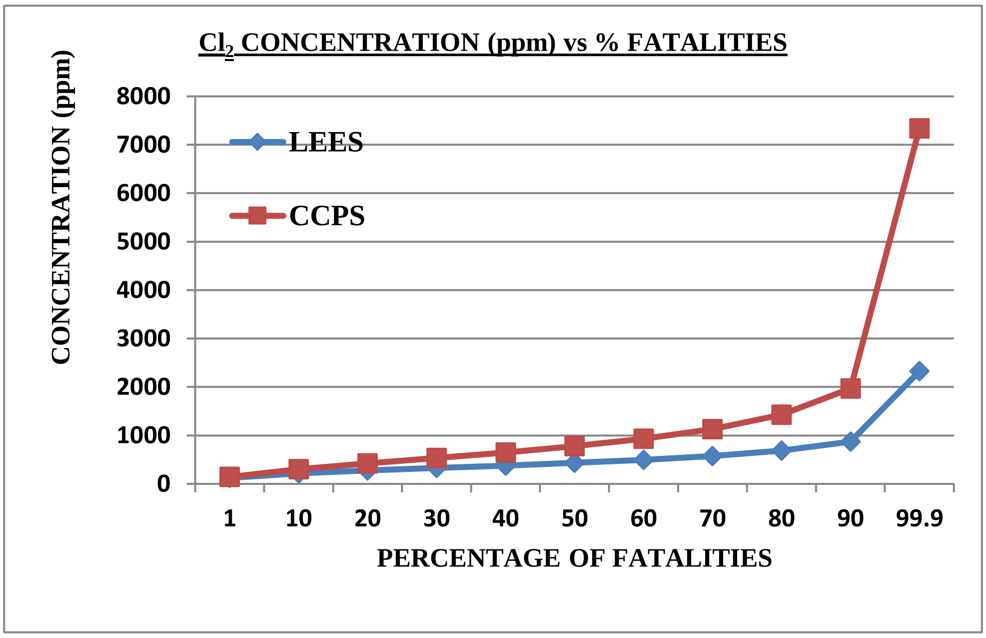


Figure3.5 - Comparison of Dose – Response relationships for Lethal Effects from Cl_2

3.2.4 PROPOSAL OF RISK ACCEPTANCE CRITERIA FOR THE CONSEQUNEC ASSESSMENT APPROACH

As described in sections 3.2.3.1, 3.2.3.2 and 3.2.3.3 the Probit functions for the Human Vulnerabilities from the following effects have been selected,

- Thermal Radiation
- Blast Overpressure
- Toxic Exposure

However, to establish suitable risk acceptance criteria an appropriate cut off limit for the end points must be selected. The following cut off is proposed,

"The percentage of a population living in the vicinity of an industry who shall be subjected to the risk of sustaining fatal effects from a Major Accident due to the operation of that particular industry shall be less than 1%."

The basis for the selection is as follows,

1. The public shall not suffer any fatalities due to the realization of a Major Accident Hazard from an Industrial Establishment that has been permitted/ licensed to operate close to a residential area
2. 1% Fatality signifies the onset of fatality; Hence, the cut off is chosen based on the prevention of any onset of fatality to the public due to a Major Accident Hazard

The relevant 1% Fatality end points needs to be calculated from the selected probits. Safety distances needs to be then calculated for each specific case, based on 1% fatality end points for the worst case scenario under consideration and the resulting maximum safety distance adopted as the safety distance to be maintained for the case Hazardous Installation under consideration. This safety distance is proposed as the societal risk acceptance criteria in this work when a consequence based analysis is carried out to a MAH installation.

3.2.5 SUMMARY OF THE SELECTED PROBITS

The selected probits in the section 3.2 are given in Table 3.11.

Table 3.11: Summary of Selected Probits

LETHAL EFFECT		PROBIT FUNCTION	COMMENTS
1	Thermal Radiation	$Y = -36.38 + 2.56 \ln(I^{4/3}t)$	This probit is proposed by Tsao& Perry. The calculation of the Thermal Dose (V) requires the determination of both Thermal Radiation Intensity (I) and Exposure Time (t). Both parameters can be calculated from Consequence Models.
2	Overpressure	$Y = 1.47 + 1.371\ln(Ps)$	This probit is proposed by UK HSE.
3	Toxicity from H_2S	$Y = -31.42+3.008\ln(C^{1.43}t)$	Exposure time t, shall be estimated from Dispersion models.
4	Toxicity from NH_3	$Y = -28.33+2.27\ln(C^{1.36}t)$	Exposure time t, shall be estimated from Dispersion models.
5	Toxicity from Cl_2	$Y = -8.29+0.92\ln(C^{2}t)$	Exposure time t, shall be estimated from Dispersion models.

3.3 DETERMINATION OF RISK ACCEPTANCE CRITERIA FOR THE PROBABILISTIC APPROACH

3.3.1 INTRODUCTION

A risk acceptance criterion which is applicable for the probabilistic risk assessment approach when conducting a quantitative risk assessment (QRA) is derived in this section. This study identifies a reference level or baseline against which acceptable societal risk criteria can be established for the Chemical Process Industry (CPI) in Sri

Lanka considering data on disasters which happened until 2014 and proposes a societal risk acceptance criterion based on the selected baseline.

Risk acceptance criteria applicable in the probabilistic approach fall into either of the two broad categories, namely individual or societal as identified in the literature review in Chapter 2. Societal risk acceptance criteria are considered to be most appropriate where a large number of people are at risk (Vannem, 2012). Societal risk is defined as, “the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards” (Jonkman et al.,2003). However, the estimation of the level of societal risk alone would not be sufficient. The level of acceptable societal risk too needs to be established as risk perception of the society is strongly dependent on the question, “how safe is safe enough?”. The process of answering this question leads to the establishment of a societal risk criterion upon which risk acceptance decisions can be based.

3.3.2 PROCESS FOR THE DERIVATION OF THE SOCIETAL RISK ACCEPTANCE CRITERION

The process or methodology for deriving the risk acceptance criterion is elaborated. In the process of deriving a risk acceptance criteria the following five aspects need to be established.

a. Definition of MAH installations
b. Selection of an approach for deriving the risk criteria
c. Definition of the concept of risk
d. Selection of a measure of risk
e. Selection of a suitable presentation of risk
f. Establishing a framework for deriving the risk criterion

3.3.2.1 MAH INSTALLATIONS

The definition given in Chapter 1, section 1.1 for a MAH installation is used in this section.

3.3.2.2 SELECTION OF AN APPROACH FOR DERIVING THE RISK ACCEPTANCE CRITERIA

Establishing societal risk criteria for a particular society is strongly dependent on historical, legal and political factors related to that society resulting in varying approaches adopted by different societies (Hartford, 2009). Sri Lanka does not have a generally accepted precedent in the use of a societal risk criterion for MAH installations. This poses a significant challenge in deriving risk criteria due to the lack of a baseline upon which the societal risk criteria can be developed. Hence, a baseline is required to be established for the level of risk from major accident events in the country.

Approaches in deriving risk criteria can be classified into four categories (Vrijling,van Gelder, Goossens, Voortman & Pandey, 2004) as follows,

1. criteria based on risk-cost-benefit measures, e.g. in complex and expensive health services
2. criteria based on past performance or revealed preferences, e.g. in major hazards licensing and rail road safety of high speed lines
3. criteria based on societal or laymen’s preferences, expressed preferences, e.g. in asbestos abatement or approaches to dioxin caused health problems
4. criteria based on natural standards, e.g. in some environmental risk criteria

The second approach stated above, that of criteria based on past performance is adopted in this work. This approach is adopted due to the need to justify the criteria in the context of public perception and demonstrate that the criteria leads to a level of risk lower than that posed by major sources of catastrophic disasters in Sri Lanka. An empirical deductive method is adopted. Three deductive methods have been identified in literature namely, expert evaluation, bootstrapping and formal analysis (Johansen, 2010). Expert evaluation involves the best available experts deciding on the level of acceptable risk based on their professional experience while integrating the risk perception of society. A bootstrapping approach considers the levels of risk tolerated in the past as a basis for evaluating future risk. Formal analysis considers the detailed analysis of tradeoffs between risk and benefits related to a risk problem.

The expert evaluation approach is highly subjective. It is strongly dependent on the judgment of the expert(s) where biases can be introduced when technical issues have to be weighed against public concerns and political interests. Formal analyses in contrast are more transparent yielding logical recommendations which can be evaluated. Techniques such as cost – benefit analysis (CBA) and decision analysis are tools which are incorporated within formal analyses. However, the implementation of these methods requires highly trained experts and are time consuming and expensive. In spite of the apparent rigor introduced in the analysis the decision as to the level of acceptable safety ultimately becomes judgmental in nature. Hence, this approach too is not considered as appropriate for deriving a societal risk criterion in this work.

The bootstrapping approach in comparison to the two methods discussed above, considers a broad range of hazards and allows the evaluation of the risks and benefits achieved in the past. The main weakness of this approach is the lack of depth and the bias towards the status quo (Johansen, 2010).However, this approach is adopted in this paper for determining the level of risk.

3.3.2.3 DEFINITION OF RISK

The definition of risk provided in chapter 2, section 2.5.2 is used in this section.

3.3.2.4 SELECTION OF A MEASURE OF SOCIETAL RISK AND PRESENTATION OF RISK

In establishing the level of risk faced by the public the following aspects are fundamentally considered in this work,

a. Hazards which pose an involuntary risk on the public
b. Severe and Catastrophic events (Disasters) faced by the public

A metric is required to be established capable of representing the factors stated above under items a and b. The metric should represent the aspects of the consequence and probability of an accident scenario as per the definition of “risk” adopted in this paper. The metric needs to be measurable and quantitative in nature. Events having fatalities of 10 or more are considered in this study in line with the definition of MAH adopted in this thesis. The probability is calculated based on the history of occurrence of the type of event as defined above within a given time period. Hence the following two metrics are used to provide a compound metric for the level of risk for a particular event,

- Consequence (n) – Number of fatalities equal to or greater than 10
- Probability (f) – Frequency of occurrence of a high consequence event (number of events per year)

The ‘risk level’ for a particular set of disasters can then be represented by a single compound variable R, as shown in equation (1) in conformance with the commonly accepted definition of Risk (R),

$$R = n \text{ x } f \tag{5}$$

However, R can have the same value for different combinations of n and f. This is an ambiguity when conducting a comparison between different categories of disasters as it does not distinguish between high consequence/ low probability events and low consequence/ high probability events.

To overcome this limitation the Cumulative Frequencies, F(N) for fatalities, N of 10 or greater are considered. In this work a plot of F vs N is used to present the data for the purpose of comparison between different categories of disasters such as technological and natural. The plotted curve is generally known as an FN Curve or complementary cumulative distribution function (CCDF) (Baybutt & Cox, 1982). Hence, the FN curve is used as the measure in this paper to represent the societal risk from hazardous events.

3.3.2.5 FRAMEWORK FOR THE DERIVATION OF SOCIETAL RISK ACCEPTANCE CRITERIA

The framework given in Figure 3.6 is adopted for deriving the societal risk acceptance criteria for major accident hazards in Sri Lanka.

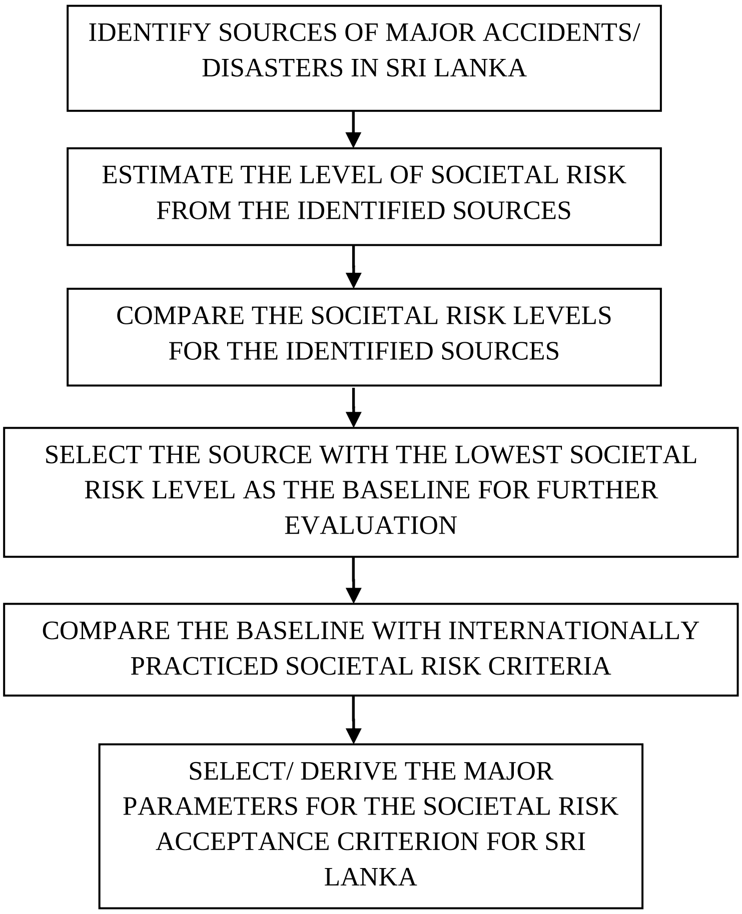


Figure 3.6 – Framework for deriving a societal risk acceptance criteria for major accident hazards in Sri Lanka

3.3.3 IDENTIFICATION OF SOURCES OF MAJOR ACCIDENTS OR DISASTERS

Major accidents or disasters are of different types. For example, natural, technological or terrorism related accidents and disasters. Each of these falls under either voluntary or involuntary type of accidents. A “voluntary” activity is considered as one where the individual uses his own value system to evaluate his experience whereas in an “involuntary” activity the options available to an individual or societal group is affected by a controlling body such as a government agency, political entity or opinion makers (Starr, 1969). It is considered that the public has limited control over MAH installations and the consequences of any catastrophic event stemming from them. Hence the risk imposed on the public by MAH installation is considered to be involuntary. For the purpose of this study, only involuntary disasters, natural and technological are considered as the 'sources of accidents or disasters'. The manmade disasters due to War, terrorism and acts of sabotage are not classified as Technological Disasters in this thesis and hence are not included.

Data for the analysis were selected from the following databases and media reports,

- Disaster Information Management System in Sri Lanka – (October 2014) www.desinventar.lk (DesInventar, 2014)
- Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database EM-DAT based in Brussels, Belgium (October 2014) - http://www.emdat.be/ (EMDAT, 2014)

Both databases maintain data accessible to the public and provide facilities for sorting the data. Data for Natural Hazards which happened in Sri Lanka were obtained from both databases whereas data for Technical Hazards which happened in Sri Lanka were obtained only from EM – DAT as sufficient data for technical hazards were not found in the Desinventar database.

The Desinventar database was accessed through the Disaster Management Center Sri Lanka (DMC- SL) website (www.desinventar.lk). EM – DAT data were obtained by accessing directly through the EM – DAT website (http://www.emdat.be/).

As per the DesInventar website its sources are the print media and government organizations. It is a database available in the public domain which can be accessed through the website of the DMC – SL.

The EM-DAT is a global database on natural and technological disasters that contains essential core data on the occurrence and effects of more than 17,000 disasters in the world from 1900 to present. EM-DAT is maintained by the Centre for

Research on the Epidemiology of Disasters (CRED) at the School of Public Health of the Universitécatholique de Louvain located in Brussels, Belgium. The database has been compiled from various sources, including UN agencies, non-governmental organizations, insurance companies, research institutes and press agencies. Priority has been given to data from UN agencies, governments and the International Federation of Red Cross and Red Crescent Societies.

Natural hazards data for Sri Lanka given in the two databases differ with respect to the categorization of event types and hence the number of fatalities. The differences in the event types are due to the different categorization of hazardous events also referred to as accident scenarios in this work which are specific to each database. For example DesInventar categorize hazardous events into 7 categories, namely cyclone, epidemic, flood, land subsidence, landslide, strong wind and tsunami. Whereas in EM-DAT, the categories of events include cyclone, epidemic, flood, landslide, local storm and tsunami. Therefore, both databases were used separately in presenting the data for natural hazards.

In this work the data for technological hazards for Sri Lanka given in the EM – DAT database were cross checked against media reports. The EM – DAT does not differentiate certain events attributed to “terrorist” activity such as “air crashes due to terrorist attack and sabotage” and includes them in the “Technical” category. Such events have not been included in this study as the causes even though are manmade cannot be directly attributed to “Technical” causes. Hence, it has to be emphasized that the disaster data in EM – DAT database were used as the basis for obtaining a majority of the data related to “Technical Causes”. The data included in this work were based on media reports of major accident hazard events in local newspapers and journal article.

The accident or disaster data used in the analysis of this work for the two natural and one technological source are shown in Tables 3.12, Table 3.13 and 3.14 respectively. All events considered were events which have caused 10 fatalities or above.

Table 3.12 – Natural Disasters of Sri Lanka from 1974 to 2012
(Source: DESINVENTAR, October 2014)

DATE	NUMBER OF DEATHS						
	CYCLONE	**EPIDEMIC**	**FLOOD**	**LAND SUBSIDENCE**	**LANDSLIDE**	**STRONG WIND**	**TSUNAMI**
1978/11/23	834						
1974/03/18		10					
1974/05/17		19					
1974/05/25		14					
1974/06/29		10					
1974/07/06		13					
1974/07/13		11					
1974/07/20		13					
1974/08/03		12					
1974/08/10		11					
1974/08/24		15					
1974/09/07		11					
1974/10/19		11					
1974/10/26		11					
1974/11/02		15					
1974/12/07		14					
1983/12/19			17				
1986/01/10			23				
1991/06/02			11				
2003/05/17			136				
2005/11/21			11				
2006/11/10			10				
2011/01/13			24				
2011/09/21			11				
2012/12/18			11				
2006/01/12				11			
2011/11/25						24	
2004/12/26							30959
1974/07/27					42		
1978/11/25					14		
1982/12/10					26		
1984/05/22					14		
1986/01/07					14		
1986/01/09					28		
1989/06/03					47		
1989/06/05					157		
1989/07/11					13		
1993/10/08					18		
2003/05/17					115		
2003/05/18					22		
2003/05/19					58		
2003/05/31					16		
2007/01/12					16		
Occurrence	1	15	9	1	15	1	1
frequency Number of Events per Year	2.50×10^{-2}	3.75×10^{-1}	2.25×10^{-1}	2.50×10^{-2}	3.75×10^{-1}	2.50×10^{-2}	2.50×10^{-2}

Table 3.13 - Natural Disasters data of Sri Lanka from 1957 to 2013 from source: EMDAT database

DATE	**NUMBER OF DEATHS PER EVENT TYPE**					
	CYCLONE	**EPIDEMIC**	**FLOOD**	**LANDSLIDE**	**LOCAL STORM**	**TSUNAMI**
1957	200					
1964	206					
1974				27		
1977				27		
1978	740					
1987		53				
1989			325			
1990			33			
1991			27			
1992			14			
1993				65		
1997			10			
1997		36				
2003			235			
2004		88				
2004						35399
2006			25			
2007			15			
2007			18			
2008			40			
2009		346				
2010			28			
2011					22	
2011			65			
2011		167				
2012			53			
2013			110			
Occurrence	3	5	13	3	1	1
frequency (Number of events per Year)	$5.36x10^{-02}$	$1.28x10^{-01}$	$3.33x10^{-01}$	$7.69x10^{-02}$	$2.56x10^{-02}$	$2.56x10^{-02}$

Note: Period considered for cyclones is from 1957 to 2013 whereas for all other events it is from 1974 – 2013

Table 3.14 - Technological Disasters of Sri Lanka from 1964 to 2013

DATE	**NUMBER OF DEATHS PER EVENT TYPE***					
	AIR	**RAIL***	**ROAD**	**STRUCTURAL**	**POISONING**	**EXPLOSION**
1964		32				
1970		14				
1974	191					
1986				126		
1989		38				
2001		14				
2005		41				
2007			19			
2008					10	
2010						21
Occurrence	1	5	1	1	1	1
frequency Number of events per Year	$2.56\text{x}10^{-02}$	$1.02\text{x}10^{-01}$	$2.56\text{x}10^{-02}$	$2.56\text{x}10^{-02}$	$2.56\text{x}10^{-02}$	$2.56\text{x}10^{-02}$

* The period considered for rail disasters is from 1964 to 2013 whereas for all other events it is from 1974 to 2013

3.3.4 ESTIMATION OF THE LEVEL OF SOCIETAL RISK FROM DIFFERENT SOURCES OF MAJOR ACCIDENTS OR DISASTERS

The risks posed by sources of natural and technological major accidents or disasters are estimated using the historical data identified in the previous section by constructing FN Curves as the following description.

For a particular source of major accidents from a specific database (e.g. Technological or Natural)

Let

n_i – number of fatalities resulting from the i^{th}accident scenario

f_i– frequency of the occurrence of the i^{th} accident scenario with n_i number of fatalities (Number of events per year)

Then a quantity $f(N_k)$ is defined such that $f(N_k)$ is the total frequency of exactly N_k number of fatalities (where more than one accident scenario or event can result in the same number of fatalities, N_k)

$$f(N_k) = \sum_{i=r}^{j} f_i \qquad (6)$$

Let the total dataset of (n_i, f_i) pairs be such that each pair has an equal number of fatalities N_k. Then the dataset is expressed as,

$$\{(n_r,f_r), (n_{r+1},f_{r+1})\ldots(n_j,f_j)\}.$$

Where,$n_r = n_{r+1} = \ldots = n_j = N_k$ with the corresponding frequencies being f_r, $f_{r+1}, \ldots, f_j$.

If p is the total number of ($f(N_k)$, N_k) pairs where,
$N_1 \leq N_K \leq N_p$ such that
N_1 – Minimum number of fatalities where $N_1 \geq 10$
N_p – Maximum number of fatalities

Then ($f(N_k)$, N_k) pairs of datasets can be expressed as,

$$\{(f(N_1), N_1),(f(N_2), N_2), \ldots,(f(N_k), N_k),\ldots,(f(N_p), N_p)\}$$

The complementary cumulative function F (N) can then be defined as,

$$F(N) = f(N_p) + f(N_p - 1) + \ldots + f(N_k) + \ldots + f(N_1) \qquad (7)$$

Where,
F (N) – The sum of the frequencies of all accident scenarios where the outcome is N fatalities or more

The above described method is adapted from the description given in research report RR 073 published by UK HSE (Evans, 2003).An FN curve can graphically be constructed as shown in Figure 3.7 by commencing from the maximum N value (N_p) at the point [F (N_p), N_p)] and by proceeding down to the minimum N value (N_1) at the point [F (N_1), N1]. FN curves are plotted on logarithmic axes (Saw, Wardman, Wilday, McGillivray, Balmforth, McManus, Reston & Rushton, 2009).

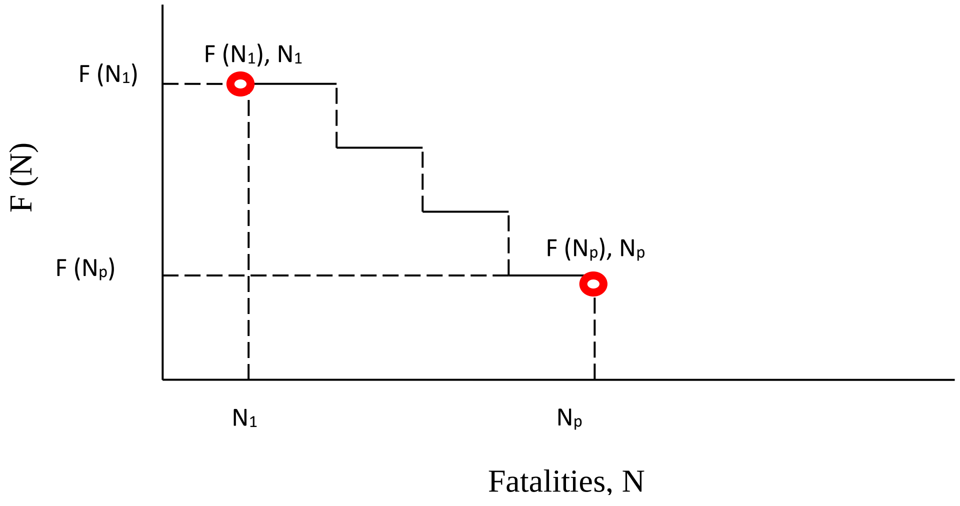


Figure 3.7 – FN Curve with Key Coordinates, Source: (Saw et al., 2009)

Three FN curves are drawn as described above for the three different data sets calculated using data in Tables 3.12, 3.13 and 3.14 and are shown in figure 3.8. These three FN curves are named as follows,

1. TECHNOLOGICAL – Technological Accident Data from local newspapers and journal articles
2. EMDAT – Natural Accident Data from the EMDAT Database
3. DESINVENTAR – Natural Accident Data from the DesInventar Database

The above datasets were plotted using logarithmic scale due to the need of representing a wide range of values. The datasets are analysed using linear regression. The “best linear fit” for the log – log plots for the respective datasets stated above are shown in Figures 3.9, 3.10 & 3.11. Plotting of graphs and curve fitting were carried out using MATLAB.

3.3.5 COMPARISON OF THE SOCIETAL RISK FOR NATURAL AND TECHNOLOGICAL DISASTERS

Analysis of the FN Curves shows that the relationship between Cumulative Frequency, F(N) and Number of Deaths, N for high consequence events (i.e. catastrophic events resulting in multiple fatalities such as tsunami, cyclones, landslides, explosion, fires and toxic exposures) has a power law relationship (refer Table 3.15).

Table 3.15 – FN Relationships for Technological and Natural Accidents

SYSTEM	NAME OF THE CURVE	LOGARITHMIC (LOG – LOG) FORM	POWER LAW FORM
Natural Disasters (DesInventar)	DESINVENTAR	$\log(F) = -0.85 \log(N) + 4.07$ (figure 3.9)	$FN^{0.85} = 10^{(4.07)}$
Natural Disasters (EMDAT)	EMDAT	$\log(F) = -0.75 \log(N) + 3.72$ (figure 3.10)	$FN^{0.75} = 10^{(3.72)}$
Technological Disasters	TECHNOLOGICAL	$\log(F) = -1.12 \log(N) + 2.45$ (figure 3.11)	$FN^{1.12} = 10^{(2.45)}$

The power law relationship as mentioned by Mannan (2012) can be generalized and written as below,

$$FN^{\alpha} = R \tag{8}$$

This representation is in accordance with the general interpretation of the meaning of risk,

Risk = Probability x Consequence.

The two databases representing natural hazard data (DesInventar and EM – DAT) follow a similar trend as seen in curves DESINVENTAR and EMDAT in Figure 3.8. Further, it shows that the risk level of technological hazards is almost an order of magnitude (10 times) less than that for natural hazards.

The analysis yields the following conclusions with respect to Sri Lanka,

1) The relationship between Cumulative Frequency, F(N) and Fatalities, N for events having 10 fatalities or more can be represented by the general relationship shown in equation (3). Values for α and R in this equation are dependent on the hazardous system under consideration

2) The risk levels from high consequence natural disasters are higher than that of high consequence technological disasters in the Sri Lankan context by an order of magnitude (approximately 10 Times).

Societal Risk Acceptance criteria can be expressed as a FN criterion line by taking the log of both sides of the power law equation,

$$\mathrm{Log}(FN^{\alpha}) = \mathrm{Log}(R) \tag{9}$$

$$\mathrm{Log}\ R = \mathrm{Log}\ F + \alpha \mathrm{Log} N \tag{10}$$

Where, R – Constant

α – Risk Aversion Factor

The risk aversion factor (α) is the slope of the criterion line. The risk aversion factor is used to represent the "aversion to risk" or "risk perception" of a particular society with regard to major accident hazards (Ball and Floyd, 1998). An aversion of -1 implies risk neutrality whereas a value of -2 implies a more risk averse society (Pasman & Vrijling, 2003). The choice of risk aversion factor is primarily a policy issue. The UK has chosenan α= -1 (Risk Neutral) whereas the Netherlands has chosen an α = -2 (Risk Averse) (Pasman & Vrijling, 2003). Even though both countries have well developed risk acceptance criteria with respect to major accident hazards, their criterion lines differ.

In the Sri Lankan context a similar criterion line can be established. The values of R and α can be derived from the FN curves derived from the historical data as shown in table 3.15.

Let the relationship for the Sri Lankan context be

$$FN^{\beta}=K \qquad (11)$$

Where,
β – “Risk Averseness” for the Sri Lankan context
K – Constant corresponding to the Sri Lankan context
The relationship can then be expressed as a log – log relationship,

$$\text{Log } K = \text{Log } F + \beta \text{ Log } N \qquad (12)$$

This has a similar form to the FN Criterion Lines shown in table 3.15. Hence appropriate values for β and K can be selected to define the reference or baseline societal risk acceptance criterion line. This selection process is discussed in the following section.

3.3.6 SELECTION OF THE REFERENCE SOCIETAL RISK ACCEPTANCE CRITERION

When comparing the risks between natural and technological accidents shown in figure 3.8, the most suitable FN Curve for selecting appropriate α and R values is the curve for technological accidents as it represents a lower level of risk. For a total of 10 fatalities or more the frequency of events per year are 0.4, 6 and 15, for TECHNOLOGICAL, EMDAT and DESINVENTAR FN curves, respectively. For 100 fatalities or more the frequency of events per year are 0.055, 1 and 1.5 for TECHNOLOGICAL, EMDAT and DESINVENTAR curves respectively. Hence, the results show that the level of risk from a technological hazard is less than that from a natural hazard with respect to major accidents. However, it must be emphasized that within the data analyzed,

- Only one major accident with multiple fatalities has occurred with regard to chemical transportation in Sri Lanka; that is the explosion of explosives in Batticaloa in 2010.

- No major accidents have occurred in the Sri Lankan Chemical Process Industry (CPI) that has caused multiple fatalities in excess of 10 fatalities with respect to the public.

One may initially conclude that the low number of major accident data in the CPI in Sri Lanka is due to the level of existing safety standards and is safe to continue with the status quo. However, this can be misleading. The lack of data on major accidents in Sri Lanka may be due to the low complexity and scale of activity at present in the CPI compared to much more industrialized countries and cannot be attributed to the prevailing Process Safety Management (PSM) practices in the country without further investigation.

The meaning of “Societal Perception of Risk” can vary widely across different stakeholders making the selection of an appropriate “risk aversion” factor a difficult task. Hence, one might not be able to arrive at an “ideal” or objective value for β. In the absence of a transparent method in selecting β, a value of -1 is proposed initially for “risk aversion” which is approximated to the β value obtained for Technological Hazards in the FN curve that is β= -1.12 (Table 3.16). A slope of the FN curve or the β value with -1 is considered as societal perception being risk neutral (Ball & Floyd, 1998). Hence, the result obtained, β = -1.12 implies slight risk averseness. Therefore, in this work a risk neutral approach is proposed to be adopted initially due to lack of conclusive evidence on whether the Sri Lankan public is actually risk averse or risk neutral. A risk prone criterion ($\beta > -1$) is not advocated as it leads to the acceptance of higher number of fatalities.

A similar dilemma exists when selecting an appropriate K value or intercept for the criterion line. The K value can be established based on the results obtained for technological hazards shown in Table 3.15. The criterion line would then be identical to the best fitted linear curve of the FN Curve for technological disaster data shown in figure 4 and would be a representation of the existing level of risk for technological disasters. However, this study does not propose the use of the best fitted linear curve for FN technological disaster data (given in Figure 3.9) when selecting the K value without addressing the following arguments,

1) Is the existing level of risk posed by technological sources safe enough?
2) Are past chemical process incidents appropriately represented in the FN curve for technological disasters?
3) Should Sri Lankan society continue to maintain the same level of risk with respect to technological disasters or target a lower risk level for the future?

In the absence of any baseline for the current level of risk in Sri Lanka from major accident hazards, question 1 remains open ended. With respect to question 2, the data analyzed in this work include only one accident which can be classified as a major accident resulting in multiple fatalities. That is the explosion of explosives in Batticaloa in 2010. Therefore it can be argued whether the FN curve determined for technological disasters is appropriately represented where the CPI is concerned, albeit if it is only a single incident.

The third question essentially decides the choice of the K value and the corresponding anchor point for the criterion line. As per the FN curve for technological disasters in Figure 3.8 (curve named as TECHNOLOGICAL), the probability of 10 fatalities from a major technological related disaster is approximately 1 per year. Hence, if the FN curve for technological disasters is chosen as the criterion line for societal risk in Sri Lanka, the anchor point will be (10, 1) with a slope of approximately -1.12, which indicates a slight risk averseness.

3.3.7 COMPARISON OF THE FN CURVE FOR TECHNOLOGICAL DISASTERS IN SRI LANKA WITH INTERNATIONAL SOCIETAL RISK ACCEPTANCE CRITERIA

In order to decide whether the current level of risk is sufficient with respect to technological systems, the FN curve for technological disasters (curve named as TECHNOLOGICAL) is compared with that of other Societal Risk Acceptance Criteria developed and used in other countries (Ball & Floyd, 1998; Pasman & Vrijling, 2003).

3.3.7.1 DETERMINING THE SOCIETAL RISK LEVEL RELATIVE TO INTERNATIONALLY ACCEPTED LEVELS

The Table 3.17 shows a summary of risk acceptance criteria developed and used by different countries in the world (Ball & Floyd, 1998). As shown in Table 3.16 majority of the countries use the anchor point (10, 10^{-4}), which implies 10 fatalities in 10,000 years. However, the FN curve derived for technological disasters in Sri Lanka has an anchor point of (10, 1). Hence, one may argue that the adoption of the FN curve for technological disasters will lead to the tolerance of a very high level of risk compared to other risk acceptance criteria currently in use internationally (refer Table 3.16). Therefore, adopting the anchor point of the FN curve derived above would lead to an acceptance of risk which is 4 orders of magnitude higher (10,000 times) than the international practice. Such a criterion with a high level of risk will create a loophole through which unsafe MAH installations can be justified. Hence, the anchor point of the FN curve for technological disasters determined in this work is further analyzed in establishing the reference or the base for societal risk acceptance criterion for Sri Lanka.

3.3.7.2 SELECTION OF MAJOR PARAMETERS FOR THE SOCIETAL RISK ACCEPTANCE CRITERION FOR SRI LANKA

The limitations of the outright adoption of the FN curve for technological disasters in Sri Lanka as a baseline for establishing a societal risk acceptance criterion were discussed in section 3.3.6. Although, the slope of this FN curve for technological disasters provides a suitable starting point for selecting the “risk averseness” that needs to be adopted in a criterion line, the anchor point is selected based on the international societal risk acceptance criteria.

As seen in Table 3.16, the anchor point of 10 fatalities per 10,000 years (10,10^{-4}) has been accepted and applied widely (CCPS,2009; Ball & Floyd, 1998). This anchor point has its origins with the work done by the Advisory Committee on Major Accident Hazards (ACMH), which in 1976 made the tentative suggestion that for any particular plant a serious accident frequency of 10^{-4} per year might be regarded as just on the borderline of acceptability (Ball and Floyd, 1998). According to Ball and

Floyd the term Serious Accident was not defined by the ACMH, but is considered by QRA practitioners to be 10 or more fatalities. It is based on professional judgment by the ACMH and is widely used in setting the FN Criteria Lines (Ball & Floyd, 1998;Trbojevic,2010;CCPS,2009). Therefore, in this work an anchor point of 10 fatalities per 10,000 years ($10,10^{-4}$) was chosen for the societal risk acceptance criterion line.

The following parameters are selected in setting a societal risk acceptance criterion line for Sri Lanka for major accident hazards,

- Slope of Criterion Line (β) : -1 (Risk Neutral)
- Anchor Point : 10 Fatalities in 10,000 years

The basis of the above selection is as follows,

- The inadequacy of the FN curve derived for major technological accidents in Sri Lanka as a baseline to provide an acceptable level of risk
- The need to benchmark Sri Lankan societal risk criteria with internationally accepted risk acceptance criteria
- To provide a level of safety to the public in Sri Lanka from major accident hazards stemming from the chemical process industry commensurate with that enjoyed by societies with a well-developed Process Safety Management (PSM) culture.

The selected societal risk criterion line along with the FN curve determined from past accident data is given in figure 3.12.

Table 3.16: Summary of Societal Risk Criteria based on the Likelihood (F per Year) of N or more fatalities

YEAR	**COUNTRY**	**ANCHOR POINT**		**SLOPE**	**COMMENTS**
		Number of Fatalities (N)	**Frequency (F)**		
1976	United Kingdom	10	10^{-4}	n/a	ACMH for Hazardous Installations : Single Point Criterion (frequency) with presumed consequences
1978	Netherlands	10	10^{-4}	-2	Groningen for Hazardous Installations
1982	United Kingdom	10	10^{-4}	-1	Revised Kinchin for Nuclear Reactors: Basis is the earlier Kinchin Curve for Nuclear Reactors which considers the limits of risks from a nuclear reactor programme should be similar to those from a meteorite
1988	Hong Kong	10	10^{-4}	-1	Societal Risk Guideline for Hazardous Installations: Limit of tolerability based on ACMH criterion and revised Kinchin Curve
1989	Netherlands	10	10^{-2}	-2	Societal Risk Guideline for Hazardous Installations: Anchor point based on Consideration of Individual Risks
1991	United Kingdom	500	$2x10^{-4}$	-1	Advisory Committee on Dangerous Substances (ACDS) – Community close to Dangerous Goods transport route
1993	United Kingdom			-1 & -1.3	Offshore Oil/Gas Platforms
1993	Hong Kong	10	10^{-4}	-1	Societal Risk Guidelines for Hazardous Installations: As 1988 criteria but ALARP region introduced
1995/6	Netherlands	10	10^{-2}	-2	Societal Risk Guidelines for Hazardous Installations: As 1989 criteria but acceptable region removed

Source: (Ball and Floyd, 1998)

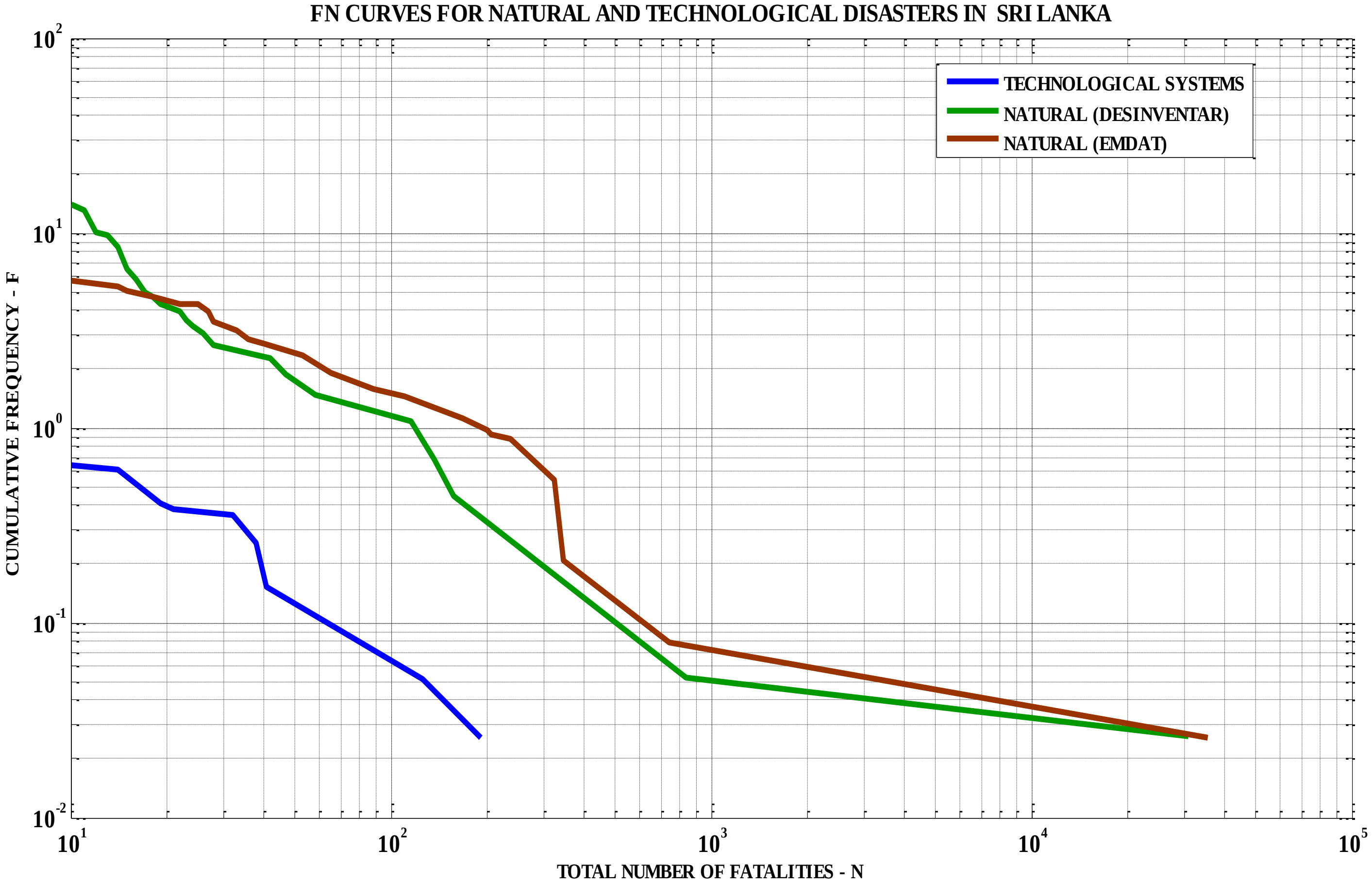


Figure 3.8 – FN Curves for Major Natural & Technological Hazards in Sri Lanka

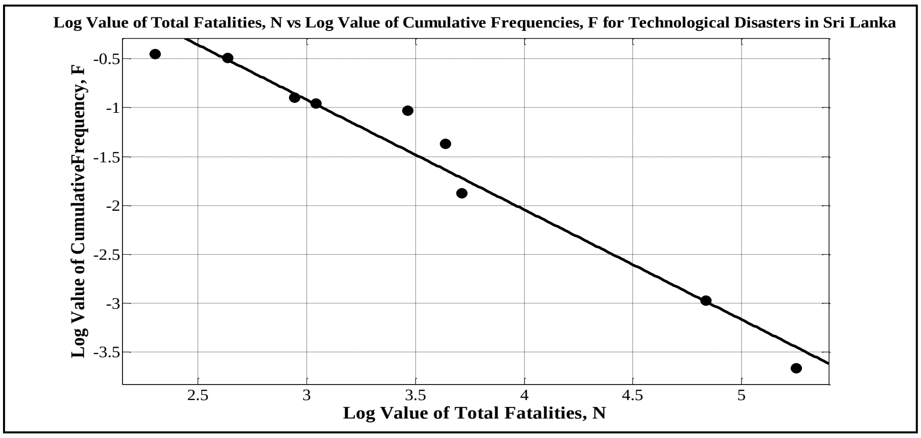


Figure 3.9 – Fitted Linear Curve for log – log plot of Total Fatalities (N) vs Cumulative Frequency (F) for Technological Disaster Data (TECHNOLOGICAL curve)

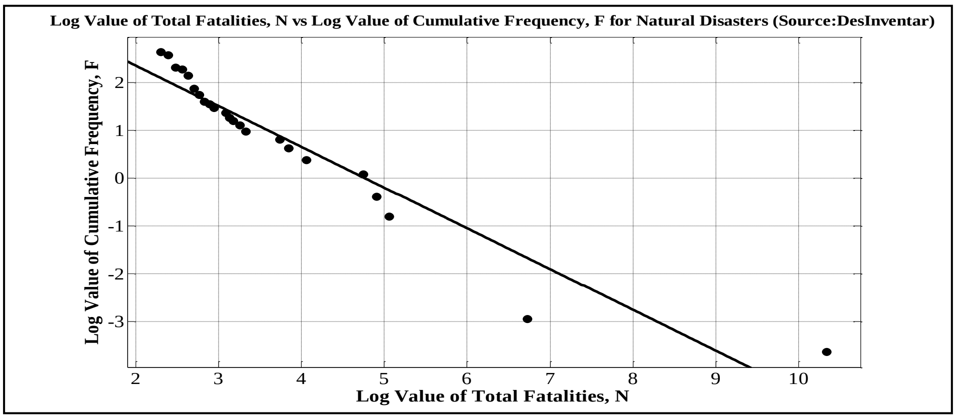


Figure 3.10 – Fitted Linear Curve for log – log plot of Total Fatalities (N) vs Cumulative Frequency (F) for NaturalDisaster Data (DESINVENTAR curve)

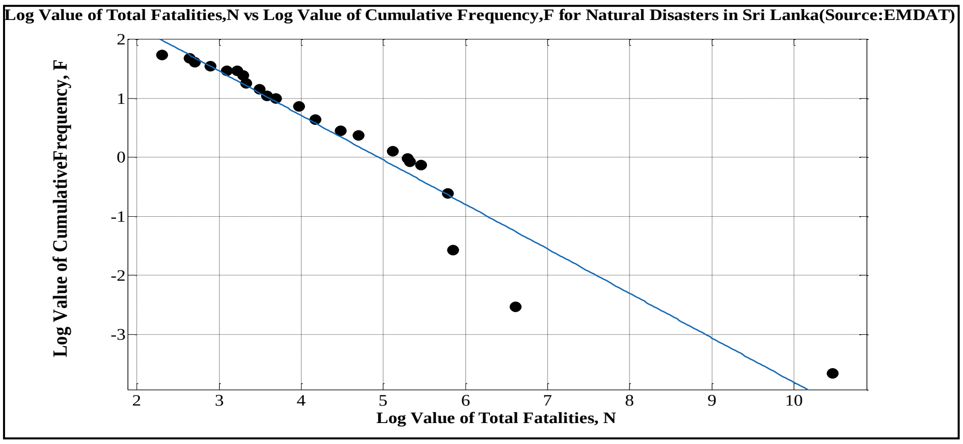


Figure 3.11 – Fitted Linear Curve for log – log plot of Total Fatalities (N) vs Cumulative Frequency (F) for Natural Disaster Data (EMDAT curve);

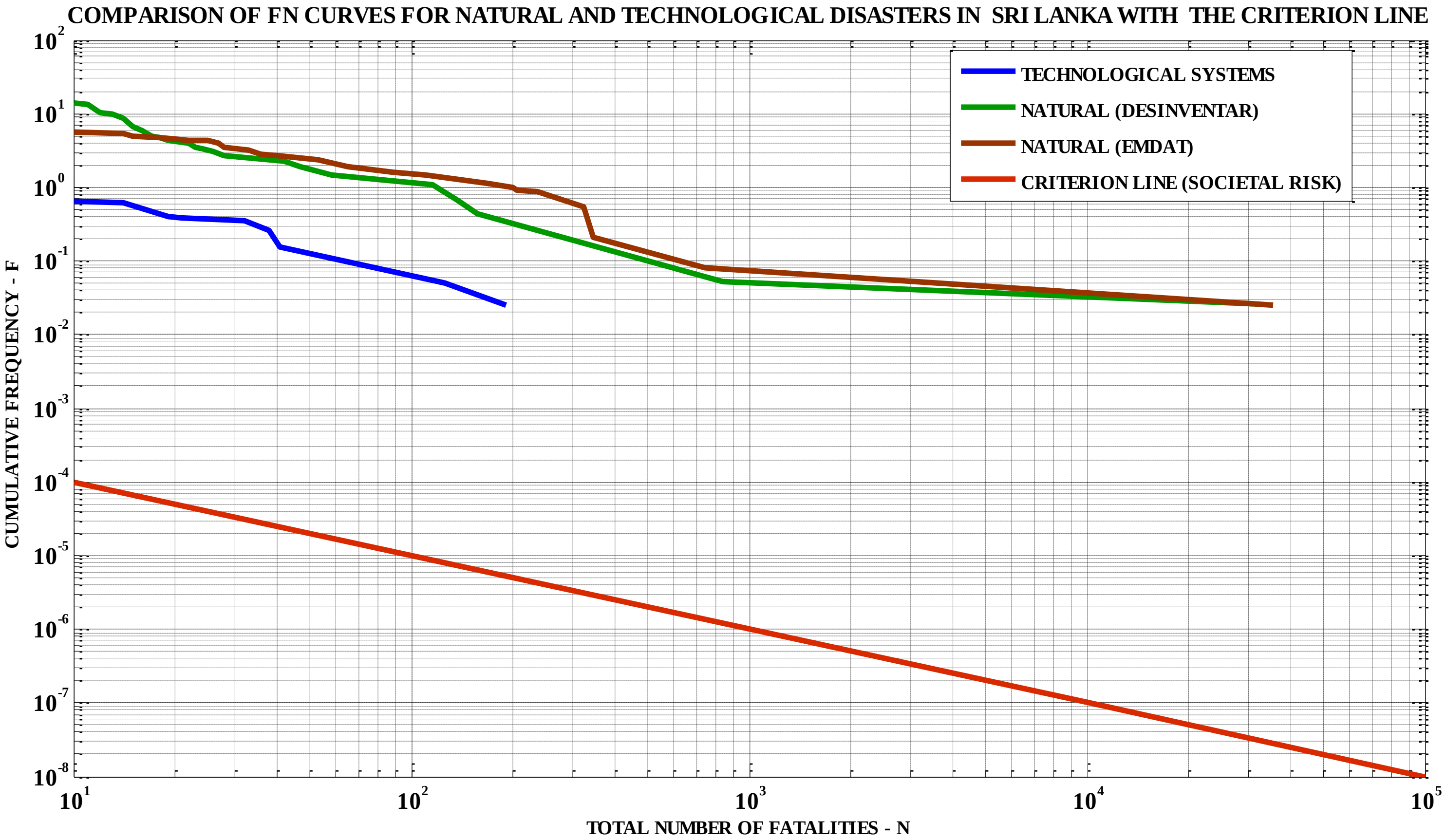


Figure 3.12 – Proposed Criteria Line for Societal Risk in the CPI for Sri Lanka

CHAPTER 4

4. APPLICATION OF THE RISK ACCEPTANCE CRITERIA IN EVALUATING THE LEVEL OF RISK FOR A BULLET TYPE PROPANE STORAGE TANK

The risk acceptance criteria derived in Chapter 3 are applied in evaluating the acceptability of risk posed by a bullet type propane storage tank. The risk acceptance criteria for the Consequence based approach, the safety distance and the societal risk acceptance criteria for the probabilistic risk assessment approach which is the FN curve are applied separately. The results are then compared for depth of analysis and gaps in information yielded.

4.1 APPLICATION OF RISK ACCEPTANCE CRITERIA USING THE CONSEQUENCE BASED APPROACH

4.1.1 INTRODUCTION

The societal risk acceptance criterion, safety distance is determined by quantifying the level of risk using consequence based analysis. In this application, the procedure followed involves selecting possible accident scenarios, identifying likely resulting events for these scenarios and modeling their consequences. Based on the application to a liquefied propane storage tank, the safety distances for four potential accident scenarios are presented in this section. This analysis considers the selected probit equations summarized and shown in table 3.11 in Chapter 3.

The consequences are modeled using ALOHA, which is a software developed by the Emergency Response Division (ERD) of US National Oceanic and Atmospheric Administration (NOAA) in collaboration with the US Environmental Protection Agency (US EPA). The latest version available as of June 2015 (Ver 5.4.4) is used. The proposed approach is applied to the Risk Analysis of a Propane Bullet Tank with respect to Major Offsite Consequences.

4.1.2 SELECTION OF ACCIDENT SCENARIOS FOR THE CONSEQUENCE ASSESSMENT APPROACH

An accident scenario essentially consists of an event sequence initiated by a “Loss of Containment (LOC)” event and a chain of events resulting in a dangerous phenomenon (Tugnoli, Gyenes, Van Wijk, Christou, Spadoni & Cozzani, 2013). A fully developed “Accident Scenario Selection Procedure” for a Quantitative Risk Analysis (QRA) will include the following,

1. Identification of LOC events (i.e. Critical Events)
2. Development of a Fault Tree for each critical event
3. Development of an Event Tree for each critical event
4. Draft a Table of Accident Scenarios based on,
    a) Experience from Analysis of Past Accidents
    b) Checklists based on Safety Reports
    c) Standard Scenarios from Guidelines
    d) Structured review using a Process Hazard Analysis method (e.g. HAZOP)
5. Ranking of the selected scenarios based on Frequency, Severity, Time Scale and Presence/ Effectiveness of Safety Barriers

However, for a risk analysis limited to a purely Consequence Assessment approach, steps 1, 3, 4 and 5 are sufficient. In consequence analysis, the analysis commences from the “Critical Event” or LOC or initiating event and considers the subsequent chain of events leading to the primary consequences such as Toxic Exposure, Fire or Explosion (if required secondary consequences/ domino effects such as a BLEVE also can be considered). Hence, event trees are used in the development of chain of resulting events to possible accident scenarios. The selection of accident scenarios is carried out on a “Worst Case Basis” and therefore, the existence of safety barriers is not considered.

4.1.2.1 SELECTION OF ACCIDENT SCENARIOS FOR A BULLET TYPE LIQUEFIED PROPANE STORAGE TANK

The case study considers the storage of liquefied propane under pressure in a stationary horizontal pressure vessel (commonly known as a Bullet Tank). The propane is assumed to be stored in a horizontal Vessel (Bullet Tank) and situated in an open area. A hypothetical case where the installation of a Propane bullet in the western province is considered. The basis for the selection of LOC Events is based on the guidelines given in the "Purple Book", CPR 18E – Guidelines for Quantitative Risk Assessment, 3rd Edition, RIVM, Netherlands (De Haag & Ale, 2005). The "Purple Book" identifies the following LOC's for Stationary Pressure Vessels,

1. Instantaneous release of the complete inventory
2. Continuous release of the complete inventory in 10 min at a constant rate of release
3. Continuous release from a hole with an effective diameter of 10mm

The following three loss of containment (LOC) events are selected for each of the aforementioned LOCs and relevant event trees developed.

1. Catastrophic Failure of the Pressure Vessel – Instantaneous Release of the Complete Inventory (Only Hot Failures are considered)

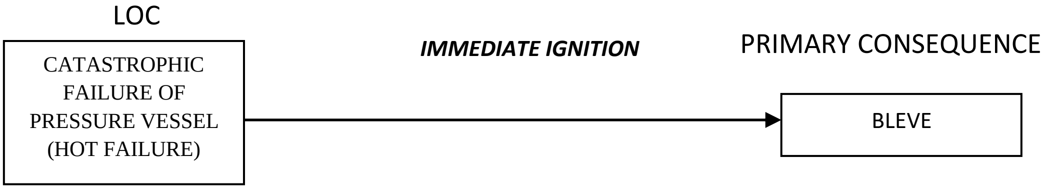


Figure 4.1 – LOC due to Catastrophic Failure of Pressure Vessel (Hot Failure)

2. Continuous Release of the Complete Inventory in 10 min

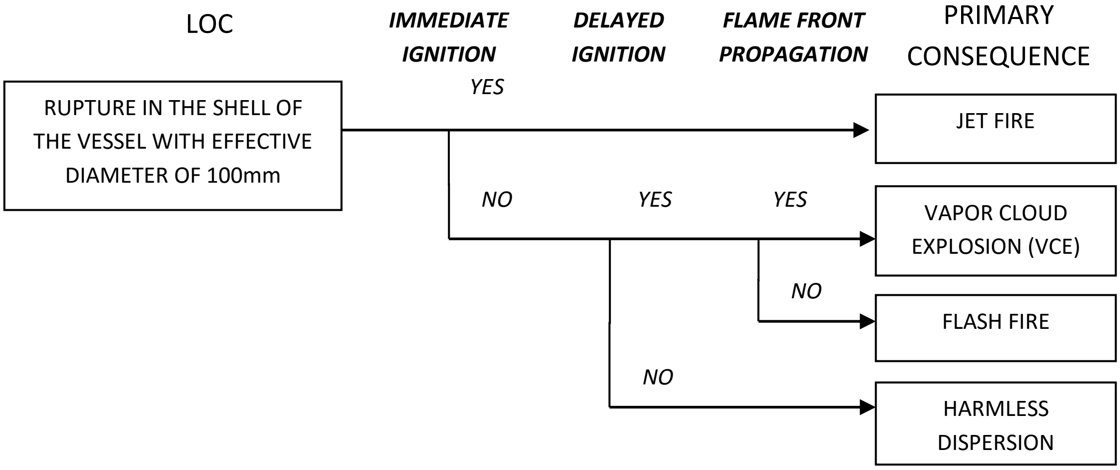


Figure 4.2 – LOC due to Rupture in the Shell of the Vessel with Effective Diameter of 100mm

3. Continuous release from a hole with an effective diameter of 10mm

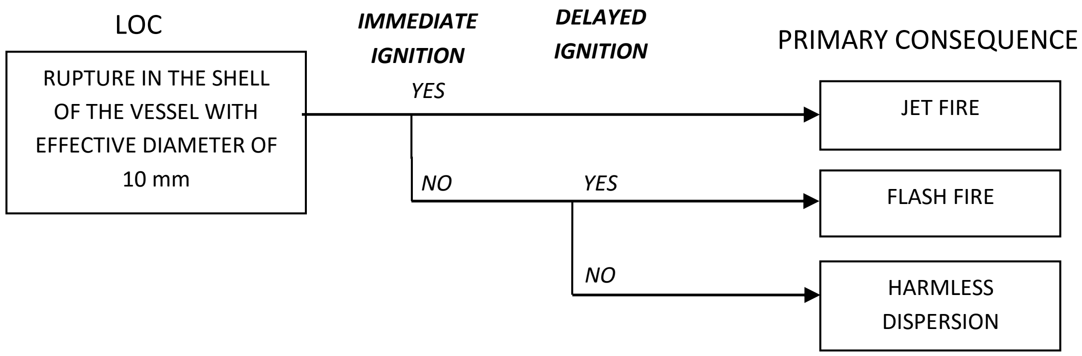


Fig 4.3 – LOC due to continuous release from a hole with an effective diameter of 10mm

The "Worst Case" scenarios are then selected based on the "event trees" considered above and the potential for harm based on records of previous accidents. The events are listed in Table 4.1.

Table 4.1 – Selected Accident Scenarios for the propane storage vessel

LOC		CONDITION	WORST CASE CONSEQUENCE	OFFSITE EFFECTS
1	Catastrophic Failure of Pressure Vessel (Hot Failure)	Immediate Ignition	Boiling Liquid Expanding Vapor Explosion (BLEVE)	1. Overpressure 2. Thermal Radiation
2	Rupture in the Shell of the Vessel with the Release of the Entire Inventory within 10 minutes	Immediate Ignition	Vapor Cloud Explosion (VCE)	1. Overpressure 2. Thermal Radiation
3	Rupture in the Shell of the Vessel with the Release of the Entire Inventory within 10 minutes	Delayed Ignition	Flash Fire	1. Thermal Radiation
4	Rupture in the Shell of the Vessel with an effective diameter of 10mm	Delayed Ignition	Flash Fire	1. Thermal Radiation

The toxicity of propane is low (National Research Council, 2012). Hence, toxicity effects of Propane are not considered in this case study. Hence, the following four major accident scenarios have been selected for the liquefied propane storage vessel for analysis,

1. Catastrophic failure of the pressure Vessel resulting in a BLEVE
2. Rupture of the shell of the pressure vessel with the release of the entire inventory of propane within 10 minutes of the LOC resulting in immediate ignition and a Vapor Cloud Explosion (VCE).
3. Rupture of the shell of the pressure vessel with the release of the entire inventory of propane within 10 minutes of the LOC resulting in delayed ignition with a Flash Fire
4. Rupture in the Shell of the Vessel with an effective diameter of 10mm with delayed ignition, resulting in a Flash Fire

Jet Fire scenarios are not included as the primary consequences are low even though jet fires can lead to secondary consequences with catastrophic outcomes such as a BLEVE. However, the effects of a BLEVE are already included in the 1st Accident Scenario.

4.1.3 APPLICATION OF CONSEQUENCE ANALYSIS FOR EACH ACCIDENT SCENARIO

The impact of each consequence identified in the scenarios given in table 4.1 is calculated and the corresponding safety distances are estimated for the hypothetical case study given below.

The case under consideration consists of a hypothetical case where propane is liquefied under pressure and stored in a horizontal storage vessel (Bullet Tank) and situated in an open area in the western province.

The Propane shall be stored under the following ambient conditions,

- Average Ambient Temperature, $T_a = 28\ ^{O}C$
- Average Atmospheric Pressure, $P_a = 14.7$ psi

The operating and design parameters of the pressure vessel are as follows,

- Operating Pressure, P_O = 6 bar(g)
- Design Pressure, P_D = 9.5 bar (g)
- Operating Temperature, T_O = 28 ^oC
- Design Temperature, T_D = 40 ^oC
- Length of the LPG Vessel = 11 m
- Diameter of the LPG Vessel = 3.658 m (Ellipsoidal Dish Heads)
- Maximum Volume of Pressure Vessel, V_{Max}= 116 m^3
- Operating Volume of Pressure Vessel, V_O = 80% of Maximum Volume
- Total Inventory of Propane in the Pressure Vessel at 80% of fill volume = 45, 621 kg (Estimated using ALOHA)

The threat zones were estimated using ALOHA using the aforementioned parameters and the maximum 1% fatality distances were determined for each respective scenario. The respective calculations are given in Appendix F. Default endpoints given in ALOHA were not used and endpoints were calculated based on the probit functions selected in Chapter 3 and given in table 3.11. Furthermore, flash fire scenarios were assessed based on a probability of 100% fatality for humans exposed within the Vapor Cloud having a LEL of 100%, whereas those outside the envelope were considered to be free from fatal effects (0% Fatality).

4.1.4 COMPARISON OF THE CONSEQUENCE EFFECTS FOR THE SELECTED SCENARIOS

A comparison of the maximum consequence distances resulting from the calculations in Appendix F are given below in table 4.2. Considering the 1% Fatality criteria the maximum consequence distance corresponds to the Vapor Cloud Explosion (VCE) in case a of scenario 2, which is 560 meters.

Table 4.2 – Comparison of Threat Distances for the Different Accident Scenarios for the Consequence Assessment approach

% Fatality	MAXIMUM CONSEQUENCE DISTANCE (m)					
	SCENARIO 1	SCENARIO 2		SCENARIO 3		SCENARIO 4
	BLEVE	VCE (Case a)	VCE (Case b)	FLASH FIRE (Case a)	FLASH FIRE (Case b)	FLASH FIRE (Case a)
100	209	Not Exceeded	Not Exceeded	525	456	0
50	266	Not Exceeded	Not Exceeded	Not Applicable	Not Applicable	Not Applicable
20	Not Applicable	Not Exceeded	Not Exceeded	Not Applicable	Not Applicable	Not Applicable
10	Not Applicable	528	402	Not Applicable	Not Applicable	Not Applicable
1	386	560	309	Not Applicable	Not Applicable	Not Applicable

4.1.5 SIGNIFICANT ASPECTS OF APPLICATION OF THE CONSEQUENCE ASSESSMENT APPROACH

The analysis of the consequences of major accident hazards poses the following challenges,

- Selection of realistic accident scenarios
- Choosing reliable Consequence Analysis models
- Application of the chosen models
- Interpreting the outcome of the analysis
- Selecting reliable Criteria for comparison

The selection of realistic accident scenarios is a major requirement for conducting an accurate analysis. A systematic method is required for selecting the accident scenarios. Methods ranged in complexity. The method proposed by Tugnoli (Tugnoli et al, 2013) was well developed and complete. Further, well developed databases such as MHIDAS are available in the public domain and have references to actual accidents that have taken place. The method proposed by Tugnoli (Tugnoli et al.,2013) was used to draw up realistic accident scenarios.

Validated consequence analysis models are available in the publications of TNO (TNO, 2005) and CCPS (CCPS, 1999). However, the majority of the models were found in TNO and CCPS publications. Models for the consequence analysis of BLEVE phenomenon were well developed for both Blast Overpressure and Thermal Radiation effects. However, no model was available to calculate the Thermal Radiation effects of a VCE other than the method of calculation for the adiabatic flame temperatures by Lees (Mannan, 2012). The models for dispersion are well developed and tried methods are available for dense gas dispersion. However, the Flash Fire threat zones were determined using LEL concentrations only. No direct Thermal Radiation calculations for Flash Fires due to Flammable Vapour Clouds were found.

The consequences in this study were modeled using ALOHA which provides extensive details on the models used and respective limitations of each model (Lehr, Simcek – Beatty & Reynolds, 2013). The only exception was the calculation of the Blast Overpressure effects for the BLEVE event where ALOHA does not model Blast Overpressure events for BLEVEs. The Blast Overpressure for the BLEVE was estimated using the BST Model.

The need to select more than one “Credible Scenario” compared to a single “worst case scenario” is evident from the analysis. If a single worst case scenario is to be chosen the obvious choice would be the BLEVE. The impact of the BLEVE can range from 100% to 1% Fatalities within the estimated distances whereas for the VCE the range is less than 20% fatalities. However, in this analysis the maximum distance for 1% fatalities with respect to a VCE is greater than that for the BLEVE even though the range of fatal effects is lower. Therefore if a safe distance is set for the 1% fatality distance based on the BLEVE only, some sectors of the public in the vicinity of the installation will suffer fatalities due to the VCE. Hence, the 1% Fatality criterion must be evaluated for all scenarios and compared; the safe distance shall be based on the largest of the maximum distances generated for each scenario.

Furthermore, applying a probit based approach in setting the endpoints provides a clear picture of the distribution of the fatalities over an exposure distance for a particular consequence.

4.2 APPLICATION OF RISK ACCEPTANCE CRITERIA FOR THE PROBABILISTIC RISK ASSESSMENT APPROACH FOR A BULLET TYPE PROPANE STORAGE TANK

The primary purpose of this exercise is to determine whether the risk acceptance criterion developed based on the FN curve can be applied practically. The societal risk acceptance criteria developed in the form of the FN curve discussed in section 3.2 is applied to the case study described in section 4.1.3. The incidents considered are hypothetical and is adopted solely for demonstrating applicability of the FN curve proposed in this work. This application is carried out estimating the risk posed by the tank using the probabilistic risk assessment approach. The probabilistic risk assessment process is discussed in Chapter 2, section 2.5.3.2 and presented graphically in figure 2.2. The following major activities are required to be carried out in determining the risk from major accident hazards using the probabilistic risk assessment process,

- Identification of hazards
- Estimation of the consequences of these accidents
- Estimation of the probability of occurrence of the potential accidents
- Integration into overall risk indices

Hence, the identification of credible accident scenarios, estimation and analysis of consequences for each scenario and calculation of accident frequencies based on event probabilities (Failure Frequency Data) and conditional modifiers (e.g. Ignition probabilities, probabilities of jet fire impingement, probability of explosion) is required to be carried out for the case study.

Accident scenarios for the case study were identified by developing event trees for the three initiating events for the loss of containment (LOC) of the pressurized storage vessel (bullet tank) as given blow,

1. Instantaneous release of the complete inventory
2. Continuous release of the complete inventory in 10 min at a constant rate of release
3. Continuous release from a hole with an effective diameter of 10mm

The failure frequency values available in literature from five sources were used and five FN curves were derived. All FN curves were compared with the societal risk acceptance criterion FN curve developed in chapter 3, section 3.2 of this work. The probabilistic risk assessment method adopted in this case study application is as prescribed by BEVI Reference Manual (National Institute of Public Health and the Environment [RIVM], 2009).

4.2.1 SELECTION OF ACCIDENT SCENARIOS FOR THE PROBABILISTIC RISK ASSESSMENT APPROACH

The selection of accident scenarios is critical in a probabilistic risk assessment (PRA) as the completeness of selection and the credibility of the selected scenarios directly impact both the consequences as well as the event frequencies. Accident scenarios can be in principle be developed from hazard identification techniques such as Hazard and Operability (HAZOP) studies, Failure Modes and Effects Analysis (FMEA) or historical records. Highly systematic methods of selecting accident scenarios have been proposed such as Maximum Credible Accident Scenarios MCAS (Khan, 2001) and Reference Criteria (Tugnoli et al.,2013); these methods propose the ranking of accident scenarios through a ranking process and their subsequent selection based on the derived ranking.

The scenarios for this study have been selected based on the reference scenarios proposed by the Reference Manual Bevi Risk Assessments by RIVM (National Institute of Public Health and the Environment), Centre for External Safety, Netherlands (RIVM, 2009). The scenario given in this manual are selected due to its relevance for the case under consideration, transparency and presentation of a complete set of scenarios.

Since the LPG Bullet Tank is an aboveground pressurized storage tank the following scenarios are selected based on the reference scenarios for the release of a liquefied flammable gas from a storage vessel as in given in Reference Manual Bevi Risk Assessment by RIVM (RIVM, 2009),

1. Instantaneous release of entire contents
2. Release of entire contents in 10 minutes in a continuous and constant stream
3. Continuous release of contents from a hole with an effective diameter of 10mm

The scope covered by the aforementioned scenarios is given in Table 4.3,

Table 4.3 – Parts included in the scenario for aboveground pressurized storage tank

SECTIONS OF THE PROPANE BULLET TANK INCLUDED IN THE CASE STUDY	**SECTIONS OF THE PROPANE BULLET TANK NOT INCLUDED IN THE CASE STUDY**
Welded stumps	Transport pipelines from the quick closing valve
Mounting Plates	Vapour Return Pipe
Instrumentation pipes	Pressure Relief Device
Pipe connections up to the first flange	Pipeline system

Source: (RIVM, 2009)

4.2.2 DEVELOPMENT OF EVENT TREES FOR THE CASE STUDY

Event trees are developed for each of the three scenarios given above in section 4.2.1. The event tree is an inductive method where the sequence of events beginning from the initiating event to the final consequence of an accident (Crowl & Louvar, 2014) can be derived and depicted graphically. The following event trees given in figure 4.4, 4.5 and 4.6 were constructed based on the scenarios selected above.

4.2.3 DETERMINATION OF EXTENT OF CONSEQUENCES

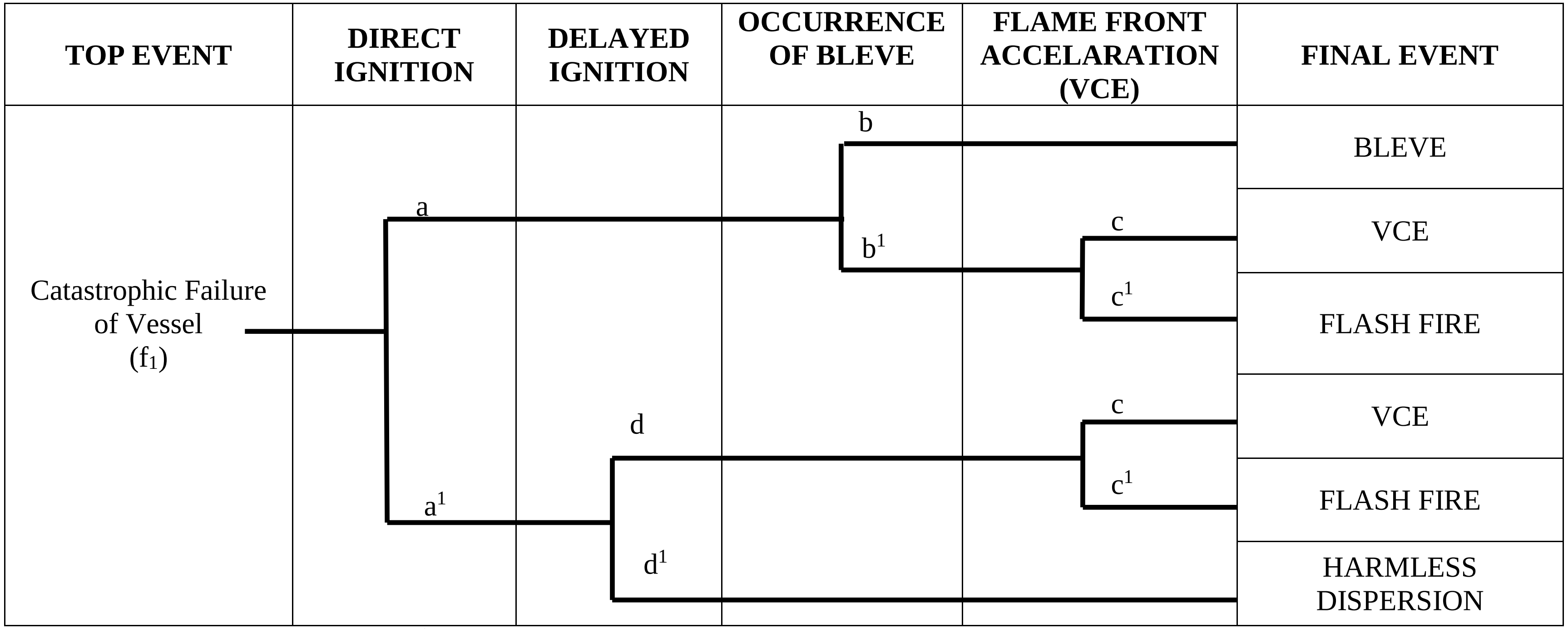
Upon completion of the selection of accident scenarios the consequences of the respective scenarios are estimated. The extents of consequences are measured in terms of the number of fatalities (N).

4.2.3.1 CONSEQUENCE MODELLING OF SCENARIOS

The events listed in Table 4.5 are modeled using ALOHA to estimate the extent of the respective consequences. The detailed evaluation is provided in Appendix E.

ALOHA is used to estimate the source terms (release rates) as well as the threat zones corresponding to each event. The boundaries of the threat zones as well as the respective probabilities of fatality for “Thermal Radiation” and “Overpressure” are determined based on the probit relationships selected in Chapter 3 (Table 3.16).

The relevant “threat zones” are then superimposed on the respective geographical location using MARPLOT; MARPLOT is mapping software which is part of the CAMEO Suite developed by US EPA and directly interfaces with ALOHA. The superimposed map is then divided into grids and the fatalities within each grid are estimated. Fatalities are calculated only for areas that are occupied (e.g. houses, buildings) or have a high likelihood of being occupied (e.g. Public Roads).



a – Probability of direct ignition, a^1 – Probability direct ignition does NOT occur

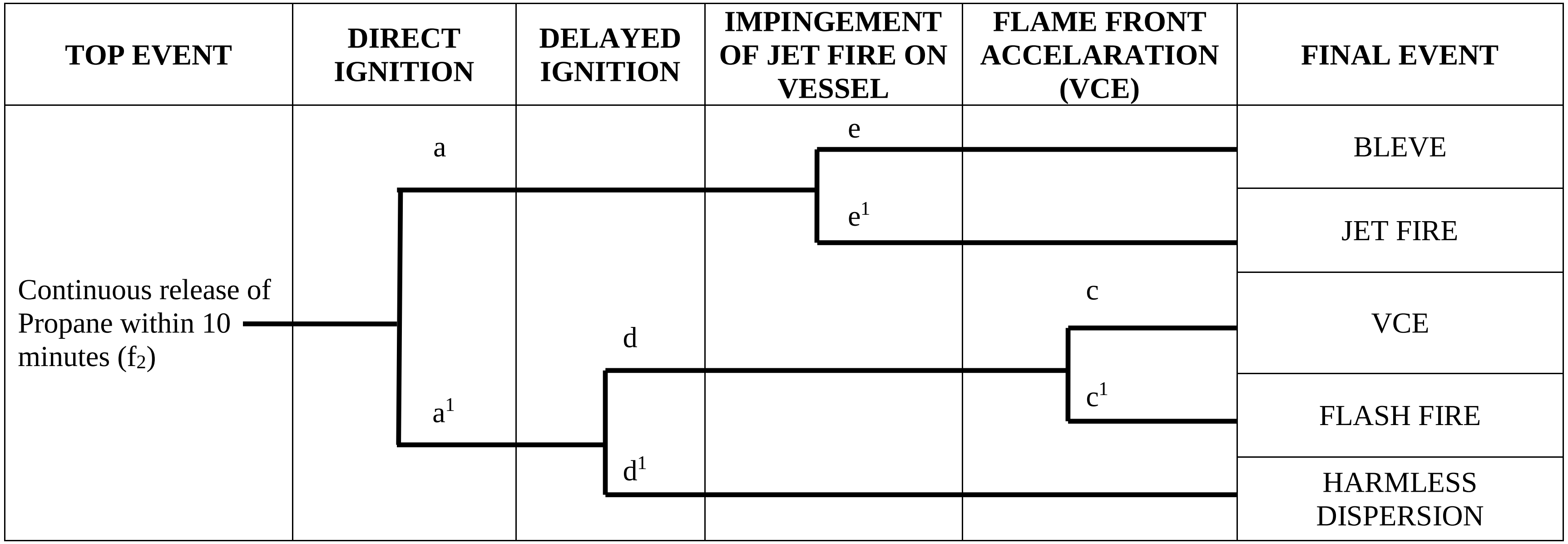
b – Probability of BLEVE occurring, b^1 – Probability BLEVE does NOT occur

c – Probability of flame front acceleration resulting in vapour cloud explosion, c^1 = Probability flame front acceleration does NOT occur

d – Probability delayed ignition occurs, d^1 = Probability delayed ignition does NOT occur

f_1 – Failure frequency for the Catastrophic Failure of the Propane Vessel

Fig 4.4 – Event tree for LOC with Catastrophic Failure of Vessel with Instantaneous Release of Pressurized Liquefied Gas



a – Probability of direct ignition, a^1 – Probability direct ignition does NOT occur

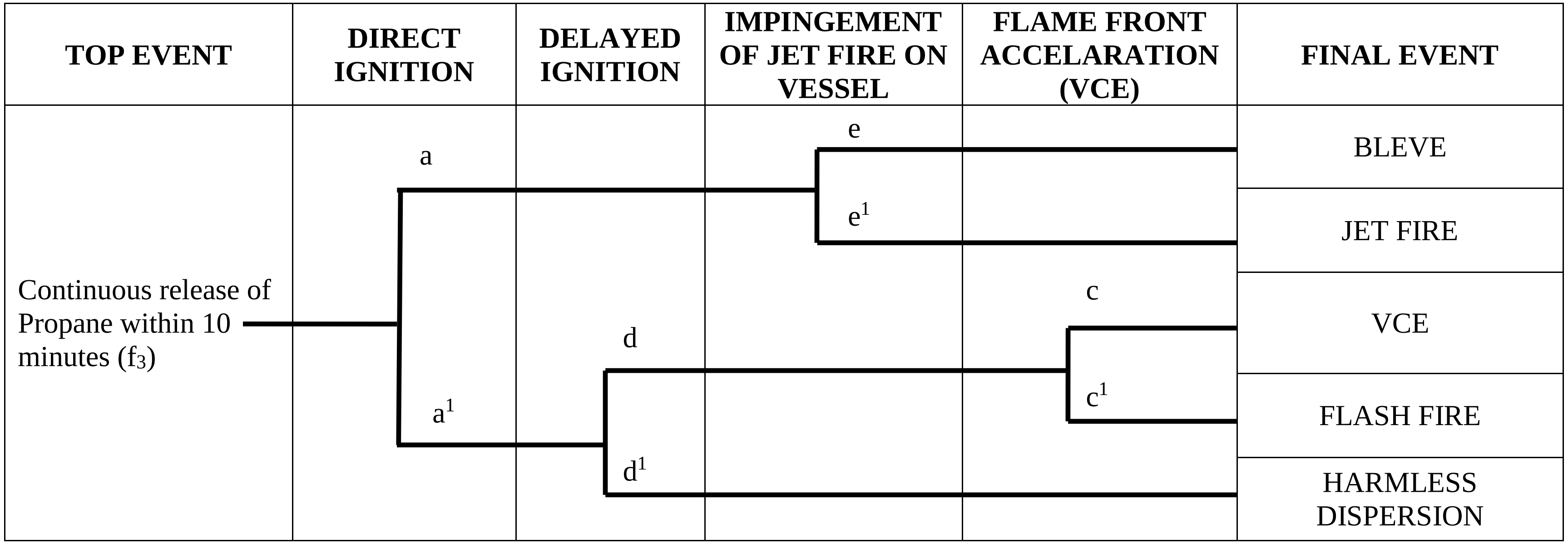
c – Probability of flame front acceleration resulting in vapour cloud explosion, c^1 = Probability flame front acceleration does NOT occur

d – Probability delayed ignition occurs, d^1 = Probability delayed ignition does NOT occur

e – Probability of Jet Flame impinging on Vessel, e^1 – Probability of Jet Flame NOT impinging on Vessel

f_2 – Failure frequency for the release of the entire content within 10 minutes

Fig 4.5 –Event tree for LOC with Release of Entire Content of Pressurized Liquefied Gas in 10 minutes



a – Probability of direct ignition, a^1 – Probability direct ignition does NOT occur

c – Probability of flame front acceleration resulting in vapour cloud explosion, c^1 = Probability flame front acceleration does NOT occur

d – Probability delayed ignition occurs, d^1 = Probability delayed ignition does NOT occur

e – Probability of Jet Flame impinging on Vessel, e^1 – Probability of Jet Flame NOT impinging on Vessel

f_1 – Failure frequency for the Catastrophic Failure of the Propane Vessel

Fig 4.6 – Event tree for Continuous release of inventory through 10 mm hole

The scenarios tabulated in Table 4.4 are selected for evaluation from the event trees in figures 4.4, 4.5 and 4.6.

Table 4.4 – List of Scenarios for LOC of a Bullet Type Propane Tank

TOP EVENT	SCENARIO	CONSEQUENCE
LOC 1 – NSTANTANEOUS RELEASE OF PRESSURIZED LIQUIFIED GAS (PROPANE)	BLEVE occurs due to hot catastrophic failure	BLEVE (Overpressure Event + Fireball)
	Immediate ignition of Vapor Cloud resulting in an explosion	Vapor Cloud Explosion resulting Overpressure Event
	Immediate ignition of Vapor Cloud resulting in Flash Fire	Flash Fire
	Delayed ignition of Vapor Cloud resulting in an explosion	Vapor Cloud Explosion resulting Overpressure Event
	Delayed ignition of Vapor Cloud resulting in a Flash Fire	Flash Fire
LOC 2 – RELEASE OF ENTIRE INVENTORY IN 10 MINUTES (CONTINUOUS AND CONSTANT RATE)	Immediate ignition of release resulting in Jet Fire impinging on propane vessel	BLEVE (Overpressure Event + Fireball)
	Immediate ignition of release resulting in Jet Fire not impinging on propane vessel	Jet Fire
	Delayed ignition of Vapor Cloud resulting in an Explosion	Vapor Cloud Explosion resulting Overpressure Event
	Delayed ignition of Vapor Cloud resulting in a Flash Fire	Flash Fire
LOC3 – CONTINUOUS RELEASE OF INVENTORY (HOLE SIZE – 10 mm)	Immediate ignition of release resulting in Jet Fire impinging on propane vessel	BLEVE (Overpressure Event + Fireball)
	Immediate ignition of release resulting in Jet Fire not impinging on propane vessel	Jet Fire
	Delayed ignition resulting in Vapour Cloud Explosion	Overpressure event
	Delayed ignition results in Flash Fire	Flash fire

Table 4.5 – List of Events for the QRA Approach

EVENT		TYPE OF RELEASE	TIMING OF IGNITION	CONSEQUENCE EFFECT
1	BLEVE	***Instantaneous*** release of entire inventory	Immediate	Fireball and Overpressure
2	Vapour Cloud Explosion (VCE)	***Instantaneous*** release of entire inventory	Immediate	Overpressure
3	Flash Fire	***Instantaneous*** release of entire inventory	Immediate	Thermal
4	Vapour Cloud Explosion (VCE)	***Instantaneous*** release of entire inventory	Delayed	Overpressure
5	Flash Fire	***Instantaneous*** release of entire inventory	Delayed	Thermal
6	BLEVE	Continuous release of entire inventory within 10 minutes	Immediate	Fireball and Overpressure
7	Jet Fire	Continuous release of entire inventory within 10 minutes	Immediate	Thermal
8	Vapour Cloud Explosion (VCE)	Continuous release of entire inventory within 10 minutes	Delayed	Overpressure
9	Flash Fire	Continuous release of entire inventory within 10 minutes	Delayed	Thermal
10	BLEVE	Continuous Release from 10mm opening	Immediate	Fireball and Overpressure
11	Jet Fire	Continuous Release from 10mm opening	Immediate	Thermal
12	Vapour Cloud Explosion (VCE)	Continuous Release from 10mm opening	Delayed	Overpressure
13	Flash Fire	Continuous Release from 10mm opening	Delayed	Thermal

4.2.3.2 SUMMARY OF CONSEQUENCE EFFECTS FOR THE PROBABILISTIC RISK ASSESSMENT APPROACH

The consequence effects for the events analysed in section 4.2.3.1 are given in table 4.6 as follows,

Table 4.6 – Summary of Consequence Effects for the Probabilistic Risk Assessment Approach

EVENT		CONSEQUENCE EFFECT (NUMBER OF FATALITIES, N)
1	BLEVE	112.8
2	Vapour Cloud Explosion	2.4
3	Flash Fire	47.4
4	Vapour Cloud Explosion	50.6
5	Flash Fire	284.5
6	BLEVE	112.8
7	Jet Fire	0
8	Vapour Cloud Explosion	36.4
9	Flash Fire	224.8
10	BLEVE	112.8
11	Jet Fire	0
12	Vapour Cloud Explosion	0
13	Flash Fire	0

4.2.4 CALCULATION OF ACCIDENT FREQUENCIES FOR THE ACCIDENT SCENARIOS

The accident frequencies for each accident event listed in table 4.6 is determined using the failure frequencies for each loss of containment (LOC) scenario, ignition probabilities and other relevant conditional probabilities such as probability of occurrence of BLEVE, probability of Jet Fire impingement on storage vessel and probability of flame front acceleration. Hence the respective failure frequencies, ignition frequencies and conditional probabilities need to be determined.

4.2.4.1 INTRODUCTION TO FAILURE FREQUENCIES

To assess the event probabilities or incident frequencies, the failure rate data or failure frequency corresponding to each loss of containment (LOC) is required. Deriving failure rate data for mechanical equipment has been a contentious issue. Here failure rates for pressure vessels (LPG vessels where possible) are taken into consideration with respect to the scope of the probabilistic risk assessment under consideration. Different sources of failure rates exist for pressure vessels. Some of the major sources of failure frequencies used for probabilistic risk assessments were compared. These are generic failure frequencies as specific failure frequencies corresponding to Sri Lanka are not in the public domain.

The sources of the failure frequencies are as follows,

1. Reference Manual BEVI Risk Assessments, Version 3.2. (RIVM, 2009)
2. Hazardous Material Release Accident Frequencies for Process Plant, Volume II, Ver 1 – Issue 7, Taylor Associates (Taylor, 2006)
3. Report No.434 – 3, Storage Incident Frequencies, March 2010, International Association of Oil & Gas Producers (OGP, 2010)
4. Handbook of Failure Frequencies, 2009, Flemish Government, LNE Department (Flemish Government, 2009)
5. API RP 581, Risk Based Inspection Technology, 2nd Edition, Sep 2008 (API RP 581, 2008)

The failure frequencies were categorised for the purpose of comparison as shown below,

- Catastrophic Rupture corresponding to instantaneous release of entire
- Large Release equivalent to a Continuous Release of Entire Content within 10 min
- Medium Scale Release equivalent to a Continuous release from a 10mm diameter hole

The failure frequencies differ according to the different data sources. Hence the sources need to be evaluated in detail prior to selecting a particular generic frequency value.

4.2.4.2 EVALUATION OF GENERIC FAILURE FREQUENCIES

In order to determine the FN curve for the propane storage tank, failure frequency data are required. As there are several sources where this data can be obtained, data from five such sources are presented in this section.

4.2.4.2.1 GENERIC FAILURE FREQUENCIES GIVEN BY RIVM

The failure frequencies used in the aforementioned source are derived from the “Purple Book (1999)”. The failure frequencies have their origin in much earlier studies carried out during the inception of detailed QRA studies in the CPI stemming back to 1974 (Pasman, 2011). Pasman (Pasman, 2011) and Nussey (Nussey, 2006) provide a clear explanation of the basis of the “Dutch Failure Frequencies”.

The initial studies by Smith & Warwick, Philips & Warwick and Bush (Pasman, 2011) are related to steam vessels in the nuclear industry and not process vessels. The vessels were fabricated to high standards. The COVO storage vessels were “base failure rate” data derived for static vessels, free of vibration, corrosion, thermal cycling and absence of human operator data. It must be emphasized that these conditions are ideal. The data derived from AKZO are mainly for Cl_2 storage vessels. Pasman (Pasman, 2011) and Beerens (Beerens, 2006) state that the “Dutch Failure Frequencies” were standardized at first by the Dutch Authorities in the IPO document in 1994. The present values of the Dutch failure frequencies took their current form in the aforementioned IPO document. They have consequently been standardized and included in the “Reference Manual BEVI Risk Assessments, Ver 3.2” (RIVM, 2010). The relevant failure frequencies for pressure vessels are as given in Table 4.7.

Table 4.7 – Failure Frequencies from RIVM

Type of Release		Frequency (per Annum)
1	Instantaneous Release of entire contents	5×10^{-7}
2	Release of entire contents in 10 min. in a continuous and constant stream	5×10^{-7}
3	Continuous release of contents from a hole with an effective diameter of 10 mm	1×10^{-5}

Source: (RIVM, 2009)

4.2.4.2.2 GENERIC FAILURE FREQUENCIES GIVEN BY TAYLOR

Taylor has conducted an extensive study of Pressure Vessel failures and gives due consideration for the fact that pressure vessels are almost always constructed to high standards (Choice of material, Class I Welding, Inspection of Weld Quality) and design requirements. Furthermore failure causes are clearly stated. The source of the data is the MHIDAS database (Major Hazard Incident Data Service – Hosted by the UK HSE) (Taylor, 2006).

Table 4.8 – Failure Frequencies from Taylor for Storage Vessels

Type of Release		Frequency (per Annum)
1	Rupture (d > 100 mm)	1×10^{-7}
2	Large (25mm < d < 100mm)	3×10^{-4}
3	Medium (5mm < d < 25mm)	8×10^{-4}
4	Small (d < 5mm)	2×10^{-3}

Source: (Taylor,2006)

4.2.4.2.3 FAILURE FREQUENCIES PUBLISHED BY THE INTERNATIONAL ASSOCIATION OF OIL & GAS PRODUCERS (OGP)

The International Association of Oil & Gas Producers (OGP) in its Report No.434 – 3 published in March 2010 provides data on failure frequencies for Pressurized Storage Vessels (OGP, 2010) but doesn't differentiate between LPG storage vessels and other pressurized storage vessels. Data sources are not specified in detail.

Table 4.9 – Failure Frequencies from OGP for Storage Vessels

HOLE DIAMETER			Leak Frequency (per year)
	Range	Nominal	
1	1 – 3 mm	2 mm	2.3×10^{-5}
2	3 – 10 mm	5 mm	1.2×10^{-5}
3	10 – 50 mm	25 mm	7.1×10^{-6}
4	50 – 150 mm	100 mm	4.3×10^{-6}
5	>150 mm	Catastrophic	4.7×10^{-7}

Source: (OGP, 2010)

4.2.4.2.4 GENERIC FAILURE FREQUENCIES GIVEN IN HANDBOOK OF FAILURE FREQUENCIES BY THE FLEMISH GOVERNMENT

The aforementioned handbook has been drawn up by the Flemish Government for preparing safety reports. According to the appendix to the "Handbook of Failure Frequencies for 2009", the origin of the failure data is attributed to Smith & Warwick (1981) and modified by Technica (Project F424 – Internal DNV Document) (Flemish Government, 2009). This document mentions the effects of operating environment, vessel material, vessel content, passive fire protection, tank inspection (radiography), stress relief and company specific factors (i.e. safety management, inspection, design codes, working pressure and temperature, low outside temperatures, age and process continuity).

Table 4.10 – Failure Frequencies from Handbook of Failure Frequencies 2009 for Storage Vessels

Type of Failure		Failure Frequency (per year)
1	Small Leak ($0.1 < d \leq 10$mm)	1.2×10^{-5}
2	Medium Leak ($10 < d \leq 50$mm)	1.1×10^{-6}
3	Large Leak ($50 < d \leq D_{max}$)	1.1×10^{-6}
4	Complete outflow in 10 min	3.2×10^{-7}
5	Rupture	3.2×10^{-7}

Source: (Flemish Government, 2009)

4.2.4.2.5 GENERIC FAILURE FREQUENCIES GIVEN IN API RP 581

The API RP 581 – Risk Based Inspection Technology (API RP581, 2008) provides generic failure frequencies for Pressure Vessels and damage factors for different damage factors. The sources of the generic failure frequencies are given as “best available sources” (not specified) and the API RBI Sponsor Group.

Table 4.11 – Failure Frequencies from API RP 581 for Vessel (Drum)

Type of Failure*		Failure Frequency (per year)
1	Small	8×10^{-6}
2	Medium	2×10^{-5}
3	Large	2×10^{-6}
4	Rupture	6×10^{-7}

Source: (API RP 581)

Note: *The range for the type of failure is not specified

The sources considered do not have a uniform definition with respect to the type of failure considered. Hence, it is difficult for a direct comparison to be conducted. Hence, the different sources of generic failure rate data are compared after categorizing under the following categories given in Table 4.12 for the purpose of comparison.

Table 4.12 – Categorization of LOC's

LOC CATEGORY		DEFINITION
1	Catastrophic Release (Rupture)	Rupture of Vessel (d > 150mm)
2	Large Scale Release	50mm < d < 150mm
3	Medium Scale Release	10mm < d< 50 mm

This is an approximate categorization for the purpose of comparison. The tabulation presented in Table 4.13 is based on the aforementioned categorization.

4.2.4.3 ANALYSIS OF GENERIC FAILURE FREQUENCY DATA SETS FOR THE CASE STUDY

In order to determine the FN curve for the propane storage tank, failure frequency data from five data bases are presented in this section.

There is a variation in data sets obtained from different data sources. In certain instances the variation is significant (Taylor – Medium and Large Scale Releases). A review of the different data sets shows that the variation can be attributed to a variety of factors such as,

a. Variation of Historical Data used to derive the base failure frequencies
b. Use of Expert Judgment which can vary from one professional to another (Subjective)
c. Variation in defining the scope to be considered as the Pressure Vessel (i.e. the vessel and any associated equipment)
d. Completeness of failure modes and causes considered in drawing up fault trees for Fault Tree Analysis

Table 4.13 – Generic Failure Frequencies for Pressure Vessels

		GENERIC FAILURE FREQUENCIES (PER YEAR)				
LOC TYPE		**RIVM**	**TAYLOR**	**OGP**	**FLEMISH**	**API RP 581**
CATASTROPHIC	**INSTATANEOUS RELEASE OF ENTIRE CONTENTS**	5.00×10^{-7}	1.00×10^{-7}	4.70×10^{-7}	3.20×10^{-7}	6.00×10^{-7}
LARGE RELEASE	**CONTIMUOUS RELEASE OF ENTIRE CONTENT WITHIN 10 MIN**	5.00×10^{-7}	3.00×10^{-4}	4.30×10^{-6}	1.10×10^{-6}	2.00×10^{-6}
MEDIUM RELEASE	**CONTINUOUS RELEASE FROM A 10mm DIAMETER HOLE**	1.00×10^{-5}	8.00×10^{-4}	7.10×10^{-6}	1.20×10^{-5}	2.00×10^{-5}

a. The adoption of modification factors to account for effects from different failure modes
b. Simplifying assumptions

Table 4.13 shows that aforementioned factors differ considerably between the different data sets. RIVM failure frequency values are an order of magnitude lower than the other data sets considered. This is attributed to the simplifying assumptions used as well as the definition of what equipment is considered as consisting within the scope of the pressure vessel. Nussey (Nussey, 2006) has highlighted this aspect with and is currently accepted. Hence, RIVM data is an optimistic estimate of failure frequencies for pressure vessels representative of very high standards of design, maintenance and operation. Taylor's failure frequency values represent an upper bound for the failure frequency data sets considered in this thesis. This can be attributed to the origins lying in a different data set and the definition of a Pressure Vessel.

Failure Rate/ Frequency data specific for Sri Lanka are not available in the public domain and have not been included here. None of the aforementioned data sets should be considered as representing conditions specific to Sri Lanka. These Data Sets are mostly representing UK, USA and EU and thus shall represent specific conditions for those regions. One may argue that as Pressure Vessel codes (ASME VIII Division 2 or BS PD 5500) are universally adhered in the Major Accident Hazard industries, and hence a suitable data set can be chosen. This may be true with respect to design, fabrication, inspection and testing of the pressure vessel. However, how the vessel is maintained and the external forces acting on the vessel will be determined by the Asset Integrity Management System (AIMS) of a particular organization, operator competence and environmental conditions which will introduce a degree of uncertainty if generic failure frequencies are used without due consideration for any modification factors.

4.2.4.4 SELECTION OF IGNITION PROBABILITIES

Three data sets for ignition probabilities are investigated and one data set is selected for application in the case study.

4.2.4.5 INTRODUCTION TO THE APPLICATION OF PROBABILITYOF IGNITION

The probability of ignition has a significant effect on the outcome of a probabilistic risk assessment study where a flammable release is the outcome of an LOC event. The nature of the ignition sources and the timing of the ignition have a significant effect on the type of consequence (Fire or Explosion) as well as the extent of the threat zone. Ignition can be categorized as follows based on the timing of the ignition as well as the location of the ignition source.

Table 4.14 – Categorization of Ignition

Based on Timing of Ignition	**Based on Location**
Immediate	Onsite (Inside the plant boundary)
Delayed	Offsite (Outside the plant boundary)

Onsite ignition sources and their effects have been extensively surveyed by various researchers (especially in the Petroleum and Hydrocarbon Industry). Hazards from onsite ignition sources are often controlled through “Hazardous Area Classification” in fixed installations storing/ processing flammable gases or liquids. However, offsite ignition sources are not controlled as it is within public premises.

The selection of ignition probabilities is complicated due to the nature of different ignition sources as well as their respective locations. The probability of ignition varies as per the source as well as where it is located.

The cause of the ignition may be the leak event itself or an external ignition source. The leak event may result in sparking due to static electricity which in turn can act as an ignition source.

Different models exist with respect to prediction ignition probabilities. The degree of analysis in deriving ignition probabilities varies from the simple to the complex. The most widely used as well as verified and validated ignition probability models are considered in this study.

Ignition probability models relate the ignition probability either one or more of the following factors,

a. Release rate (flammable gas cloud size)
b. Location
c. Density (Number of ignition source per unit area)
d. Type of ignition source

Simple models consider the release rate only while complex models usually consider all four factors. Complex models also require the identification of individual ignition sources and release locations at the site where the probabilistic risk assessment is carried out; hence a detailed assessment of ignition sources is required.

4.2.4.5.1 REVIEW OF IGNITION PROBABILITY VALUES

Values given by the following models were reviewed for estimating ignition probabilities,

1. Model proposed by the International Association of Oil & Gas Producers (OGP) (OGP, 2010)
2. Model proposed by Crosthwaite (Crosthwaite, Fitzpatrick & Hurst, 1988)
3. Reference Manual BEVI Risk assessments (RIVM, 2009)

4.2.4.5.2 IGNITION PROBABILITY MODEL PROPOSED BY THE INTERNATIONAL ASSOCIATION OF OIL & GAS PRODUCERS ASSOCIATION (OGP)

OGP presents a look up table which relate ignition probabilities in air to release rates for typical scenarios encountered in both the onshore and offshore Oil and Gas Industry. The values presented are “total ignition probabilities” and is defined as follows,

$$T_I = I_I + D_I$$

Where,

T_I - Total Ignition Probability, I_I - Immediate Ignition Probability and D_I - Delayed Ignition Probability

Here immediate ignition is defined as a situation where the fluid ignites immediately on release through either of the following mechanisms,

- Auto – ignition
- Release event itself provides an ignition source (e.g. Sparking due to electrostatic discharge)

Delayed ignition is defined as the ignition of a flammable vapour cloud by a source remote from the release source. However, OGP recommends these values for a QRA where only a coarse assessment is required.

This method assumes that the immediate ignition probability is independent of the release rate and recommends an immediate ignition probability of 0.001. Delayed ignition probability is estimated by subtracting this value from the total ignition probability.

This method gives due consideration for the following (Mansfield, Aberdeen, Stephen, Connolly and Scanlon, 2006),

1. Plant Area – Origination of the leak
2. Adjacent Plant Area – Other plant areas around the Plant Area mentioned in 1 above
3. Site Area – Remaining area within the installation boundary
4. Offsite area – Area outside the site boundary (i.e. Public)

However, it was observed that these considerations are applied only qualitatively when selecting the ignition probability values and are subject to the analyst's judgment.

However, this model distinguishes between gaseous and liquid phase releases.

For the release of propane from a Bullet Tank, scenario 14, "Tank Gas LPG Plant" consisting of gas or LPG release from onshore tank farm within the plant is chosen. The following "total" ignition probability values are obtained based on the release rates determined in the consequence analysis phase.

Table 4.15 – Total Probability of Ignition for an LPG Leak

Release Rate	Total Probability of Ignition
760 kg/s	1.0
144 kg/s	0.9776
1.44 kg/s	0.00208

Source: (OGP,2010)

The immediate ignition probability is 0.001 as specified by the OGP report. Delayed ignition probability is calculated can then be determined.

4.2.4.5.3 IGNITION PROBABILITY VALUES PROPOSED BY CROSSTHWAITE et al.

Crosstwaite provides a set of values for immediate as well as delayed ignition probability (Mansfield et al., 2006; Crossthwaite, Fitzpatrick & Hurst, 1988). These values are essentially qualitative and were derived for use in an off – site ignition probability model (LPG RISKAT) (Mansfield et al.,2006). Hence, it is highly likely that these values are expert judgments. The ignition probability values are given in table 4.16,

Table 4.16 – Probability of Ignition for LPG Releases from Pressure Vessels

Type of Failure	Immediate Ignition	Delayed Ignition at Source	Delayed Ignition (Drifting over industrial land)
Vessel Failure	0.05	N/A	0.2 (13 mm)
			0.6 (25 mm)
			0.9 (50mm)

Source: (Mansfield et al., 2006)

The probability of ignition is applied to the industrial site as a whole but not estimated for different parts of the site.

4.2.4.5.4 IGNITION PROBABILITY VALUE PROPOSED BY THE NATIONAL INSTITUTE OF PUBLIC HEALTH AND THE ENVIRONMENT (RIVM), NETHERLANDS

The “Reference Manual BEVI Risk Assessments Version 3.2” (RIVM, 2009) provides a detailed and systematic method of selecting ignition probabilities. The probability of direct ignition and delayed ignition are clearly defined. The probability of direct ignition for fixed installations is categorized under the reactivity of each substance and release rate. The term reactivity in this context implies the susceptibility to flame acceleration for the substance considered and is an indication of the flammability of the substance.

Propane with an ambient boiling point of - 42 ^{o}C and Flash point of -104.4 ^{o}C falls into Category 0 (Extremely Flammable). The probability of direct ignition for Category 0 substances are as follows (Table 4.17).

Table 4.17 – Probability of Direct Ignition for Category 0 Substances at Fixed Installations

Release Rate Continuous	Release Rate Instantaneous	Probability of Direct Ignition
<10 kg/s	<1000 kg	0.2
10 – 100 kg/s	1000 – 10000 kg	0.5
>100 kg/s	>10000 kg	0.7

Source: (RIVM, 2009)

The term direct ignition implies immediate ignition.

Societal Risk calculation requires all ignition sources to be accounted including those due to population. The following guideline is provided,

Table 4.18 – Probability of Delayed Ignition (Onsite vs Offsite)

Substance Category	Probability of Delayed Ignition for the Biggest Cloud Size (Onsite Ignition)	Probability of Delayed Ignition (Offsite Ignition)
Category 0	$1 - P_{\text{direct Ignition}}$	Ignition sources
Category 1	$1 - P_{\text{direct Ignition}}$	Ignition sources
Category 2	0	0
Category 3	0	0
Category 4	0	0

Source: (RIVM, 2009)

The “Purple Book” (TNO, 2005) which is the predecessor of the Reference Manual provides a detailed table on offsite data sources. Refer Tables 4.19 to 4.21.

Table 4.19 – Probability of ignition for a time interval of one minute for Point sources

Point Source	Probability of Ignition in one Minute
Motor Vehicle	0.4
Flare	1.0
Outdoor Furnace	0.9
Indoor Furnace	0.45
Outdoor Boiler	0.45
Indoor Boiler	0.23
Ship	0.5
Ship Transporting flammable	0.3
Fishing vessel	0.2
Pleasure craft	0.1
Diesel train	0.4
Electric Train	0.8

Source: (TNO, 2005)

Table 4.20 – Probability of ignition for a time interval of one minute for Line sources

Line Source	Probability of Ignition in one Minute
Transmission Line	0.2 per 100m
Road	Function of average traffic density
Railway	Function of average traffic density

Source: (TNO, 2005)

Table 4.21 – Probability of ignition for a time interval of one minute for Area sources

Population Source	Probability of Ignition in one Minute
Residential	0.01 per person
Employment Force	0.01 per person

Source: (TNO, 2005)

Table 4.22 – Probability of ignition for a time interval of one minute for Population Sources

Area Source	Probability of Ignition in one Minute
Chemical Plant	0.9 per site
Oil Refinery	0.9 per site
Heavy Industry	0.7 per site
Light Industrial Warehousing	As for population

Source: (TNO, 2005)

For a residential area probability of ignition for a grid cell for a time interval of 0 to t (s) is given by,

$$P(t) = (1 - e^{-n\omega t}) \qquad (13)$$

Where, ω – the ignition effectiveness of a single person (s^{-1})

n – the average number of people present in the grid cell

4.2.4.5 SELECTING AN IGNITION PROBABILITY MODEL FOR APPLICATION IN THE CASE STUDY

Detailed models exist but it is difficult to separate immediate ignition probabilities and delayed ignition probabilities. Cox, Lee and Ang (Mannan, 2012) provide a comprehensive model for determining ignition probabilities but no guidance is given on estimating delayed ignition probabilities. Rew, Spencer and Franks (Rew, Spencer & Franks, 1997) proposes a detailed model on determining the ignition probability of flammable gas clouds; however, immediate or event initiated ignition is not specifically considered. Hence, only RIVM, Crossthwaite and OGP ignition probability values were considered. OGP and RIVM offer a more detailed method of determining ignition probabilities than Crossthwaite. However, the ignition probabilities given by Crossthwaite are for a specific case (LPG) whereas the OGP/RIVM are more generic with a wider scope.

Hence, the OGP and RIVM ignition probability values are applied for generating FN Curves using the procedure set out by RIVM in estimating accident event frequencies (RIVM, 2009).

Furthermore, it is considered that a vapour cloud has 0.4 probability of resulting in an explosion whereas a probability of 0.6 exists for a flash fire. RIVM considers the probability of a BLEVE occurring due to a catastrophic release as being 0.7 and a 0.3 probability of the event ending up as either a VCE or Flash fire. The probability of a Jet fire impinging on a storage vessel is given as 0.5 by Taylor (Taylor, 2006)

4.2.5 ESTIMATING THE ACCIDENT FREQUENCIES

The accident frequencies are calculated for each accident scenario using the five failure frequencies discussed in section 4.2.4.2.1, the ignition probabilities and the conditional probabilities.The accident frequencies calculated for each failure frequency data set are given in Appendix H, tables H.1, H.2, H.3, H.4 and H.5 respectively.The different accident frequencies and the corresponding consequence value for each failure frequency data set is given in table 4.23. The FN curve for each data set is plotted and presented in figure 4.7. Analysis of the FN curves for the propane bullet considered in this case study and presented in figure 4.7 reveal the following features,

- The total variation between FN curves (Lowest Risk to Highest Risk) is almost two orders of magnitude (100)
- The RIVM, FLEMISH, API RP 581 and OGP FN curves are within the same order of magnitude
- The Taylor FN Curve is considerably higher than RIVM, FLEMISH, API RP 581 and OGP FN Curves
- Sections of the Taylor curves fall outside the Risk Acceptance Criterion line

A two order of magnitude variation for the same case under consideration brings into focus the subjective nature of selecting generic failure frequencies and the associated uncertainty. Hence, it can be deduced that the selection of generic failure frequencies by a risk analyst can lead to a subjective conclusion which does not actually represent the actual risk.

The criteria for decision making when an FN Curve exceeds the criterion line partially with the majority of the curve lying in the acceptable region is not available in literature. However, this aspect is related more to the properties of an FN Curve and its interpretation rather than the nature of generic failure frequencies. According to figure 4.7, FN curves determined for the propane storage tank using failure frequencies of RIVM, FLEMISH, API RP 581 and OGP show that risk on the society as acceptable. However, for the Taylor FN curve such an acceptability conclusion cannot be given as it exceeds the risk acceptance criterion line.

Table 4.23 – Cumulative Frequencies (F) vs Total Fatalities (N) for different failure frequency datasets

TOTAL NUMBER OF FATALITIES	**CUMULATIVE FREQUENCY (F) FOR DIFFERENT FAILURE FREQUENCY DATASETS**				
	RIVM	**OGP**	**TAYLOR**	**FLEMISH**	**API RP 581**
284.6	9.00×10^{-8}	8.46×10^{-8}	1.80×10^{-8}	5.76×10^{-8}	1.08×10^{-7}
224.8	1.80×10^{-7}	8.59×10^{-7}	5.40×10^{-5}	2.56×10^{-7}	4.68×10^{-7}
112.8	4.10×10^{-6}	5.08×10^{-6}	4.39×10^{-4}	5.00×10^{-6}	8.46×10^{-6}
50.7	4.16×10^{-6}	5.14×10^{-6}	4.39×10^{-4}	5.04×10^{-6}	8.53×10^{-6}
47.4	4.22×10^{-6}	5.19×10^{-6}	4.39×10^{-4}	5.08×10^{-6}	8.61×10^{-6}

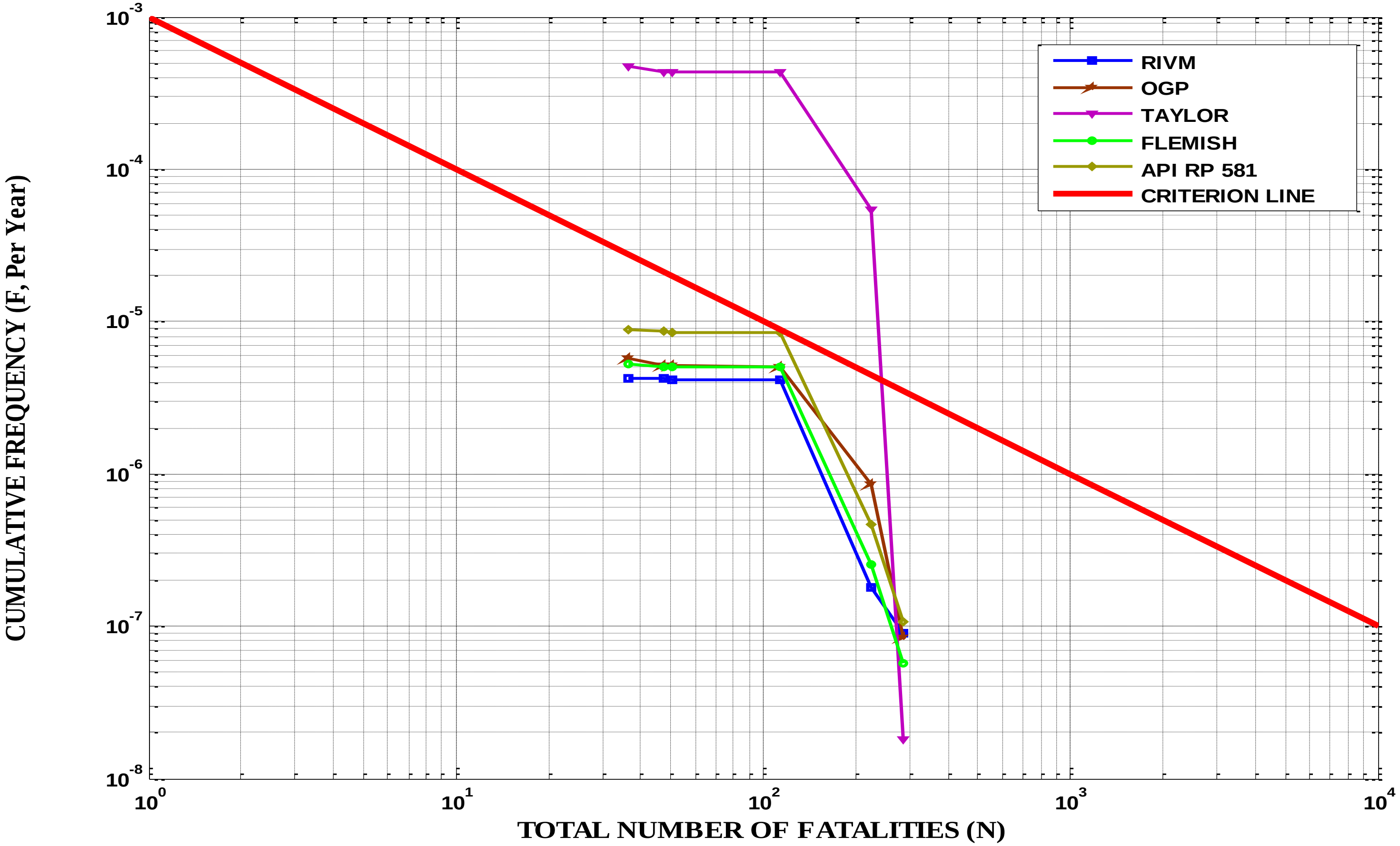


Fig 4.7 – Comparison of FN Curves having different Failure Frequencies with FN criterion for Sr Lanka

CHAPTER 5

5.0 SELECTION OF AN APPROPRIATE RISK ACCEPTANCE CRITERION AND DEVELOPMENT OF THE DECISION MAKING FRAMEWORK

In this chapter a framework is proposed for applying risk acceptance criteria developed for Sri Lanka in the earlier section of this work. The framework proposed consists of two approaches. One on consequence based assessment called the “modified consequence assessment” method and the other is a probabilistic based assessment called the “upper bound FN curve” method. Initially a comparison of the procedures used in applying the risk acceptance criteria, safety distance and FN curve in chapter 4 is presented followed by a discussion on uncertainties involved in risk informed decision making.

5.1 COMPARISON OF THE CONSEQUENCE ASSESSMENT (CA) APPROACH VS THE PROBABILISTIC RISKASSESSMENT APPROACH (PRA)

Two different criteria were proposed in accepting the risk posed to the public from a loss of containment (LOC) event in a chemical process plant in the chapter 3 of this work. These approaches were,

1. Determination of Safety Distances based on purely Consequence Assessment (CA)
2. Determination of Societal Risk in terms of Cumulative Frequency (F) and Fatalities (N) based on Probabilistic Risk Assessment (PRA)

The algorithm used in applying the risk acceptance criteria for safety distance and FN curve in a loss of containment scenario are presented in figure 5.2 and figure 5.3 respectively. The two different risk assessment approaches stated above are compared in table 5.1with respect to the following factors,

1. Transparency of application
2. Availability of input data
3. Availability of verified and validated models for consequence and risk estimation

4. Uncertainty
5. Presentation of Risk Assessment Outcome
6. Limitations

The process/ procedure of assessment for both approaches are transparent and can be inspected by a third party (Refer Figures 5.1 and 5.2 for the flow diagram of the consequence assessment and probabilistic risk assessment processes).

Table 5.1 – Comparison of the Consequence Assessment Approach vs the Probabilistic Risk Assessment Approach in Sri Lanka

EVALUATION FACTOR		**CONSEQUENCE ASSESSMENT APPROACH**	**PROBABILISTIC RISK ASSESSMENT**
1	Transparency of	The process is transparent	The process is transparent
2	Availability of Input Data	Data required for a purely consequence assessment approach is readily available in terms of, 1. Thermochemical Data 2. Weather Data	Certain critical Data required is not publicly available in Sri Lanka such as equipment Failure Frequencies and Ignition Probabilities
3	Availability of Simulation Models (Verified	Available but may differ from source to source	Available but may differ from source to source
4	Uncertainty	Uncertainty is inherent in the method (Number of factors contributing to uncertainty is less than the probabilistic approach)	Uncertainty is inherent in the method (Higher number of factors contributing to uncertainty than the CA
5	Presentation of Risk Assessment Outcome	Can be shown using hazard threat zones and easily communicated to the public	Expressed using FN Curves; difficult for the public to grasp
6	Limitations	1. Probabilistic aspects are not specifically included(Failure Frequencies, Ignition Probabilities)	1. Large variation in different failure frequency data sets 2. Interpreting non – compliance where only a portion of the FN curve exceeds the criterion line

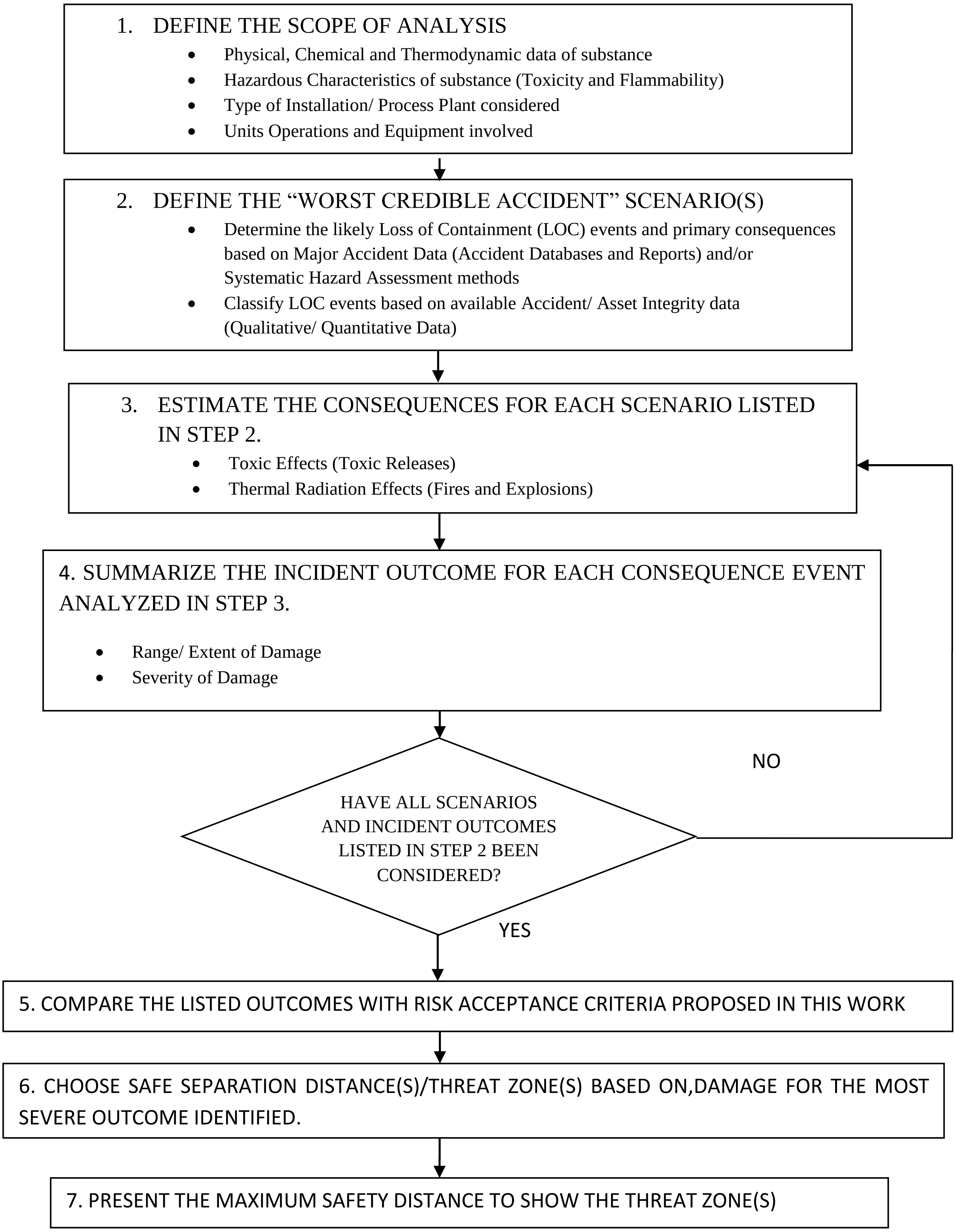


Figure 5.1 – Methodology for applying the safety distance risk acceptance criterion using Consequence Assessment (CA) Approach for the worst case scenario.

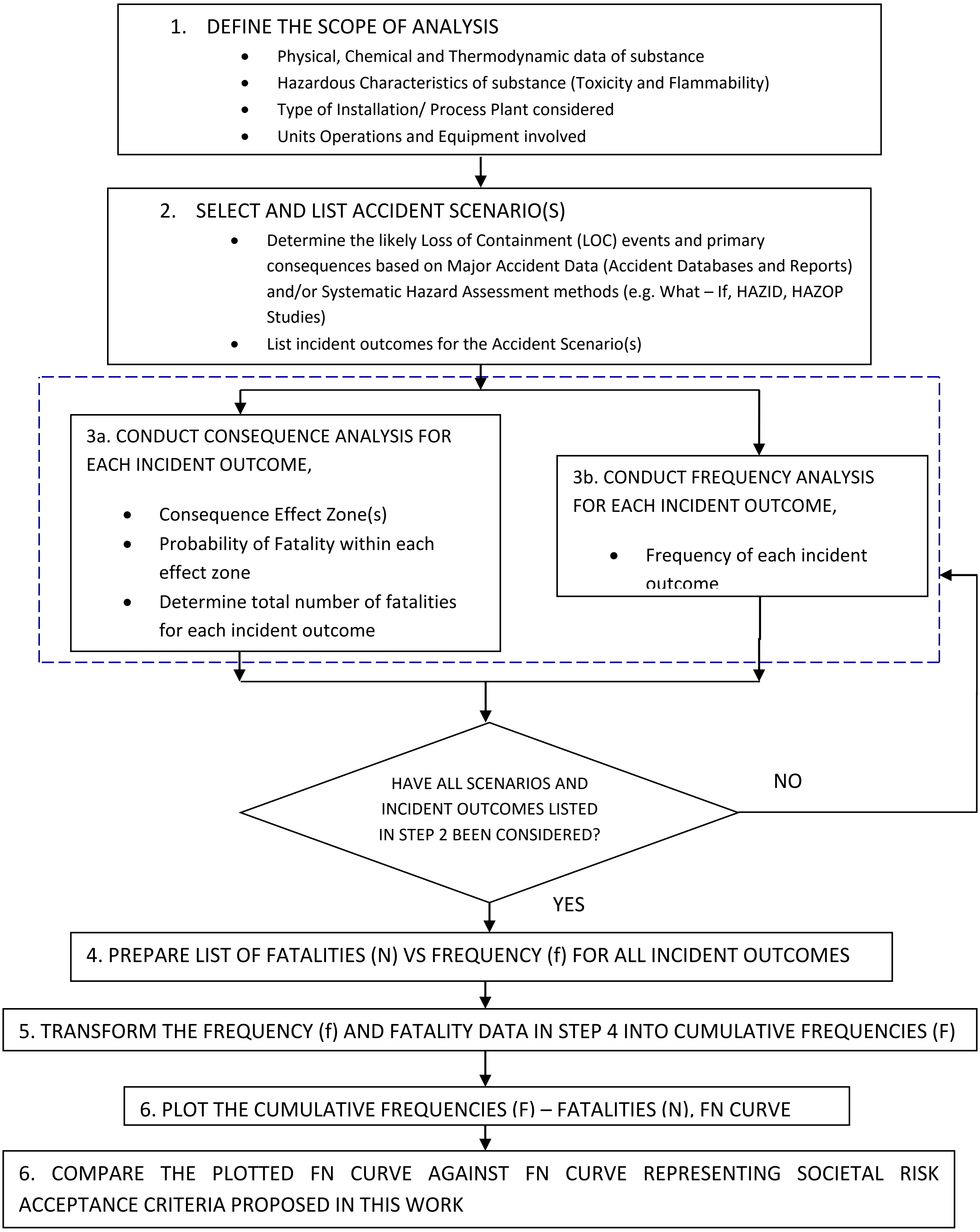


Figure 5.2 – Methodology for applying the FN curve risk acceptance criterion using the Probabilistic Risk Assessment Approach

The probabilistic terms of the probabilistic risk assessment approach such as failure frequencies and ignition probabilities are not specifically defined for Sri Lanka; this is a shortcoming. Hence, such values have to be taken from generic sources. However, it was shown in chapter 4, section 4.2 that generic frequencies can lead to a wide variation in the FN curves generated. Hence this can result in varying interpretations of the FN Curves by different analysts.

Validated consequence effect models are available in the public domain and most of the simulation software is based on them. This study used the ALOHA software which also comes with technical documentation explaining the different models used. Other validated risk assessment software is available such as PHAST by DNV and RiskCurves by TNO.

Both approaches generate uncertainty at each activity level involved in the risk assessment process (Refer Tables 5.2 &5.3). The number of factors contributing towards uncertainty is less in the CA Approach in comparison with the probabilistic risk assessment Approach; however, the number of factors does not necessarily imply a higher or lower degree of uncertainty. Whether the CA or probabilistic risk assessment approach yields a higher degree of uncertainty can be established based only on a quantitative assessment. It must be emphasized that the FN Curves showed a wide variation for different failure frequency data sets and it is concluded that failure frequencies contribute significantly towards uncertainty. Hence, the inclusion of probabilistic terms has potential for increasing the uncertainty.

The CA approach is easier to present and explain to a layman. Risk communication is a significant factor where the public is concerned. A limitation in the CA approach is the inability to capture probabilistic aspects of a risk assessment even though it is

Table 5.2 – Factors contributing to Uncertainty in the purely Consequence Assessment (CA) Approach

MAIN ACTIVITY		SUB ACTIVITY	POTENTIAL UNCERTAINTY	COMMENTS
1.	Define scope of equipment	Not Applicable	Incomplete scope of equipment	The scope of the equipment will impact the following, 1. Set of LOC events considered 2. Number of scenarios considered
2.	Define Accident Scenarios	List of LOC scenarios	Incomplete list of LOC events	Incorrect selection of LOC events or lack of data
		Preparation of accident event tree	Incomplete selection of consequence effects (Fire, explosion or toxicity)	Incomplete number of accident outcomes; total set of “worst case” scenarios is not considered
		Choice of “Worst Case” accident scenario	Incorrect selection of “Worse Case” accident	Safety distance selected will be less than the actual required
3.	Estimate extent of consequence	Select modeling approach, 1. Manual calculation 2. Simulation software	1. Range and applicability of currently available models 2. Accuracy of models 3. Potential for human error 4. Completeness, accuracy and access to a thermochemical database	The modeling approach will determine, 1. The extent of human labour required 2. Resource requirements and choice of models 3. The ease of presenting the hazard footprint and damage results 4. Accuracy of consequence assessments and estimated damage values
4.	Select input data	Define endpoints for the consequences	1. Selection of probit equations 2. Accuracy of probit equations	The endpoint directly impacts the Safety Distance
		Define source terms	Accuracy of estimated release rates from a loss of containment event	The estimated release rate directly impacts, 1. Severity of consequence 2. Extent of the hazard foot print
		Define metrological conditions	Accuracy and variability of metrological conditions	Impacts the accuracy and extent of the consequences and damage values
		Select a consequence prediction model	1. Choice of unsuitable model 2. Difficulty in interpreting information generated by the model 3. Modeling process is not transparent (Governing equations, Boundary conditions and assumptions are not known)	Impacts the accuracy and extent of the consequences and damage values
5.	Estimation/ mapping of threat zone and calculation of safety distance	Superimpose the threat zone on the physical location and calculate the safety distance	1. Ability superimpose the output generate from a model on an actual location 2. Accuracy of mapping process (Manual vs Software)	The mapping process or method can impact the accuracy and clarity of displaying the threat zone

Table 5.3 - Factors contributing to Uncertainty in the purely Probabilistic Risk Assessment Approach

MAIN ACTIVITY		SUB ACTIVITY	POTENTIAL UNCERTAINTY	COMMENTS
1.	Define scope of equipment	Not Applicable	Incomplete scope of equipment	The scope of the equipment will impact the following, 1. Set of LOC events considered 2. Number of scenarios considered 3. Selection of failure frequencies
2.	Define Accident Scenarios	List of LOC scenarios	Incomplete list of LOC events	Incorrect selection of LOC events or lack of data
		Preparation of accident event tree	Incomplete selection of consequence effects (Fire, explosion or toxicity)	Incomplete number of accident outcomes; total set of “worst case” scenarios is not considered
		Choice of “Worst Case” accident scenario	Incorrect selection of “Worse Case” accident	Safety distance selected will be less than the actual required
3.	Estimate extent of consequence	Select modeling approach, 1. Manual calculation 2. Simulation software	1. Range and applicability of currently available models 2. Accuracy of models 3. Potential for human error 4. Completeness, accuracy and access to a thermochemical database	The modeling approach will determine, 1. The extent of human labour required 2. Resource requirements and choice of models 3. The ease of presenting the hazard footprint and damage results 4. Accuracy of consequence assessments and estimated damage values
4.	Select input data for the consequence assessment	Define endpoints for the consequences	1. Selection of probit equations 2. Accuracy of probit equations	The endpoint directly impacts the Safety Distance
		Define source terms	Accuracy of estimated release rates from a loss of containment event	The estimated release rate directly impacts, 1. Severity of consequence 2. Extent of the hazard foot print
		Define metrological conditions	Accuracy and variability of metrological conditions	Impacts the accuracy and extent of the consequences and damage values
		Select a consequence prediction model	1. Choice of unsuitable model 2. Difficulty in interpreting information generated by the model 3. Modeling process is not transparent (Governing equations, Boundary conditions and assumptions are not known)	Impacts the accuracy and extent of the consequences and damage values
5.	Estimation/ mapping of threat zone and calculation of safety distance	Superimpose the threat zone on the physical location and calculate the safety distance	1. Ability superimpose the output generate from a model on an actual location 2. Accuracy of mapping process (Manual vs Software)	The mapping process or method can impact the accuracy and clarity of displaying the threat zone
6.	Estimation of fatalities for each accident event	Divide threat zones into grids	Variation in grid size	Grid size impacts the estimation of population data and consequence/ damage value
		Estimate damage value for each grid	1. Size of the gird (damage value is estimated at center of grid) 2. Capability of the modeling software to provide “damage value” at a given point	The damage value is estimated at the center of the grid. The software must be capable of generating the damage values at a given location. |Otherwise, a manual method is required.
		Estimate probability of fatality	1. Selection of probit equations 2. Accuracy of probit equations	The probability of fatality may vary with the probit equations chosen
		Estimate number of fatalities	1. Level of analysis of Demographic Data (Detailed assessment onsite vs Published Data) 2. Accuracy of Demographic Data (Population density and distribution) 3. Percentage occupancy (Time of day)	The level of detail used in demographic data may vary from generic databases to detailed onsite assessment data. |Occupancy of residential areas and industrial areas can vary with the time of day and percentage occupancy indoor and outdoor
7.	Selection of failure frequencies	Selection of generic failure frequency data sets	Variability in different data sets, when using generic failure frequency data sets	The choice of the data set may depend on the analyst’s expert judgment and different data sets may be chosen by different analysts for the same case. The analyst must have access to a complete set of verified and validated data source for generic failure frequencies.
		Industry/ country specific failure frequencies	Accuracy and completeness of baseline failure frequencies and modification factors	Access to country specific asset integrity databases are required. Fault tree analysis and expert judgment is required where accident history is not available.
8.	Selection of conditional probabilities	Estimation of ignition probabilities and other conditional probabilities such as flame front propagation, probability of BLEVE, probability of explosion and flash fire	Lack of completeness and accuracy in estimating factors such as release rates, type of ignition sources, density of ignition sources, process plant layout	The models used for calculating the conditional probabilities can differ from analyst to analyst

implicitly used when deriving “accident scenarios”. Hence, the CA approach does not perform the complete function of a true “Risk” assessment. The probabilistic risk assessment approach provides a higher level of insight into the different factors contributing towards the “Risk”.

The CA approach does not provide provision for accounting for the effects of layers of protection on the level of risk. Since the effect of a protection layer is measured and expressed in terms of a probabilistic term, “Probability of Failure on Demand (PFD)”, it cannot be included in a purely consequence assessment approach. Hence, the consequence assessment (CA) approach will be limited to estimating “Worst Case” safety distances for “Land Use Planning (LUP)” exercises.

The probabilistic risk assessment approach has the flexibility to account for improvements in safety due to the presence or introduction of layers of protection. The “PFD” for the layers of protection can be included in a bow tie diagram and accounted for. However, the accuracy of the “PFD” value will impact the accuracy of the accident frequency. If the accuracy is not known, this would introduce an additional uncertainty term. Furthermore, the FN Curve used in presenting the Societal Risk in the probabilistic risk assessment approach leads to ambiguities due to the difficulty in determining compliance with the risk criteria when only a portion of the curve exceeds the criteria.
Hence, it can be concluded that,

1. A purely CA approach does not account for the “probabilistic” aspects of a Risk Analysis
2. A purely probabilistic risk assessment approach requires the degree of “uncertainty” to be estimated if meaningful information is to be derived; however, the probabilistic terms available at present cannot be accurately established
3. The FN curve representation is difficult to explain to the public and any ambiguities arising out of it’s interpretation has to be accounted for.

5.2 THE IMPACT OF UNCERTAINTY IN RISK INFORMED DECISION MAKING

The concept of “Risk” goes hand in hand with uncertainty. Any risk assessment includes a certain level of uncertainty irrespective of whether the assessment methods are deterministic in nature (e.g. consequence assessment) or probabilistic. Each step of the analysis process introduces uncertainties resulting in a wide spectrum of uncertainties. These uncertainties can be determined either qualitatively or quantitatively resulting of different levels of uncertainty assessment. Uncertainty is fundamentally categorized into two broad categories as follows (Abrahamsson, 2002; Zio & Pedroni, 2012),

- Epistemic Uncertainty
- Aleatory Uncertainty

Epistemic uncertainty deals with the uncertainty in knowledge regarding a particular parameter, phenomena or system whereas aleatory uncertainty relates to stochastic effects. Aleatory uncertainty occurs due to variability or randomness in nature and is irreducible. However, epistemic uncertainty occurs due to ambiguity, ignorance or lack of knowledge about fundamental phenomena (Abrahamsson, 2002) and hence is reducible. Both types of uncertainty typically affect the following (Zio & Pedroni, 2012),

- Conditional probabilities such as accident frequencies
- Modeling of the accident scenarios using event trees and fault trees
- Modeling of the consequences of the accident scenarios (e.g. mathematical models as well as any modeling software used)

Uncertainty is a critical factor in risk characterization and risk informed decision making. However, there are many contributing factors and different levels of determining the uncertainty. Hence, it is difficult if not impossible to develop a truly objective or absolute measure of risk.

“Pate – Cornell” proposes six levels of quantification of uncertainty in risk analysis (Pate – Cornell, 2002; Pate – Cornell, 1996) (Refer Fig 5.3). The six levels are elaborated further as given below,

1. Level 0 – Simple identification of a hazard
2. Level 1 – Worst Case Approach
3. Level 2–Quasi Worst Case &Plausible Upper Bounds
4. Level 3 – Best Estimates
5. Level 4 – 1st order probabilistic risk analysis
6. Level 5 – 2nd order probabilistic risk analysis

Level 0 (hazard identification) is sufficient if, the hazard is clearly defined and the hazard can be contained using a simple solution. Level1 approach is essentially qualitative; no attempt is made to assess the risk in a quantitative manner. It is sufficient where Zero – risk policies and low cost solutions are applicable. (Pate – Cornell, 1996)

Level 1 (worst case analysis) is sufficient provided the worst case scenario is identified and well defined. However, the major drawback is whether it is possible to identify the full set of worst case scenarios. Furthermore, worst case scenarios can be identified with highly unlikely outcomes where the solutions would lie outside the bounds of practicality. The notion of probability is not considered (Pate – Cornell, 1996).

Level 2 (Quasi Worst Case – Plausible Upper Bounds Analysis), is a truncation of the probability of the potential loss distribution (Pate – Cornell, 2002); the focus is on an extreme feature of the potential loss distribution function leading to the interpretation “maximum credible” or “maximum probable” event. The terms “maximum credible” or “maximum probable” are subjective. The notion of probability may be considered but not in depth.

Level 3 (Best Estimate Analysis), considers the “center” of the probability density function for the potential loss distribution function giving rise to the notion of “best estimate” (Pate – Cornell, 2002). The focus is on a central value (mean, median or mode) of the outcome distribution (Pate – Cornell, 2002).

Levels 4&5 are heavily dependent on probabilistic risk analysis (PRA) with Level 4 analysis focusing on mean probabilities and Level 5 analysis involving detailed separation of aleatory and epistemic uncertainties (Pate – Cornell, 2002). Level 4 involves only aleatory uncertainties (Pate – Cornell, 1996). Level 4 risks are most often presented as a single risk curve.

Level 5 allows the uncertainties to be displayed using a family of curves. However, the choice of the family of curves is subjective requiring either a “Bayesian Inference” or “Expert Judgment”. Level 5 allows for the representation of both “aleatory” and “epistemic” uncertainties. It can be done using analytical techniques or Monte Carlo simulation (Pate – Cornell, 1996). It must be emphasized that the level of analysis of uncertainties increases with the respective level. Level 5 analysis is carried out in the “Nuclear Industry”.

This thesis essentially consider uncertainty at Level 4 as the “conditional probability” terms such as “failure frequencies” and “ignition probabilities” are mostly generic. A conservative approach is considered to account for the uncertainties (Goodstein, 2005). However, the likely contributors towards uncertainty are identified (Refer Tables 5.2 and 5.3).

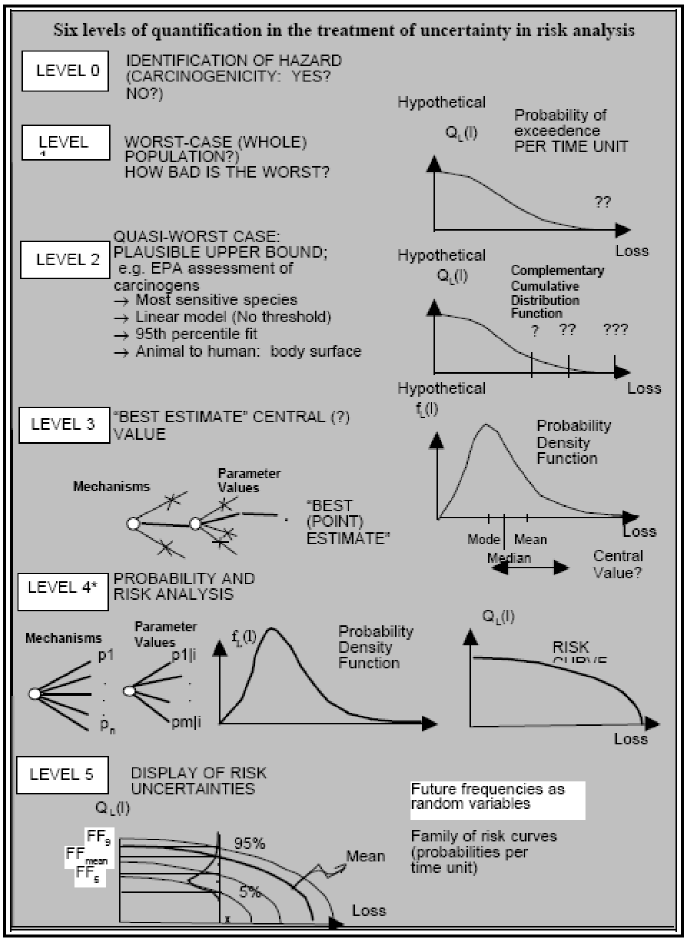


Figure 5.3 – The six levels of complexity in the Characterization of Risk

Source: (Pate – Cornell, 2002)

5.3 RISK ASSESSMENT FRAMEWORK FOR THE SRI LANKAN CONTEXT

In light of the aforementioned shortcomings or weaknesses, the following two methods are proposed to be studied further as risk assessment approached in the Sri Lankan context,

1. A modified “Consequence Assessment Approach”
2. “Probabilistic Risk Assessment Approach” based on the construction of a FN Curve based on Upper Bound Data

The two aforementioned methods are explained in detail as follows.

5.3.1 THE MODIFIED “CONSEQUENCE ASSESSMENT” APPROACH

The modified consequence assessment approach is essentially the consequence assessment method used in the probabilistic risk assessment approach; it includes the consideration of generic failure frequencies when determining accident scenarios and generating a detailed set of event trees for the different accident scenarios. A complete set of the accident events are evaluated instead of the perceived “Worst Case” thereby leading to a more complete assessment of the accident scenarios. The “Safety Distance” is chosen corresponding to the consequence effect with the maximum (i.e. longest) 1% Fatality distance.

This approach would ensure a more complete set of scenarios to be considered thereby overcoming the weakness of focusing on a single “Worst Case Scenario” or perceived “Worst Case Scenarios”. Generic failure frequencies are be used to aid the selection of accident events to be included in the event tree. However, it can be argued whether the “Safety Distance” chosen is actually proportionate to the “Risk”. The choice of a “maximum” 1% fatality distance is a “conservative” estimation in the absence of the following aspects in the calculation,

1. Accident Frequencies for each event
2. Quantification of uncertainty/ confidence bounds

It is proposed that fatality numbers for each event be estimated and tabulated, even though it is not directly used in determining the Safety Distance; such tabulation can lead to the choice of alternate sites with less population density. A direct application of Safety Distances without considering the population density in the neighbourhood is not advocated. The method is given in Figure 5.4.

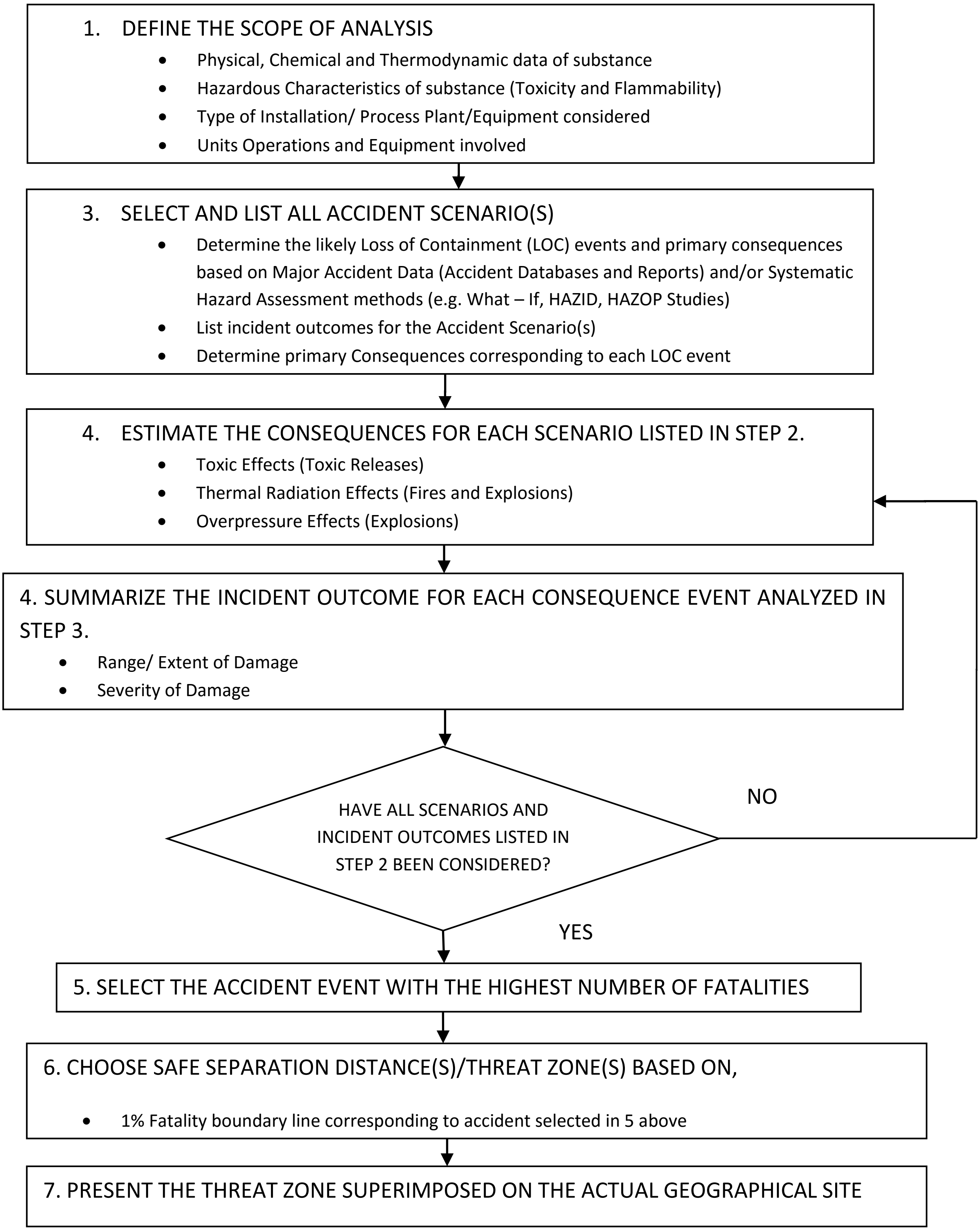


Figure 5.4 –The modified Consequence Assessment Approach for the safety distance risk acceptance criteria

5.3.2 THE “UPPER BOUND FN CURVE” METHOD

The FN curve is a representation of the overall “Risk” posed to the public. Hence, an accurately constructed FN curve with both accurate “Accident Frequencies” and “Consequence Effects” would provide a “risk measure” that is reliable and can be used for determining the level of risk to the public. However, the probabilistic risk assessment exercise carried out in Chapter 4, clearly demonstrates the wide variability in the FN curves with respect to the different “failure frequency” data sets. Hence, it was established that “failure frequency” data representative of site specific factors such as the type of installation, asset integrity management practices and environmental conditions were needed. The use of Generic data is applicable at best only if the level of uncertainty can be established. Sri Lanka at present does not have country specific “failure rates” for major accident hazard installations. Hence any probabilistic risk assessment done for Sri Lanka is dependent on generic “failure rate” data.

To account for the aforementioned shortcomings it is proposed that a conservative approach in interpreting FN curves be adopted due to the difficulty in estimating the uncertainty (Goodstein, 2005) from FN curves derived using “generic” failure rate data. The conservative approach proposed involves the determination of upper bound FN curves (henceforth denoted as local FN Curves) for each process node/ equipment using “generic” failure rate data sets and the construction of an FN Curve for the complete installation under assessment using the failure rates corresponding to the respective FN curves for each process node/ equipment. This would represent the upper bound of the level of “risk” the public is exposed to based on currently available data. Here, the focus is once again on a “Worst Case” outcome but with the “Accident Frequencies” represented in detail in the analysis. The algorithm for constructing the Upper Bound FN Curve using the “Upper Bound FN Curve” method is given in Figure 5.5.

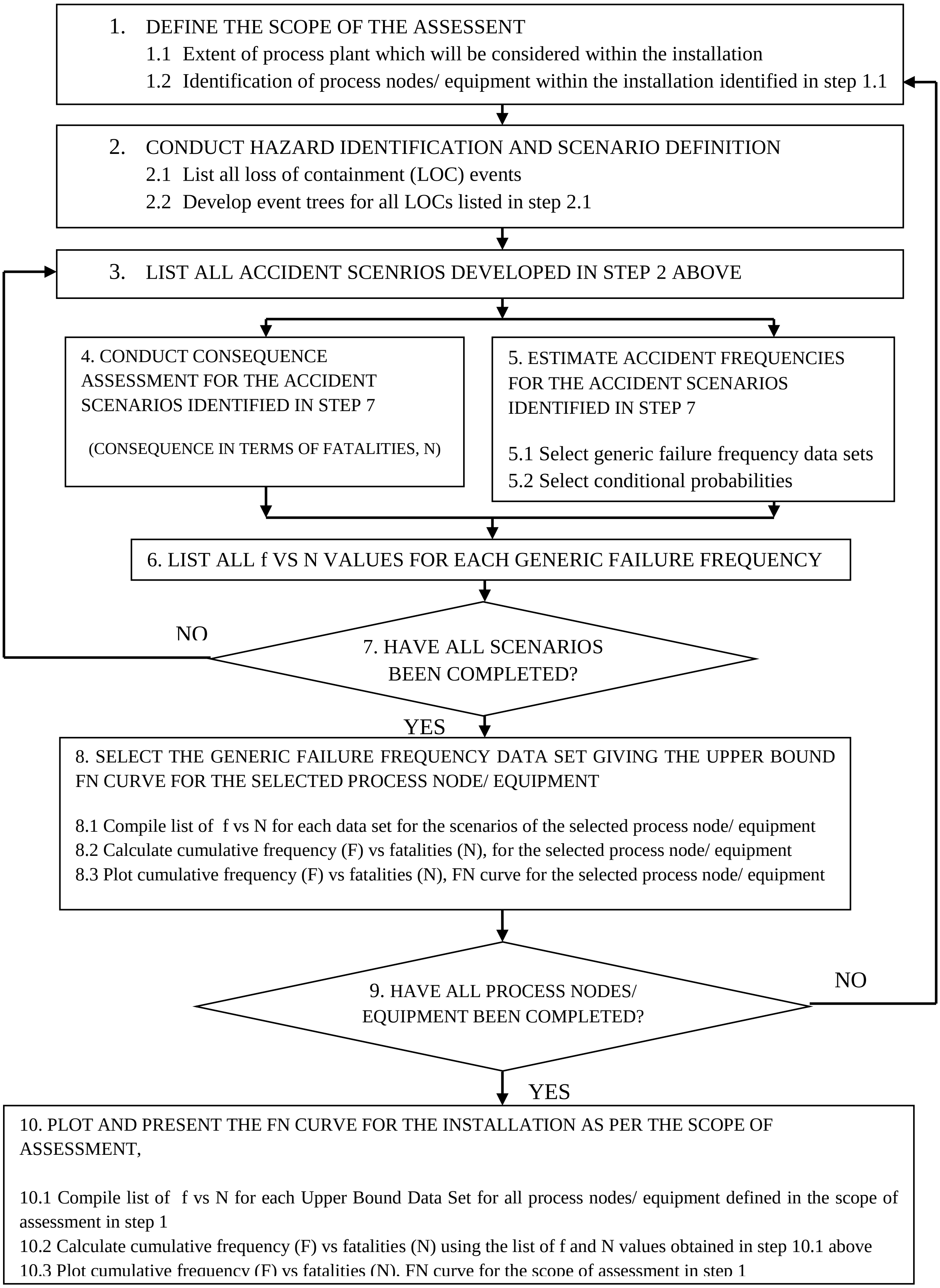


Figure 5.5 – The flowchart for The Upper Bound FN Curve Method

5.3.3 COMPARISON OF THE PROPOSED “MODIFIED CONSEQUENCE ASSESSMENT APPROACH” VS THE “UPPER BOUND FN CURVE” METHOD

The “modified Consequence Assessment” approach is simple to use. There is no test of acceptability as in the probabilistic risk assessment approach, only the establishment of a “Safety Distance” based on the maximum 1% fatality distance. The 1% fatality distance can be reduced by reducing the source terms as it is a function of the inventory of the hazardous material and process conditions. The calculation and tabulation of fatality numbers for the events shall aid in choosing between alternative sites. The modified consequence assessment approach provides the following advantages as opposed to a purely “Consequence Assessment” approach,

1. Choice and evaluation of more accident events
2. Factoring of Population Density into the decision making process

However, the modified “consequence assessment” process lacks the following advantages inherent in a probabilistic risk assessment approach,

1. Representing the overall risk
2. Measuring the reduction in risk offered by alternative mitigation options

The probabilistic risk assessment method proposed in section 5.3.2 is more rigorous than the “modified consequence assessment process”. It requires yields more information on the probabilistic aspects when making an informed decision. However, the immediate outcome of the probabilistic risk assessment method is not a “Safety Distance” that can be readily communicated to the public. It is a “pass/fail” test which is difficult to communicate to the public. When any part of the “upper bound” of the FN curve for the installation lies above the criterion line, the installation is considered to pose an unacceptable level of risk to the public. However, if the “upper bound” lies completely below the criterion line, the installation is considered to pose an acceptable level of risk. It must be emphasized that, decisions based on the location of the “upper bound” FN Curve with respect to the criterion line would primarily act as a “Pass/ Fail” test when comparing MAH installations with different levels of complexity and scale. However, the probabilistic risk assessment method offers the advantage of incorporating the effects of risk reduction efforts that represent reduction in both "Consequence Effects" and "Accident Frequencies" by incorporating the following course of actions,

1. Introduction of Layers of Protection , safety barriers or safeguards
2. Choosing alternate sites with a lower population density

Hence, a contribution to risk reduction from either reduction of "Consequence Effects" and/or "Accident Frequencies" can be accounted for in this approach. A MAH installation initially failing the criterion can be upgraded or sited at an alternate location to achieve the acceptability criterion. The probabilistic risk assessment approach offers more flexibility as well as improved insight in the decision making process. A project proponent can in principle incorporate risk reduction measures and demonstrate to the regulator as to how the level of risk is reduced to an acceptable level. A primary shortcoming in the probabilistic risk assessment approach is the lack of a risk measure that can be clearly communicated to the public such as a "Safety Distance". However, a safety distance can in principle be derived proportionate to the overall level of risk and is further elaborated in the following section.

5.3.4 RELATIVE RISK REDUCTION FACTOR

A relative risk reduction factor (RRRF) is introduced for the FN curve based on upper bound data method in order to establish a Safety Distance proportionate to the overall level of risk. The "theoretical basis" for the representation of overall risk as the area under the FN curve is given in Appendix J.

A relative risk reduction factor (RRRF) is proposed and defined as given below,

$$\mathrm{RRRF} = (A2/A1) \qquad (14)$$

Where,

A1 – Area bounded by "Criterion Line, Cumulative Frequency, Total Fatalities and N_{MAX} (Figures 5.6 and 5.7)

A2 - Area bounded by "FN Curve, Cumulative Frequency, Total Fatalities and N_{MAX} (Figure 5.6 and 5.8)

The "Safety Distance", D_S is defined as,

$$D_S = \text{(Maximum 1\% Fatality Distance) x RRRF} \qquad (15)$$

However, a limit is set where D_S must be maintained such that,

$D_S \geq$ Minimum 1% Fatality Distance

Where Minimum 1% Fatality Distance is the minimum consequence distance from an event producing fatalities of 10 or closest to 10.

D_S is then used to set the "Safety Distance" and can be used in communicating the risk to the public. Adopting this approach in setting safety distances would allow the regulator to choose a safety distance that is more or less proportionate to the level of risk rather than always selecting the "Safety Distance" for the "Worst Case Scenario". It must be emphasized that more than one 1% fatality distance can be derived for the accident events for a particular installation.

The 1% fatality distances (D_i) would vary as follows,

$$D_{min} \leq D_i \leq D_{max}$$

Where,

D_{max} – Maximum 1% Fatality Distance

D_{min} – Minimum 1% Fatality Distance corresponding to 10 fatalities or higher

By using the factor RRRF, the regulator can set a safety distance proportionate to the overall risk posed by the installation. By setting D_{min} as the minimum Safety Distance allowable, the regulator ensures that even for a low relative risk, a safety distance corresponding to a minimum of 10 fatalities is set. The number of minimum number of fatalities allowable is based on the definition of a MAH (Ball & Floyd, 1998).Therefore compared to the "modified consequence assessment" approach, the "Upper Bound FN Curve" approach results in a Safety Distance that is proportionate to the level of risk.

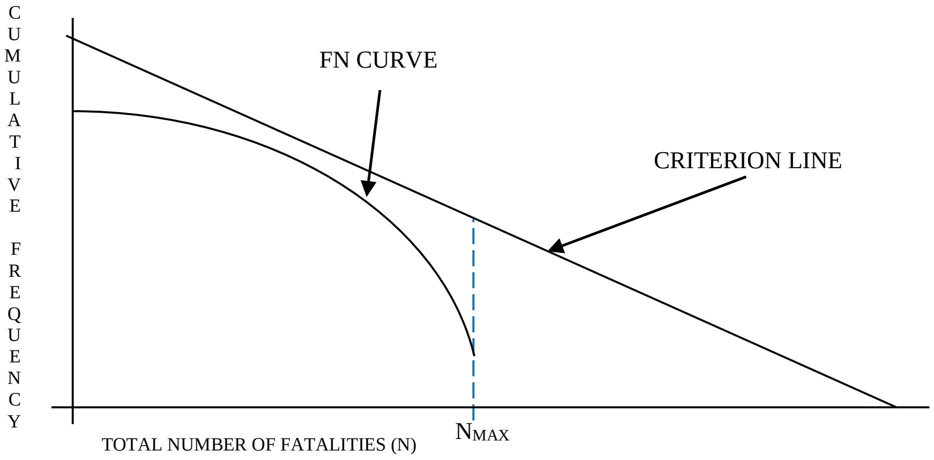


Figure 5.6 - Areas for RRRF Calculation from the FN Curve

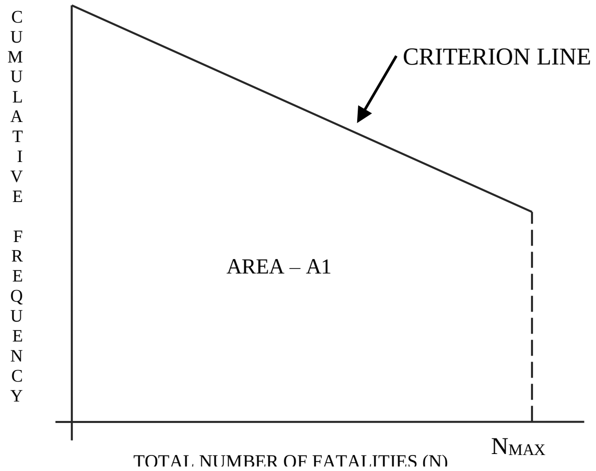


Figure 5.7 - Area A1 bounded by “Criterion Line, Cumulative Frequency, Total Fatalities and NMAX

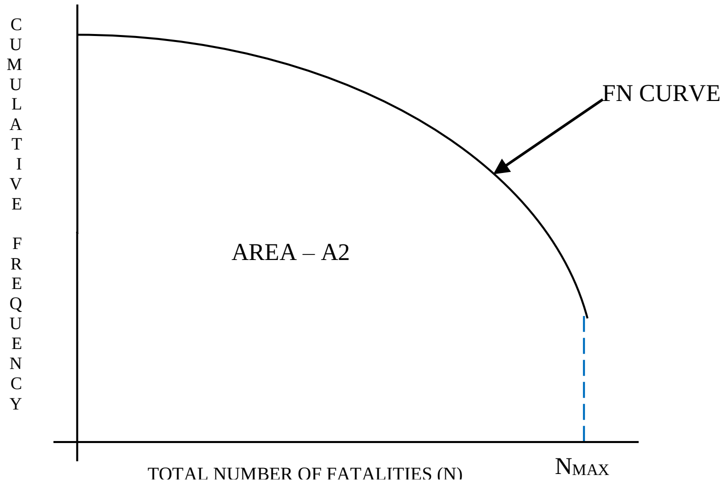


Figure 5.8 - Area A2 bounded by “FN Curve, Cumulative Frequency, Total Fatalities and NMAX

5.4 DECISION MAKING GUIDELINES FOR THE “UPPER BOUND FN CURVE” METHOD

A set of prescriptive rules or guidelines are established to ensure the consistency in application of the “Upper Bound FN Curve Method”. The guidelines pertaining to decision making when using the “Upper Bound FN Curve” method proposed in this work are as follows,

1. If any part of the FN curve lies above the criterion line, it is deemed as unacceptable
2. All parts of the FN curve must lie below the criterion line for it to be acceptable
3. RRRF will be used only as a scaling factor in determining Safety Distances based on the Maximum 1% Fatality Distance
4. RRRF will be calculated only for FN Curves deemed acceptable as per guideline point number 2
5. If the risk level posed by a MAH Installation cannot be reduced to an acceptable level after incorporating the necessary safeguards (e.g. Layers of Protection, Reduction in scale of operation, alternate sites), the Installation is deemed as posing an unacceptable level of risk to the public
6. If a MAH installation is deemed acceptable as per guideline number 2, it is still required to maintain a safe distance equal to “RRRF x Maximum 1% Fatality Distance”
7. The safe distance calculated shall never be less than the 1% Fatality Distance resulting in 10 deaths; if the minimum number of deaths is greater than 10, then the 1% Fatality Distance corresponding to this minimum value is chosen
8. An installation deemed acceptable as per number 2 shall not be exempted from following best available practices, relevant industrial standards, mandatory safety requirements or further risk reduction options as deemed necessary by the regulator

The decision making process for the “Upper Bound FN Curve” method is given in Fig 5.9.

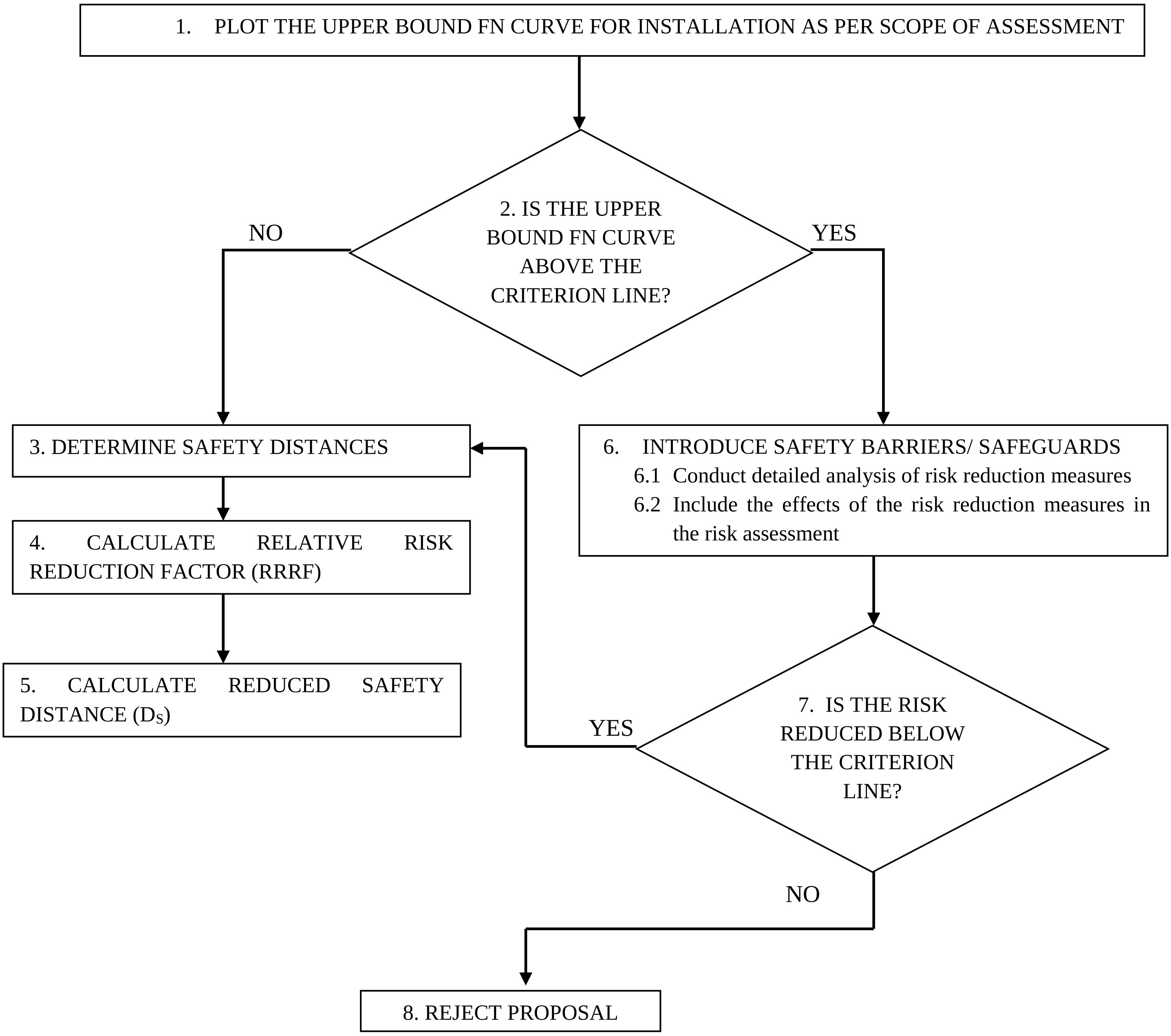


Figure 5.9 – Decision making process using the “Upper Bound FN Curve Method”

5.5 SELECTION OF THE UPPER BOUND FN CURVE METHOD AS THE RISK ASSESSMENT METHOD

It was clearly established that “Risk Assessment” of MAH installations in Sri Lanka in addition to the lack of a “Risk Acceptance” criteria is constrained by the lack of a country and industry specific set of “failure rate” date. Hence, in the development of an appropriate "risk acceptance" criteria for Sri Lanka three routes for the development are obvious,

1. Develop a set of country specific "failure rate" data
2. Adopt a method that does not require in depth application of "failure rate" data (specific or generic)
3. Adopt a method that uses "generic failure rate data".

The first option requires the access to a reliable "Asset Integrity" database in the CPI. Provided, such access is granted, the data mining, compilation, categorization and analysis of the relevant reliability data would be time consuming. This option is not considered as being able to provide a suitable dataset within the next three years. Hence, option 1 is not considered in this study.

The second method is a consequence based decision making approach. A modified consequence assessment approach was developed as opposed to a purely "worst case" consequence assessment approach. While this approach provides the consequence assessment of more accident events, it does not yield an outcome that is proportionate to the level of risk. This approach is consistently "conservative" or "worst case". Furthermore, the lack of its ability to include "probabilistic aspects" reduces the depth of assessment. Hence, the 2nd option too is not considered further.

The third option includes "probabilistic aspects". However, the wide variation in "generic failure rate" data poses a significant constraint. This is accounted for by selecting "failure rate" data sets that yield "Upper Bound" FN Curves. This provides an upper limit for the FN curves which represents the highest risk level possible. This curve can then be used to define a "relative risk reduction factor" which is used to scale the "safety distances". This approach ensures that both "consequence effects" and "probabilistic effect" are considered to a great extent in the decision making process. Hence, option 3 is adopted as appropriate for Sri Lanka.

CHAPTER 6

6. DEMONSTRATING THE APPLICABILITY OF THE “UPPER BOUND FN CURVE” METHOD

6.1 INTRODUCTION

The applicability of the “Upper Bound FN Curve” method is demonstrated in this chapter. The “Upper Bound FN Curve” derived for the case under consideration (i.e. Taylor FN Curve) does not meet the risk acceptance criteria (Refer Figure 4.7) as it lies above the criterion line. Hence, the next step is to apply mitigation measures to reduce the level of risk.

6.2 RISK REDUCTION MEASURES FOR THE “UPPER BOUND FN CURVE” METHOD

Risk reduction measures or safeguards as highlighted in the guideline No.5 in chapter 5, section 5.4 are required to lower the level of risk in order to meet the acceptance criteria. Two risk reduction measures or courses of action are proposed; namely,

1. Introduction of safeguards/ safety barriers
2. Relocation of process plant to an alternative site

The consideration of the 1st option takes into consideration the inclusion of “layers of protection” or “safety barriers” which reduce either the frequency of occurrence of the accidents or their consequence. Option 2, considers the relocation of the installation to an area with a lower population density, thereby reducing the potential number of fatalities.

The flexibility of relocating an installation or finding alternative sites is low. However, the inclusion of “safety barriers” is flexible and can be applied to any MAH installation. It is logical to apply the safety barriers first and consider the reduction in the level of the risk. A direct approach in selecting an alternative site without due consideration for risk reduction will drive the decision towards the selection of a site in a region with low population density; this is a “zero risk” approach. Such a “Zero Risk” approach in decision making will bias the decision maker to select sites with “zero risk” outside the boundary of the installation. Unfortunately, it is not a viable option as land is a scarce resource. It is proposed that alternative sites be considered if the risk level cannot be reduced further after incorporating “safety barriers”. Hence, this thesis chooses the “safety barrier” approach to reduce the risk from the Propane Bullet Tank to an acceptable level.

6.3 SELECTION OF SAFETY BARRIERS

The applicability of layers of protection and respective safety barriers are considered for each scenario identified in Chapter 4 (Refer Figure 4.13, 4.14 and 4.15). The safety barriers are given in Table 6.1. The safety barriers are selected in accordance with international industrial standards such as API 2510A (American Petroleum Institute [API], 1996). Safety barriers can in general be categorized as follows (CCPS, 2001; Skelt,2006),

- Passive barriers
- Activated barriers
- Human actions
- Symbolic barriers

Passive barriers are functional on a permanent basis. They require no human action, energy sources or information sources (CCPS, 2001). The “Fire Proofing” proposed for the pressure vessel belongs to this category.

Activated barriers require precondition to be activated and are either automated or manual (CCPS, 2001). The “Water Deluge System” and “Gas Detection System” belong to this category. Human actions consist of safety functions where humans are involved in a detection – diagnosis – action sequence. Activation of emergency response due to a gas leak belongs to this category. Symbolic barriers require interpretation by a human and can consist of a passive warning (e.g. keep out sign, no smoking sign). Such barriers are not considered in this thesis as the probability of failure is not possible to quantify.

The following safeguards are selected for the propane storage tank case,

- Fire Proofing of the pressure vessel
- Gas Detection System coupled with Emergency response

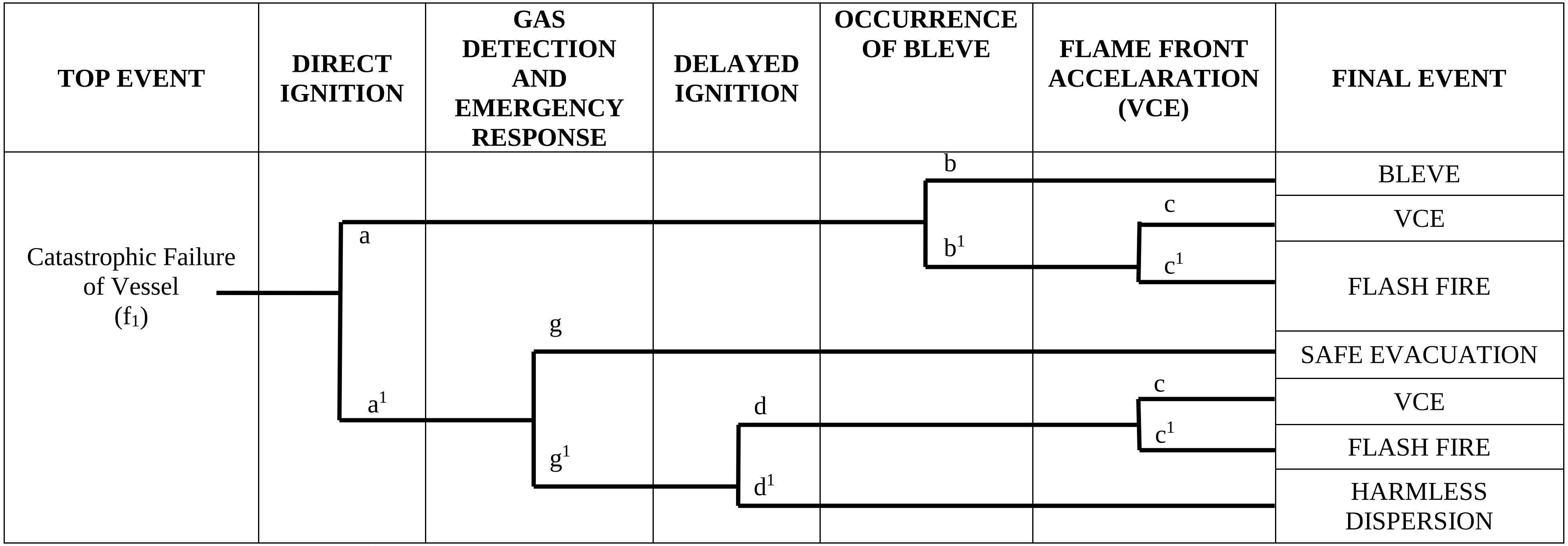
The precursor of a hot catastrophic failure of a propane pressure vessel is flame impingement leading to a weakening of the vessel material and overpressure due to propane evaporating within the closed storage vessel; the final outcome is a BLEVE if not controlled. Application of fireproofing of the structure and vessel body provides a barrier of protection from flame impingement.

The provision of an emergency response function consisting of a “Hydrocarbon Gas Detection System” and “Onsite Emergency Response” is also considered. It is envisaged that the activation of the “Emergency Response” includes the activation of “Emergency Responders” and “Community Response” within 10 minutes of the release. Community response includes safe evacuation and closure of roads to public transport (except for evacuation routes). However, it must be emphasized that this safety function is less reliable than the Passive and Activated barriers mentioned above (CCPS, 2001).

Each event can be mitigated only by a specific set of barriers; all barriers do not prove applicable for all events. Certain events occur within 5 minutes of release which do not provide sufficient time for emergency response event if gas detection is successful. Hence, emergency response is not considered for such events. Events which occur close to 10 minutes or with a higher delay can make use of emergency response. Furthermore, the provision of fireproofing is specifically targeted in preventing a BLEVE event. Hence, these barriers are considered where BLEVEs are concerned.

6.4 DEVELOPMENT OF EVENT TREES WITH THE SAFETY BARRIERS

Safety barriers identified in section 6.3 were incorporated into the accident scenarios identified in chapter 4, section 4.2 and the respective event trees were developed giving the sequence of events from the initial loss of containment to the final consequence. The event trees with the safety barriers are given in figures 6.1, 6.2 and 6.3.



a – Probability of direct ignition, a^1 – Probability direct ignition does NOT occur

b – Probability of BLEVE occurring, b^1 – Probability BLEVE does NOT occur

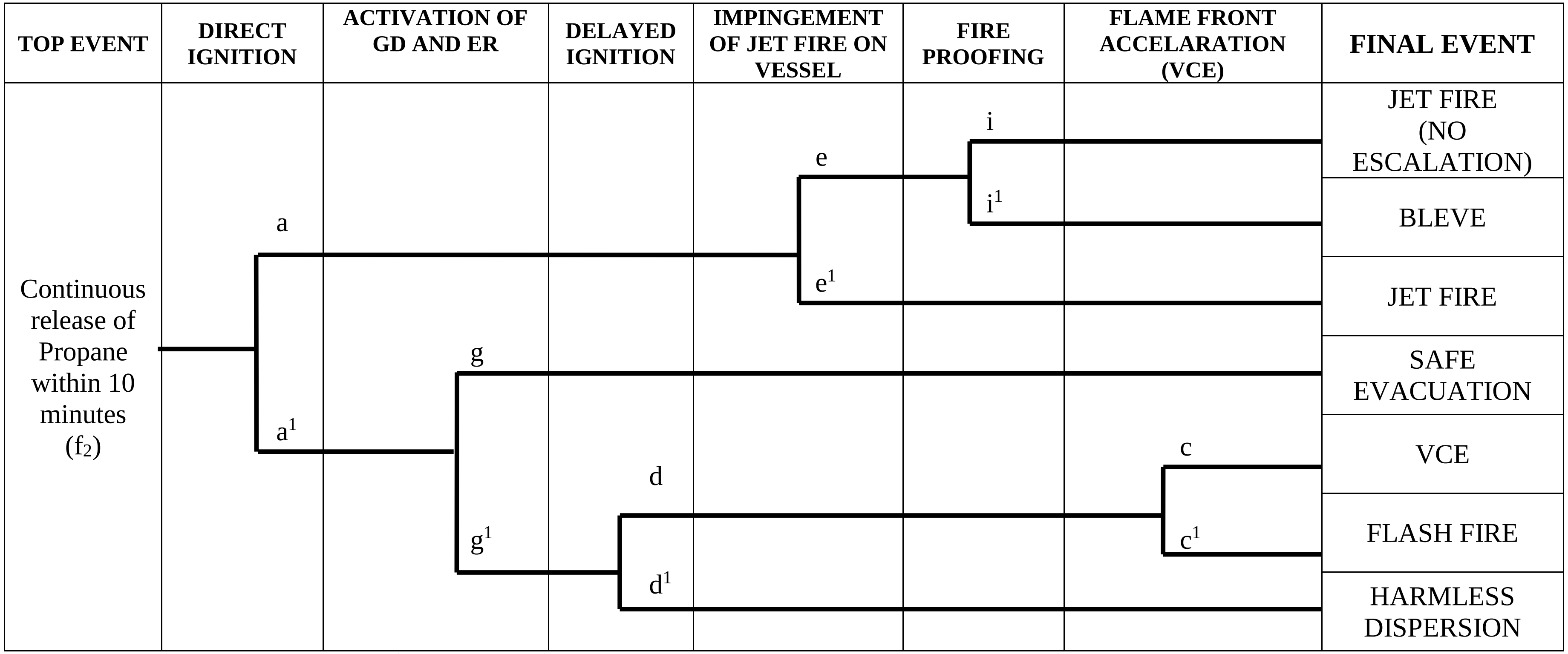
c – Probability of flame front acceleration resulting in vapour cloud explosion, c^1 = Probability flame front acceleration does NOT occur

d – Probability delayed ignition occurs, d^1 = Probability delayed ignition does NOT occur

g – Probability of activation of Gas Detection AND Emergency Response (ER), g^1 – Probability of failure of Gas Detection AND ER

f_1 – Failure frequency for the Catastrophic Failure of the Propane Vessel

Figure 6.1 – Event tree for the instantaneous release of entire inventory (with Safety Barriers)



a – Probability of direct ignition, a^1 – Probability direct ignition does NOT occur

c – Probability of flame front acceleration resulting in vapour cloud explosion, c^1 = Probability flame front acceleration does NOT occur

d – Probability delayed ignition occurs, d^1 = Probability delayed ignition does NOT occur

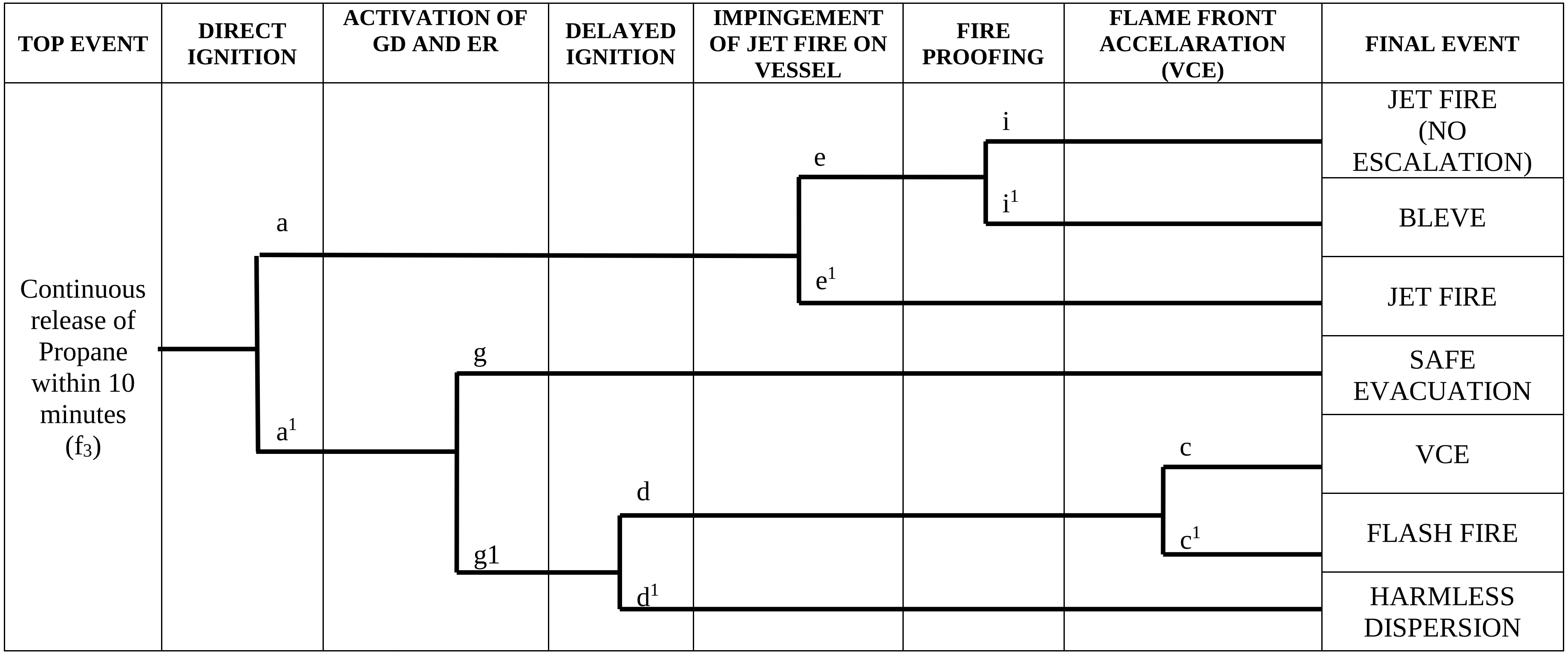
e – Probability of Jet Flame impinging on Vessel, e1 – Probability of Jet Flame NOT impinging on Vessel

g – Probability of activation of Gas Detection(GD) AND Emergency Response (ER), g1 – Probability of failure of Gas Detection AND ER

i – Fire proofing does not fail, i^1 – Fire proofing fails,

f_2 – Failure frequency for the release of entire inventory within 10 minutes

Figure 6.2 – Event tree for the release of entire inventory within 10 minutes (with Safety Barriers)



a – Probability of direct ignition, a^1 – Probability direct ignition does NOT occur

c – Probability of flame front acceleration resulting in vapour cloud explosion, c^1 = Probability flame front acceleration does NOT occur

d – Probability delayed ignition occurs, d^1 = Probability delayed ignition does NOT occur

e – Probability of Jet Flame impinging on Vessel, e1 – Probability of Jet Flame NOT impinging on Vessel

g – Probability of activation of Gas Detection(GD) AND Emergency Response (ER), g1 – Probability of failure of Gas Detection AND ER

i – Fire proofing does not fail, i^1 – Fire proofing fails

f_3 – Failure frequency for the release of inventory through a 10mm hole

Fig 6.3 – Event tree for the Continuous release of inventory through 10 mm hole

6.5 SELECTION OF THE PROBABILITY OF FAILURE ON DEMAND (PFD) FOR THE SAFETY BARRIERS

Each safety barrier selected in section 6.3 has a probability of failure defined as "probability of failure on demand (PFD)". The respective PFD values for the chosen safety barriers are as follows,

Table 6.1 – PFD values for the selected Safety Barriers

SAFETY BARRIER	PFD VALUE (per year)	SOURCE OF DATA
Fire proofing on pressure vessel	1×10^{-2}	(CCPS, 2001)
Gas Detection System	1×10^{-1}	Assuming a minimum safety integrity level (SIL) rating of 1 required for refinery service
Human Action with 10 minutes response time for emergency response	1×10^{-1}	(CCS,2001)

The PFD values given in table 6.1 are typical values and are generic for the particular application. Specific failure rate data from site specific routine tests or product manufacturers can be a reliable source. The PFD values modify the accident frequency, $f_{Accident}$ as shown below,

$$f_{Accident} = f_{LOC} X \prod P_{conditional\ modifiers} X \prod PFD_{Safety\ Barriers} \tag{16}$$

$P_{ConditionalModifiers}$ – probability of ignition, probability of explosion

$P_{Safety\ Barriers}$ –PFD values for the Safety Barriers

$\prod$ - implies "Product of"

6.6 PLOTTING OF "UPPER BOUND FN CURVE" AFTER INCORPORATING SAFETY BARRIERS

The accident frequencies are now calculated with the PFDs of the safety barriers to determine the reduction in the level of risk for the case under consideration. The accident frequency (f) vs fatalities (N) for each accident scenario depicted in figures

6.1, 6.2 and 6.3 are given in table 6.1. The cumulative frequencies (F) for the number of fatalities (N) calculated from the data in table 6.1 are presented in table 6.2**.** The extent of the consequences remains unchanged as the neither the release rates nor populations densities have changed. Hence, the number of fatalities remains unchanged for each respective accident event of the case study as estimated in section 4.2 and given in Table 6.3. However, the introduction of the safety barriers reduces the accident frequency for each accident event.

Table 6.2 – Cumulative Frequency (F) vs Fatalities (N) for the Uppper Bound FN Curve with Safety Barriers

TOTAL NUMBER OF FATALITIES, N	CUMULATIVE FREQUENCY, F
284.6	1.80 X 10^{-10}
224.8	5.40 X 10^{-07}
112.8	4.44 X 10^{-06}
50.7	4.44 X 10^{-06}
47.4	4.45 X 10^{-06}
36.4	4.81 X 10^{-06}

The Upper Bound FN curve after the inclusion of safety barriers is plotted using MATLAB and shown in figure 6.4. The Upper Bound Curves with and without safety barriers are compared in figure 6.4.

6.7 CALCULATION OF THE RELATIVE RISK REDUCTION FACTOR (RRRF)

The RRRF can be calculated from figure 6.5. The method of calculation is given in section 5.3.3. From the definition of the RRRF equation 14 is applied,

RRRF = (A2/A1)

Where,

A1 – Area bounded by “Criterion Line, Cumulative Frequency, Total Fatalities and N_{MAX}

A2 - Area bounded by “FN Curve, Cumulative Frequency, Total Fatalities and N_{MAX}

A1 for the case under study is the Area bounded by Red, blue and brown lines in figure 6.5

A2 for the case under study is the Area bounded by Green, blue and brown lines in figure 6.5

A2 = 4.12 and A1 = 4.29 (Areas were estimated by taking the log values of the respective coordinates and calculating the relevant portions of the areas)

Hence RRRF = (A2/A1) = 0.96

6.8 ESTIMATION OF THE SAFETY DISTANCE

The set of impact distances for the accident events for the case under consideration is given in Table 6.11. Therefore the set of distances for the onset of fatality, D_{Fatal} is as follows,

D_{Fatal}(m) = {381,440,497,525,550}

If a purely deterministic approach is taken, the obvious choice would be the maximum distance, D_{Max} = 550 m. This is the most conservative choice and it is selected to account for the uncertainty arising due to the gap in knowledge on how failure frequencies will impact the level of risk. However, the “Upper Bound FN Curve” method proposed in chapter 5, section 5.3 of this thesis provides an understanding of how the accident frequencies will impact the level of safety albeit the use of general failure frequencies. Hence, a safety distance can be chosen between D_{Min} and D_{Max} (381m to 550m) as the safe distance proportionate to the level of risk.

Hence, the safety distance for the case under consideration as given in equation 15 is as follows,

$$
\begin{aligned}
D_{Safety} &= RRRF*D_{Max} \\
&= 0.96 \text{ x } 550\text{m} \\
&= 528 \text{ m}
\end{aligned}
$$

No public activity shall be allowed within a radius of 528m from the point of release provided the level of risk is reduced by applying the safety barriers as a minimum.

Table 6.3 – 1% Fatality Distances (Downwind Direction)

EVENT		TYPE OF RELEASE	TIMING OF IGNITION	FATALITIES	DISTANCES TO 1% FATALITY (m) (100% Fatality in Flash Fires only) Derived from ALOHA Threat Zones
1	BLEVE due to catastrophic rupture	***Instantaneous*** release of entire inventory	Immediate	112.8	381
2	Vapour Cloud Explosion	***Instantaneous*** release of entire inventory	Immediate	2.4	Not estimated as the number of fatalities is less than 10
3	Flash Fire	***Instantaneous*** release of entire inventory	Immediate	47.4	525
4	Vapour Cloud Explosion	***Instantaneous*** release of entire inventory	Delayed	50.6	550
5	Flash Fire	***Instantaneous*** release of entire inventory	Delayed	284.5	525
6	BLEVE due to hot rupture from impingement of Jet Fire	Continuous release of entire inventory within 10 minutes	Immediate	112.8	381
7	Vapour Cloud Explosion	Continuous release of entire inventory within 10 minutes	Delayed	36.4	497
8	Flash Fire	Continuous release of entire inventory within 10 minutes	Delayed	224.8	440
9	BLEVE due to hot rupture from impingement of Jet Fire	Continuous release of entire inventory within 10 minutes	Immediate	112.8	381

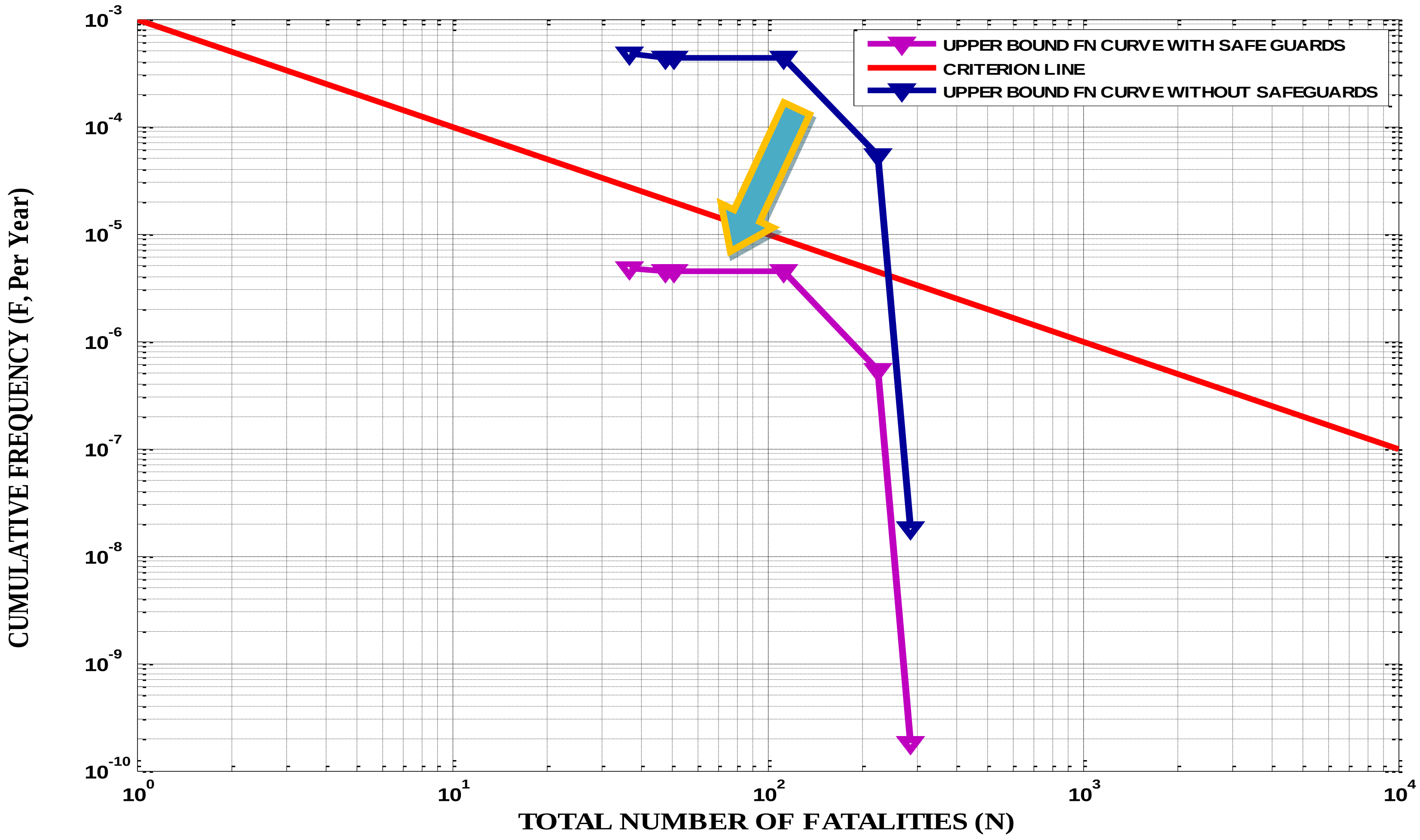


Figure 6.4 – Comparison of “Upper Bound” FN Curves with and without Safety Barriers

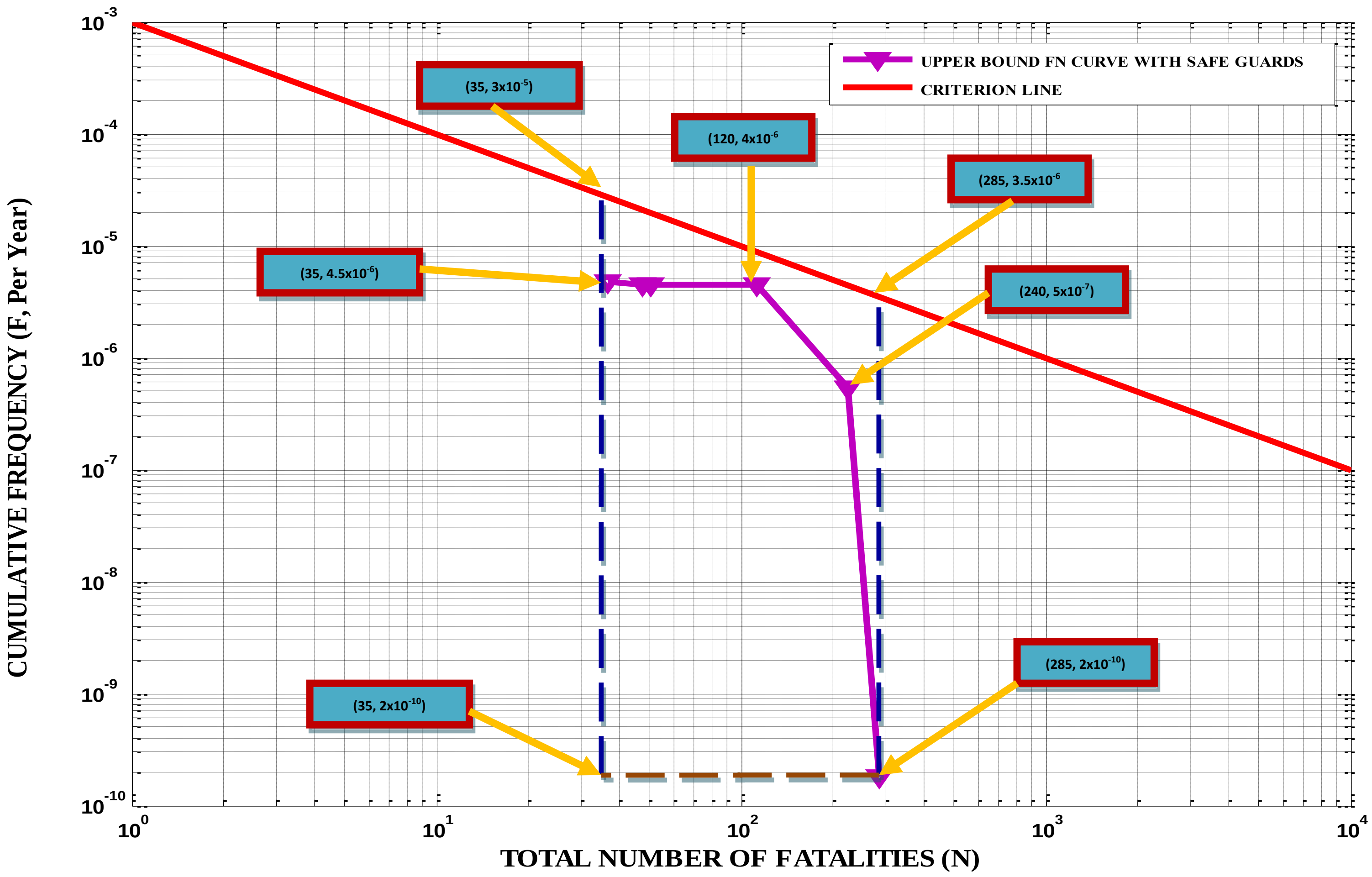


Figure 6.5 – Areas Marked for Calculation of Relative Risk Reduction Factor (RRRF)

CHAPTER 7

7. CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

7.1 CONCLUSIONS

This research addressed a significant but much overlooked gap in Sri Lanka's approval process of industrial installations with potential for "Major Accident Hazards". This work considered the development of a suitable "Risk Acceptance Criteria" and "Framework for applying the risk acceptance criteria" for the Chemical Process Industry in Sri Lanka. The "Risk Acceptance Criteria" forms the benchmark against which the level of risk posed by a MAH installation in the CPI is compared. The "Framework" provides the method and guidelines as to how the "Risk Acceptance Criteria" is applied in the process of making decisions.

In this work, the definition of risk selected is essentially focused on "Technological Systems" as opposed to "Financial or Political" systems. The relevant methodologies or approaches of risk assessment are identified as per the chosen definition of risk and are then analysed in detail. The study shows that the "Risk Assessment Approach" and "Risk Acceptance Criteria" are tightly coupled and inter - dependent. A particular "Risk Assessment Approach" will be meaningful with only specific type of "Risk Acceptance Criteria". Hence, the choice of the most appropriate "Risk Assessment Approach" is of paramount importance.

Separate "Risk Assessment Criteria" were developed based on the Sri Lankan context. The criteria developed are shown in Table 7.1. The risk acceptance criteria developed which can be applied for the "Consequence Assessment Approach" is a safety distance within which no public occupation can be permitted. Whereas, in the criterion line, Cumulative Frequency (F) vs Fatalities (N) Curve or FN curve that represents the overall risk which cannot be exceeded by the MAH installation can be applied using probabilistic risk assessment approach. Both proposed criteria for the Sri Lankan context are societal risk acceptance criteria.

Table 7.1 – Summarized Table of Risk Acceptance Criteria for Sri Lanka

RISK ACCEPTANCE APPROACH	RISK ACCEPTANCE CRITERIA PROPOPOSED FOR SRI LANKA
Consequence Assessment	Safety Distance maintained up to a distance of 1% Fatality for the “Worst Case” scenario
Probabilistic Risk Assessment	Societal risk acceptance criterion line with Anchor Point (10, 10^{-4}) and slope of -1 on a log – log plot of Cumulative Frequency (F) vs Fatalities (N) also known as an FN Curve (Refer Graph 3.12).

The two risk acceptance criteria which were developed, namely safety distance and the FN curve were applied in a case of a bullet type propane storage tank using both the Consequence Assessment (CA) approach and the probabilistic risk assessment approach respectively. These two approaches were then compared in the first section of chapter 5. Comparison of both approaches led to the realization that a “Probabilistic Risk Assessment Approach” is more suitable for Sri Lanka than a “Consequence Assessment Approach” due to the following factors,

1. Higher depth of analysis
2. Includes “Probabilistic” aspects and thereby is a more accurate representation of the definition of risk
3. Flexibility in including a wider range of risk reduction measures

Therefore, a framework for using the FN curve risk acceptance criterion with upper bound failure frequency data based on “Probabilistic Risk Assessment Approach” was proposed to suit requirements in Sri Lanka and to circumvent the constraints mentioned above. This method uses “generic Failure Rate” data that uses “Upper Bound” FN Curve for a particular MAH installation. This curve is then compared against the Societal Risk acceptance “Criterion Line” for acceptability as per the “guidelines for decision making” proposed in this work. Furthermore, a scaling factor RRRF (Relative Risk Reduction Factor) is introduced to establish Safety Distances that are proportionate to the level of overall risk. The Safety Distances are used to establish safety distances and support communication of the level of risk to the public. The decision making framework consists of the "Upper Bound FN Curve" method including "guidelines for the decision making process".

7.2 RECOMMENDATIONS

The following recommendations are proposed as possible future research studies

1. Establishment of a national regulatory framework for "safety risk assessment" for MAH installations
2. developing "Failure Rate or Failure Frequency" and "Ignition Probability" data for the CPI in Sri Lanka and collecting, verifying and validating any such data
3. Development of a procedure to incorporate the risk acceptance criteria and the framework developed to apply these criteria in safety risk assessment process in this thesis into the current legal instrument/system in Sri Lanka

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Appendix – A: Description of the Probit Analysis Method

The probability unit method or “probit” method is a widely used method for predicting the probability of a Toxic, Fire or Explosion exposure effect. It is a statistical curve fitting technique (Jonkman, van Gelder & Vrijling, 2003) and has it’s roots in the prediction of toxic exposure. However, Dose – Response curves can be constructed for a number of exposures such as heat, pressure, radiation, impact and sound (Jonkman, Vrijling & van Gelder, 2006).

Exposure data is usually non – linear and the probit method provides a convenient technique of providing a linear relationship between the dosage and response. The relationship between the probit variable Y and probability P is as follows,

$$P = (1/(2\Pi)^{(1/2)})\int_{-\infty}^{Y-5} \exp\left(-\frac{u^2}{2}\right) du$$

Here u is an integration variable.

A plot of this relationship is as follows,

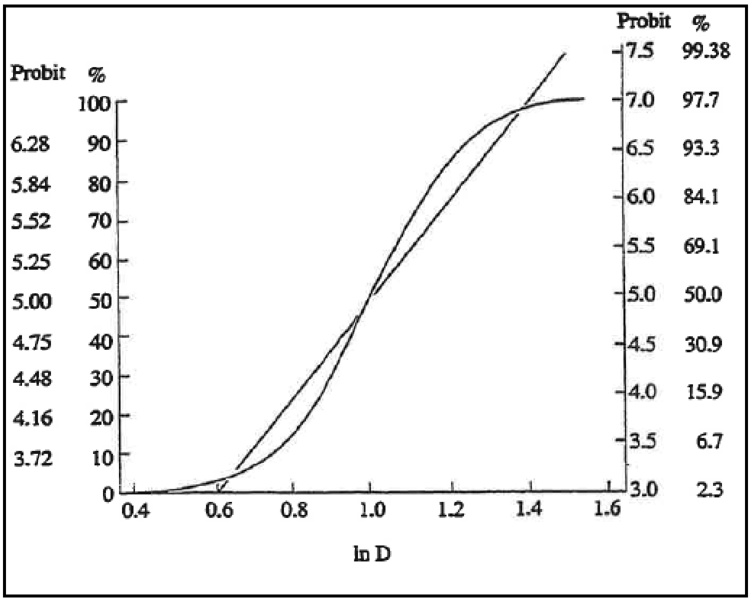


Fig A.1 – Probit Transformation, Source: (TNO, 1996)

The probit transformation converts the response versus log dose curve which is sigmoidal into a straight line when plotted on a linear probit scale (Jonkman, Vrijling

& van Gelder, 2006). The probit variable Y can then be represented in log normal form as follows,

$$Y = k_1 + k_2 \ln(V)$$

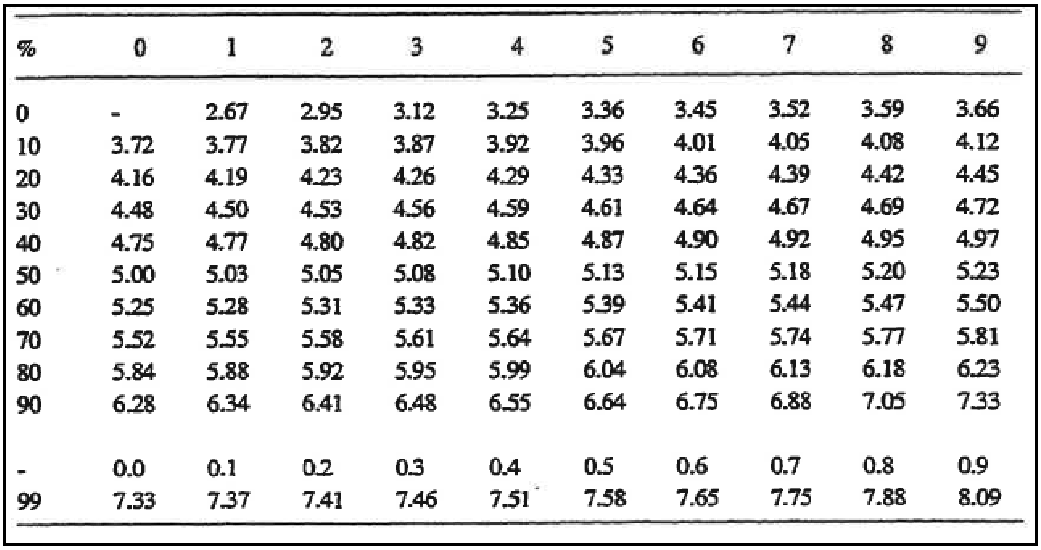
Where,

k1 and k2 are probit parameters specific to the hazardous agent

V – Dose

This is a convenient form when carrying out analysis of exposure events. The probit and probability transformation can also be determined using the tabular form of the relationship given in Fig A1.

Table A.1 – Tabular form of the Probit – Probability relationship



%	0	1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.82	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.18	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33
-	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
99	7.33	7.37	7.41	7.46	7.51	7.58	7.65	7.75	7.88	8.09

Source: (TNO, 1996)

Appendix – B: Major Technological Systems related accidents in Sri Lanka

PERIOD: 1964 TO 2013

Table B.1 – Major Technological Accidents in Sri Lanka

YEAR	EVENT	DISASTER TYPE	NUMBER OF FATALITIES	SOURCE
1964	Derailment of train at Vilwatte, Mirigama	Rail	32	Sunday Island, 15 Nov 2009, Daya Lelwala
1970	Palavi Level Crossing	Rail	14	Ceylon Today, 23 Jan 2014, E. Shelton De Silva
1974	Martin Air Flight 138, crash at Saptakanya	Air	191	Sunday Times, 30 Nov 2014, Donald Rosa
1986	Breach of the Kantale Dam	Structural	126	Sunday Times, 11 May 2011, Malaka Rodrigo
1989	Collision of bus with train at level crossing, Ahungalla	Rail	38	Ceylon Today, 23 Jan 2014, E. Shelton De Silva
2001	Derailment of train, Nittambuwa	Rail	14	Sunday Times 20 Jan 2002, Nilika De Silva
2005	Train and bus collision at Yaangalmodera, Polgahawela	Rail	41	Sunday Times 07 April 2013, Wasantha Ramanayaka
2007	Bus and Truck collision at Induruwa	Road	19	Forensic Research 2012, Ruwanpura et al
2008	Poisoning due to consumption of illicit liquor, Gampaha	Poisoning	10	Sunday Times 28 September 2008, Himal Kotelawala and Damith Wickremesekara
2010	Explosion of explosives under storage at the Karadiyanaru Police Station Premises, Batticaloa	Explosion	21	Country Situation Report CAPP Sri Lanka Task Force, Task Force on Chemical Accident Prevention and Preparedness Programme in Sri Lanka

Appendix – C: Gaseous Leaks in Sri Lanka with Potential for Public Exposure

PERIOD CONSIDERED – 2005 TO 2014

Table C.1 – Major Gas Leaks in Sri Lanka

ACCIDENT		LOCATION	YEAR
1	Ammonia leak	Biyagama EPZ	2007
2	Chlorine Leak	PCC, Fullerton Industrial Zone, Nagoda , Kalutara	2012
3	Flare Gas leak containing H_2S	CPC Oil Refinery, Sapugaskanda	2012

Source: (Task Force on Chemical Accident Prevention and Preparedness Programme in Sri Lanka [CAPP – SL], 2013)

Appendix – D: Meteorological Data for Consequence Assessment

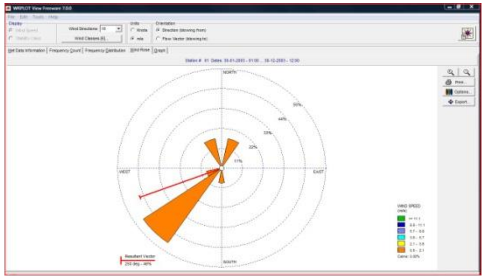
Meteorological data plays a crucial role in the accuracy of the consequences modeled with respect to the effects as well as topographical extent. Wind data in particular contributes towards a significant variation in the accuracy of the consequences modelled. Wind data such as wind speed, wind direction and stability class is essential for conducting an accurate consequence assessment as the extent of the consequence for most LOC cases vary according to the variation in meteorological conditions. Hence, an understanding of the variation in wind data for a particular site or installation is essential.

This study uses wind data for the Western Province. The Department of Meteorology, Sri Lanka maintains two monitoring stations in Colombo and Katunayaka situated in the same province (Western Province) and has a comprehensive collection of validated and verified wind data accessible to the public on request. Resultant wind data for Colombo was adopted for use in the analysis. wind data for Colombo for the consecutive years from 2003 to 2013 was analysed for average wind speed and wind direction. Wind Roses for each year were plotted using a software (freeware) known as "WRPLOT View Ver 7.0" developed by Lakes Environmental Software (www.weblakes.com) based in Canada. The wind roses are given in figure D.1.

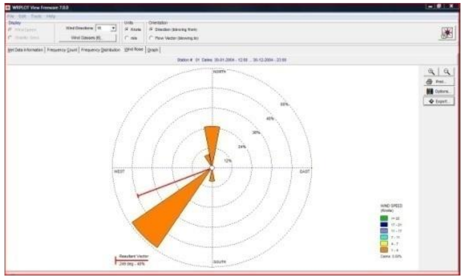
The yearly average wind speed and directions calculated from the resultant wind data for the years 2003 to 2013 are given in table D.1. The average wind speed for the period under consideration was 1.38 ms^{-1} (Measured at a 3m height) and the direction was 236^0. These average values were then used for the consequence analysis. However, it must be emphasized that these values represent the most frequent wind conditions whereas there may be seasonal variations in wind speed and direction for a given year.

Table D.1: Yearly Average Wind Speeds and Directions (2003 – 2013)

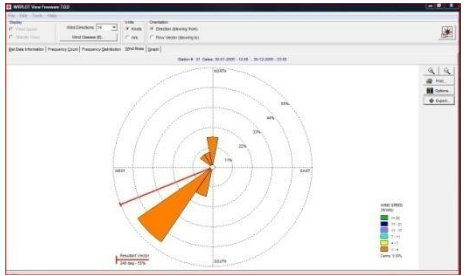
YEAR	AVERAGE WIND SPEED (ms^{-1})	DIRECTION (BLOWING FROM)
2003	1.13	250^0
2004	1.37	249^0
2005	1.22	248^0
2006	1.27	228^0
2007	1.33	265^0
2008	1.45	217^0
2009	1.46	244^0
2010	1.38	236^0
2011	1.57	234^0
2012	1.38	225^0
2013	1.61	211^0



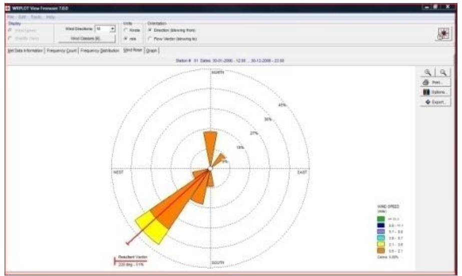
YEAR - 2003



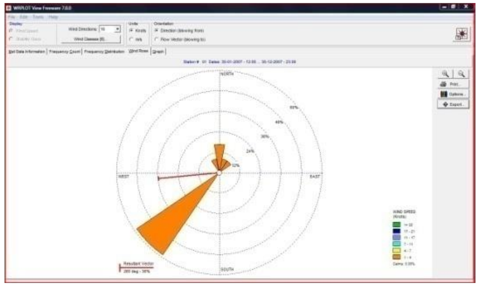
YEAR - 2004



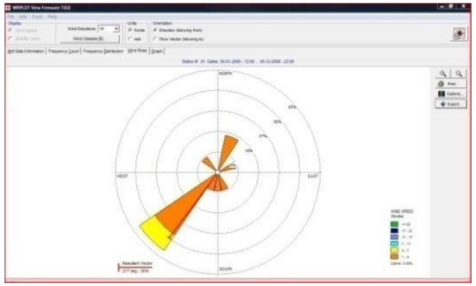
YEAR - 2005



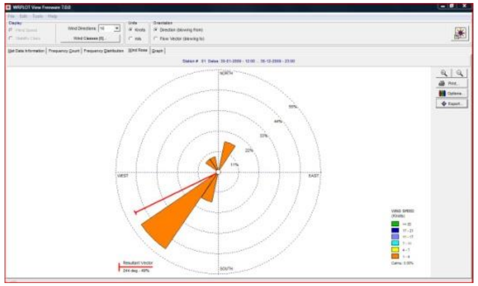
YEAR - 2006



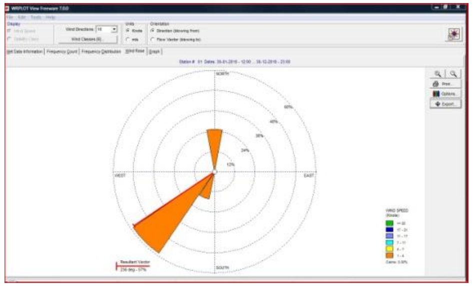
YEAR - 2007



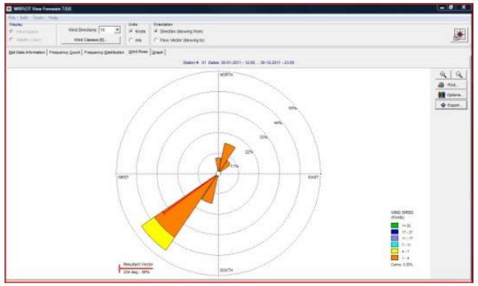
YEAR - 2008



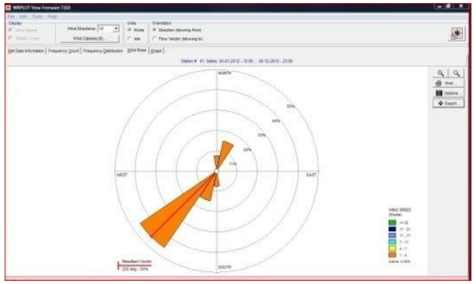
YEAR - 2009



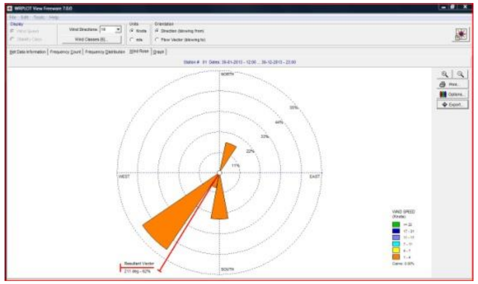
YEAR - 2010



YEAR - 2011



YEAR - 2012



YEAR - 2013

Figure D.1 – Wind Rose for Colombo (2003 – 2013)

Table D.2: General Meteorological and Topographical Conditions

PARAMETER		VALUE	COMMENTS
1	Ground roughness	Open Country	It is assumed that the propane storage tank is located in open terrain
2	Cloud Cover	Partly Cloudy	
3	Average ambient temperature	28 °C	
4	Stability Class	B	This is automatically generated by ALOHA based on the given data
5	Relative Humidity	65%	
6	Inversion	None	Assumption

Appendix – E: Estimation of Consequence Impacts for the Consequence Assessment (CA) Approach

1.0 INTRODUCTION

The following accident scenarios as identified in Chapter 4, section 4.1 are evaluated and the maximum 1% fatality distances are estimated.

1. Catastrophic failure of the pressure vessel (hot failure) and BLEVE
2. Rupture of the vessel with immediate ignition and vapour cloud explosion (VCE)
3. Rupture of the vessel with delayed ignition and flash fire
4. Rupture of the vessel with continuous release and delayed ignition

1.1 ACCIDENT SCENARIO 1: CATASTROPHIC FAILURE OF THE PRESSURE VESSEL (HOT FAILURE) AND BLEVE

A “Boiling Liquid Expanding Vapour Explosion” or BLEVE is considered to be the worst possible outcome when a storage tank containing a flammable substance is exposed to fire (Tellez & Pena, 2002). The BLEVE occurs due to a phenomenon known as “spontaneous nucleation” which consists of a massive, instantaneous formation of tiny bubbles within the liquid mass, caused by a sudden depressurization of the vessel contents. When a pressure vessel containing a flammable substance is exposed to continuous heating due to fire or flame impingement, the integrity of the vessel will fail leading to a sudden rupture which will result in a sudden depressurization leading to conditions suitable for a BLEVE.

A BLEVE results in the following effects,

1. Thermal Radiation
2. Overpressure Effects
3. Fragment Projection (Missiles)

The thermal radiation effects of the BLEVE were modelled using ALOHA.

1.1.2 ESTIMATION OF THERMAL RADIATION EFFECTS

A BLEVE involving a flammable material is followed by a fireball and intense thermal radiation. The thermal energy is usually released within a time frame of less than 40 seconds; however the duration is a function of the mass in the tank.The parameters of concern to be estimated for the fire ball are as follows (Satyanarayan, Borah & Rao, 1999),

- Diameter of the fireball
- Duration
- Thermal radiation at a given distance from the fireball

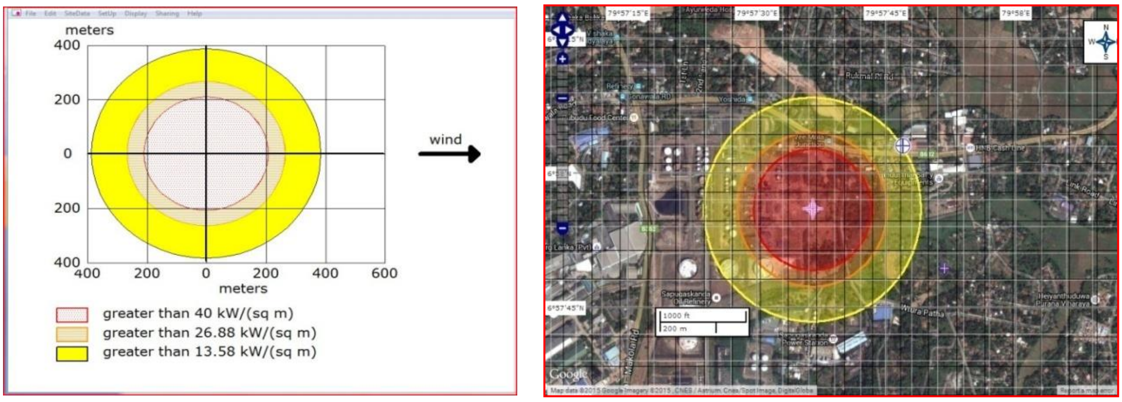


Fig E.1 : BLEVE – Threat Zones for BLEVE

The threat zones have been estimated using ALOHA and are shown in figure F.1. The threat zones were superimposed on the location using MARPLOT and Google Earth. MARPLOT is mapping software developed by the US EPA to be used in Emergency Response.

The threat parameters obtained from calculation are as follows,

Diameter of Fireball (D_{FB}) = 207m

Duration of fireball (t) = 13 seconds

The threat zones (vulnerability distance) correspond to the Human Vulnerability (Fatality) distances calculated using the selected probit (table 3.11) given below,

$Y = -36.38 + 2.56 \ln (I^{4/3}t)$ -----------------> (Based on Tsao& Perry)

Where,

Y – Probit

I – Thermal Radiation Intensity (W/m^2)

t – Exposure time (s)

The Thermal Radiation Intensity corresponding to 1%, 50% and 100% Fatality was estimated using the aforementioned probit. The corresponding intensities (I) and distances are as follows in Table E.1,

Table E.1 – Impact Distances for Thermal Radiation from fireball

% Fatality	Thermal Radiation Intensity (kW/m2)	Maximum Distance (m)
100	40	209
50	26.88	266
1	13.58	386

1.1.3 ESTIMATION OF OVERPRESSURE EFFECTS

The mechanical energy released in a BLEVE explosion is generally distributed as follows,

- Energy of the pressure waves
- Kinetic Energy of the Projectiles
- The potential energy of the fragments (Deformation plastic energy absorbed by the fragments)
- Heating of the environment

Accurate estimation of the amount of mechanical energy contributing to the pressure wave is difficult. The type of failure (fragile or ductile) has a significant bearing on the mechanical energy contribution. Approximately 80% of the mechanical energy released will contribute towards the creation of the pressure wave, whereas the contribution from a ductile fracture is only 40%.

The Blast Overpressure from the BLEVE is estimated using the TNT Equivalency Method. This method considers that the flammable material will behave like exploding TNT on an equivalent energy basis.

The equivalent mass of TNT, W_{TNT} (in kg) is estimated as follows,

$W_{TNT} = ((0.021P_oV^*)/(\gamma-1))(1-(P_a/P_o)^{((\gamma-1)/\gamma)})$

Where,

P_o – Pressure in the vessel just before the explosion (bar)

P_a – Atmospheric Pressure (bar)

V^* – Initial Volume of the Vapor (m^3)

γ – Ratio of Specific Heats

Since, the vessel contains liquefied Propane which has a Normal Boiling Point of -42.25 ^oC, the liquid is in a superheated state. As a result part of the liquid mass will vaporize suddenly when reaching the atmospheric pressure. Hence, the volume of this vapour at the pressure in the vessel just before the explosion must be calculated resulting in the following expression for V*,

$V^* = V + V_lf(\rho_l/\rho_v)$

Where,

V – Volume of vapor inside the vessel before the explosion (m^3)
V_l – Volume of liquid in the vessel before the explosion (m^3)
f – The fraction of liquid which vaporizes during the depressurization (i.e. flash fraction)

f is expressed as follows,

$$f = 1 – \exp(-2.63(C_p/H_v)(T_c – T_b)(1-((T_c-T_o)/(T_c-T_b))^{0.38}))$$

Where,
T_c – Critical Temperature of Propane (K)
T_b – Normal Boiling Point of Propane (K)

T_o – Temperature of Propane at the time of the Explosion (K)
H_v – Enthalpy of Vaporization of Propane (kJ/kg)
C_p – Specific Heat Capacity of Propane (kJ/kgK)

$T_c = 369.7$ K
$T_b = 230.9$ K
$T_o = 323$ K ($1.25 \times T_D$)
$H_v = 348$ kJ/kg
$C_p = 2.37$ kJ/kgK

By substituting these values in equation14, fraction of liquid which vaporizes during the depressurization can be estimated as,

$f = 0.569$

From equation 13 the volume of vapour can be calculated, is

$V^* = \quad = 657\ m^3$

Then the equivalent mass of TNT can be calculated using the equation given below,
$W_{TNT} = ((0.021 x 9.5\ x 657)/(1.14-1))(1-(1.01/9.5)^{((1.14-1)/1.14)})$
$= 307$ kg

Calculation of Peak Side on Pressure p_o (bar):

The relationship for TNT detonation and Overpressures is well defined and expressed in terms of scaled peak side – on overpressure and scaled impulse correlated as a function of the scaled distance Z, defined as,

$$Z = R/(W_{TNT})^{1/3}$$

Where R – Distance from the centre of Explosion

The relationship between the parameters is given in Figure E.2 – Scaled Overpressure and Impulse Curves for a TNT Explosion on a surface (Crowl, 2003).

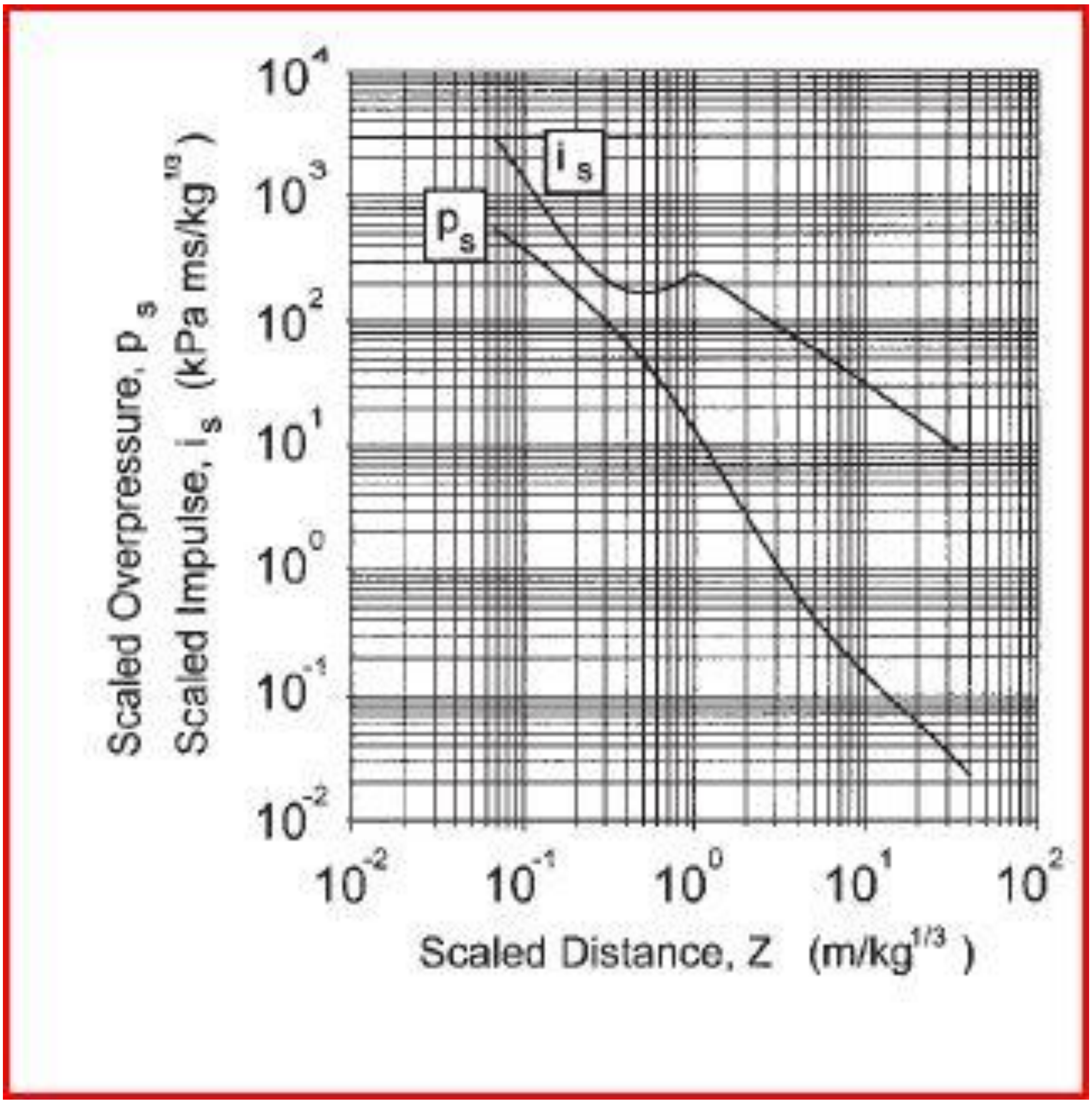


Figure E.2 – Scaled Overpressure and Impulse Curves for a TNT Explosion on a Surface, Source: (Crowl, 2003)

The Peak Side on Pressures are then estimated and are shown in table E.2.

Table E.2 – Overpressure Effects due to BLEVE

Distance from the Explosion Center, R (m)	50	100	150	200	250
Scaled Distance, Z (m/kg$^{1/3}$)	7.4	14.8	22.2	29.7	37.1
Scaled Overpressure, p_s	0.10	0.09	0.05	0.04	0.04
Peak Side - On Pressure, p_O (bar)	0.10	0.09	0.05	0.04	0.04

1.2 ACCIDENT SCENARIO 2: RUPTURE OF SHELL OF PRESSURE VESSEL WITH IMMEDIATE IGNITION RESULTING IN VAPOUR CLOUD EXPLOSION (VCE)

The maximum nominal diameter of the rupture is assumed or considered to be 100 mm (OGP, 2010).

A vapour cloud explosion (VCE) occurs when a large quantity of flammable vapour/ gas is released, mixes with air and is then ignited. The subsequent explosion can produce the following consequences,

a. Overpressure propagating outwards from the explosion site as a blast wave
b. Thermal Radiation due to the resulting Fireball

However, the following conditions are required to be fulfilled for a VCE to result in damaging overpressure (Crowl, 2003),

1) The released material must be flammable
2) A cloud of sufficient size must form prior to ignition
3) The vapour cloud must mix with air to produce a sufficient mass in the flammable range of the material released
4) The speed of the flame propagation must accelerate as the vapour cloud undergoes combustion

The major concern for a VCE is the overpressure/ and or impulse as a function of distance from the explosion. Furthermore, most VCE's are deflagrations and detonations are unlikely, especially in open spaces. However, it must be emphasized that out of the 10 largest property losses in the Process Industry seven were due to VCEs.

1.2.1 OVERVIEW OF EXISTING VAPOUR CLOUD EXPLOSION MODELS

The "Yellow Book" published by TNO (TNO, 2005) provides two groups of models as follows,

1. Methods based on TNT charge blast (TNT Equivalency Models)
2. Methods based on Fuel – Air Charge Blast

The first group of models (i.e. TNT Equivalency Models) does not correspond well with VCE blast characteristics as VCE blast strength varies. TNT blasts are essentially detonations whereas VCE blasts are mostly deflagrations. The "Yellow Book" identifies the TNT model as a poor model for VCEs due to the following reasons,

a. A TNT blast produces a shock – wave of a very high amplitude and short duration
b. A VCE produces a blast wave of lower amplitude and longer duration
c. TNT blast models do not take into account the variability of explosion strengths
d. TNT blast models over predict nearby pressure effects

The "Yellow Book" recommends the use of "Fuel Air Charge Blast Models" for VCEs. The most widely used models belonging to this group are as follows,

- The Multi – Energy Method
- The Baker – Strehlow – Tang (BST) Method

The basis of the so called "TNO Multi Energy Method" is that the energy of explosion is highly dependent on the level of confinement and congestion but less dependent on the flammable material in the cloud. The "Multi Energy Method" requires the location and volume of the flammable vapour cloud to be known or assumed. The TNO model considers multiple blast sources emanating from a single release.The Baker – Strehlow – Tang (BST) method is based on flame speed and its selection is based on three factors. Namely,

1) The reactivity of the released material
2) The flame expansion characteristics of the process unit under consideration (degree of confinement and spatial configuration)
3) Obstacle density within the process unit

A set of semi – empirical curves derived to represent the aforementioned factors are used to predict the overpressure for a particular scenario. The BST method also incorporates elements from the TNO method, such as multiple blast sources from a single release. Furthermore, the energy term is determined using the TNO method. The semi – empirical curves correlate the combined effects of flammable material reactivity, obstacle density and confinement. 27 possible combinations of the aforementioned factors are presented based on 1D, 2D, 2.5D and 3D flame expansions[46]. The flame expansion scenarios are as follows,

- 3D Flame Expansion – Under 3D symmetry the flame is free to expand spherically from a point ignition source. Flow velocities are considered to be low and flow field disturbances by obstacles are small
- 2.5 D Flame Expansion – Has more restrictive confinement than 3D but does not merit a 2D rating. A typical condition is a light weight roof which blows off during an explosion creating a vent in its place.
- 2D Flame Expansion – Under 2D symmetry, a cylindrical flame restricted between two plates is considered. Deformation of the flame surface due to the restriction is considered to have a stronger effect than the point ignition case in 3D Flame Expansion
- 1D Flame Expansion – Under 1D symmetry a planar flame in a tube is considered. However, it is rarely encountered in actual plants

ALOHA is used to model the overpressure effects. ALOHA uses Baker – Strehlow – Tang (BST) model as the basis for its overpressure calculations (Jones et al., 2013).

1.2.1.1 ESTIMATION OF BLAST OVERPRESSURE FROM THE VCE

It is assumed that the pressure vessels are located in an open space with a low to medium degree of confinement.

Hence,

- 3D Symmetry for flame expansion can be considered.
- Medium obstacle density is considered due to the location of LPG Tanks and greenery; hence the congestion is considered to be of a medium degree

Reactivity of the Flammable Materials are categorized as low, medium and high according to the following rules,

1. Hydrogen, acetylene, ethylene, ethylene oxide and propylene oxide are considered to be highly reactive
2. Methane and Carbon Monoxide are the only material considered to be low reactivity
3. All flammable materials not mentioned under 1 or 2 above are considered to have medium reactivity

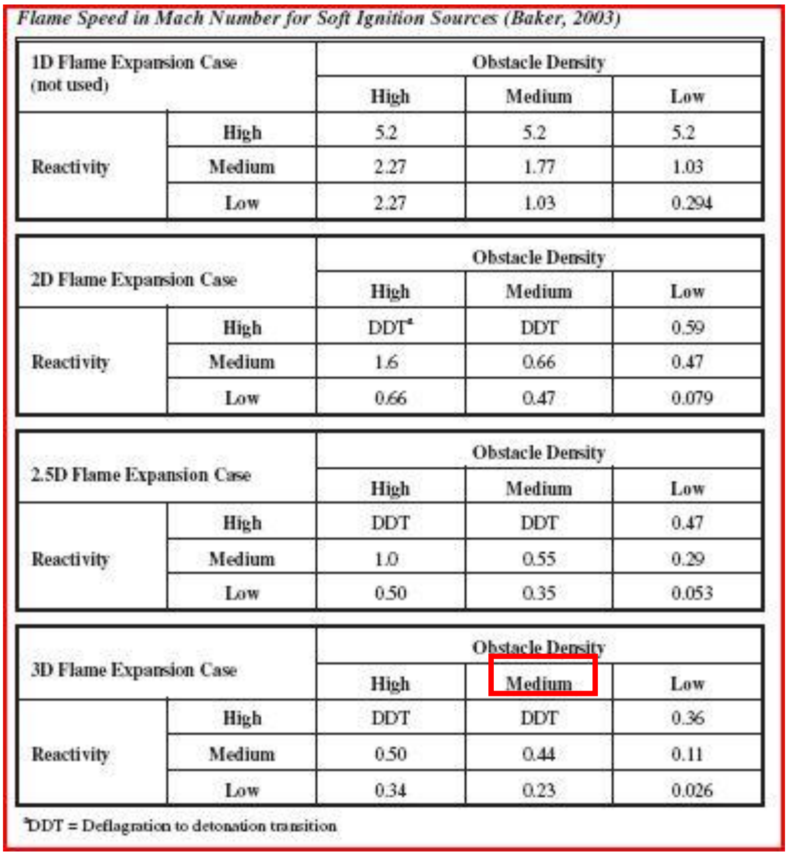
Hence, Propane is classified as a medium reactive material. Therefore, the VCE scenario under consideration can be defined as given in table E.3.

Table E.3 – Parameters for the VCE

PARAMETER		**STATUS**
1	Geometric Consideration	3D Flame Expansion
2	Confinement Considerations	Obstacle density is
3	Reactivity of Propane	Medium
4	Flame Speed (in Mach Number)	0.44

Note: The Flame Speed is determined from table E.4

Table E.4 – Flame Speed in Mach Numbers for Soft Ignition Sources



Flame Speed in Mach Number for Soft Ignition Sources (Baker, 2003)

1D Flame Expansion Case (not used)		Obstacle Density		
		High	Medium	Low
Reactivity	High	5.2	5.2	5.2
	Medium	2.27	1.77	1.03
	Low	2.27	1.03	0.294

2D Flame Expansion Case		Obstacle Density		
		High	Medium	Low
Reactivity	High	DDT[a]	DDT	0.59
	Medium	1.6	0.66	0.47
	Low	0.66	0.47	0.079

2.5D Flame Expansion Case		Obstacle Density		
		High	Medium	Low
Reactivity	High	DDT	DDT	0.47
	Medium	1.0	0.55	0.29
	Low	0.50	0.35	0.053

3D Flame Expansion Case		Obstacle Density		
		High	Medium	Low
Reactivity	High	DDT	DDT	0.36
	Medium	0.50	0.44	0.11
	Low	0.34	0.23	0.026

[a] DDT = Deflagration to detonation transition

Source: (Crowl, 2003)

Two cases are considered based on the release location as follows,

a. The release occurs at the bottom of the tank
b. The release occurs at the top liquid level or at the liquid – vapour interface

1.2.1.1.1 Case a: Propane is released at the bottom of the tank (0m)

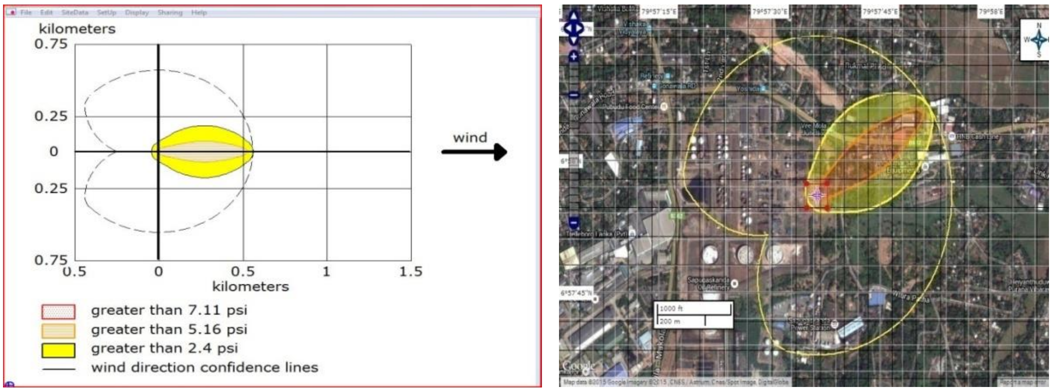


Fig E.3: Threat Zones for a Vapor Cloud Explosion (VCE) for Case a

The threat zones are determined based on the endpoints for blast overpressures derived from the selected probit given below,

$Y = 1.47 + 1.371\ln(P_s)$ --------------------------> (UK HSE)

The effects and maximum distance of the threat zones are as follows in Table E.5,

Table E.5 – Impact Distances for Case a

% Fatality	Blast Overpressure (P_s) (psig)	Maximum distance (m)
20	7.11	Not Applicable
10	5.10	528
1	2.4	560

The result in table E.5 show that 20% Fatality is never exceeded.

1.2.1.1.2 Case b: Propane is released at the Liquid – Vapour Interface (3m)

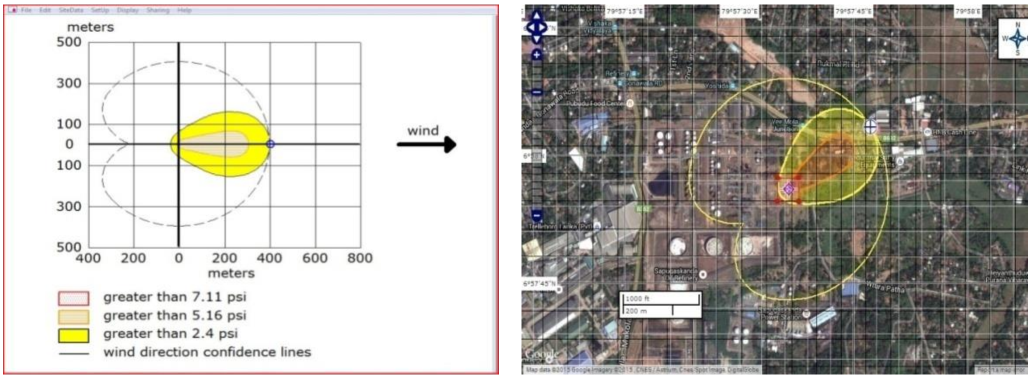


Fig E.4: Threat Zones for a Vapor Cloud Explosion (VCE) for Case b

The threat zones were calculated similarly to Case a and is as follows in Table E.6,

Table E.6 – Impact Distances for Case b

% Fatality	Blast Overpressure (P_s) (psig)	Maximum distance (m)
20	7.11	Not Applicable
10	5.10	309
1	2.4	402

The result in table F.6 show that 20% Fatality is never exceeded.

The maximum distance for 1% fatality for Case a is 560m whereas it is 402m for Case b. Hence, the maximum distance for 1% fatality occurs for Case a.

1.3 Accident Scenario 3: Rupture of Shell of Pressure Vessel with delayed ignition resulting in a Flash Fire

In this accident scenario the dispersion of the vapour cloud and the consequences of delayed ignition are considered. Dispersion of a flammable vapour cloud following a LOC incident is likely. The degree of dispersion and the delay in ignition (if at all) will determine the consequences and effected area. The dispersion calculation provides an estimate of the affected area and the average vapour concentrations expected (Crowl, 2003). The calculations require the following as a minimum,

- Release rate of the vapour/gas (also known as Source Terms)
- The atmospheric conditions (i.e. Wind Speed, Time of Day, Cloud Cover)
- Surface roughness
- Temperature
- Pressure
- Release diameter

Three types of Vapour Cloud Behaviour and three release time – modes are defined (Crowl, 2003),

1. Neutrally buoyant gas
2. Positively buoyant gas
3. Dense (or negatively) buoyant gas

Nature of Release,

1. Instantaneous (Puff)
2. Continuous release (Plume)
3. Time varying continuous

The most widely used models for studying gas/ vapour dispersion are the Gaussian Models. The Gaussian Models describe the behaviour of neutrally buoyant gases and positively buoyant gases. They are usually modelled as Puffs or Plumes. However, dense gases cannot be modelled accurately using Gaussian Models when modelling near field effects. It must be emphasized that dense gas releases will mix and be diluted with fresh air as the gas travels downwind leading to its behaviour approximating neutrally buoyant gas characteristics. The application of Gaussian Models to a dense gas release will provide conservative results, over predicting the affected area. According to the publication "Guidelines for Chemical Process Quantitative Risk Analysis", (2nd Edition) by CCPS, the result yielded through a Gaussian approach may be orders of magnitude larger.

Furthermore, field experiments (Crowl, 2003) have confirmed that the mechanism of dense gas dispersion differs significantly from neutrally buoyant clouds. Dense gases tend to slump towards the ground after initial release. Neutrally buoyant gases tend to move downwind whereas dense gases move both downwind and upwind.

Hence, clearly a Gaussian Model cannot be applied to a dense gas release with sufficient accuracy, especially where land use planning is concerned due to its uncertainty. Propane (i.e. the flammable material under consideration) has a density higher than ambient air requiring it to be classified as a dense gas. Hence, any modeling of a propane release has to be modeled as a dense gas.

Dense gas modeling approaches can be classified into 3 distinct groups as follows,

- Mathematical
- Dimensional
- Physical

Out of these models the dimensional analysis method proposed by Britter & McQuaid (1988) provides a simple but effective correlation for modelling dense gas releases (CCPS, 1999). This approach reduces the analysis to the examination of a set of dimensionless groups which have been correlated with data derived from actual field tests of dense gas releases. The relationship is presented as a nomograph. It must be emphasized that atmospheric stability has a significant effect on Gaussian Models whereas dense gas release are not significantly affected. The Britter & McQuaid method does not include the effects of atmospheric stability.

The Britter & McQuaid method essentially estimates the following,

a) Average concentration levels along the plume axis for continuous releases
b) Maximum concentration levels along the downwind cloud path for instantaneous releases
c) Iso – continuous contours

The Britter & McQuaid method is desirable where the estimation has to be done manually. The dispersion of the vapor cloud and flash fire upon iginition is modelled in this study using ALOHA. ALOHAestimates the threat zone as the extent within the lower flammability limit or lower explosive limit of the vapor or gas cloud. However, ALOHA does not directly model the thermal radiation associated with a flash fire. Thermal radiation from Flash fires of premixed clouds are highly transient unlike that of a fire ball. Furthermore, using the surface temperature of the flash fire or adiabatic temperature to estimate the thermal radiation at a distance would greatly exagerate the effects and lead to overly conservative threat zones and distances.

ALOHA models Heavy or Dense gas dispersion using the DEGADIS (Dense Gas Dispersion) Model of the US EPA which is also an adaptation of the Shell HEGADAS (Heavy Gas Dispersion from Area Sources) model (Jones et al., 2013) and does not use the Britter Mcquaid model. ALOHA models bouyant gases using Gausian Dispersion.

Two cases are considered based on the release location as follows,

a. The release occurs at the bottom of the tank
b. The release occurs at the top liquid level or at the liquid – vapour interface

1.3.1 Case a: Propane is released at the bottom of the tank (0m)

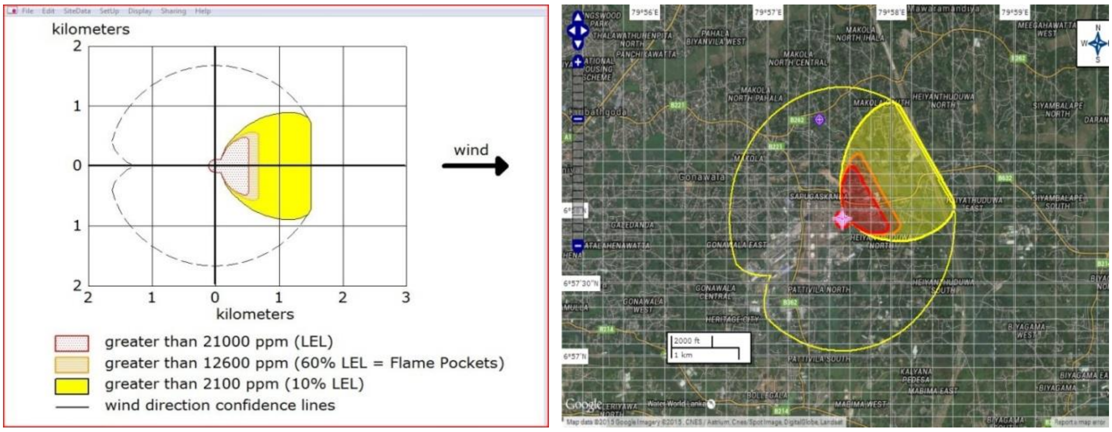


Fig E.5: Threat Zone for Flash Fire Case (a) in Accident Scenario 3

The threat of a flash fire arises due to delayed ignition after the dispersion of the gas cloud. A flash fire is highly transient and the duration would be much lower than that of a fire ball resulting in considerably lower exposure. However, it may be assumed that any person within the Vapor/ Gas Cloud would be enveloped by the flame and suffer fatality. Hence, it is assumed that anyone within the LEL of the Vapor Cloud has a 100% probability of fatality if a flash fire occurs. Anyone outside the LEL envelope of the Vapor Cloud will not suffer any fatality (Fatality – 0%). The threat zones obtained for flash fire are as follows in Table E.7,

Table E.7 – Impact Distances for Case a in Accident Scenario 3

EFFECT	CONCENTRATION	Maximum
LEL	21000	525
60% LEL	12600	685
10% LEL	2100	1500

1.3.2 Case b: Propane is released at the Vapor – Liquid Interface (3m)

The threat zone of a flash fire due to delayed ignition of the vapour cloud due to the release of propane at the vapour – liquid interface of the pressure vessel is given in figure E.6. The impact distances resulting from the flash fire are given in Table E.8.

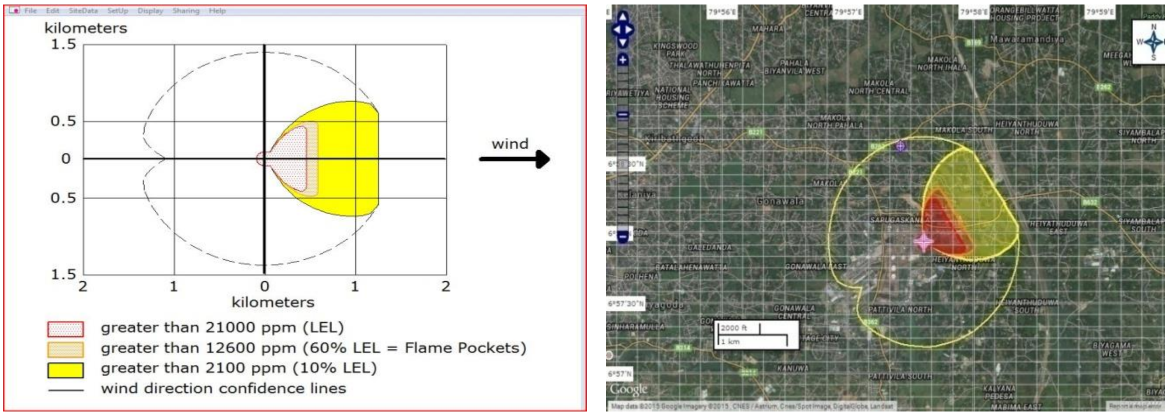


Fig E.6 - Threat Zone for a Flash Fire (Case b) in Accident Scenario 3

Table E.8 – Impact Distances for Case b in Accident Scenario 3

EFFECT	CONCENTRATION (ppm)	Maximum Distance (m)
LEL	21000	456
60% LEL	12600	587
10% LEL	2100	1300

1.4 Accident Scenario 4: Rupture of Shell of Pressure Vessel with continuous release and delayed ignition

The analysis is similar to Accident Scenario 3, except that the release occurs continuously through a rupture of the shell of the pressure vessel equivalent to a 10mm diameter hole.

Here too, two cases are considered where the rupture occurs at the bottom of the vessel and at the liquid – vapour interface respectively.

1.4.1 Case a: Propane is released at the bottom of the tank (0m)

The threat zone of a flash fire due to delayed ignition of the vapour cloud in accident scenario 4 is given in figure F.7. The impact distances resulting from the flash fire are given in Table E.9.

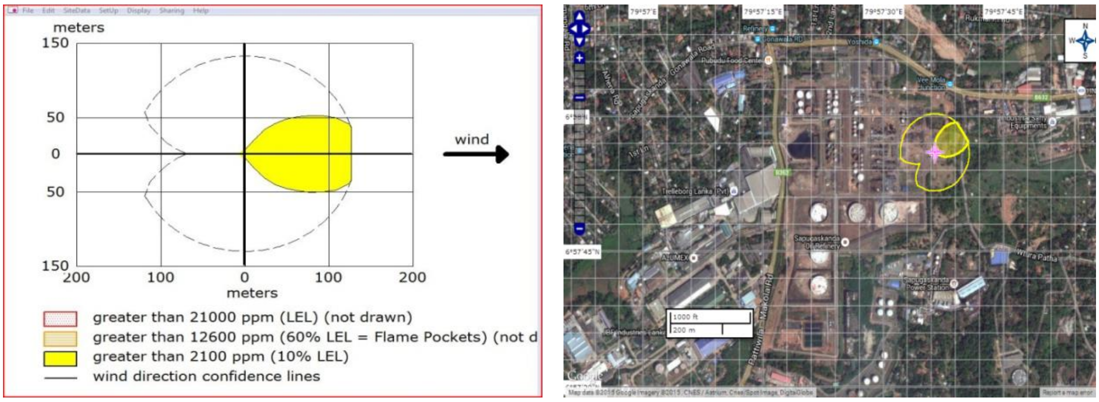


Fig E.7 – Area within the LEL for continuous Release of Propane (Hole Size - 10 mm) (Case a)

Table E.9 – Impact Distances for Case a in accident scenario 3

EFFECT	CONCENTRATION (ppm)	Maximum Distance (m)
LEL	21000	0
60% LEL	12600	0
10% LEL	2100	127

The envelope of the Vapor Cloud will not attain concentrations within the LEL or 60%LEL. However, the envelope upto a distance of 127m in the direction of the wind will have a maximum concentration of 10% LEL.

As the Vapor Cloud does not attain concentrations corresponding to the LEL, a flash fire is unlikely and the secnario will not cause any fatalities.

Appendix – F: Estimation of Consequence Impacts for the Probabilistic Risk Assessment Approach

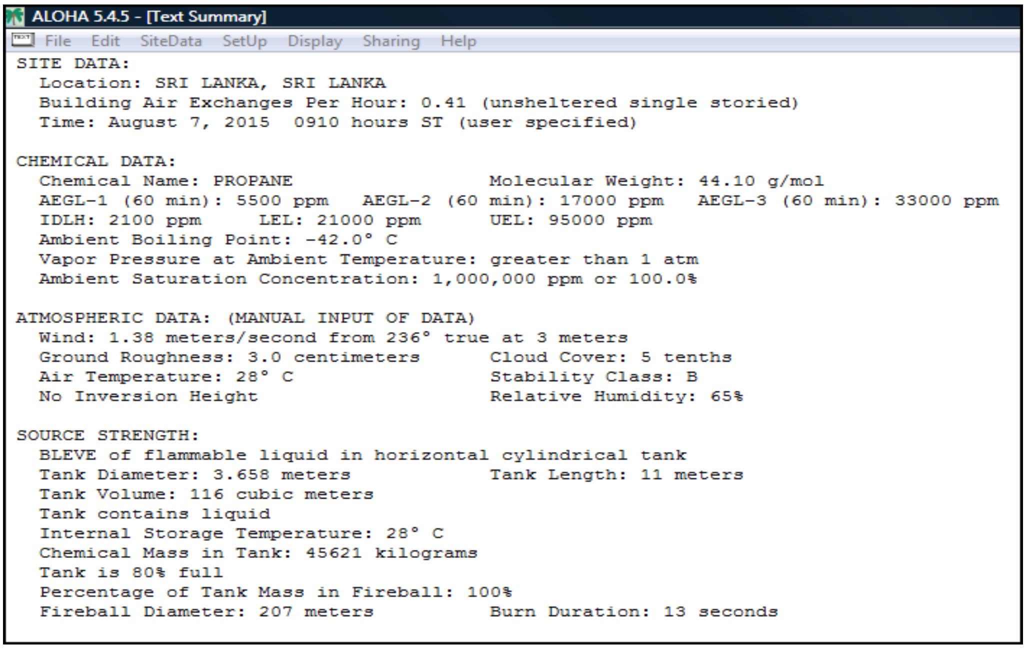
1.2 INTRODUCTION

The extents of the impacts of consequences for the scenarios listed in Chapter 4, section 4.2 (Table 4.5) are evaluated in detail. The impacts are quantified in terms of fatalities.

1.1 Consequence Assessment of Event 1 – Instantaneous release of entire inventory and immediate ignition due to hot catastrophic rupture resulting in BLEVE

Cold catastrophic failure is not considered here. Hot catastrophic failure due to flame impingement on the tank or exposure to a pool fire is considered here; hence the event expected is a hot catastrophic failure with immediate ignition resulting in a BLEVE. For the given event ALOHA shows that the BLEVE will result in a fireball having the following properties,

Diameter of Fireball = 207m
Duration = 13 s
The result is as follows,



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: August 7, 2015  0910 hours ST (user specified)

CHEMICAL DATA:
  Chemical Name: PROPANE                 Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.38 meters/second from 236° true at 3 meters
  Ground Roughness: 3.0 centimeters      Cloud Cover: 5 tenths
  Air Temperature: 28° C                 Stability Class: B
  No Inversion Height                    Relative Humidity: 65%

SOURCE STRENGTH:
  BLEVE of flammable liquid in horizontal cylindrical tank
  Tank Diameter: 3.658 meters            Tank Length: 11 meters
  Tank Volume: 116 cubic meters
  Tank contains liquid
  Internal Storage Temperature: 28° C
  Chemical Mass in Tank: 45621 kilograms
  Tank is 80% full
  Percentage of Tank Mass in Fireball: 100%
  Fireball Diameter: 207 meters          Burn Duration: 13 seconds
```

Fig F.1 – Summary of the BLEVE Event

The threat zone is then generated by ALOHA and superimposed on the geographic location using MARPLOT as shown in Figure F.2. The threat zone is broken into 30m x 30m grid and the thermal radiation intensity of each grid is estimated using MARPLOT's "Threat at a point" function. The probability of fatality for each grid is then determined using the Tsao & Perry probit relationship.

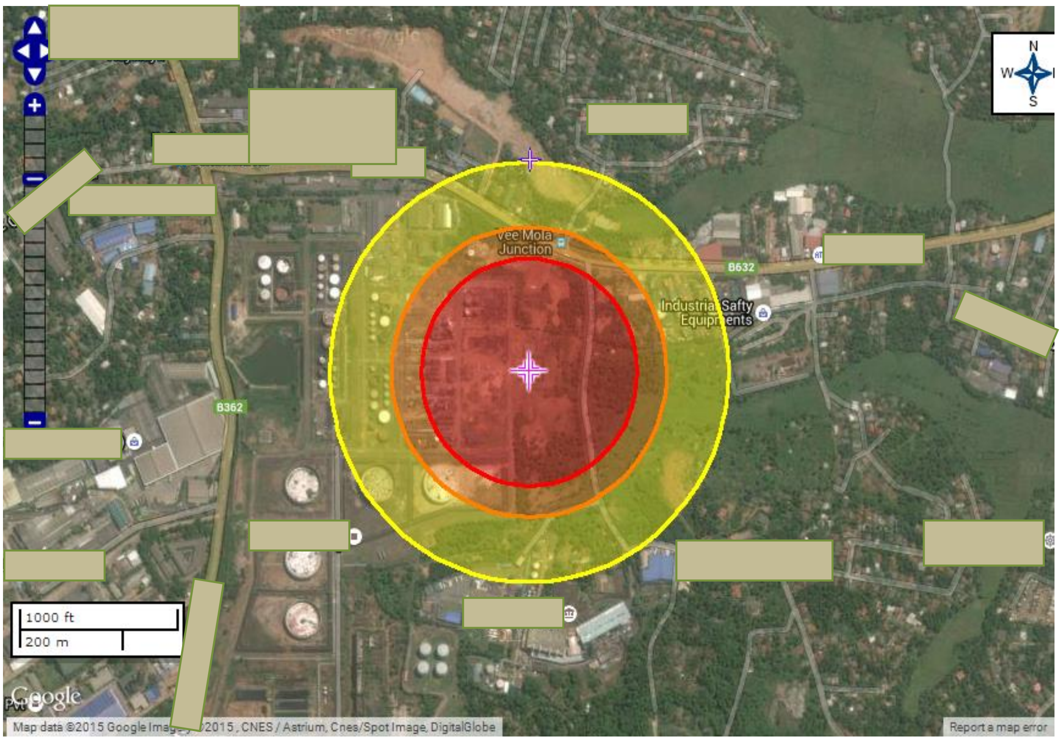


Fig F.2 – Threat Zone for the BLEVE Event

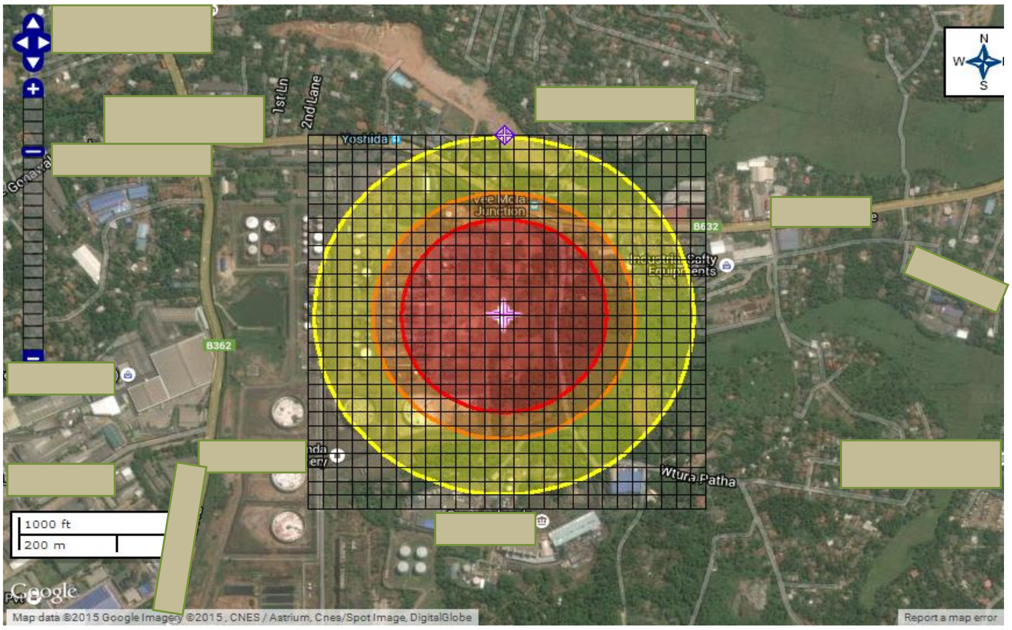


Fig F.3 – 30m x 30m Grid for the BLEVE Threat Zone

The probit is as follows,

$Y = -36.38 + 2.56 \ln (I^{4/3}t)$ -----------------> (Based on Tsao & Perry)

This is the most conservative probit selected earlier during the endpoint selection stage in Chapter 3, section 3.1 (Table 3.16).

However, all grids within the radius of the fireball (207m) are considered as having a probability of fatality of 1. The probits are converted to probability values. The site specific fatalities for the BLEVE are then estimated using population density data. The population density data used here is that of Biyagama in the western province of Sri Lanka as per the national census of 2012. It is assumed that the bullet tank is hypothetically located in the western province.

Number of inhabitants = 186585
Area of Biyagama = 59 km^2
Population Density = 3162.5 inhabitants per sq.km

It is assumed that the population is uniformly distributed. The fatalities are only estimated at locations showing human habitation and probable activity on the map (Houses, Warehouses, Factories, Roads etc.) (Refer Table F.5, grids highlighted in yellow). The total fatalities are then estimated by summing the fatalities in each grid of Table G.5. The total number of fatalities expected from the BLEVE event is 112.8 fatalities.

	CONSEQUENCE EFFECT (kW/m^2)																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1										13.6	13.6	14	14.2	14.4	14.3	14.2	13.8	13.6									
2								13.8	14.6	15.1	15.9	16.4	16.7	16.7	16.6	16.4	15.8	14.6	13.7	13.4							
3						13.5	14	15.4	16.7	17.3	18.7	19.4	19.6	19.6	19.9	19.1	18	17.3	16.1	14.6	13.5						
4					13.7	15.2	16.3	18.1	19.8	20.8	22	22.6	23.5	23.6	22.6	22.5	21.5	20.5	18.5	17.3	15.6	13.6	13.4				
5				13.7	15.3	17	18.5	21	23.1	24.5	27	27.6	28.6	28.8	28.7	27.1	25.6	23.8	22.2	19.2	17.1	15.6	14	13.1			
6			13.9	15	16.7	18.7	20.7	23.8	26.4	29.1	31.4	33.4	34.8	34.9	34.1	31.5	30.3	27.5	24.6	22.2	19.6	17.3	15.4	14			
7			13.9	16.5	18.7	20.9	25.1	28.4	31	35.2	40	40	40	40	40	40	36.7	33.6	29.6	26.4	22.5	19.8	17	15	13.3		
8		13.6	15.5	17.8	20.8	24.1	27.8	32	37.5	40	40	40	40	40	40	40	40	40	35.1	30.1	25.7	22.2	19.2	16.8	14.2		
9		14.2	16.3	19.1	22.4	26.7	31.3	37.4	40	40	40	40	40	40	40	40	40	40	40	34.4	28.1	23.4	20.4	17.2	15	13.4	
10		14.7	17.4	20.5	24.3	28.9	34.7	40	40	40	40	40	40	40	40	40	40	40	40	40	32.9	27.1	21.9	18.5	16.3	14	
11	13.7	15.6	18	21.2	26.2	32.1	38	40	40	40	40	40	40	40	40	40	40	40	40	40	35	28.7	23.5	19.3	17	14.2	
12	13.7	16	18.6	22.3	27.5	33.2	40	40	40	40	40	40	40	40	40	40	40	40	40	40	36.5	30	24.3	20.6	16.8	14.9	12.3
13	13.8	16.4	19	23.1	27.6	34.7	40	40	40	40	40	40	40	40	40	40	40	40	40	40	37.7	30.4	24.8	21.2	17.8	14.9	13.2
14	14.4	15.8	19	23.8	28.1	33.6	40	40	40	40	40	40	40	40	40	40	40	40	40	40	37.7	30.5	24.5	20.7	17.8	14.9	13.1
15	13.5	15.7	18.7	22.1	27.5	33.4	40	40	40	40	40	40	40	40	40	40	40	40	40	40	37	30.8	25.6	20.2	16.9	14.7	12.6
16	13.5	15.4	18.4	21.9	25.9	31.8	38.3	40	40	40	40	40	40	40	40	40	40	40	40	40	34.1	28.1	24	19.9	16.6	14.8	
17		14.7	17.6	20.5	24.7	29.2	35.6	40	40	40	40	40	40	40	40	40	40	40	40	40	32.1	26.1	22.3	19.1	16.1	13.7	
18		14.5	16.3	19.3	22.9	26.8	32.5	38	40	40	40	40	40	40	40	40	40	40	40	34.7	29.3	24.6	21.3	17.9	15.2	13.6	
19		13.8	15.7	18	21.3	24.7	27.8	32.9	34.3	40	40	40	40	40	40	40	40	40	34.5	30.2	26.7	22.1	19	16.6	14.6		
20			13.9	16.6	18.7	21.1	24.9	28	32.2	36.8	40	40	40	40	40	40	38.1	34.3	30.5	26.6	23.1	20.1	17.4	15.8	13.2		
21			13.6	14.9	17.3	19.5	21.5	24.1	27.4	29.8	32.7	34.3	37.5	36.4	35.6	33.6	31.7	29.1	26	23.5	20.3	17.7	15.9	14.2			
22				13.9	15.2	17.1	18.9	21.3	24.4	26.2	26.9	28	30.7	29.4	29.2	27.6	26.3	24.5	22.3	20	17.7	16.1	14.2				
23					13.8	15	16.8	17.8	20	21.5	23.1	23.7	24.7	24.1	24.1	23	21.9	20.4	18.4	17.2	15.8	14.4					
24						13.6	14.9	15.6	17.3	18.4	19.2	19.8	20.5	20.6	20.9	19.7	19.1	17.8	16	15.2	13.8						
25							14	14.6	15.5	16	16.5	16.8	17.3	17.1	16.2	16	15.7	15.5	14.5	13.8							
26									13.3	13.9	14.2	14.5	14.7	14.4	14.5	13.5	13.3										

Table F.1 – Consequence Effects of the BLEVE Event

	DOSE																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	0	0	0	0	0	0	0	0	0	4220157	4220157	4386459	4470209	4554353	4512232	4470209	4303107	4220157	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	4303107	4638887	4851909	5197640	5416705	5549220	5549220	5504960	5416705	5154100	4638887	4261581	4137612	0	0	0	0	0	0	0
3	0	0	0	0	0	4178833	4386459	4980860	5549220	5816631	6452562	6776607	6869916	6869916	7010475	6637245	6132535	5816631	5284994	4638887	4178833	0	0	0	0	0	0
4	0	0	0	0	4261581	4894798	5372711	6178003	6963543	7436372	8013832	8306561	8750519	8800203	8306561	8257591	7771914	7293710	6360711	5816631	5067295	4220157	4137612	0	0	0	0
5	0	0	0	4261581	4937782	5682532	6360711	7531863	8552492	9250491	10530000	10843150	11370112	11476250	11423150	10582032	9808365	8899780	8111117	6683619	5727145	5067295	4386459	4014564	0	0	0
6	0	0	4344733	4809114	5549220	6452562	7388742	8899780	10219161	11635919	12878033	13983159	14770063	14826680	14375265	12932746	12280052	10790799	9300868	8111117	6869916	5816631	4980860	4386459	0	0	0
7	0	0	4344733	5460788	6452562	7484080	9553774	11264220	12659764	14996857	17783750	17783750	17783750	17783750	17783750	17783750	15854946	14094913	11903252	10219161	8257591	6963543	5682532	4809114	4096493	0	0
8	0	4220157	5024031	6041851	7436372	9049670	10948041	13207177	16317428	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	14940077	12172095	9859484	8111117	6683619	5593570	4470209	0	0
9	0	4470209	5372711	6637245	8208694	10374290	12823379	16259436	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	14544137	11105849	8700906	7246310	5771844	4809114	4137612	0
10	0	4681300	5861503	7293710	9149943	11529412	14713500	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	13704753	10582032	7965301	6360711	5372711	4386459	0
11	4261581	5067295	6132535	7627657	10116068	13262235	16608159	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	14883352	11423150	8750519	6730073	5682532	4470209	0
12	4261581	5241272	6406595	8159869	10790799	13871629	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	15739847	12118207	9149943	7341187	5593570	4766413	3691052
13	4303107	5416705	6590952	8552492	10843150	14713500	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	16433566	12334119	9401827	7627657	6041851	4766413	4055477
14	4554353	5154100	6590952	8899780	11105849	14094913	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	16433566	12388246	9250491	7388742	6041851	4766413	4014564
15	4178833	5110651	6452562	8062438	10790799	13983159	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	16027987	12550980	9808365	7151742	5638007	4681300	3811572
16	4178833	4980860	6314909	7965301	9961920	13097232	16783211	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	14375265	11105849	8999637	7010475	5504960	4723809	0
17	0	4681300	5951506	7293710	9351314	11689264	15224511	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	13262235	10064620	8159869	6637245	5284994	4261581	0
18	0	4596572	5372711	6730073	8453904	10426129	13483040	16608159	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	14713500	11742670	9300868	7675668	6087151	4894798	4220157	0
19	0	4303107	5110651	6132535	7675668	9351314	10948041	13704753	14487791	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	17783750	14600536	12226044	10374290	8062438	6590952	5504960	4638887	0	0
20	0	0	4344733	5504960	6452562	7579722	9452408	11053184	13317351	15912574	17783750	17783750	17783750	17783750	17783750	17783750	16666458	14487791	12388246	10322515	8552492	7104575	5861503	5154100	4055477	0	0
21	0	0	4220157	4766413	5816631	6823222	7771914	9049670	10738512	12010609	13593784	14487791	16317428	15682376	15224511	14094913	13042346	11635919	10013237	8750519	7198987	5996636	5197640	4470209	0	0	0
22	0	0	0	4344733	4894798	5727145	6544740	7675668	9200183	10116068	10478032	11053184	12496676	11796137	11689264	10843150	10167582	9250491	8159869	7057486	5996636	5284994	4470209	0	0	0	0
23	0	0	0	0	4303107	4809114	5593570	6041851	7057486	7771914	8552492	8849957	9351314	9049670	9049670	8503162	7965301	7246310	6314909	5771844	5154100	4554353	0	0	0	0	0
24	0	0	0	0	0	4220157	4766413	5067295	5816631	6314909	6683619	6963543	7293710	7341187	7484080	6916690	6637245	6041851	5241272	4894798	4303107	0	0	0	0	0	0
25	0	0	0	0	0	0	4386459	4638887	5024031	5241272	5460788	5593570	5816631	5727145	5328808	5241272	5110651	5024031	4596572	4303107	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	4096493	4344733	4470209	4596572	4681300	4554353	4596572	4178833	4096493	0	0	0	0	0	0	0	0	0	0

Table F.2 – Exposure Levels (DOSE) for the BLEVE Event

	PROBIT																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1										2.67	2.67	2.77	2.82	2.87	2.85	2.82	2.72	2.67									
2								2.72	2.92	3.03	3.21	3.31	3.37	3.37	3.35	3.31	3.19	2.92	2.70	2.62							
3						2.65	2.77	3.10	3.37	3.50	3.76	3.89	3.92	3.92	3.97	3.83	3.63	3.50	3.25	2.92	2.65						
4					2.70	3.05	3.29	3.65	3.96	4.12	4.32	4.41	4.54	4.56	4.41	4.39	4.24	4.07	3.72	3.50	3.14	2.67	2.62				
5				2.70	3.08	3.44	3.72	4.16	4.48	4.68	5.01	5.09	5.21	5.23	5.22	5.03	4.83	4.58	4.35	3.85	3.46	3.14	2.77	2.55			
6			2.75	3.01	3.37	3.76	4.11	4.58	4.94	5.27	5.53	5.74	5.88	5.89	5.81	5.54	5.41	5.08	4.70	4.35	3.92	3.50	3.10	2.77			
7			2.75	3.33	3.76	4.14	4.77	5.19	5.49	5.92	6.36	6.36	6.36	6.36	6.36	6.36	6.06	5.76	5.33	4.94	4.39	3.96	3.44	3.01	2.60		
8		2.67	3.12	3.59	4.12	4.63	5.11	5.59	6.14	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.91	5.39	4.85	4.35	3.85	3.40	2.82		
9		2.82	3.29	3.83	4.38	4.98	5.52	6.13	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.84	5.15	4.53	4.06	3.48	3.01	2.62	
10		2.94	3.51	4.07	4.65	5.25	5.87	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.69	5.03	4.30	3.72	3.29	2.77	
11	2.70	3.14	3.63	4.19	4.91	5.61	6.18	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.90	5.22	4.54	3.87	3.44	2.82	
12	2.70	3.23	3.74	4.36	5.08	5.72	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.04	5.37	4.65	4.09	3.40	2.99	2.33
13	2.72	3.31	3.82	4.48	5.09	5.87	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.15	5.42	4.72	4.19	3.59	2.99	2.57
14	2.87	3.19	3.82	4.58	5.15	5.76	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.15	5.43	4.68	4.11	3.59	2.99	2.55
15	2.65	3.16	3.76	4.33	5.08	5.74	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.09	5.46	4.83	4.02	3.42	2.94	2.41
16	2.65	3.10	3.71	4.30	4.87	5.57	6.21	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.81	5.15	4.61	3.97	3.35	2.96	
17		2.94	3.55	4.07	4.71	5.28	5.96	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.61	4.90	4.36	3.83	3.25	2.70	
18		2.89	3.29	3.87	4.45	4.99	5.65	6.18	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.87	5.29	4.70	4.21	3.61	3.05	2.67	
19		2.72	3.16	3.63	4.21	4.71	5.11	5.69	5.83	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	5.85	5.40	4.98	4.33	3.82	3.35	2.92		
20			2.75	3.35	3.76	4.17	4.74	5.14	5.62	6.07	6.36	6.36	6.36	6.36	6.36	6.36	6.19	5.83	5.43	4.96	4.48	4.01	3.51	3.19	2.57		
21			2.67	2.99	3.50	3.90	4.24	4.63	5.06	5.35	5.67	5.83	6.14	6.03	5.96	5.76	5.56	5.27	4.89	4.54	4.04	3.57	3.21	2.82			
22				2.75	3.05	3.46	3.80	4.21	4.67	4.91	5.00	5.14	5.45	5.31	5.28	5.09	4.92	4.68	4.36	3.99	3.57	3.25	2.82				
23					2.72	3.01	3.40	3.59	3.99	4.24	4.48	4.57	4.71	4.63	4.63	4.47	4.30	4.06	3.71	3.48	3.19	2.87					
24						2.67	2.99	3.14	3.50	3.71	3.85	3.96	4.07	4.09	4.14	3.94	3.83	3.59	3.23	3.05	2.72						
25							2.77	2.92	3.12	3.23	3.33	3.40	3.50	3.46	3.27	3.23	3.16	3.12	2.89	2.72							
26									2.60	2.75	2.82	2.89	2.94	2.87	2.89	2.65	2.60										

Table F.3 – Probit Values for the BLEVE Event

	PROBABILITY OF FATALITY																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1										0.010	0.010	0.013	0.015	0.017	0.016	0.015	0.011	0.010									
2								0.011	0.019	0.024	0.036	0.046	0.052	0.052	0.050	0.046	0.035	0.019	0.011	0.009							
3						0.009	0.013	0.029	0.052	0.066	0.108	0.133	0.140	0.140	0.152	0.122	0.085	0.066	0.040	0.019	0.009						
4					0.011	0.026	0.044	0.088	0.148	0.191	0.247	0.277	0.323	0.328	0.277	0.272	0.223	0.177	0.101	0.066	0.032	0.010	0.009				
5				0.011	0.027	0.059	0.101	0.200	0.302	0.376	0.506	0.536	0.584	0.593	0.588	0.511	0.434	0.339	0.257	0.125	0.061	0.032	0.013	0.007			
6			0.012	0.023	0.052	0.108	0.186	0.339	0.475	0.606	0.702	0.771	0.811	0.813	0.791	0.706	0.658	0.531	0.381	0.257	0.140	0.066	0.029	0.013			
7			0.012	0.048	0.108	0.195	0.407	0.574	0.687	0.821	0.912	0.912	0.912	0.912	0.912	0.912	0.856	0.777	0.629	0.475	0.272	0.148	0.059	0.023	0.008		
8		0.010	0.030	0.080	0.191	0.354	0.545	0.724	0.872	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.819	0.650	0.439	0.257	0.125	0.054	0.015		
9		0.015	0.044	0.122	0.267	0.491	0.698	0.870	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.800	0.560	0.318	0.173	0.064	0.023	0.009	
10		0.020	0.069	0.177	0.365	0.597	0.808	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.755	0.511	0.242	0.101	0.044	0.013	
11	0.011	0.032	0.085	0.209	0.465	0.727	0.881	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.816	0.588	0.323	0.129	0.059	0.015	
12	0.011	0.038	0.104	0.262	0.531	0.764	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.852	0.646	0.365	0.182	0.054	0.022	0.004
13	0.011	0.046	0.118	0.302	0.536	0.808	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.876	0.663	0.391	0.209	0.080	0.022	0.008
14	0.017	0.035	0.118	0.339	0.560	0.777	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.876	0.667	0.376	0.186	0.080	0.022	0.007
15	0.009	0.033	0.108	0.252	0.531	0.771	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.862	0.679	0.434	0.165	0.057	0.020	0.005
16	0.009	0.029	0.098	0.242	0.449	0.717	0.886	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.791	0.560	0.349	0.152	0.050	0.021	
17		0.020	0.074	0.177	0.386	0.611	0.831	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.727	0.460	0.262	0.122	0.040	0.011	
18		0.018	0.044	0.129	0.292	0.496	0.741	0.881	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.808	0.615	0.381	0.213	0.082	0.026	0.010	
19		0.011	0.033	0.085	0.213	0.386	0.545	0.755	0.797	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.912	0.803	0.654	0.491	0.252	0.118	0.050	0.019		
20			0.012	0.050	0.108	0.204	0.397	0.555	0.731	0.858	0.912	0.912	0.912	0.912	0.912	0.912	0.883	0.797	0.667	0.485	0.302	0.160	0.069	0.035	0.008		
21			0.010	0.022	0.066	0.136	0.223	0.354	0.526	0.637	0.748	0.797	0.872	0.849	0.831	0.777	0.713	0.606	0.455	0.323	0.169	0.077	0.036	0.015			
22				0.012	0.026	0.061	0.115	0.213	0.370	0.465	0.501	0.555	0.675	0.620	0.611	0.536	0.470	0.376	0.262	0.156	0.077	0.040	0.015				
23					0.011	0.023	0.054	0.080	0.156	0.223	0.302	0.333	0.386	0.354	0.354	0.297	0.242	0.173	0.098	0.064	0.035	0.017					
24						0.010	0.022	0.032	0.066	0.098	0.125	0.148	0.177	0.182	0.195	0.144	0.122	0.080	0.038	0.026	0.011						
25							0.013	0.019	0.030	0.038	0.048	0.054	0.066	0.061	0.042	0.038	0.033	0.030	0.018	0.011							
26									0.008	0.012	0.015	0.018	0.020	0.017	0.018	0.009	0.008										

Table F.4 – Probability of Fatalities for the BLEVE Event

	FATALITIES																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1											0.028	0.037	0.042	0.047	0.044	0.042	0.032	0.028									
2											0.104	0.130	0.148	0.148	0.142	0.130	0.099	0.053									
3									0.148	0.188	0.306	0.378	0.399	0.399	0.433	0.346	0.243	0.188									
4									0.422	0.542	0.702	0.787	0.919	0.934	0.787	0.773	0.634	0.505									
5									0.860	1.069	1.439	1.524	1.661	1.687	1.674	1.454	1.234	0.964									
6																	1.874	1.510	1.084	0.730	0.399	0.188	0.081	0.037			
7																	2.436	2.210	1.789	1.352	0.773	0.422	0.167	0.066			
8																		2.597	2.330	1.850	1.249	0.730	0.356	0.154			
9																		2.597	2.597	2.276	1.593	0.904	0.492	0.181			
10																		2.597	2.597	2.597	2.148	1.454	0.689	0.287			
11																		2.597									
12					1.510	2.175												2.597									
13					1.524	2.300												2.597									
14					1.593	2.210												2.597									
15																		2.597									
16																		2.597									
17																		2.597									
18																		2.597									
19																		2.597									
20																		2.268									
21																		1.726									
22																		1.069									
23																		0.492									
24																		0.227									
25																		0.086									
26																											
	0.000	0.000	0.000	0.000	4.628	6.685	0.000	0.000	1.430	1.799	2.580	2.857	3.169	3.216	3.081	2.745	6.552	42.487	10.396	8.806	6.162	3.699	1.786	0.726	0.000	0.000	0.000

Table F.5 – Site Specific Fatalities for the BLEVE Event

1.2 Consequence Assessment of Event 2 – Instantaneous release of entire inventory and immediate ignition resulting in a Vapour Cloud Explosion

The guidelines set by RIVM also include the likelihood of a Vapour Cloud Explosion (VCE) during an instantaneous release with immediate ignition. This VCE is modelled using ALOHA and the threat zones are estimated and superimposed on the geographical location consisting of the point of release. The extent of damage (i.e. fatalities) is then estimated.

Immediate ignition is considered as ignition occurring within 1 minute of the release. The entire content of the Propane Bullet is considered to have been released. The rate of release is assumed to be constant and is modeled as such. The release rate is shown below,

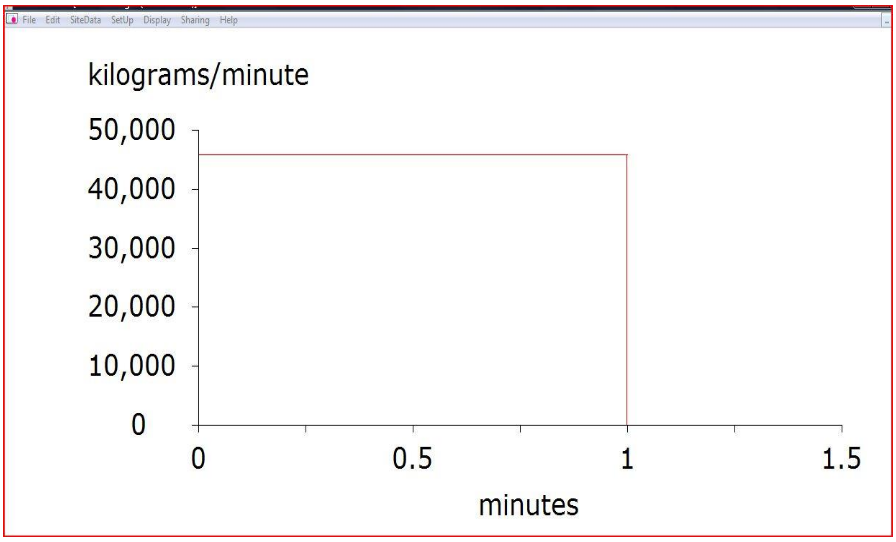


Fig F.4 – Rate of release of entire content of Propane Bullet within 1 minute

Fatalities are related to the side – on overpressure generated by the explosion and the levels of concern or end points are estimated as per the following probit,

$Y = 1.47 + 1.371\ln (P_s)$ --------------------------> (UK HSE)

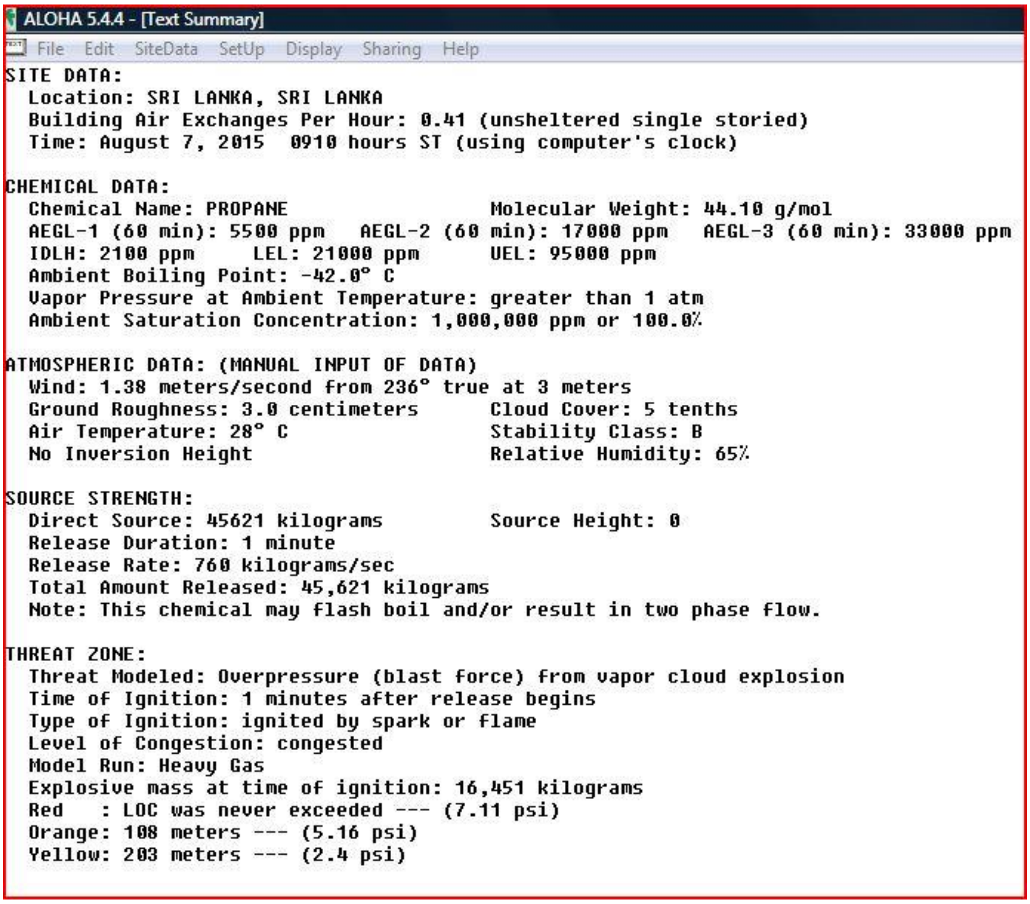
This probit was selected during the end point determination stage for consequence analysis and is the most conservative of the probits that were studied. The following end points are shown on the threat zones,

Table F.6 – Endpoints for VCE Overpressure

% Fatality	Blast Overpressure (P_S) (psig)	Maximum distance (m)
20	7.11 (49 kPa)	Not Applicable
10	5.10 (35.16 kPa)	108
1	2.4 (16.55 kPa)	203

20% fatality is not exceeded.

ALOHA provides the following summary of the VCE event.



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: August 7, 2015  0910 hours ST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: PROPANE                      Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm           UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.38 meters/second from 236° true at 3 meters
  Ground Roughness: 3.0 centimeters           Cloud Cover: 5 tenths
  Air Temperature: 28° C                      Stability Class: B
  No Inversion Height                         Relative Humidity: 65%

SOURCE STRENGTH:
  Direct Source: 45621 kilograms              Source Height: 0
  Release Duration: 1 minute
  Release Rate: 760 kilograms/sec
  Total Amount Released: 45,621 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Threat Modeled: Overpressure (blast force) from vapor cloud explosion
  Time of Ignition: 1 minutes after release begins
  Type of Ignition: ignited by spark or flame
  Level of Congestion: congested
  Model Run: Heavy Gas
  Explosive mass at time of ignition: 16,451 kilograms
  Red   : LOC was never exceeded --- (7.11 psi)
  Orange: 108 meters --- (5.16 psi)
  Yellow: 203 meters --- (2.4 psi)
```

Figure F.5 – Summary of Event 2

The threat zone is as follows,

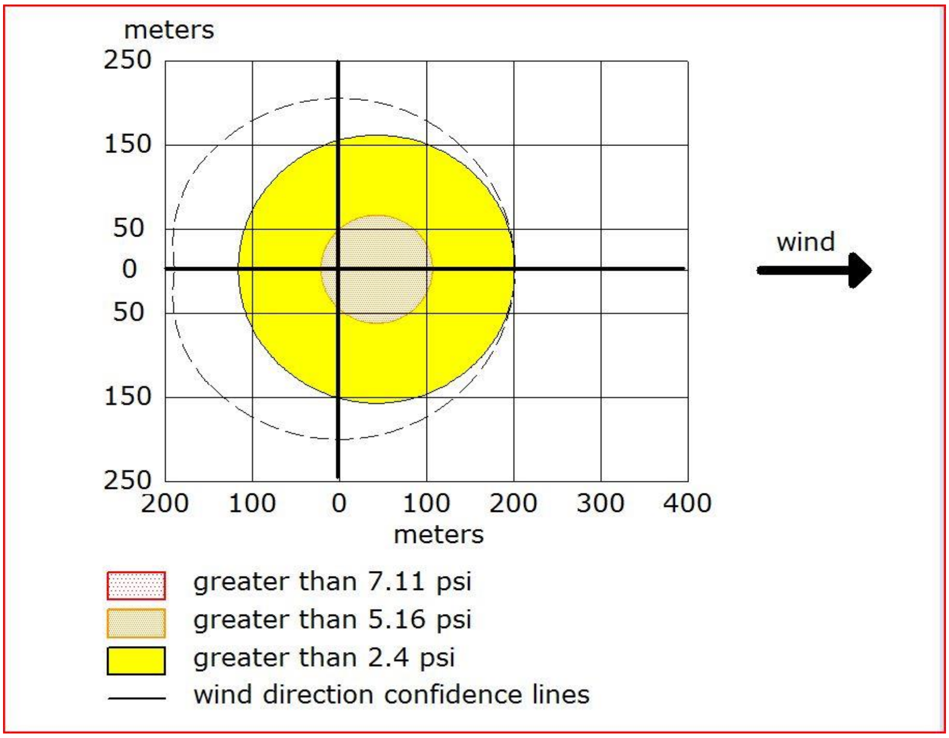


Fig F.6 – Threat Zone for Event 2

The threat zone is then superimposed on the geographical location using MARPLOT as shown below in Fig G.7.

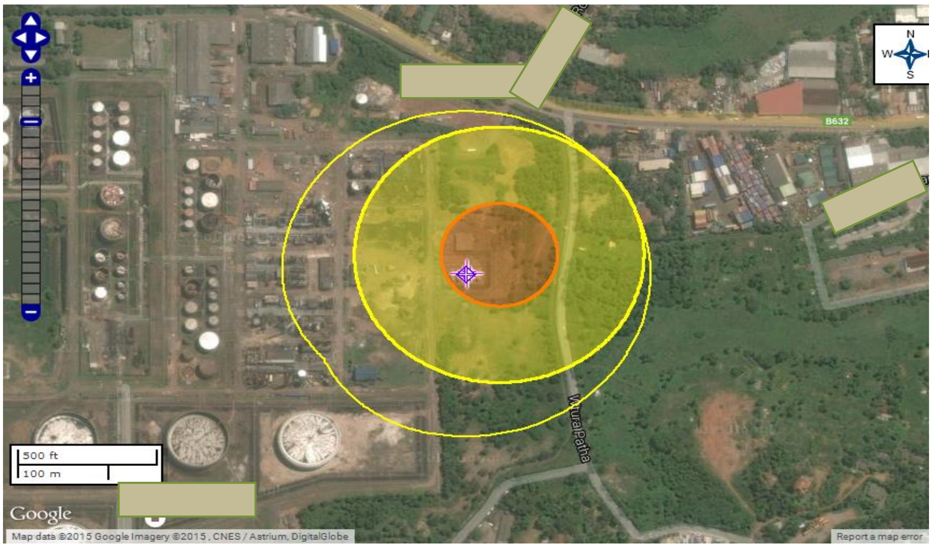


Fig F.7 – Threat Zone superimposed on the Geographical Location of the release for Event 2

The threat zone is then divided into a 50m X 50m grid for assessment of fatalities (Refer Figure F.8)

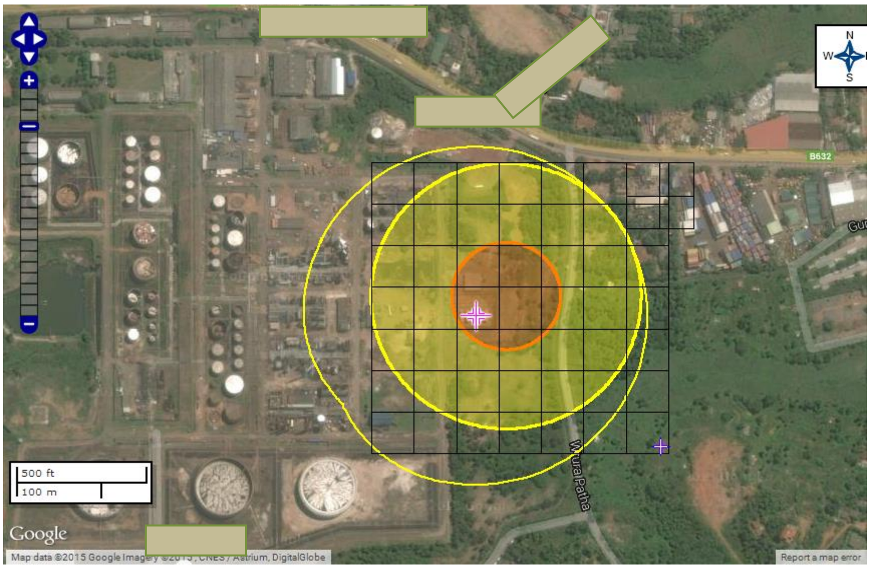


Fig F.8 – 50m x 50m Grid for the VCE Threat Zone

The overpressure value for each grid is determined using MARPLOT's "threat at a point" function. The value at the centre of the grid is chosen and is used to represent the threat level within the respective grid.

Table F.7 – Exposure Levels (Overpressure) for Event 2

	OVERPRESSURE (psi) AT GRID POINTS						
	`1	2	3	4	5	6	7
1	2	2.4	2.66	2.71	2.45	2.2	
2	2.42	2.95	3.71	4.04	3.3	2.58	
3	2.7	3.72	5.96	6.36	4.44	3.01	2.3
4	2.74	4.18	6.36	6.36	4.9	3.24	2.37
5	2.6	3.62	5.25	5.75	4.02	2.98	2.29
6	2.24	2.83	3.36	3.41	3.04	2.4	
7		2.42	2.54	2.5	2.38		

Table F.8 – Probit Values

	PROBIT VALUES						
	1	2	3	4	5	6	7
1	2.420305	2.670268	2.811285	2.836817	2.698537	2.550975	
2	2.681645	2.953155	3.267425	3.384251	3.106868	2.769419	
3	2.831748	3.271115	3.917332	4.006389	3.513687	2.98076	2.611918
4	2.85191	3.430957	4.006389	4.006389	3.648841	3.081711	2.653022
5	2.780006	3.233756	3.743431	3.868153	3.377447	2.967027	2.605945
6	2.575678	2.896219	3.131571	3.151823	2.994357	2.670268	
7		2.681645	2.747997	2.726235	2.658795		

Table F.9 – Probability of Fatality

	PROBABILITY OF FATALITY						
	1	2	3	4	5	6	7
1	0.004944	0.00991	0.014309	0.015264	0.010683	0.007162	2.87E-07
2	0.010215	0.020337	0.041586	0.053074	0.02917	0.012854	2.87E-07
3	0.01507	0.041915	0.139478	0.160206	0.068598	0.021731	0.008468
4	0.015853	0.058319	0.160206	0.160206	0.088322	0.027537	0.009463
5	0.01321	0.038677	0.104455	0.128849	0.052343	0.021028	0.008332
6	0.007669	0.017699	0.030851	0.032288	0.022447	0.00991	2.87E-07
7	2.87E-07	0.010215	0.012161	0.01149	0.009611	2.87E-07	2.87E-07

Table F.10 – Site Specific Fatalities for Event 2

	FATALITIES						
	1	2	3	4	5	6	7
1	0.039085	0.07834	0.113111	0.120658	0.084447	0.056617	
2	0.08075	0.160761	0.328734	0.419553	0.23059	0.101614	
3	0.119127	0.331337	1.102573	1.266429	0.542269	0.171785	0.066942
4	0.12532	0.461011	1.266429	1.266429	0.698188	0.217682	0.074807
5	0.104422	0.305745	0.825716	1.018555	0.413768	0.166223	0.065861
6	0.06062	0.139909	0.243878	0.255239	0.177445	0.07834	
7		0.08075	0.096133	0.090829	0.075973		

The area considered as being occupied is highlighted in yellow. Fatalities are calculated from the highlighted cells only. The total number of deaths for Event 2 is 2.4.

1.3 Consequence Assessment of Event 3– Instantaneous release of entire inventory and immediate ignition resulting in a Flash Fire

The guidelines set by RIVM include in addition to a BLEVE and VCE, the likelihood of a Flash Fire during an instantaneous release with immediate ignition. This flash fire is modeled using ALOHA and the threat zones are estimated and superimposed on the geographical location consisting of the point of release. The extent of damage (i.e. fatalities) is then estimated.

Immediate ignition is considered as ignition occurring within 1 minute of the release. The entire content of the Propane Bullet is considered to have been released. The rate of release is assumed to be constant and is modeled as such. The release rate is as shown in Fig F.5.

The threat zone is generated for the following end points,

- 10% of LEL – 2100 ppm (Propane)
- 60% of LEL – 12600 ppm (Propane)
- 100% of LEL – 21000 ppm (Propane)

Fatalities are only estimated within the flame envelope as the vapour cloud can ignite to form a flash fire. Any person within the flame envelope is considered to have a probability of fatality of 1 as he/she will be engulfed by the fire while the probability of failure outside the flame envelope is zero and serious injury outside the flame envelope is considered as not being likely. A probability of 1 within flame envelope and 0 outside is standard practice (LaChance et al., 2011; Satyanarayan, 1991).

However, different criteria exist in determining the extent of the flame envelope. ALOHA considers 60% LEL as the level of concern for defining the threat zone. ALOHA uses time averaging when calculating the average concentration and tries to account for the possibility of fluctuating concentration which might exceed the average LEL value. CCPS (CCPS, 1996) recommends using 50% LEL as the defining threat zone but does not provide the basis for the selection. However, these values seem to be highly conservative with regard to the fundamentals of combustion. As per the fundamentals, combustion should occur between the combustion limits of UFL and LFL. Hence, it is more realistic considering 100% LFL as a defining value for the flame envelope even though a probability exists for ignition at 60% of LEL as explained in ALOHA. ALOHA does not state what the probability is and does not provide a method of determining this probability except for the qualitative explanation given above. By considering ALOHA‘s definition of a flame envelope, a degree of uncertainty is also introduced which otherwise can be avoided if 100% LEL is defined as the end point for the flame envelope.

ALOHA indicates all locations within the defined level of concern as the threat zone for the period where the level of concern is exceeded but does not provide a means of visualizing the growth of the vapour cloud for the particular period. However, this limitation can be overcome as concentration profiles at a given distance can be estimated using the “threat at a point” function. The profile is plotted in terms of concentration vs time at a given location. Hence, by obtaining concentration vs time profiles for successive distances one can obtain a fairly accurate idea on how the vapour cloud will progress over time.

Fig F.10 provides such a profile. From the profile it can be estimated that an area limited at a distance of 100m downwind will be vulnerable within the 1st minute after release. As ignition for this event (event 3) is assumed to occur at 1 minute after release the maximum distance that will be vulnerable within this period is 100m and the area extending from the release point to the 100m distance downwind of the release is taken as being the threat zone. The threat zone as generated by ALOHA is as given below,

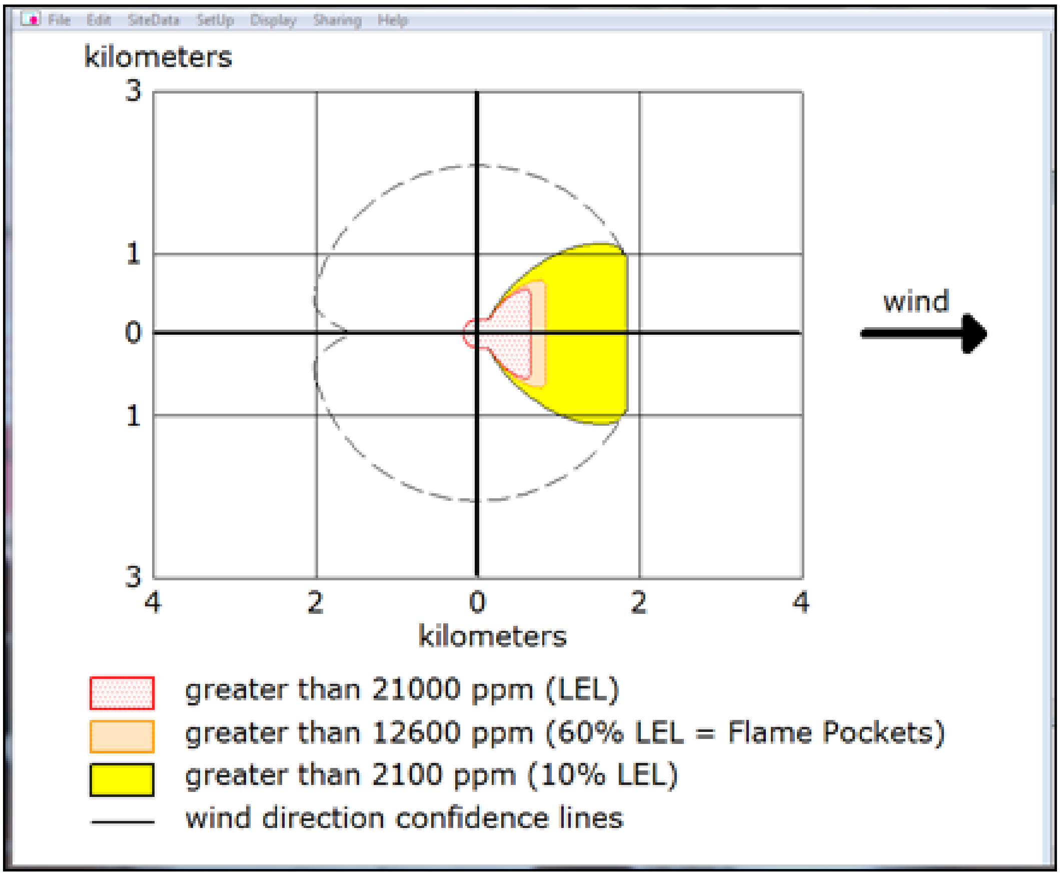
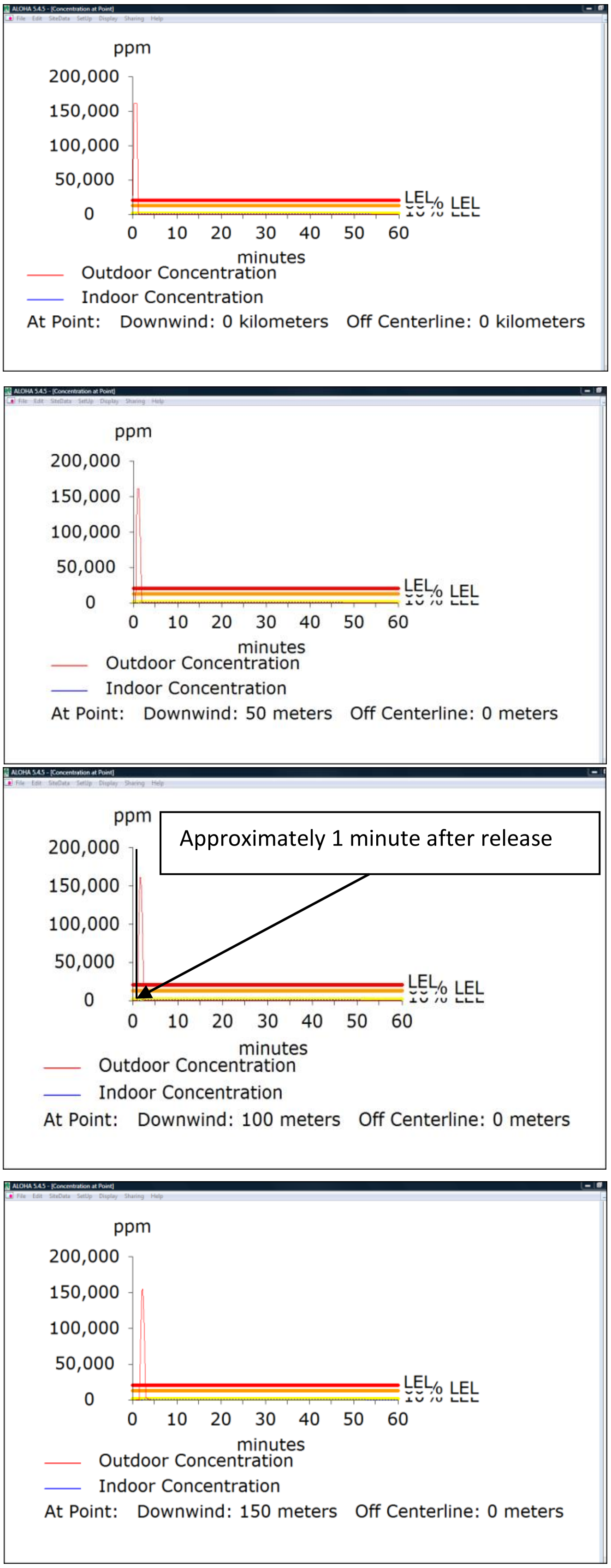


Fig F.9 - Threat Zone generated by ALOHA for Event 3



At Point: Downwind: 0 kilometers Off Centerline: 0 kilometers

At Point: Downwind: 50 meters Off Centerline: 0 meters

Approximately 1 minute after release

At Point: Downwind: 100 meters Off Centerline: 0 meters

At Point: Downwind: 150 meters Off Centerline: 0 meters

Fig F.10 – Concentration vs Time after release for Event 3

The threat zone for the flash fire is superimposed on the geographical location of the release along with the demarcation line for the 100 m downwind distance (Refer Fig F.11 below).

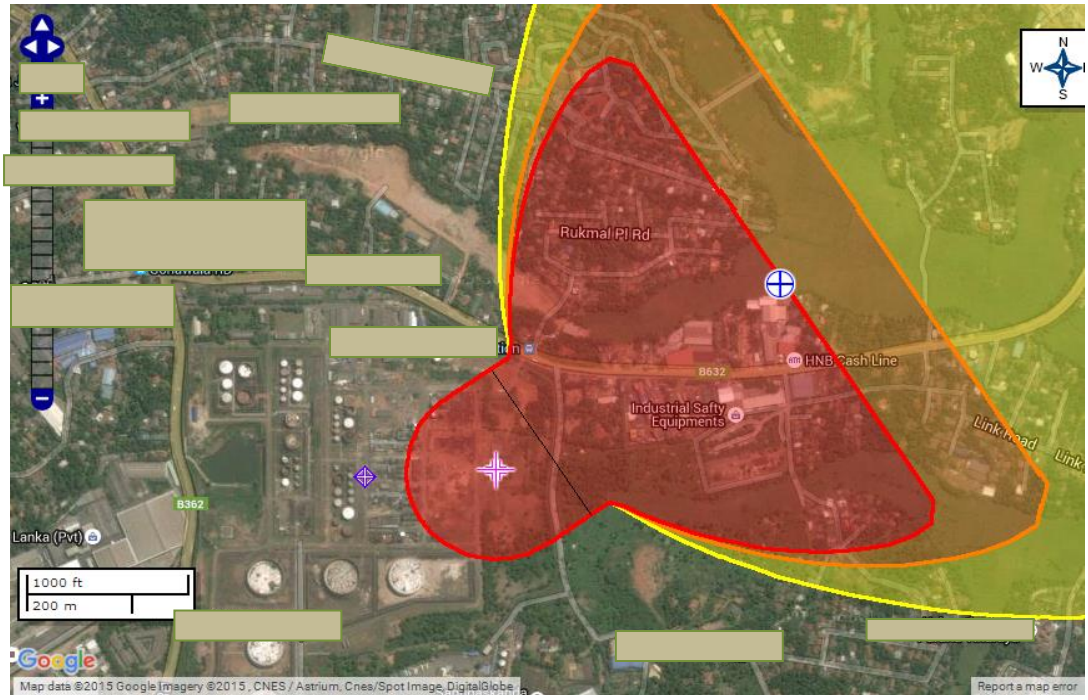


Fig F.11 – Threat Zone with 100m demarcation line

The selected zone is then divided into 50m X 50m grid for estimating fatality values (Refer Fig F.12).

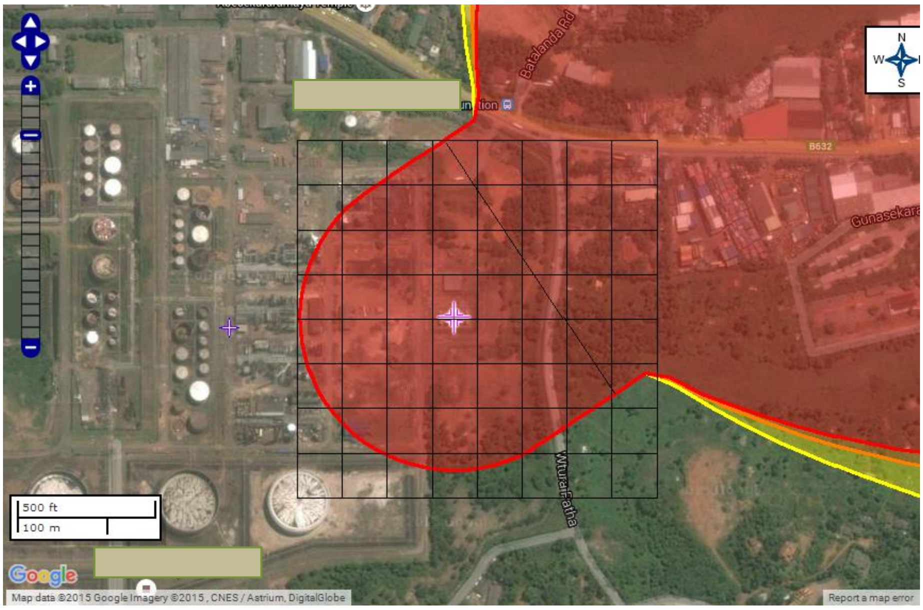


Fig F.12 – 50m X 50m Grid for Event 3

Table F.11 – Probability of Death

	PROBABILITY OF FATALITY							
	1	2	3	4	5	6	7	8
1								
2								
3								
4	1					1		
5	1					1		
6						1		
7						1		
8								

Table F.12 – Fatalities for Event 3

	FATALITIES							
	1	2	3	4	5	6	7	8
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	7.905	0	0	0	0	7.905	0	0
5	7.905	0	0	0	0	7.905	0	0
6	0	0	0	0	0	7.905	0	0
7	0	0	0	0	0	7.905	0	0
8	0	0	0	0	0	0	0	0

Only locations that are inhabited are included as being occupied. In this case the following areas,

- Control room of the plant
- Road

The total number of fatalities expected is 47.4.

1.4 Consequence Assessment of Event 4 – Instantaneous release of entire inventory and delayed ignition resulting in a VCE

A delayed ignition of the entire inventory in an instantaneous release can result in any of the following three consequences,

1. Vapour Cloud Explosion
2. Flash Fire
3. No consequence

Here we consider the consequence due to a VCE from delayed ignition. Delayed ignition is considered as occurring at anytime 1 minute after the release. ALOHA does not have the facility to dynamically model the progress of the vapour cloud. However, it does provide the facility of estimating overpressure events (explosions) at different time intervals. This facility is used to determine the extent of the hazard footprint at successive time intervals from the time of release (Δt) and the time interval with the largest hazard footprint is chosen as being representative of the consequence of the delayed ignition event. This is a "worst case approach" and is conservative. The extent of consequences at successive time intervals from the time of release is shown below in Figure F.14.

Fatalities are related to the side – on overpressure generated by the explosion and the levels of concern or end points are estimated as per the following probit,

$Y = 1.47 + 1.371\ln(P_s)$ -------------------------> (UK HSE)

This probit was selected during the end point determination stage for consequence analysis and is the most conservative of the probits that were studied. The following end points are shown on the threat zones,

Table F.13 – Endpoints for VCE Overpressure

% Fatality	Blast Overpressure (P_s) (psig)	Maximum distance (m)
20	7.11 (49 kPa)	Not Applicable
10	5.10 (35.16 kPa)	108
1	2.4 (16.55 kPa)	203

20% fatality is not exceeded in any of the events, hence only fatality endpoints of 10% (Orange) and 1% (Yellow) are indicated on the hazard footprint. A review of the hazard footprints at successive time intervals shows that the maximum amount of damage (i.e. loss of life) can occur between the time intervals Δt = 4.5 min and Δt = 5.0 min due to the inclusion of both the main road and buildings within the 10% Fatality zone (Orange Circle). This is a qualitative selection based on visual inspection. VCE at Δt = 5.0 min is selected. Hence, an ignition event 5 minutes after the initiation of the release of propane is considered to result in the maximum loss of life due to the VCE.

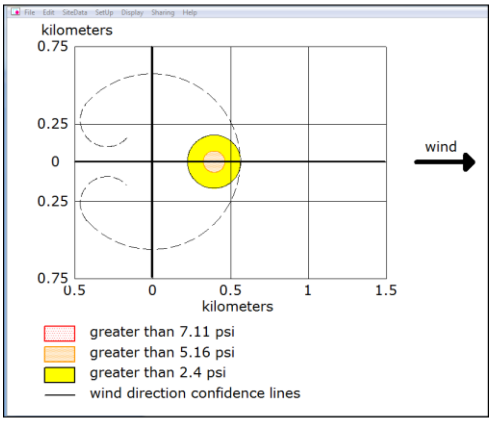
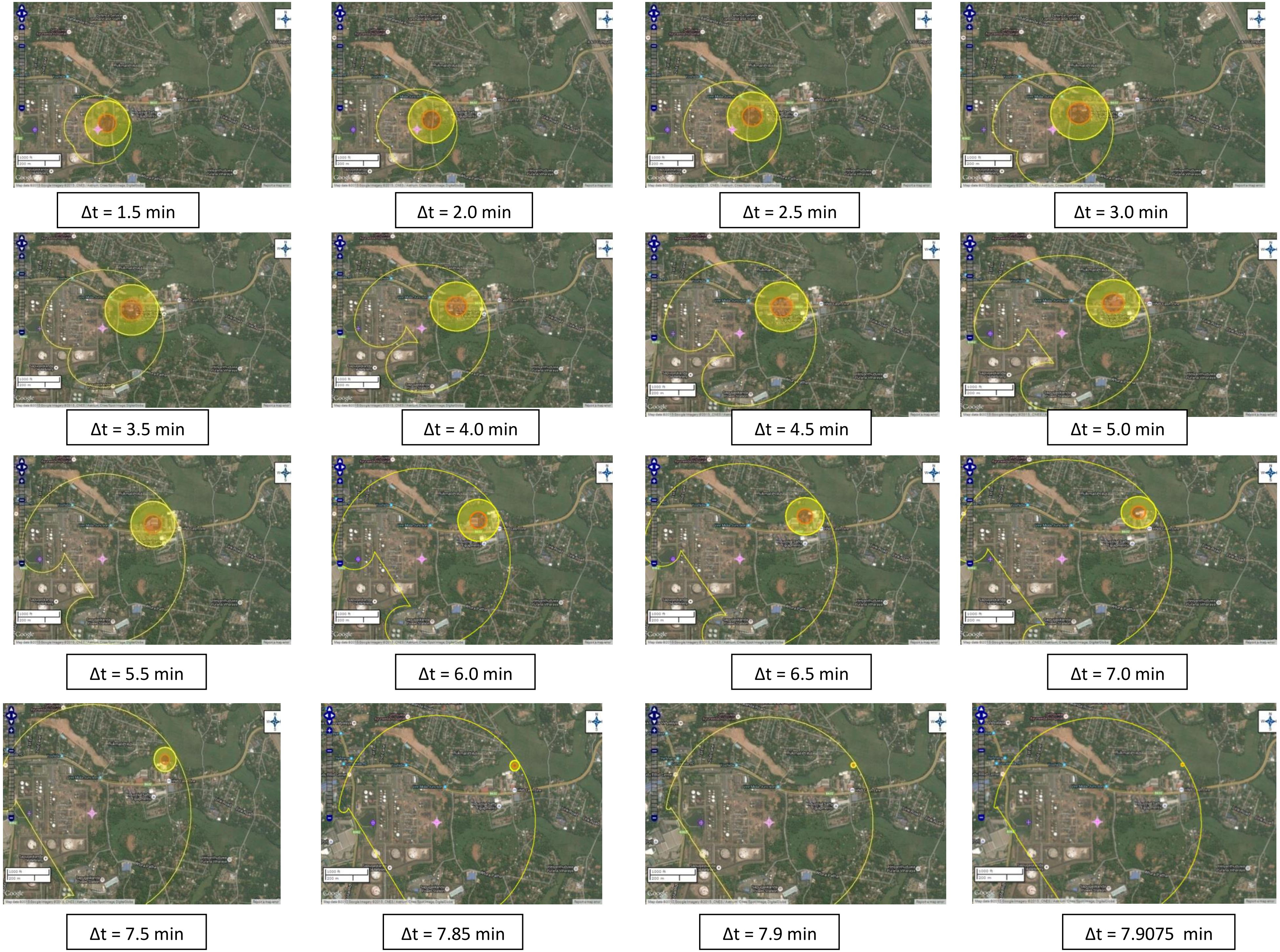


Fig F.13 – Threat Zone due to VCE if ignition occurs at Δt = 5 min



Δt = 1.5 min

Δt = 2.0 min

Δt = 2.5 min

Δt = 3.0 min

Δt = 3.5 min

Δt = 4.0 min

Δt = 4.5 min

Δt = 5.0 min

Δt = 5.5 min

Δt = 6.0 min

Δt = 6.5 min

Δt = 7.0 min

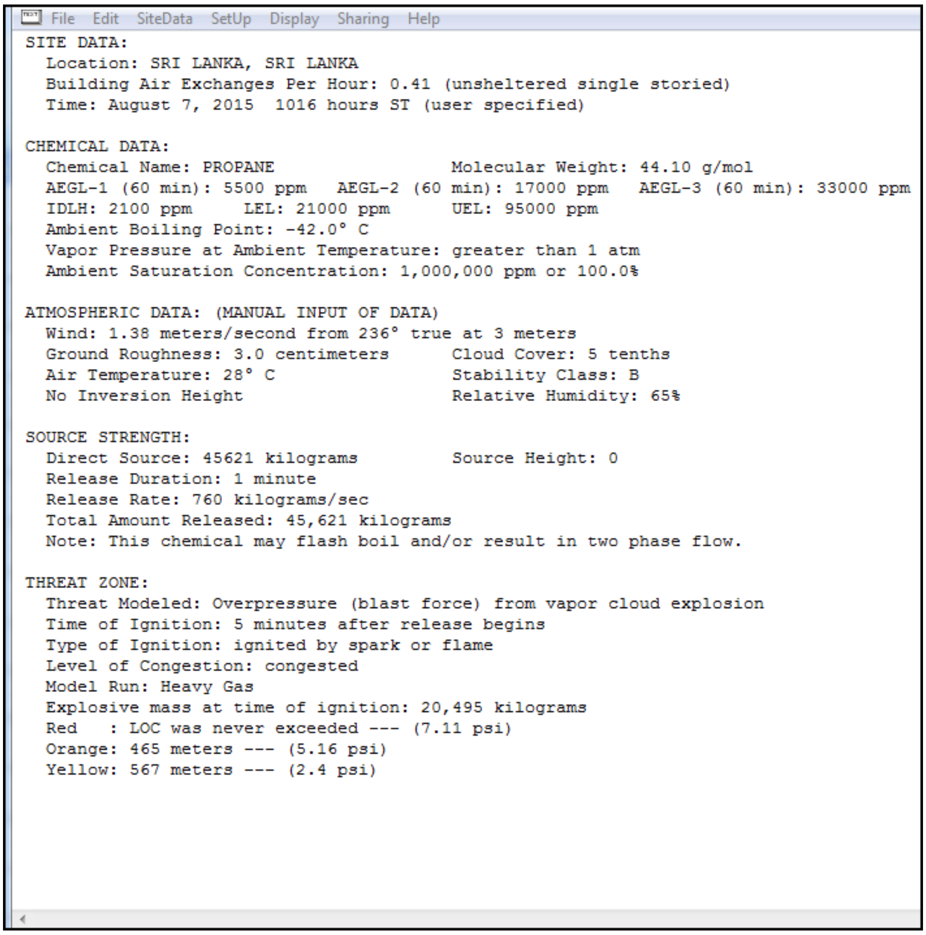
Δt = 7.5 min

Δt = 7.85 min

Δt = 7.9 min

Δt = 7.9075 min

Fig F.14 – VCE Threat Zones at different time intervals for Event 4



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: August 7, 2015  1016 hours ST (user specified)

CHEMICAL DATA:
  Chemical Name: PROPANE                    Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.38 meters/second from 236° true at 3 meters
  Ground Roughness: 3.0 centimeters       Cloud Cover: 5 tenths
  Air Temperature: 28° C                  Stability Class: B
  No Inversion Height                     Relative Humidity: 65%

SOURCE STRENGTH:
  Direct Source: 45621 kilograms          Source Height: 0
  Release Duration: 1 minute
  Release Rate: 760 kilograms/sec
  Total Amount Released: 45,621 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Threat Modeled: Overpressure (blast force) from vapor cloud explosion
  Time of Ignition: 5 minutes after release begins
  Type of Ignition: ignited by spark or flame
  Level of Congestion: congested
  Model Run: Heavy Gas
  Explosive mass at time of ignition: 20,495 kilograms
  Red   : LOC was never exceeded --- (7.11 psi)
  Orange: 465 meters --- (5.16 psi)
  Yellow: 567 meters --- (2.4 psi)
```

Fig F.15 – Summary of the VCE at Δt = 5 min

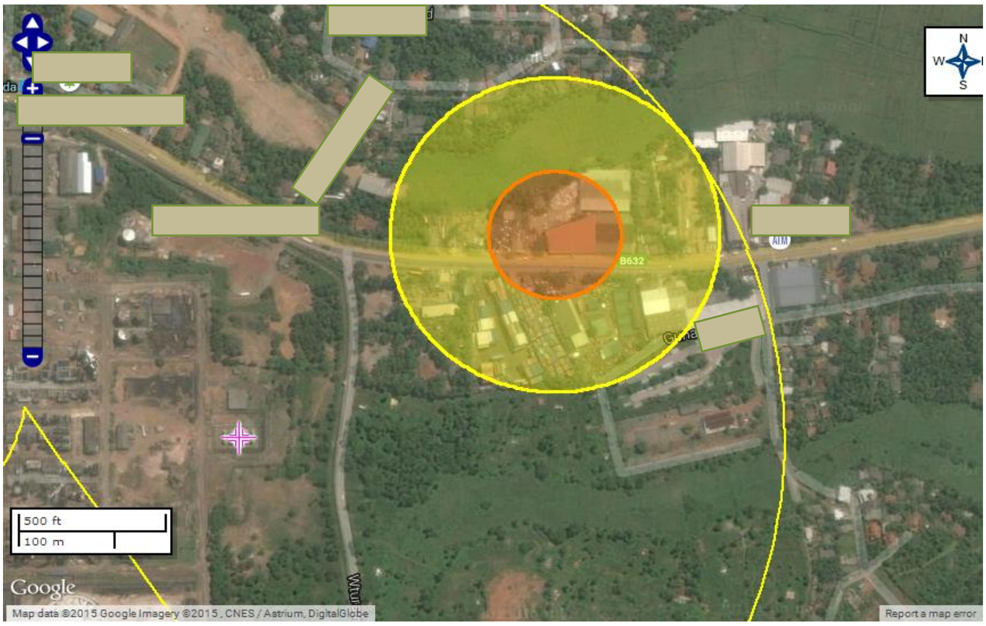


Fig F.16 – Hazard footprint (Threat Zone) superimposed on the Geographical location

The threat zone is then divided into a 25m x 25m grid and the overpressure value at the centre of each grid is then determined using ALOHA's threat at a point function. The probability of fatality is then determined for each grid using the probit selected (UK HSE) for overpressure. The 25m x 25m grid is shown in figure F.17.

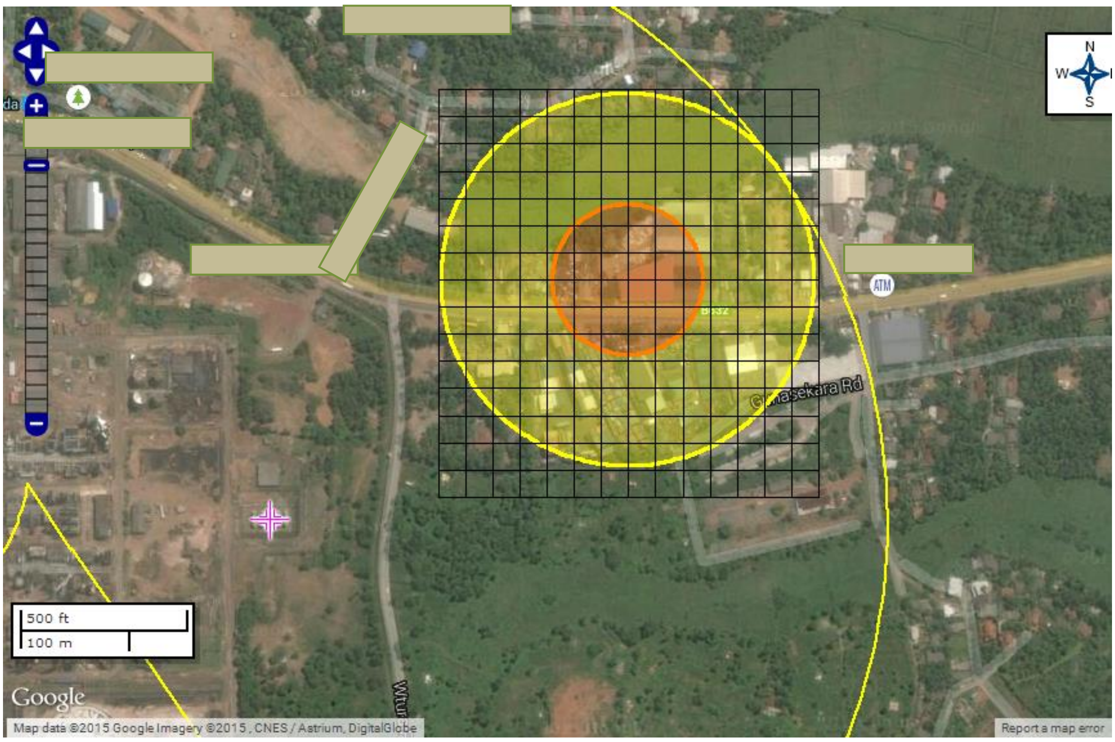


Fig F.17 – 25m X 25m Grid for VCE at Δt = 5 min

The fatalities are then determined as follows,

Table F.14 – Consequence Effects

	OVERPESSURE (psi)													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1					2.42	2.53	2.58	2.56	2.5	2.43				
2			2.41	2.61	2.8	2.93	3	3.05	2.9	2.76	2.53	2.32		
3		2.4	2.66	2.97	3.17	3.5	3.55	3.62	3.47	3.22	2.91	2.59	2.32	
4		2.57	2.91	3.29	3.73	4.13	4.41	4.45	4.11	3.72	3.32	2.85	2.5	
5	2.42	2.77	3.24	3.74	4.51	5.17	5.64	5.5	5.12	4.32	3.71	3.15	2.69	2.36
6	2.52	2.92	3.43	4.14	5.09	6.36	6.36	6.36	6.03	4.88	4.07	3.42	2.83	2.42
7	2.57	2.98	3.56	4.42	5.53	6.36	6.36	6.36	6.36	5.27	4.35	3.51	2.92	2.52
8	2.55	2.97	3.59	4.45	5.56	6.36	6.36	6.36	6.36	5.27	4.19	3.44	2.93	2.5
9	2.52	2.92	3.47	4.08	5.16	6.15	6.36	6.36	5.91	4.86	3.96	3.32	2.8	2.41
10	2.40	2.72	3.12	3.73	4.53	5.07	5.58	5.48	4.99	4.34	3.6	3.09	2.63	2.36
11		2.52	2.85	3.27	3.67	4.01	4.31	4.16	3.97	3.6	3.18	2.79	2.49	
12		2.34	2.57	2.85	3.07	3.33	3.48	3.44	3.31	3.11	2.82	2.55	2.28	
13			2.29	2.5	2.65	2.82	2.86	2.87	2.81	2.65	2.48	2.31		
14				2.4	2.52	2.54	2.52	2.58	2.48	2.43				

Table F.15 – Probit Values

	PROBIT													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1					2.68	2.74	2.77	2.76	2.73	2.69				
2			2.68	2.78	2.88	2.94	2.98	3.00	2.93	2.86	2.74	2.62		
3		2.67	2.81	2.96	3.05	3.19	3.21	3.23	3.17	3.07	2.93	2.77	2.62	
4		2.76	2.93	3.10	3.27	3.41	3.50	3.52	3.41	3.27	3.11	2.90	2.73	
5	2.68	2.87	3.08	3.28	3.53	3.72	3.84	3.81	3.71	3.47	3.27	3.04	2.83	2.65
6	2.74	2.94	3.16	3.42	3.70	4.00	4.00	4.00	3.93	3.64	3.39	3.15	2.90	2.68
7	2.76	2.97	3.21	3.51	3.81	4.00	4.00	4.00	4.00	3.75	3.48	3.19	2.94	2.74
8	2.75	2.96	3.22	3.52	3.82	4.00	4.00	4.00	4.00	3.75	3.43	3.16	2.94	2.73
9	2.74	2.94	3.17	3.40	3.72	3.96	4.00	4.00	3.90	3.64	3.36	3.11	2.88	2.68
10	2.67	2.84	3.03	3.27	3.54	3.69	3.83	3.80	3.67	3.48	3.22	3.02	2.79	2.65
11		2.74	2.90	3.09	3.25	3.37	3.47	3.42	3.36	3.22	3.05	2.88	2.72	
12		2.63	2.76	2.90	3.01	3.12	3.18	3.16	3.11	3.02	2.89	2.75	2.60	
13			2.61	2.73	2.81	2.89	2.91	2.91	2.89	2.81	2.71	2.62		
14				2.67	2.74	2.75	2.74	2.77	2.71	2.69				

Table F.16 – Probability of Fatality

	PROBABILITY OF FATALITY													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	2.9E-07	2.9E-07	2.9E-07	2.9E-07	1.0E-02	1.2E-02	1.3E-02	1.2E-02	1.1E-02	1.0E-02	2.9E-07	2.9E-07	2.9E-07	2.9E-07
2	2.9E-07	2.9E-07	1.0E-02	1.3E-02	1.7E-02	2.0E-02	2.1E-02	2.3E-02	1.9E-02	1.6E-02	1.2E-02	8.7E-03	2.9E-07	2.9E-07
3	2.9E-07	9.9E-03	1.4E-02	2.1E-02	2.6E-02	3.5E-02	3.6E-02	3.9E-02	3.4E-02	2.7E-02	1.9E-02	1.3E-02	8.7E-03	2.9E-07
4	2.9E-07	1.3E-02	1.9E-02	2.9E-02	4.2E-02	5.6E-02	6.7E-02	6.9E-02	5.6E-02	4.2E-02	3.0E-02	1.8E-02	1.1E-02	2.9E-07
5	1.0E-02	1.6E-02	2.7E-02	4.2E-02	7.1E-02	1.0E-01	1.2E-01	1.2E-01	9.8E-02	6.4E-02	4.1E-02	2.5E-02	1.5E-02	9.3E-03
6	1.2E-02	2.0E-02	3.3E-02	5.7E-02	9.7E-02	1.6E-01	1.6E-01	1.6E-01	1.4E-01	8.7E-02	5.4E-02	3.2E-02	1.8E-02	1.0E-02
7	1.3E-02	2.1E-02	3.7E-02	6.8E-02	1.2E-01	1.6E-01	1.6E-01	1.6E-01	1.6E-01	1.1E-01	6.5E-02	3.5E-02	2.0E-02	1.2E-02
8	1.2E-02	2.1E-02	3.8E-02	6.9E-02	1.2E-01	1.6E-01	1.6E-01	1.6E-01	1.6E-01	1.1E-01	5.9E-02	3.3E-02	2.0E-02	1.1E-02
9	1.2E-02	2.0E-02	3.4E-02	5.4E-02	1.0E-01	1.5E-01	1.6E-01	1.6E-01	1.4E-01	8.6E-02	5.0E-02	3.0E-02	1.7E-02	1.0E-02
10	9.9E-03	1.5E-02	2.4E-02	4.2E-02	7.2E-02	9.6E-02	1.2E-01	1.2E-01	9.2E-02	6.4E-02	3.8E-02	2.4E-02	1.4E-02	9.3E-03
11	2.9E-07	1.2E-02	1.8E-02	2.8E-02	4.0E-02	5.2E-02	6.3E-02	5.7E-02	5.0E-02	3.8E-02	2.6E-02	1.7E-02	1.1E-02	2.9E-07
12	2.9E-07	9.0E-03	1.3E-02	1.8E-02	2.3E-02	3.0E-02	3.4E-02	3.3E-02	2.9E-02	2.4E-02	1.7E-02	1.2E-02	8.2E-03	2.9E-07
13	2.9E-07	2.9E-07	8.3E-03	1.1E-02	1.4E-02	1.7E-02	1.8E-02	1.9E-02	1.7E-02	1.4E-02	1.1E-02	8.6E-03	2.9E-07	2.9E-07
14	2.9E-07	2.9E-07	2.9E-07	9.9E-03	1.2E-02	1.2E-02	1.2E-02	1.3E-02	1.1E-02	1.0E-02	2.9E-07	2.9E-07	2.9E-07	2.9E-07

Table F.17 – Estimation of Fatalities

	FATALITIES													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1					0.08	0.09	0.10	0.10	0.09	0.08				
2			0.08	0.11	0.13	0.16								
3		0.08	0.11	0.16										
4												0.14	0.09	
5	0.08							0.92	0.78	0.50	0.33	0.20	0.12	0.07
6	0.09				0.76	1.26	1.26	1.26	1.13	0.69	0.43	0.26	0.14	0.08
7	0.10	0.17	0.29	0.53	0.93	1.26	1.26	1.26	1.26	0.83	0.51	0.28	0.15	0.09
8	0.10	0.16	0.30	0.54	0.94	1.26	1.26	1.26	1.26	0.83	0.46	0.26	0.16	0.09
9	0.09	0.15	0.27	0.43	0.79	1.18	1.26	1.26	1.08	0.68	0.40	0.23	0.13	0.08
10	0.08	0.12	0.19	0.33	0.57	0.76	0.95	0.91	0.73	0.51	0.30	0.19	0.11	0.07
11		0.09	0.14	0.22	0.32	0.41	0.50	0.45	0.40	0.30	0.20	0.13	0.09	
12		0.07	0.10	0.14	0.18	0.24	0.27	0.26	0.23	0.19	0.14	0.10	0.06	
13			0.07	0.09	0.11	0.14	0.14	0.15	0.14	0.11	0.09	0.07		
14				0.08	0.09	0.10	0.09	0.10	0.09	0.08				

The fatalities are estimated only at locations having a likelihood of being occupied by humans (Roads and Buildings). The selected locations are highlighted in yellow.

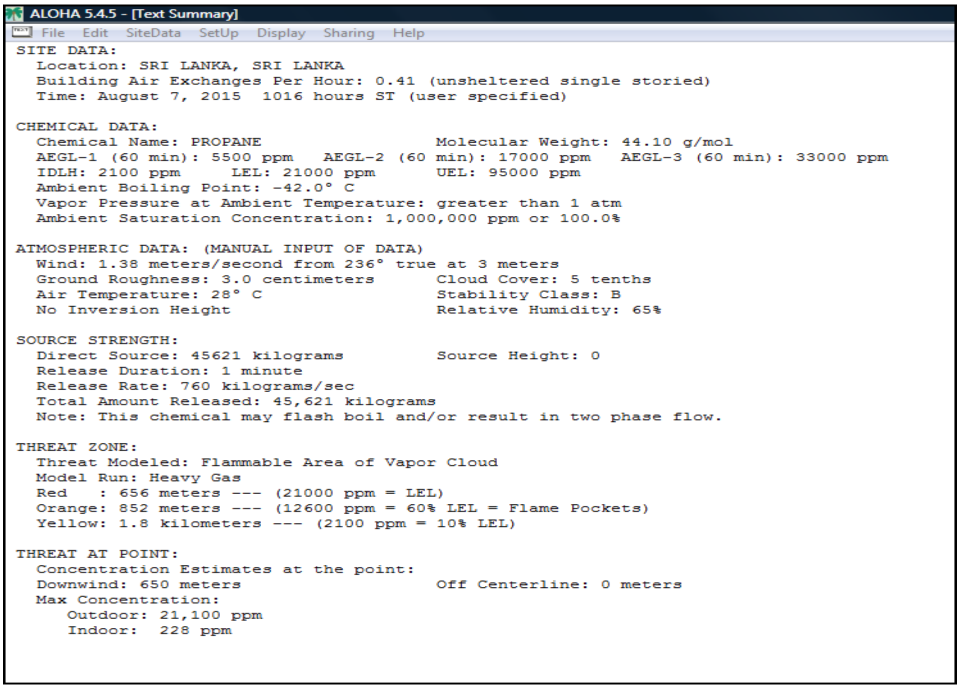
The total number of fatalities estimated is 50.6 for a VCE due a delayed ignition at a Δt = 5 min.

1.5 Consequence Assessment of Event 5 – Instantaneous release of entire inventory and delayed ignition resulting in a Flash Fire

The flash fire event is modelled similarly to event 3 in section 1.3 of Appendix F. However there are some fundamental differences as given below,

- Delayed ignition is considered (time of ignition > 1 min).
- The entire threat zone generated by ALOHA is not considered in the analysis

As explained in section 1.3 of appendix F, ALOHA generates the threat zone for the whole duration for which the vapour cloud remains above the given level of concern. Hence it is not representative of the vulnerability of a particular location at a given instance but the area traversed by the vapour cloud during the entirety of the duration. However, when calculating the fatalities of consequences for delayed ignition one needs to know the area of vulnerability at that point of time; if the whole threat zone generated by ALOHA is considered it will result in an overestimation of the fatalities. The summary of the flash fire event is given below in figure F.18,



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: August 7, 2015  1016 hours ST (user specified)

CHEMICAL DATA:
  Chemical Name: PROPANE                 Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.38 meters/second from 236° true at 3 meters
  Ground Roughness: 3.0 centimeters      Cloud Cover: 5 tenths
  Air Temperature: 28° C                 Stability Class: B
  No Inversion Height                    Relative Humidity: 65%

SOURCE STRENGTH:
  Direct Source: 45621 kilograms         Source Height: 0
  Release Duration: 1 minute
  Release Rate: 760 kilograms/sec
  Total Amount Released: 45,621 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Threat Modeled: Flammable Area of Vapor Cloud
  Model Run: Heavy Gas
  Red   : 656 meters --- (21000 ppm = LEL)
  Orange: 852 meters --- (12600 ppm = 60% LEL = Flame Pockets)
  Yellow: 1.8 kilometers --- (2100 ppm = 10% LEL)

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 650 meters                   Off Centerline: 0 meters
  Max Concentration:
     Outdoor: 21,100 ppm
     Indoor:  228 ppm
```

Fig F.18 – Summary of Event 5

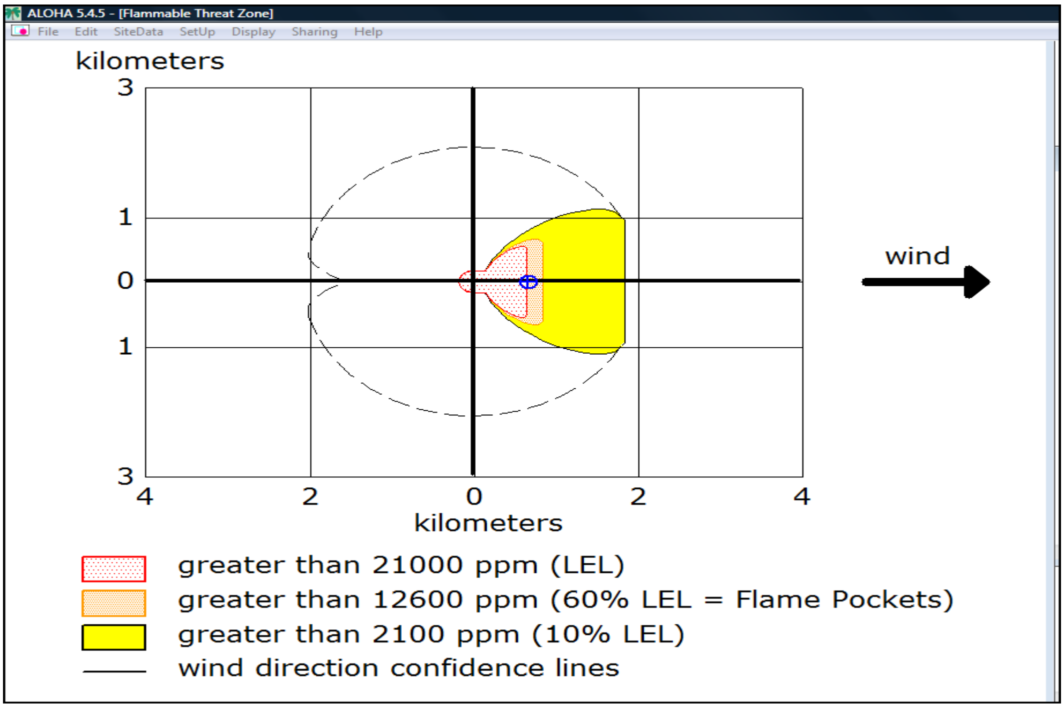


Fig F.19 – Threat Zone of Event 5

The threat zone is shown in figure F.19. The concentration vs time profiles for successive distances downwind is used to get an idea about the vulnerability (exposure time) for a given area. The concentration vs time profiles for different downwind distances are given in figure F.20.

The largest area vulnerable for a flash fire event is at an approximate distance of 300m to 450m between 5 to 6 minutes after the initial release. Therefore it is considered that the largest threat zone will be the zone encompassing the area demarcated by 300m to 450m and initiation of ignition at 5.5 minutes after the commencement of the release (shown with red broken lines). Therefore the area within this area at 5.5 minutes is considered as the flame envelope with a probability of fatality 1. It is shown below in Fig F.21.

At Point: Downwind: 0 kilometers Off Centerline: 0 kilometers

At Point: Downwind: 50 meters Off Centerline: 0 meters

At Point: Downwind: 100 meters Off Centerline: 0 meters

At Point: Downwind: 150 meters Off Centerline: 0 meters

At Point: Downwind: 200 meters Off Centerline: 0 meters

At Point: Downwind: 250 meters Off Centerline: 0 meters

At Point: Downwind: 300 meters Off Centerline: 0 meters

At Point: Downwind: 350 meters Off Centerline: 0 meters

At Point: Downwind: 400 meters Off Centerline: 0 meters

At Point: Downwind: 450 meters Off Centerline: 0 meters

At Point: Downwind: 500 meters Off Centerline: 0 meters

At Point: Downwind: 550 meters Off Centerline: 0 meters

At Point: Downwind: 600 meters Off Centerline: 0 meters

At Point: Downwind: 650 meters Off Centerline: 0 meters

Figure F.20 – Concentration vs Time variation within ALOHA Threat

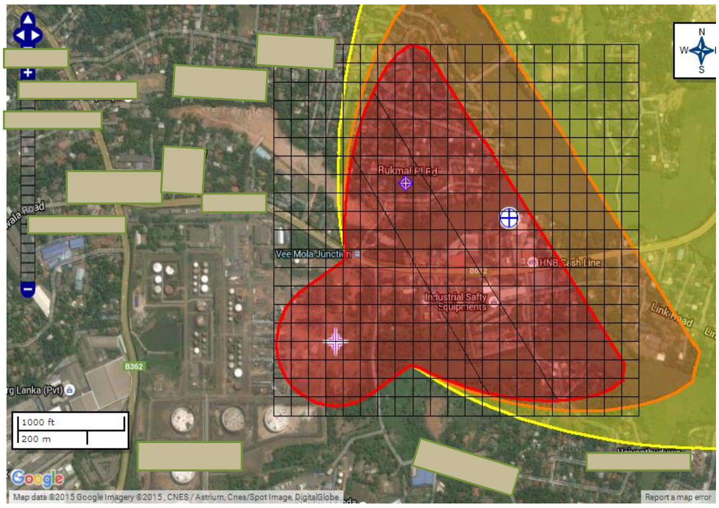


Fig F.21 – Threat Zone with 300m & 450m demarcation lines (Grid – 50m X 50m)

Table F.18 – Probability of Fatality for Event 5

	PROBABILITY OF FATALITY																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1																			
2																			
3																			
4						1	1												
5						1	1												
6					1	1	1	1											
7						1	1	1											
8						1	1	1											
9							1	1	1										
10																			
11																			
12									1	1	1								
13									1	1	1	1							
14										1	1	1	1						
15											1	1	1	1					
16												1	1	1					
17																			
18																			
19																	1		
20																			

Table F.19 – Estimated Fatalities due to Event 5

	FATALITIES																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	7.91	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	7.91	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.91	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The total number of fatalities for event 5 is estimated as 284.5.

1.6 Consequence Assessment of Event 6– Continuous release of entire inventory within 10minutes and immediate ignition resulting in a VCE

The scenario here is that of a very large release with continuous release of the entire inventory within 10minutes. The size of the orifice/ opening of the release needs to be determined as this is not a catastrophic rupture of the vessel. However, a large opening is considered and the hole is considered to be of 100 mm diameter for this event. The value is chosen from the summary of pressure vessel leak frequencies given in Table 4 of the OGP Report on Storage Incident Frequencies (OGP, 2010). A hole size >150mm is considered as catastrophic, therefore a nominal hole size of 100mm in the range 50mm ~ 150mm is selected. The source terms (emissions rates) are calculated based on this diameter.

ALOHA provides the following rate of release profile as shown in Fig G.22.

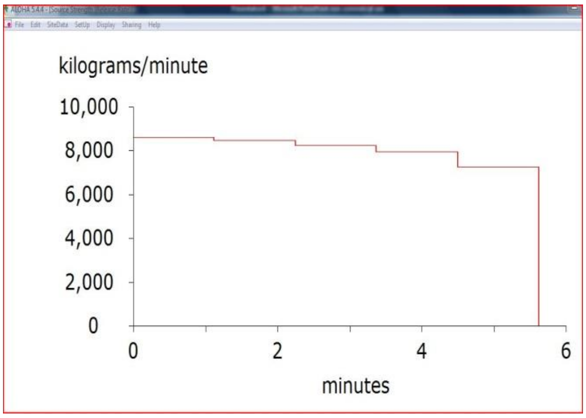
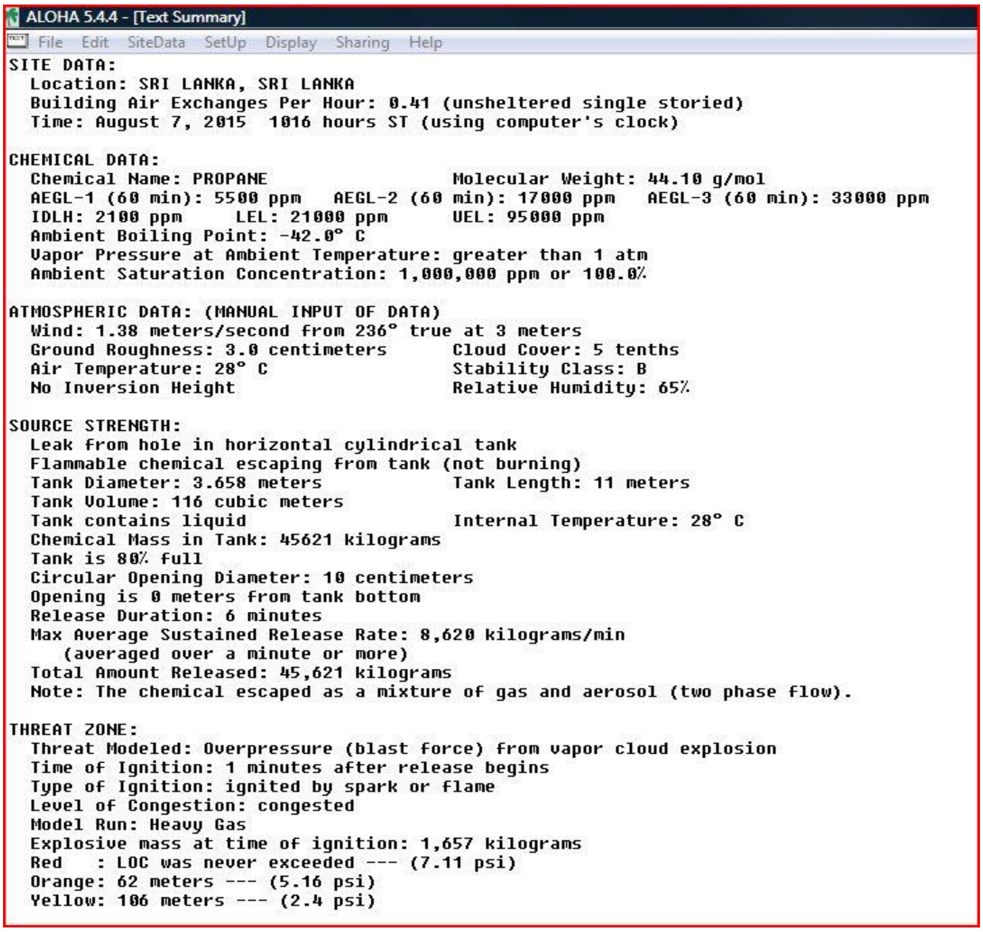


Fig F.22 – Rate of Release of Entire Content within 10 minutes

The threat zone does not extend into the public area; fatalities are unlikely. Hence, this event is not analysed further for fatalities.



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: August 7, 2015  1016 hours ST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: PROPANE                 Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.38 meters/second from 236° true at 3 meters
  Ground Roughness: 3.0 centimeters      Cloud Cover: 5 tenths
  Air Temperature: 28° C                 Stability Class: B
  No Inversion Height                    Relative Humidity: 65%

SOURCE STRENGTH:
  Leak from hole in horizontal cylindrical tank
  Flammable chemical escaping from tank (not burning)
  Tank Diameter: 3.658 meters            Tank Length: 11 meters
  Tank Volume: 116 cubic meters
  Tank contains liquid                   Internal Temperature: 28° C
  Chemical Mass in Tank: 45621 kilograms
  Tank is 80% full
  Circular Opening Diameter: 10 centimeters
  Opening is 0 meters from tank bottom
  Release Duration: 6 minutes
  Max Average Sustained Release Rate: 8,620 kilograms/min
     (averaged over a minute or more)
  Total Amount Released: 45,621 kilograms
  Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).

THREAT ZONE:
  Threat Modeled: Overpressure (blast force) from vapor cloud explosion
  Time of Ignition: 1 minutes after release begins
  Type of Ignition: ignited by spark or flame
  Level of Congestion: congested
  Model Run: Heavy Gas
  Explosive mass at time of ignition: 1,657 kilograms
  Red    : LOC was never exceeded --- (7.11 psi)
  Orange: 62 meters --- (5.16 psi)
  Yellow: 106 meters --- (2.4 psi)
```

Figure F.23 – Summary of Event 7

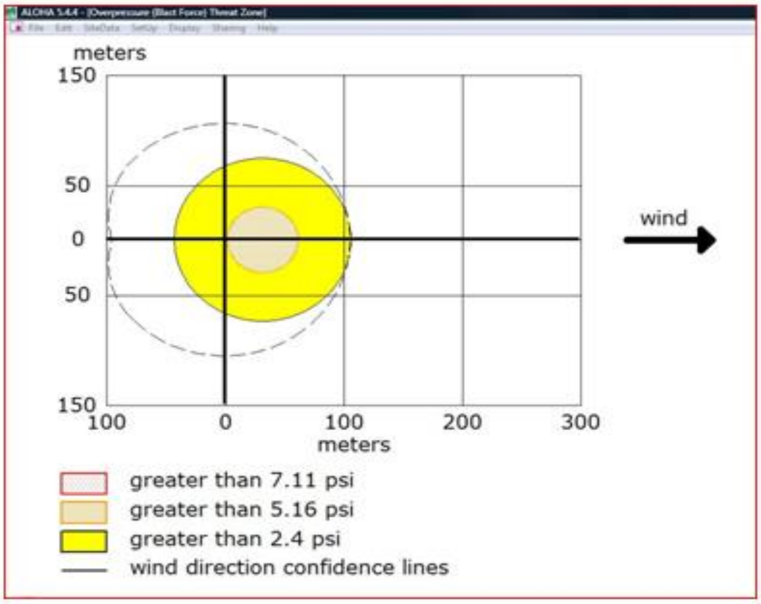


Fig F.24 – Threat Zone of Event 7

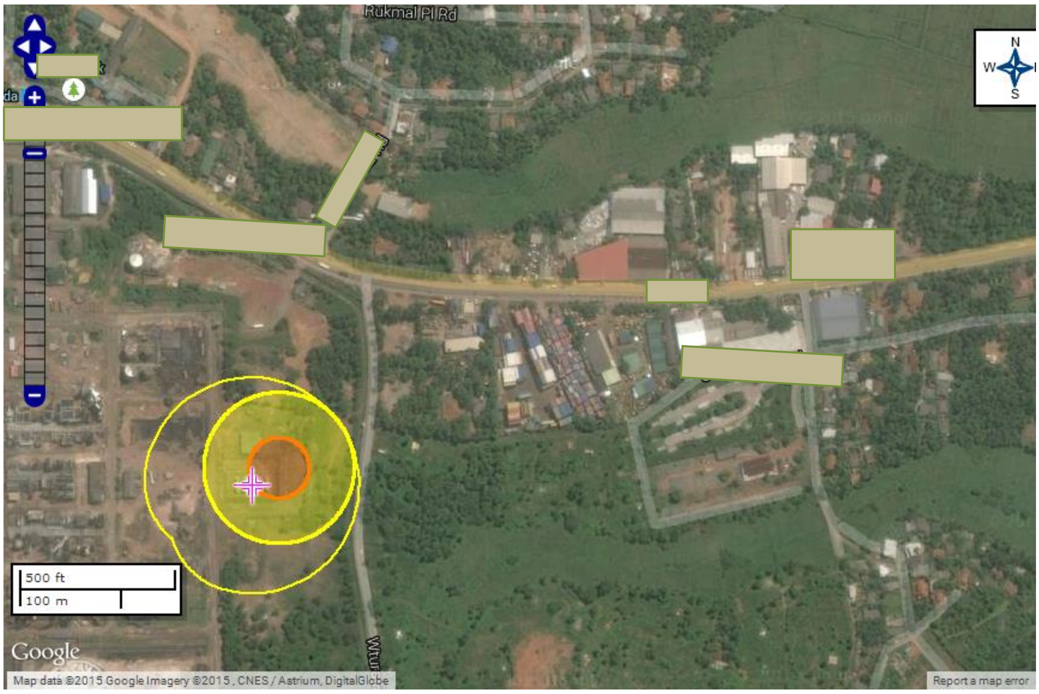
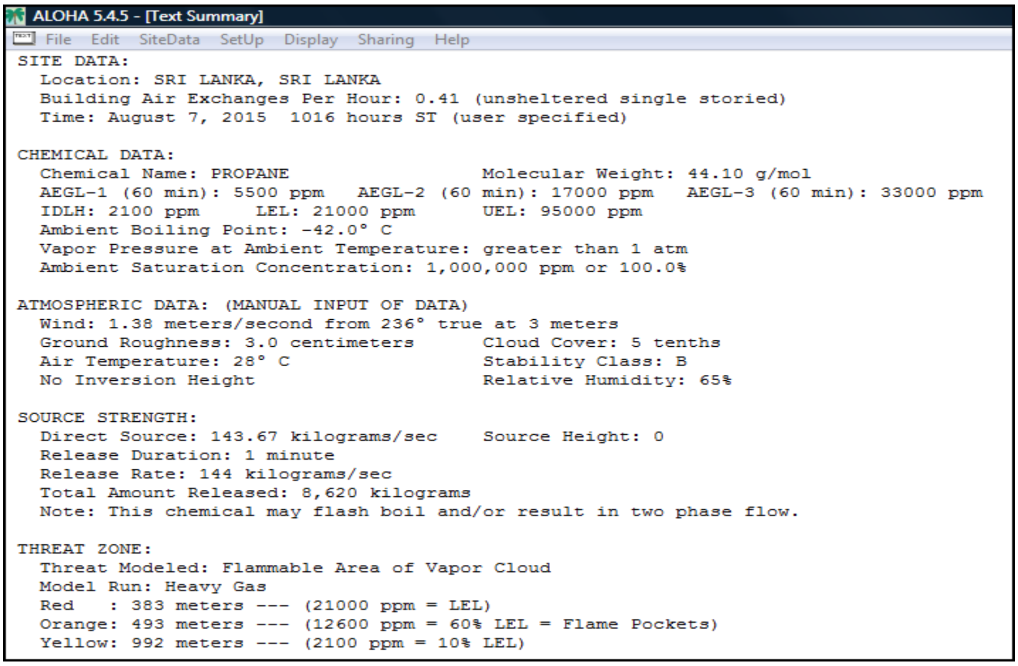


Fig F.25 – Threat Zone superimposed on geographical location

1.7 Consequence Assessment of Event 7– Continuous release of entire inventory within 10minutes and immediate ignition resulting in a Flash Fire

The source terms of the release remain unchanged as in section 1.6 of appendix F. The summary of the release is given below in figure F.26.



```
SITE DATA:
   Location: SRI LANKA, SRI LANKA
   Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
   Time: August 7, 2015  1016 hours ST (user specified)

CHEMICAL DATA:
   Chemical Name: PROPANE                    Molecular Weight: 44.10 g/mol
   AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
   IDLH: 2100 ppm     LEL: 21000 ppm         UEL: 95000 ppm
   Ambient Boiling Point: -42.0° C
   Vapor Pressure at Ambient Temperature: greater than 1 atm
   Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
   Wind: 1.38 meters/second from 236° true at 3 meters
   Ground Roughness: 3.0 centimeters         Cloud Cover: 5 tenths
   Air Temperature: 28° C                    Stability Class: B
   No Inversion Height                       Relative Humidity: 65%

SOURCE STRENGTH:
   Direct Source: 143.67 kilograms/sec       Source Height: 0
   Release Duration: 1 minute
   Release Rate: 144 kilograms/sec
   Total Amount Released: 8,620 kilograms
   Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
   Threat Modeled: Flammable Area of Vapor Cloud
   Model Run: Heavy Gas
   Red    : 383 meters --- (21000 ppm = LEL)
   Orange: 493 meters --- (12600 ppm = 60% LEL = Flame Pockets)
   Yellow: 992 meters --- (2100 ppm = 10% LEL)
```

Fig F.26 – Summary of Event 7

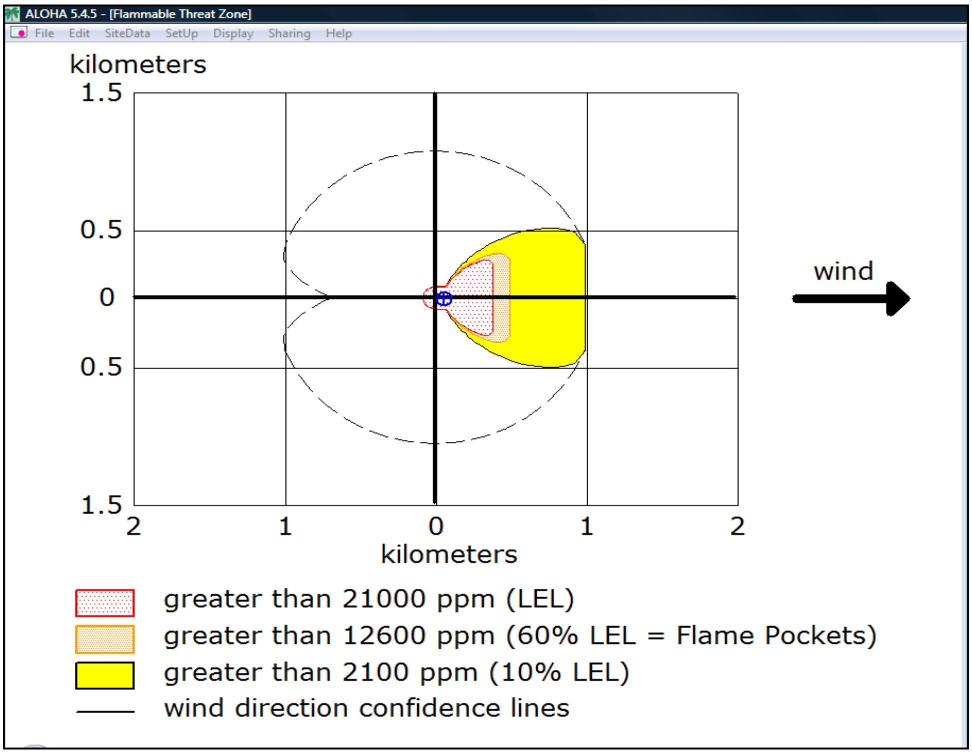


Fig F.27 – Threat Zone for Event 7

Similar to event 3, only the threat zone corresponding to 1 minute after release is considered in determining the flame envelope.

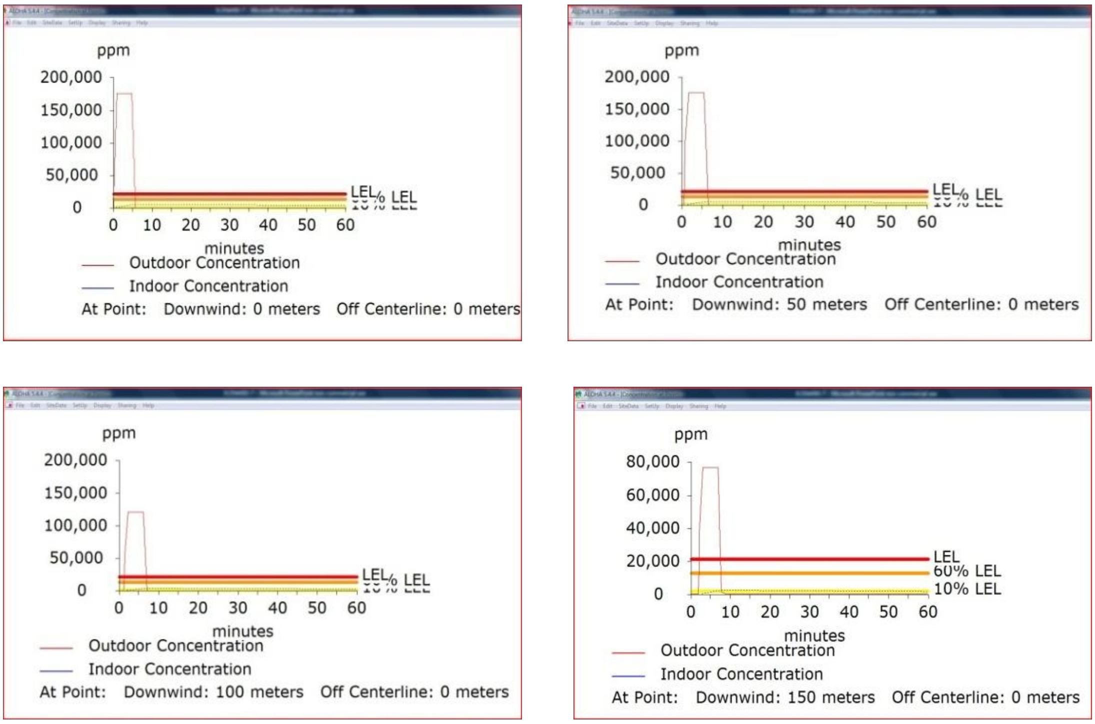


Fig F.28 – Concentration vs Time profile

The concentration vs time profile (Fig G.28) shows that during the first minute an area extending a distance of 100m downwind has an LEL in excess of the end point (100% LEL). This estimate is qualitative and obtained by visually inspecting Fig F.29; hence it is an approximation. A demarcation line is drawn at the 100m downwind distance.

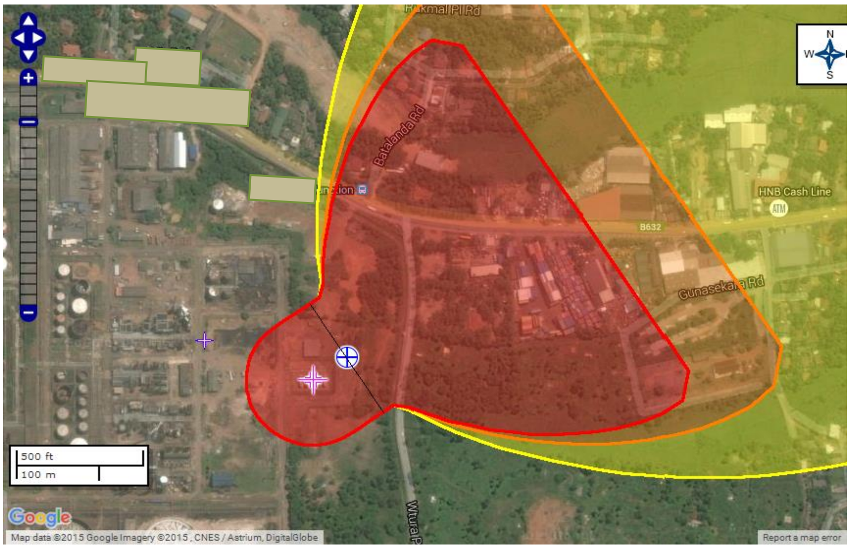
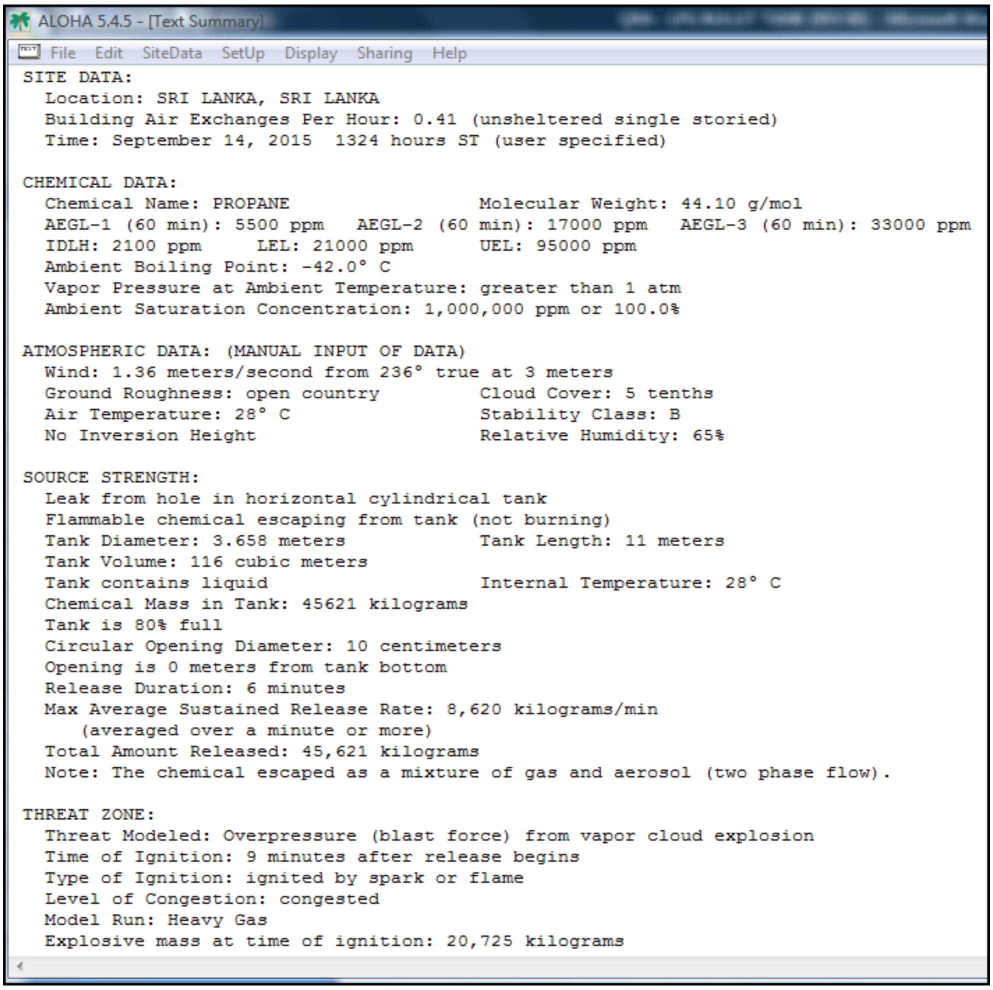


Fig F.29 – The Threat Zone for Event 7

The threat zone at 1 min after release is within the plant limits and no fatalities are expected for the public. Therefore this event is not investigated further for fatalities.

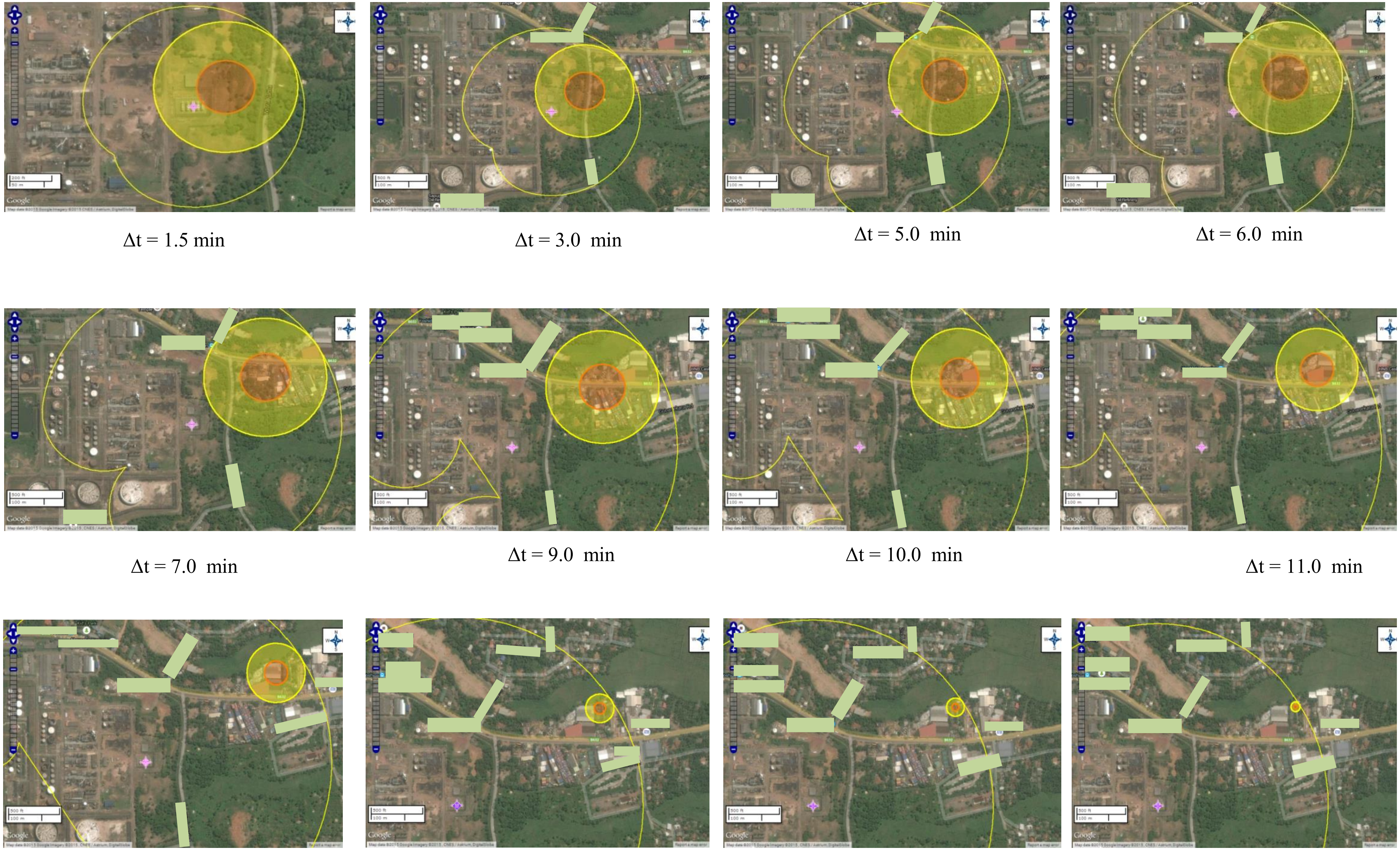
1.8 Consequence Assessment of Event 8 – Continuous release of entire inventory within 10minutes and delayed ignition resulting in a VCE

The source terms of the release remain unchanged as in section 1.6 of appendix F. The time interval during which the threat zone is maximum needs to be determined; the corresponding time is chosen as the time of ignition. The threat zone at successive time intervals is determined using ALOHA as shown below in Fig F.31 and superimposed on the geographical location using MARPLOT.



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: September 14, 2015  1324 hours ST (user specified)

CHEMICAL DATA:
  Chemical Name: PROPANE                  Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm       UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.36 meters/second from 236° true at 3 meters
  Ground Roughness: open country          Cloud Cover: 5 tenths
  Air Temperature: 28° C                  Stability Class: B
  No Inversion Height                     Relative Humidity: 65%

SOURCE STRENGTH:
  Leak from hole in horizontal cylindrical tank
  Flammable chemical escaping from tank (not burning)
  Tank Diameter: 3.658 meters             Tank Length: 11 meters
  Tank Volume: 116 cubic meters
  Tank contains liquid                    Internal Temperature: 28° C
  Chemical Mass in Tank: 45621 kilograms
  Tank is 80% full
  Circular Opening Diameter: 10 centimeters
  Opening is 0 meters from tank bottom
  Release Duration: 6 minutes
  Max Average Sustained Release Rate: 8,620 kilograms/min
     (averaged over a minute or more)
  Total Amount Released: 45,621 kilograms
  Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).

THREAT ZONE:
  Threat Modeled: Overpressure (blast force) from vapor cloud explosion
  Time of Ignition: 9 minutes after release begins
  Type of Ignition: ignited by spark or flame
  Level of Congestion: congested
  Model Run: Heavy Gas
  Explosive mass at time of ignition: 20,725 kilograms
```

Fig F.30 – Summary of Event 8


Δt = 1.5 min

Δt = 3.0 min

Δt = 5.0 min

Δt = 6.0 min

Δt = 7.0 min

Δt = 9.0 min

Δt = 10.0 min

Δt = 11.0 min

Δt = 12.0 min

Δt = 12.7 min

Δt = 12.8 min

Δt = 12.85 min

Fig F.31 – VCE Threat Zones at different time

The maximum vulnerability is considered to occur 9 minutes (Δt = 9 min) after the release as it contains the largest segment of the main road and encloses a densely populated area within the threat zone. This is done by visually inspecting the VCE threat zones for successive time intervals as shown in Fig F.31; hence, it is an approximation.

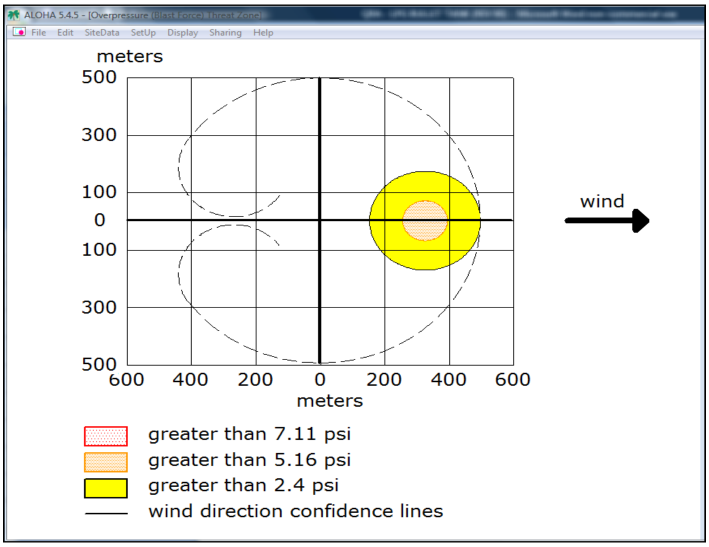


Fig F.32 – VCE Threat Zone for delayed ignition at Δt = 9 min

The threat zone is superimposed on the geographical location and 30m X 30m grid is constructed. Each grid is then evaluated for fatalities. The following probit is chosen to derive probability of fatalities from consequence data (i.e. overpressure at centre of each grid).

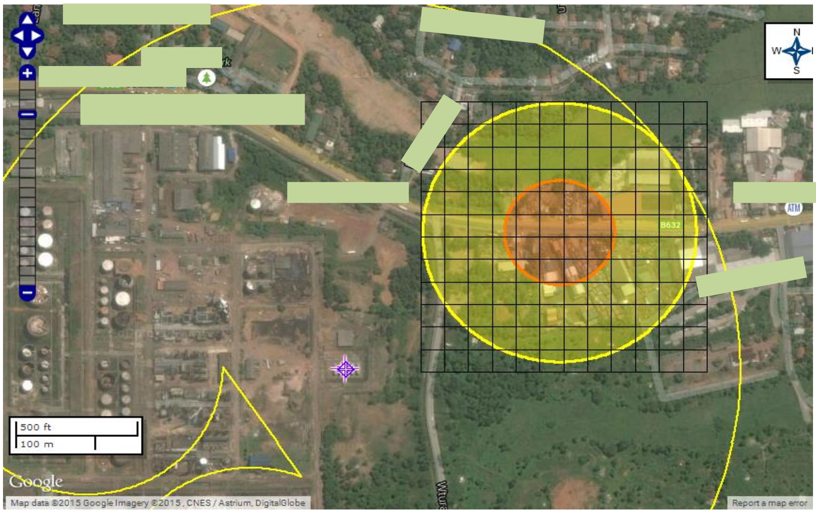


Fig F.33 – Threat Zone of Event 8 (Grid : 30m X 30m)

Table F.20 – Consequence Effects of Event 8

	OVERPESSURE (psi)											
	1	2	3	4	5	6	7	8	9	10	11	12
1				2.4	2.6	2.6	2.6	2.5	2.3			
2		2.3	2.5	2.8	3.0	3.1	3.1	2.9	2.7	2.4		
3		2.4	2.9	3.3	3.7	4.0	4.0	3.6	3.2	2.8	2.4	
4	2.4	2.7	3.3	3.9	4.7	5.2	4.9	4.4	3.8	3.1	2.6	
5	2.5	3.0	3.8	4.6	5.9	6.4	6.4	5.5	4.4	3.3	2.8	2.4
6	2.6	3.1	3.9	5.1	6.4	6.4	6.4	6.3	4.7	3.7	2.9	2.4
7	2.6	3.0	3.9	5.0	6.4	6.4	6.4	6.2	4.6	3.5	2.9	2.4
8	2.5	3.0	3.5	4.5	5.3	6.2	6.2	5.1	4.1	3.4	2.8	2.4
9	2.4	2.7	3.1	3.7	4.3	4.5	4.5	4.3	3.6	3.0	2.6	
10		2.4	2.8	3.2	3.4	3.6	3.5	3.4	3.0	2.7	2.4	
11			2.4	2.6	2.9	2.9	2.9	2.7	2.6	2.3		
12					2.4	2.4	2.4	2.4				

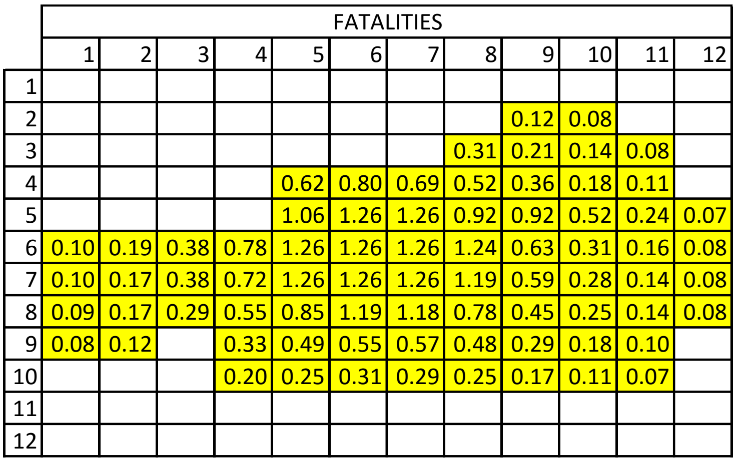
Table F.21 – Probit Values for Event 8

	PROBIT											
	1	2	3	4	5	6	7	8	9	10	11	12
1				2.68	2.75	2.79	2.77	2.70	2.62			
2		2.59	2.73	2.87	2.97	3.02	3.02	2.94	2.83	2.68		
3		2.68	2.92	3.11	3.27	3.36	3.35	3.24	3.06	2.89	2.68	
4	2.69	2.85	3.09	3.34	3.58	3.73	3.64	3.49	3.31	3.00	2.78	
5	2.73	2.97	3.28	3.56	3.89	4.00	4.00	3.81	3.81	3.49	3.12	2.65
6	2.78	3.03	3.33	3.71	4.00	4.00	4.00	3.99	3.59	3.24	2.94	2.69
7	2.77	2.98	3.33	3.66	4.00	4.00	4.00	3.97	3.56	3.19	2.90	2.67
8	2.72	2.97	3.20	3.52	3.76	3.97	3.96	3.71	3.42	3.13	2.89	2.66
9	2.66	2.84	3.02	3.26	3.46	3.52	3.54	3.45	3.21	2.99	2.76	
10		2.67	2.86	3.04	3.15	3.24	3.20	3.14	2.98	2.81	2.64	
11			2.68	2.79	2.91	2.93	2.91	2.85	2.78	2.63		
12					2.65	2.69	2.68	2.67				

Table F.22 – Probability of Fatality for Event 8

	PROBABILITY OF FATALITY											
	1	2	3	4	5	6	7	8	9	10	11	12
1				0.01	0.01	0.01	0.01	0.01	0.01			
2		0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01		
3		0.01	0.02	0.03	0.04	0.05	0.05	0.04	0.03	0.02	0.01	
4	0.01	0.02	0.03	0.05	0.08	0.10	0.09	0.07	0.05	0.02	0.01	
5	0.01	0.02	0.04	0.08	0.13	0.16	0.16	0.12	0.12	0.07	0.03	0.01
6	0.01	0.02	0.05	0.10	0.16	0.16	0.16	0.16	0.08	0.04	0.02	0.01
7	0.01	0.02	0.05	0.09	0.16	0.16	0.16	0.15	0.08	0.04	0.02	0.01
8	0.01	0.02	0.04	0.07	0.11	0.15	0.15	0.10	0.06	0.03	0.02	0.01
9	0.01	0.02	0.02	0.04	0.06	0.07	0.07	0.06	0.04	0.02	0.01	
10		0.01	0.02	0.03	0.03	0.04	0.04	0.03	0.02	0.01	0.01	
11			0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01		
12					0.01	0.01	0.01	0.01				

Table F.23 – Distribution of Fatality Values for Event 8

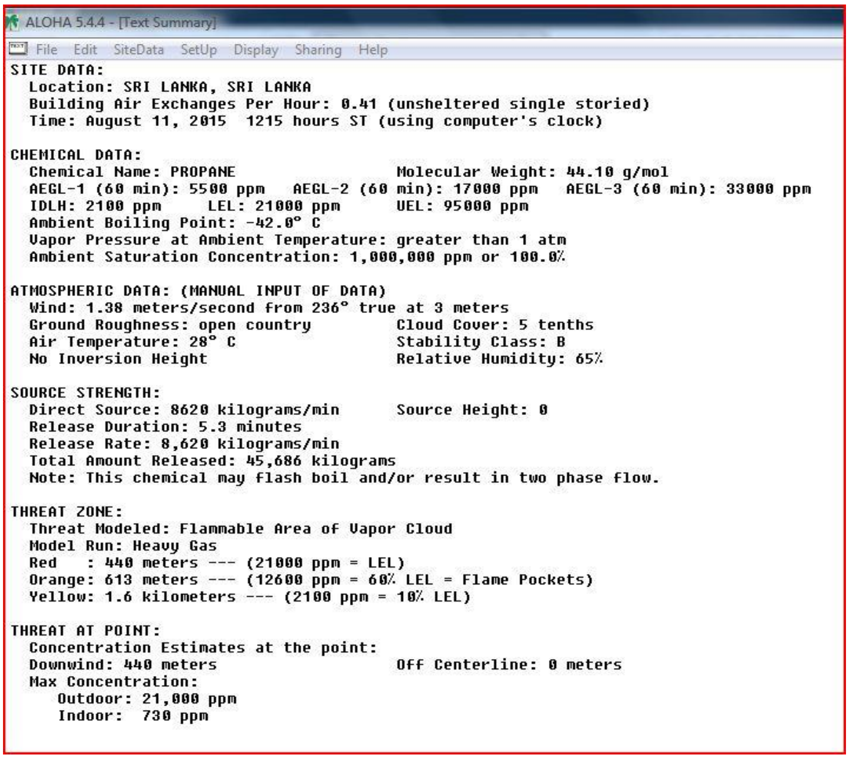


	FATALITIES											
	1	2	3	4	5	6	7	8	9	10	11	12
1												
2									0.12	0.08		
3								0.31	0.21	0.14	0.08	
4					0.62	0.80	0.69	0.52	0.36	0.18	0.11	
5					1.06	1.26	1.26	0.92	0.92	0.52	0.24	0.07
6	0.10	0.19	0.38	0.78	1.26	1.26	1.26	1.24	0.63	0.31	0.16	0.08
7	0.10	0.17	0.38	0.72	1.26	1.26	1.26	1.19	0.59	0.28	0.14	0.08
8	0.09	0.17	0.29	0.55	0.85	1.19	1.18	0.78	0.45	0.25	0.14	0.08
9	0.08	0.12		0.33	0.49	0.55	0.57	0.48	0.29	0.18	0.10	
10				0.20	0.25	0.31	0.29	0.25	0.17	0.11	0.07	
11												
12												

The total number of fatalities for Event 8 is 36.4. (Summation of fatality values in each grid)

1.9 Consequence Assessment of Event 9 – Continuous release of entire inventory within 10minutes and delayed ignition resulting in a Flash Fire

The source terms of the release remain unchanged as in section 1.6 of appendix F. The summary of the event is as follows,



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: August 11, 2015  1215 hours ST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: PROPANE                  Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm       UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.38 meters/second from 236° true at 3 meters
  Ground Roughness: open country          Cloud Cover: 5 tenths
  Air Temperature: 28° C                  Stability Class: B
  No Inversion Height                     Relative Humidity: 65%

SOURCE STRENGTH:
  Direct Source: 8620 kilograms/min       Source Height: 0
  Release Duration: 5.3 minutes
  Release Rate: 8,620 kilograms/min
  Total Amount Released: 45,686 kilograms
  Note: This chemical may flash boil and/or result in two phase flow.

THREAT ZONE:
  Threat Modeled: Flammable Area of Vapor Cloud
  Model Run: Heavy Gas
  Red   : 440 meters --- (21000 ppm = LEL)
  Orange: 613 meters --- (12600 ppm = 60% LEL = Flame Pockets)
  Yellow: 1.6 kilometers --- (2100 ppm = 10% LEL)

THREAT AT POINT:
  Concentration Estimates at the point:
  Downwind: 440 meters                    Off Centerline: 0 meters
  Max Concentration:
     Outdoor: 21,000 ppm
     Indoor:  730 ppm
```

Fig F.34 – Summary of Event 9

The total extent of the threat zone during the entire period of vulnerability is as follows,

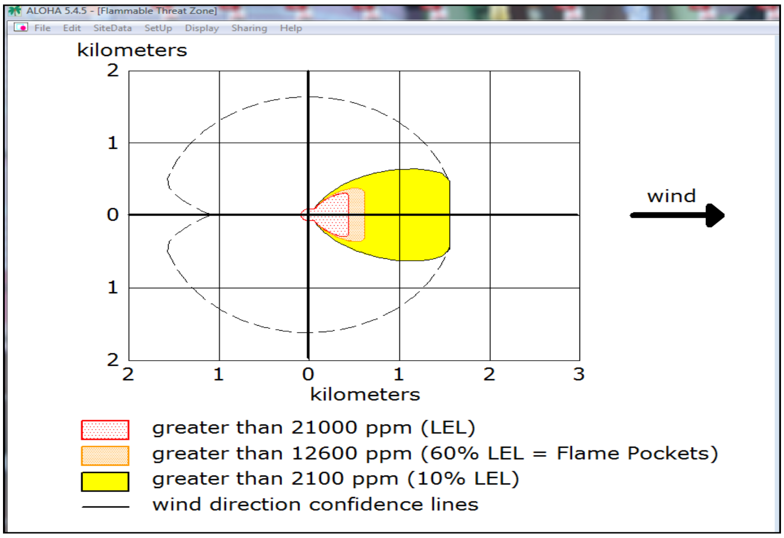


Fig F.35 – Threat Zone during the vulnerable period

The time intervals under which successive downwind distances are vulnerable (i.e. forms a flame envelope) are then estimated. The threat zone at Δt = 7 min is taken as causing the maximum loss of life. The area under consideration is bounded by a demarcation line at 100m downwind and the vapour cloud envelope upto a distance of 450m.

Fig F.36 – Flame Envelope at 7 min from release

The threat zone is then assessed for fatalities using a 30m X 30m grid as shown in figure F.37.

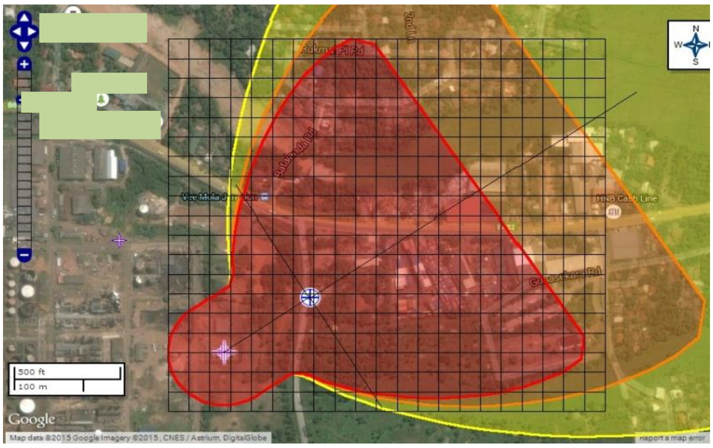
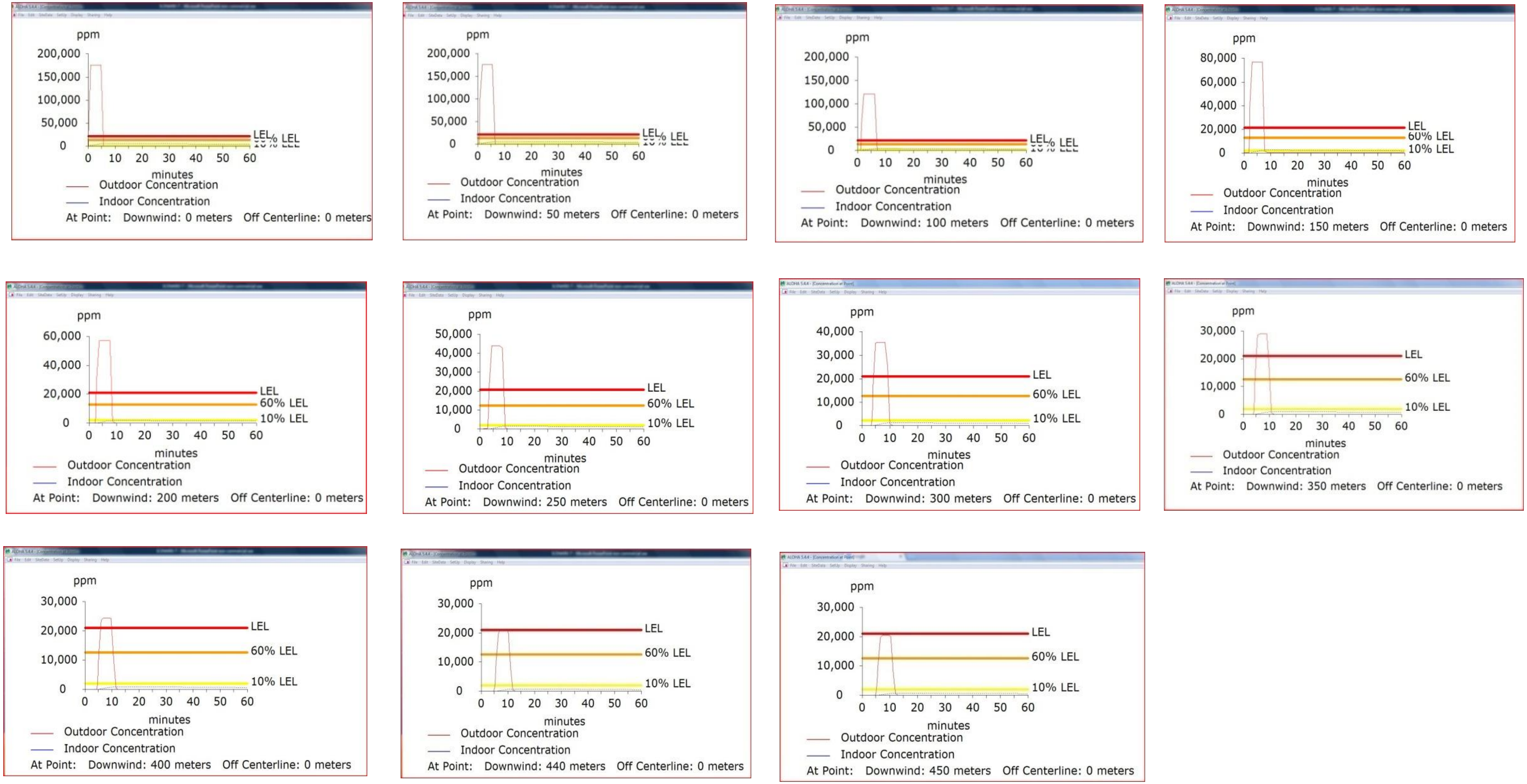


Fig F.37 – 30m x 30m Grid for Event 9

The probability of fatality within the flame envelope is considered as 1 and 0 for outside the enveloped.

Table F.24 – Probability of Fatality for Event 9

	PROBABILITY OF FATALITY															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1																
2																
3			1	1	1	1	1									
4			1	1	1	1	1	1								
5				1												
6				1												
7			1													
8		1														
9	1					1	1	1	1	1						
10		1	1	1	1	1	1	1	1	1	1	1				
11			1				1	1	1	1	1	1	1			
12			1			1		1	1	1	1	1	1			
13			1					1	1	1	1	1	1	1		
14								1	1	1	1	1	1	1	1	
15												1	1	1	1	1
16												1	1	1	1	1
17												1	1	1	1	1
18													1			



At Point: Downwind: 0 meters Off Centerline: 0 meters

At Point: Downwind: 50 meters Off Centerline: 0 meters

At Point: Downwind: 100 meters Off Centerline: 0 meters

At Point: Downwind: 150 meters Off Centerline: 0 meters

At Point: Downwind: 200 meters Off Centerline: 0 meters

At Point: Downwind: 250 meters Off Centerline: 0 meters

At Point: Downwind: 300 meters Off Centerline: 0 meters

At Point: Downwind: 350 meters Off Centerline: 0 meters

At Point: Downwind: 400 meters Off Centerline: 0 meters

At Point: Downwind: 440 meters Off Centerline: 0 meters

At Point: Downwind: 450 meters Off Centerline: 0 meters

Fig F.38 – Concentration vs Time profiles for successive downwind distances

Table F.25 – Distribution of Fatality Values for Event 9

	FATALITIES															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	2.85	2.85	2.85	2.85	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	2.85	2.85	2.85	2.85	2.85	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	2.85	0.00	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	0.00	0.00	0.00	0.00
11	0.00	0.00	2.85	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85	2.85	2.85	0.00	0.00	0.00
12	0.00	0.00	2.85	0.00	0.00	2.85	0.00	2.85	2.85	2.85	2.85	2.85	2.85	0.00	0.00	0.00
13	0.00	0.00	2.85	0.00	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85	2.85	2.85	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85
16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85
17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.85	2.85	2.85	2.85	2.85

The total fatalities suffered due to event 9 is 224.8

1.10 Consequence Assessment of Event 10 – Continuous release of inventory through a 10mm diameter opening with immediate ignition resulting in a Jet fire.

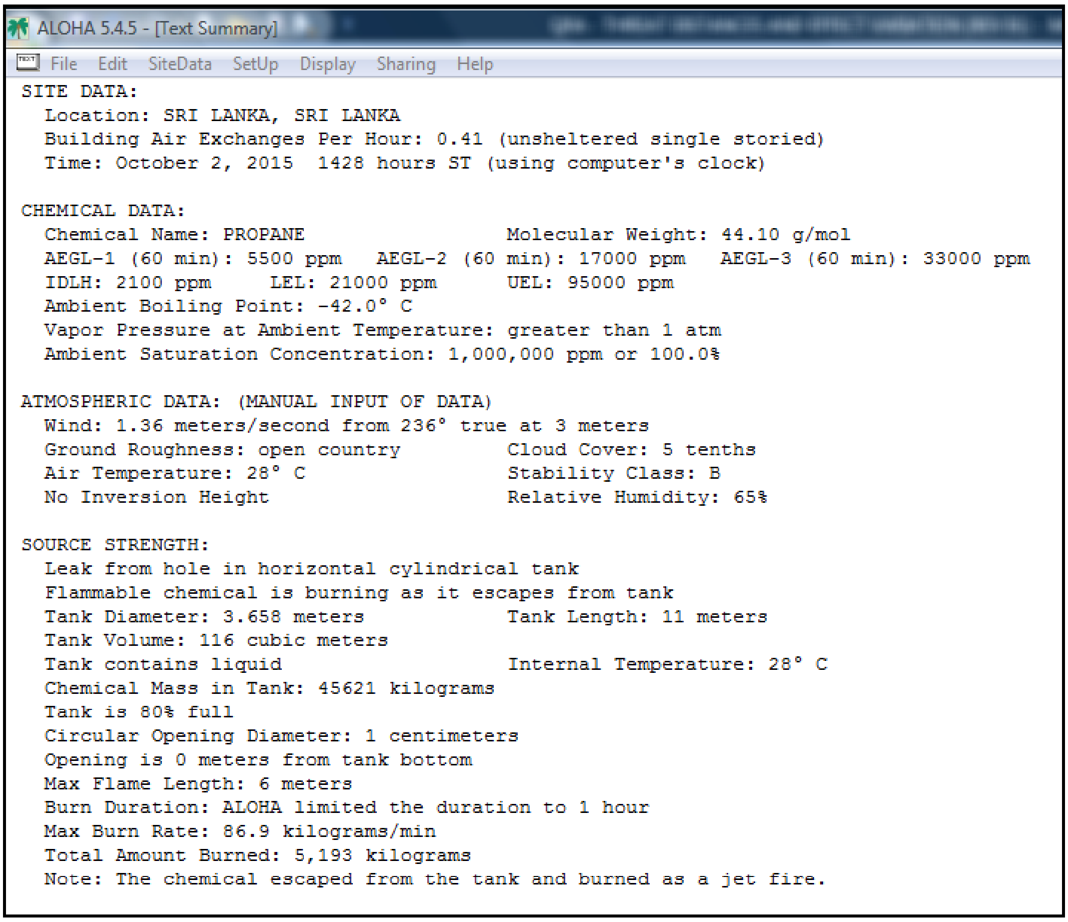
It is considered that a release takes place from the vessel through a 10mm diameter hole with ignition occurring at 1min after initiation of release. This event is modelled as a jet fire using ALOHA. The levels of concern are derived from the probit selected for thermal radiation effects based on Tsao & Perry.

$$Y = -36.38 + 2.56 \ln (I^{4/3}t) \text{ -----------------> (Based on Tsao \& Perry)}$$

The levels of concern used in the ALOHA model derived from the probit given above is as follows,

% Fatality	Thermal Radiation Intensity (kW/m2)
100	40.00
50	26.88
1	13.58

Table F.26 – Endpoints for Thermal Radiation Effects



```
SITE DATA:
  Location: SRI LANKA, SRI LANKA
  Building Air Exchanges Per Hour: 0.41 (unsheltered single storied)
  Time: October 2, 2015  1428 hours ST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: PROPANE                  Molecular Weight: 44.10 g/mol
  AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
  IDLH: 2100 ppm     LEL: 21000 ppm      UEL: 95000 ppm
  Ambient Boiling Point: -42.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.36 meters/second from 236° true at 3 meters
  Ground Roughness: open country          Cloud Cover: 5 tenths
  Air Temperature: 28° C                  Stability Class: B
  No Inversion Height                     Relative Humidity: 65%

SOURCE STRENGTH:
  Leak from hole in horizontal cylindrical tank
  Flammable chemical is burning as it escapes from tank
  Tank Diameter: 3.658 meters             Tank Length: 11 meters
  Tank Volume: 116 cubic meters
  Tank contains liquid                    Internal Temperature: 28° C
  Chemical Mass in Tank: 45621 kilograms
  Tank is 80% full
  Circular Opening Diameter: 1 centimeters
  Opening is 0 meters from tank bottom
  Max Flame Length: 6 meters
  Burn Duration: ALOHA limited the duration to 1 hour
  Max Burn Rate: 86.9 kilograms/min
  Total Amount Burned: 5,193 kilograms
  Note: The chemical escaped from the tank and burned as a jet fire.
```

Fig F.39 – Summary of Event 10

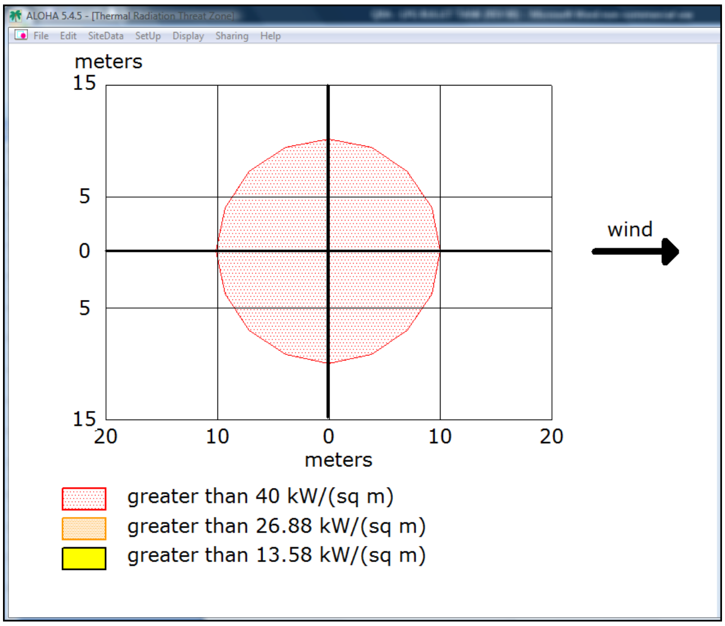


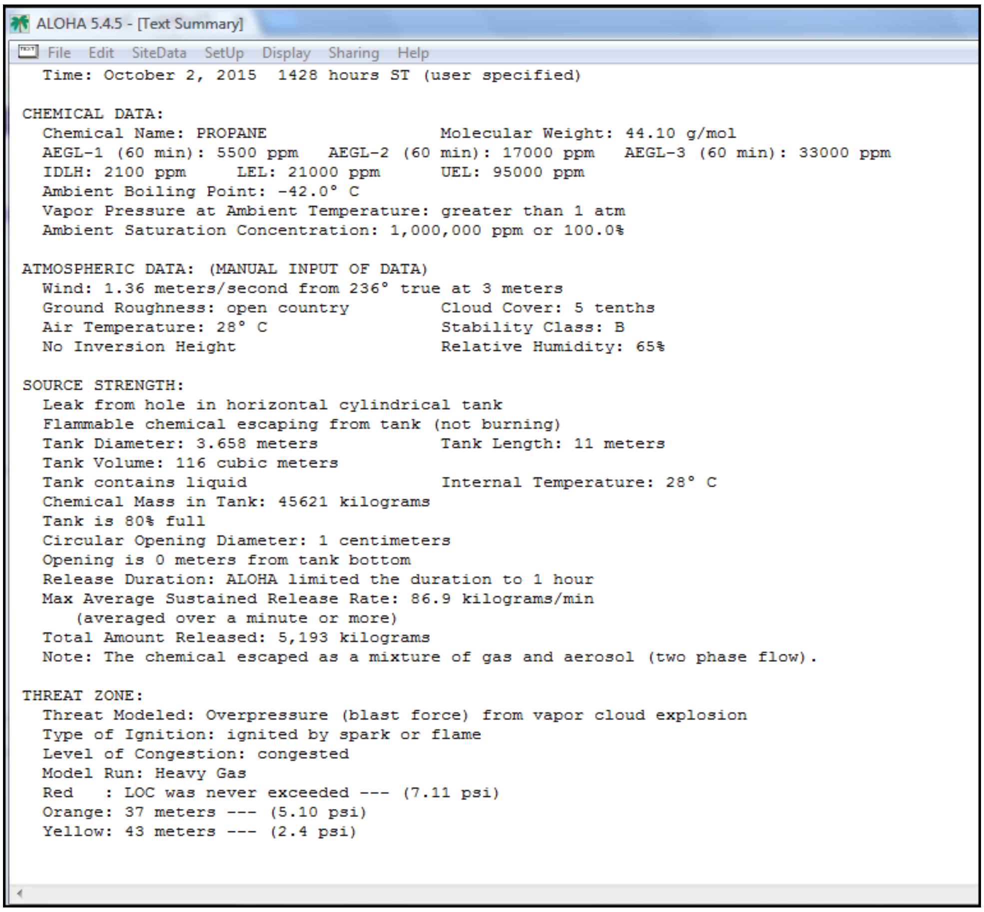
Fig F.40 – Threat Zone for Event 10

The threat zone does not extend into the public area; hence there is no direct threat to the public. However, the jet fire can lead to domino effects on any adjacent bullets which can result in a hot rupture and BLEVE event. BLEVE effects are covered in section 1.1 of appendix F. Fatalities from a jet fire due to direct effects are not investigated further as the effects are localized.

1.11 Consequence Assessment of Event 11 – Continuous release of inventory through a 10mm diameter opening with delayed ignition resulting in a VCE.

The source terms (release rate) remains as in section 1.10 of appendix F.

The threat zone over all possible ignition times is modelled using ALOHA. Figure F.40 shows that the threat zone does not extend outside to the boundary demarcated by the public road for all ignition times; hence the public does not face a direct threat. The threat zone is not investigated further for fatalities.



```
   Time: October 2, 2015  1428 hours ST (user specified)

 CHEMICAL DATA:
   Chemical Name: PROPANE                  Molecular Weight: 44.10 g/mol
   AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
   IDLH: 2100 ppm     LEL: 21000 ppm       UEL: 95000 ppm
   Ambient Boiling Point: -42.0° C
   Vapor Pressure at Ambient Temperature: greater than 1 atm
   Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

 ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
   Wind: 1.36 meters/second from 236° true at 3 meters
   Ground Roughness: open country           Cloud Cover: 5 tenths
   Air Temperature: 28° C                   Stability Class: B
   No Inversion Height                      Relative Humidity: 65%

 SOURCE STRENGTH:
   Leak from hole in horizontal cylindrical tank
   Flammable chemical escaping from tank (not burning)
   Tank Diameter: 3.658 meters              Tank Length: 11 meters
   Tank Volume: 116 cubic meters
   Tank contains liquid                     Internal Temperature: 28° C
   Chemical Mass in Tank: 45621 kilograms
   Tank is 80% full
   Circular Opening Diameter: 1 centimeters
   Opening is 0 meters from tank bottom
   Release Duration: ALOHA limited the duration to 1 hour
   Max Average Sustained Release Rate: 86.9 kilograms/min
      (averaged over a minute or more)
   Total Amount Released: 5,193 kilograms
   Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).

 THREAT ZONE:
   Threat Modeled: Overpressure (blast force) from vapor cloud explosion
   Type of Ignition: ignited by spark or flame
   Level of Congestion: congested
   Model Run: Heavy Gas
   Red   : LOC was never exceeded --- (7.11 psi)
   Orange: 37 meters --- (5.10 psi)
   Yellow: 43 meters --- (2.4 psi)
```

Fig F.41 – Summary of Event 11

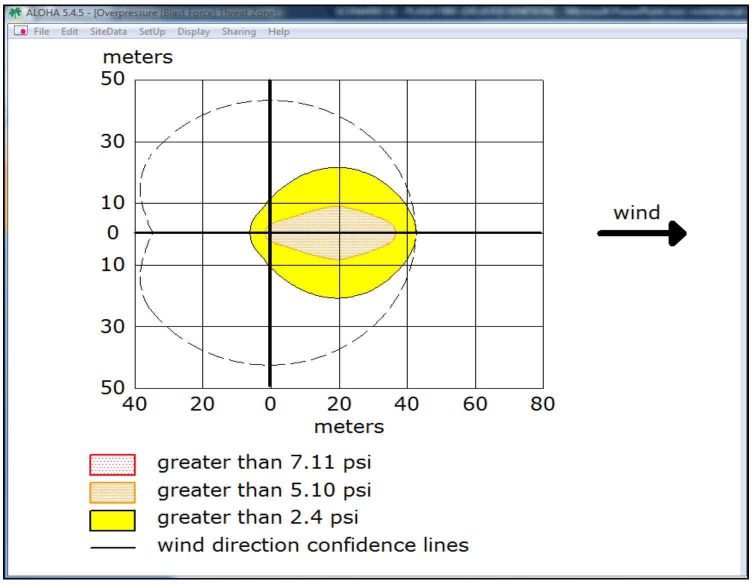


Fig F.42 – Threat Zone due to VCE for all ignition times

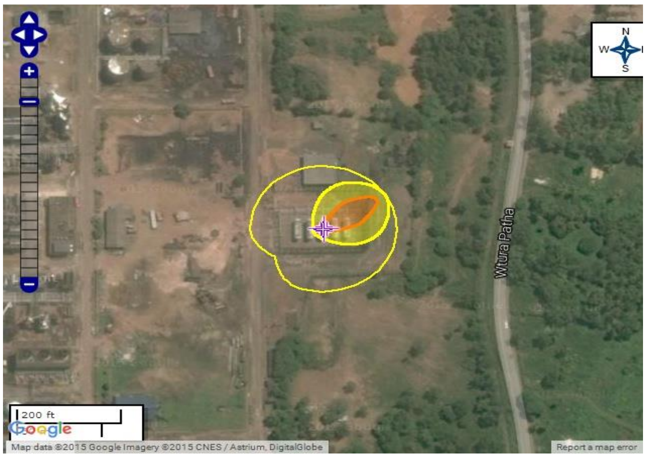
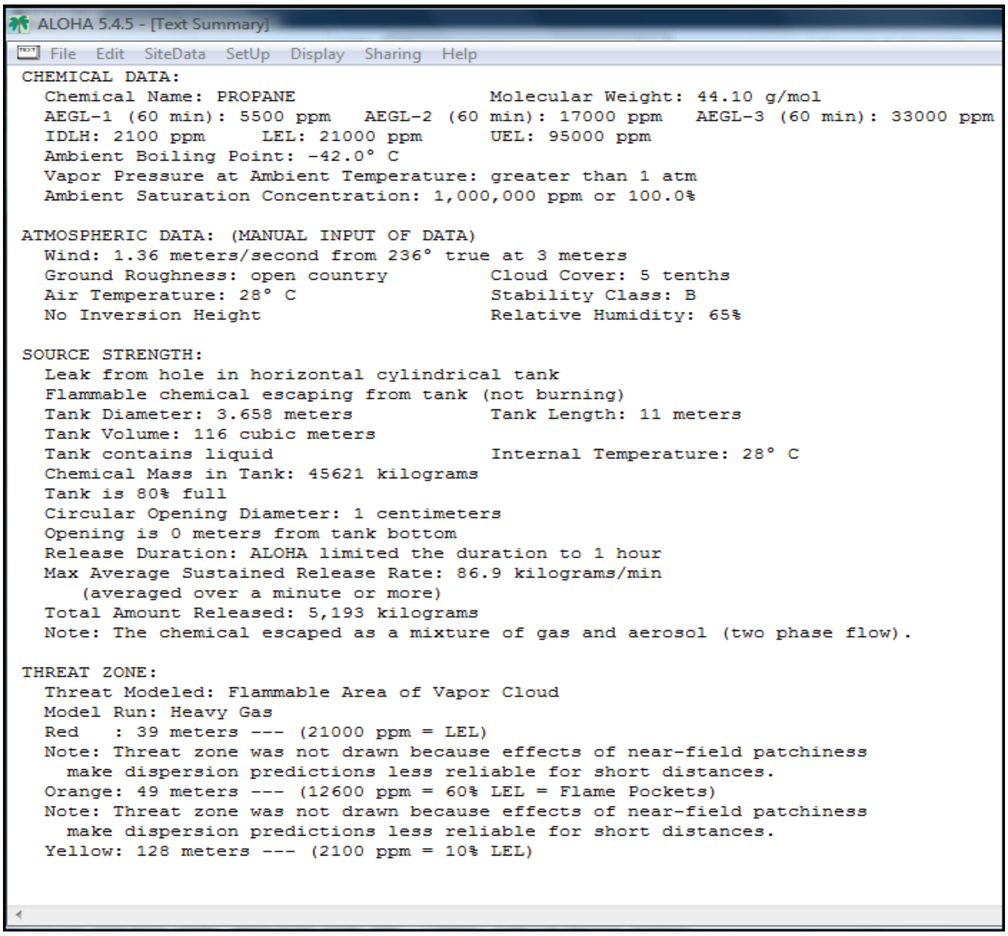


Fig F.43 – Threat Zone superimposed on the geographical location

1.12 Consequence Assessment of Event 10 – Continuous release of inventory through a 10mm diameter opening with delayed ignition resulting in a flash fire.

The source terms (release rate) remains as in section 1.10.

The threat zone is given in Fig F.44. It is superimposed on the geographical location in figure F.45. The end point of 100% LEL is never met; hence a flame envelope shall not form capable of causing a flash fire. Fatalities to the public as well as onsite are zero.



```
CHEMICAL DATA:
   Chemical Name: PROPANE                         Molecular Weight: 44.10 g/mol
   AEGL-1 (60 min): 5500 ppm   AEGL-2 (60 min): 17000 ppm   AEGL-3 (60 min): 33000 ppm
   IDLH: 2100 ppm      LEL: 21000 ppm      UEL: 95000 ppm
   Ambient Boiling Point: -42.0° C
   Vapor Pressure at Ambient Temperature: greater than 1 atm
   Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
   Wind: 1.36 meters/second from 236° true at 3 meters
   Ground Roughness: open country                 Cloud Cover: 5 tenths
   Air Temperature: 28° C                         Stability Class: B
   No Inversion Height                            Relative Humidity: 65%

SOURCE STRENGTH:
   Leak from hole in horizontal cylindrical tank
   Flammable chemical escaping from tank (not burning)
   Tank Diameter: 3.658 meters                    Tank Length: 11 meters
   Tank Volume: 116 cubic meters
   Tank contains liquid                           Internal Temperature: 28° C
   Chemical Mass in Tank: 45621 kilograms
   Tank is 80% full
   Circular Opening Diameter: 1 centimeters
   Opening is 0 meters from tank bottom
   Release Duration: ALOHA limited the duration to 1 hour
   Max Average Sustained Release Rate: 86.9 kilograms/min
      (averaged over a minute or more)
   Total Amount Released: 5,193 kilograms
   Note: The chemical escaped as a mixture of gas and aerosol (two phase flow).

THREAT ZONE:
   Threat Modeled: Flammable Area of Vapor Cloud
   Model Run: Heavy Gas
   Red   : 39 meters --- (21000 ppm = LEL)
   Note: Threat zone was not drawn because effects of near-field patchiness
     make dispersion predictions less reliable for short distances.
   Orange: 49 meters --- (12600 ppm = 60% LEL = Flame Pockets)
   Note: Threat zone was not drawn because effects of near-field patchiness
     make dispersion predictions less reliable for short distances.
   Yellow: 128 meters --- (2100 ppm = 10% LEL)
```

Fig F.44 – Summary of event 12

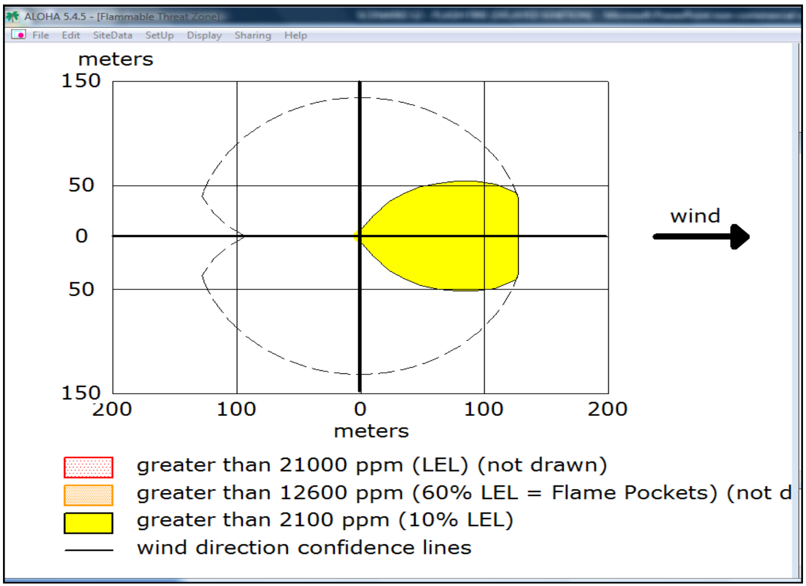


Fig F.45 – Threat Zone for Flash Fire due to Event 12

Fig F.46 - Threat Zone superimposed on the geographical location

Appendix – G: Comparison of Factors Contributing to Variations in the Failure Rate/ Failure Frequency Data Set

Table G.1 – Likely factors contributing to variations in the failure rate/ failure frequency data set

FACTOR		GENERIC FAILURE FREQUENCY DATA SET				
		RIVM	**TAYLOR**	**OGP**	**FLEMISH**	**API RP 581**
1	Historical Data Sources	Directly linked to the FF in PB 99 which is based on IPO data (1994) derived from earlier studies such the COVO Study (1981)[1,2,3]	Failure causes based on the MHIDAS database. HSE Offshore and US RMP data are considered. Credit is given to work by Phillips and Warwick (1970's and 1980's)[6]	Mainly historical data (Global Events)	Originates in the study by Smith & Warwick (1981) and modified by Technica (Project F424)[7]	Credits "Best Available Data Sources" and API RBI Sponsor Group. However, the data sources are not defined specifically. Most likely drawn from the Petroleum Refining Industry.
2	Use of Expert Judgement	Nussey[2] states that professional judgement has been used in interpreting older data sets	Expert judgement used	Cannot confirm	Expert judgement is used	Likely. Cannot confirm.
3	Definition of Pressure Vessel	Vessel, welded stumps, mounting plates, pipe connections up to the first flange, instrumentation pipes	Not clearly defined. States "Vessel and all its associated fittings". However, the introduction of uncertainty due to such a definition is duly recognized.	Must operate under a pressure of at least 0.5 bar. Vessel with any equipment directly associated (nozzles and instrumentation with associated flanges, manway and connection points upto the first flange – flange is not included).	The installation part 'pressure tank' consists of the vessel including the manhole, instrumentation connections and pipe connections up to the first flange. Leaks in the corresponding pipe system are not included.	Vessel (Drum) is chosen
4	Use of FTA	Used in deriving Catastrophic Failure Frequencies	Used extensively	Not known	Not known	Not known
5	Modification Factors	None. The default failure frequencies are used	Included and listed in detail	Not known	Modification factors such as effects from operating environment, vessel material, effect of tank inspections (radiography), stress relief has been considered	Well identified and included into the evaluation framework.

Appendix – H: Accident Frequencies (f) and Fatalities (N) for Generic Failure Frequency Data Sets

Table H.1 – Fatalities (N) vs Accident Frequency (f) for RIVM Failure Frequencies

SCENARIO/ EVENT			TYPE OF RELEASE	FAILURE FREQUENCY	PROBABILITY OF DIRECT IGNITION	PROBABILTY OF DIRECT IGNITION **NOT** OCCURING	PROBABILITY A BLEVE WILL OCCUR	PROBABILITY A BLEVE WILL **NOT** OCCUR	PROBABILITY OF DELAYED IGNITION	PROBABILITY OF DELAYED IGNITION **NOT** OCCURING	PROBABILITY OF FLAME FRONT PROPAGATION	PROBABILITY OF FLAME FRONT PROPAGATION **NOT** OCCURING	PROBABILITY OF JET FIRE IMPINGING ON VESSEL	PROBABILITY OF JET FIRE **NOT** IMPINGING ON VESSEL	ACCIDENT FREQUENCY	NUMBER OF FATALITIES
FINAL CONSEQUENCE		SEQUENCE OF EVENTS LEADING TO FINAL CONSEQUENCE		ff_j	a	a^1	b	b^1	d	d^1	c	c^1	e	e^1	f	N
1	BLEVE	$(ff_1)(a)(b)$	Instantaneous	5.00×10^{-7}	0.7	-	0.7	-	-	-	-	-			2.45×10^{-7}	112.8
2	VCE	$(ff_1)(a)(b^1)(c)$	Instantaneous	5.00×10^{-7}	0.7			0.3			0.4				4.20×10^{-8}	2.4
3	FLASH FIRE	$(ff_1)(a)(b^1)(c^1)$	Instantaneous	5.00×10^{-7}	0.7			0.3				0.6			6.30×10^{-8}	47.4
4	VCE	$(ff_1)(a^1)(d)(c)$	Instantaneous	5.00×10^{-7}		0.3			1		0.4				6.00×10^{-8}	50.7
5	FLASH FIRE	$(ff_1)(a^1)(d)(c^1)$	Instantaneous	5.00×10^{-7}		0.3			1			0.6			9.00×10^{-8}	284.6
6	BLEVE	$(ff_2)(a)(e)$	Continuous (Within 10 minutes)	5.00×10^{-7}	0.7								0.5		1.75×10^{-7}	112.8
7	VCE	$(ff_2)(a^1)(d)(c)$	Continuous (Within 10 minutes)	5.00×10^{-7}		0.3			1		0.4				6.00×10^{-8}	36.4
8	FLASH FIRE	$(ff_2)(a^1)(d)(c^1)$	Continuous (Within 10 minutes)	5.00×10^{-7}		0.3			1			0.6			9.00×10^{-8}	224.8
9	BLEVE	$(ff_3)(a)(e)$	Continuous (10 mm Hole)	1.00×10^{-5}	0.7								0.5		3.50×10^{-6}	112.8

Note: The index j in failure frequencies (ff_j) is as follows,

1. j = 1 for instantaneous release of entire inventory of the storage vessel
2. j = 2 for continuous release of entire inventory within 10 minutes
3. j = 3 for continuous release through a 10mm hole in the vessel

Table H.2 - Fatalities (N) vs Accident Frequency (f) for OGP Failure Frequencies

SCENARIO/ EVENT			TYPE OF RELEASE	FAILURE FREQUENCY	PROBABILITY OF DIRECT IGNITION	PROBABILTY OF DIRECT IGNITION **NOT** OCCURING	PROBABILITY A BLEVE WILL OCCUR	PROBABILITY A BLEVE WILL **NOT** OCCUR	PROBABILITY OF DELAYED IGNITION	PROBABILITY OF DELAYED IGNITION **NOT** OCCURING	PROBABILITY OF FLAME FRONT PROPAGATION	PROBABILITY OF FLAME FRONT PROPAGATION **NOT** OCCURING	PROBABILITY OF JET FIRE IMPINGING ON VESSEL	PROBABILITY OF JET FIRE **NOT** IMPINGING ON VESSEL	ACCIDENT FREQUENCY	NUMBER OF FATALITIES
FINAL CONSEQUENCE		SEQUENCE OF EVENTS LEADING TO FINAL CONSEQUENCE		ff_j	a	a^1	b	b^1	d	d^1	c	c^1	e	e^1	f	N
1	BLEVE	$(ff_1)(a)(b)$	Instantaneous	4.70×10^{-7}	0.7	-	0.7	-	-	-	-	-			2.30×10^{-7}	112.8
2	VCE	$(ff_1)(a)(b^1)(c)$	Instantaneous	4.70×10^{-7}	0.7			0.3			0.4				3.95×10^{-8}	2.4
3	FLASH FIRE	$(ff_1)(a)(b^1)(c^1)$	Instantaneous	4.70×10^{-7}	0.7			0.3				0.6			5.92×10^{-8}	47.4
4	VCE	$(ff_1)(a^1)(d)(c)$	Instantaneous	4.70×10^{-7}		0.3			1		0.4				5.64×10^{-8}	50.7
5	FLASH FIRE	$(ff_1)(a^1)(d)(c^1)$	Instantaneous	4.70×10^{-7}		0.3			1			0.6			8.46×10^{-8}	284.6
6	BLEVE	$(ff_2)(a)(e)$	Continuous (Within 10 minutes)	4.30×10^{-6}	0.7								0.5		1.51×10^{-6}	112.8
7	VCE	$(ff_2)(a^1)(d)(c)$	Continuous (Within 10 minutes)	4.30×10^{-6}		0.3			1		0.4				5.16×10^{-7}	36.4
8	FLASH FIRE	$(ff_2)(a^1)(d)(c^1)$	Continuous (Within 10 minutes)	4.30×10^{-6}		0.3			1			0.6			7.74×10^{-7}	224.8
9	BLEVE	$(ff_3)(a)(e)$	Continuous (10 mm Hole)	7.10×10^{-6}	0.7								0.5		2.49×10^{-6}	112.8

Note: The index j in failure (ff_j) is as follows,

1. j = 1 for instantaneous release of entire inventory of the storage vessel
2. j = 2 for continuous release of entire inventory within 10 minutes
3. j = 3 for continuous release through a 10mm hole in the vessel

Table H.3 - Fatalities (N) vs Accident Frequency (f) for Taylor Failure Frequencies

SCENARIO/ EVENT			TYPE OF RELEASE	FAILURE FREQUENCY	PROBABILITY OF DIRECT IGNITION	PROBABILTY OF DIRECT IGNITION **NOT** OCCURING	PROBABILITY A BLEVE WILL OCCUR	PROBABILITY A BLEVE WILL **NOT** OCCUR	PROBABILITY OF DELAYED IGNITION	PROBABILITY OF DELAYED IGNITION **NOT** OCCURING	PROBABILITY OF FLAME FRONT PROPAGATION	PROBABILITY OF FLAME FRONT PROPAGATION **NOT** OCCURING	PROBABILITY OF JET FIRE IMPINGING ON VESSEL	PROBABILITY OF JET FIRE **NOT** IMPINGING ON VESSEL	ACCIDENT FREQUENCY	NUMBER OF FATALITIES
FINAL CONSEQUENCE		SEQUENCE OF EVENTS LEADING TO FINAL CONSEQUENCE		ff_j	a	a^1	b	b^1	d	d^1	c	c^1	e	e^1	f	N
1	BLEVE	$(ff_1)(a)(b)$	Instantaneous	1.00×10^{-7}	0.7	-	0.7	-	-	-	-	-			4.90×10^{-8}	112.8
2	VCE	$(ff_1)(a)(b^1)(c)$	Instantaneous	1.00×10^{-7}	0.7			0.3			0.4				8.40×10^{-9}	2.4
3	FLASH FIRE	$(ff_1)(a)(b^1)(c^1)$	Instantaneous	1.00×10^{-7}	0.7			0.3				0.6			1.26×10^{-8}	47.4
4	VCE	$(ff_1)(a^1)(d)(c)$	Instantaneous	1.00×10^{-7}		0.3			1		0.4				1.20×10^{-8}	50.7
5	FLASH FIRE	$(ff_1)(a^1)(d)(c^1)$	Instantaneous	1.00×10^{-7}		0.3			1			0.6			1.80×10^{-8}	284.6
6	BLEVE	$(ff_2)(a)(e)$	Continuous (Within 10 minutes)	3.00×10^{-4}	0.7								0.5		1.05×10^{-4}	112.8
7	VCE	$(ff_2)(a^1)(d)(c)$	Continuous (Within 10 minutes)	3.00×10^{-4}		0.3			1		0.4				3.60×10^{-5}	36.4
8	FLASH FIRE	$(ff_2)(a^1)(d)(c^1)$	Continuous (Within 10 minutes)	3.00×10^{-4}		0.3			1			0.6			5.40×10^{-5}	224.8
9	BLEVE	$(ff_3)(a)(e)$	Continuous (10 mm Hole)	8.00×10^{-4}	0.7								0.5		2.80×10^{-4}	112.8

Note: The index j in failure (ff_j) is as follows,

1. j = 1 for instantaneous release of entire inventory of the storage vessel
2. j = 2 for continuous release of entire inventory within 10 minutes
3. j = 3 for continuous release through a 10mm hole in the vessel

Table H.4 - Fatalities (N) vs Accident Frequency (f) for Flemish Failure Frequencies

SCENARIO/ EVENT			TYPE OF RELEASE	FAILURE FREQUENCY	PROBABILITY OF DIRECT IGNITION	PROBABILTY OF DIRECT IGNITION **NOT** OCCURING	PROBABILITY A BLEVE WILL OCCUR	PROBABILITY A BLEVE WILL **NOT** OCCUR	PROBABILITY OF DELAYED IGNITION	PROBABILITY OF DELAYED IGNITION **NOT** OCCURING	PROBABILITY OF FLAME FRONT PROPAGATION	PROBABILITY OF FLAME FRONT PROPAGATION **NOT** OCCURING	PROBABILITY OF JET FIRE IMPINGING ON VESSEL	PROBABILITY OF JET FIRE **NOT** IMPINGING ON VESSEL	ACCIDENT FREQUENCY	NUMBER OF FATALITIES
FINAL CONSEQUENCE		SEQUENCE OF EVENTS LEADING TO FINAL CONSEQUENCE		ff_j	a	a^1	b	b^1	d	d^1	c	c^1	e	e^1	f	N
1	BLEVE	$(ff_1)(a)(b)$	Instantaneous	3.20×10^{-7}	0.7	-	0.7	-	-	-	-	-			1.57×10^{-7}	112.8
2	VCE	$(ff_1)(a)(b^1)(c)$	Instantaneous	3.20×10^{-7}	0.7			0.3			0.4				2.69×10^{-8}	2.4
3	FLASH FIRE	$(ff_1)(a)(b^1)(c^1)$	Instantaneous	3.20×10^{-7}	0.7			0.3				0.6			4.03×10^{-8}	47.4
4	VCE	$(ff_1)(a^1)(d)(c)$	Instantaneous	3.20×10^{-7}		0.3			1		0.4				3.84×10^{-8}	50.7
5	FLASH FIRE	$(ff_1)(a^1)(d)(c^1)$	Instantaneous	3.20×10^{-7}		0.3			1			0.6			5.76×10^{-8}	284.6
6	BLEVE	$(ff_2)(a)(e)$	Continuous (Within 10 minutes)	1.10×10^{-6}	0.7								0.5		3.85×10^{-7}	112.8
7	VCE	$(ff_2)(a^1)(d)(c)$	Continuous (Within 10 minutes)	1.10×10^{-6}		0.3			1		0.4				1.32×10^{-7}	36.4
8	FLASH FIRE	$(ff_2)(a^1)(d)(c^1)$	Continuous (Within 10 minutes)	1.10×10^{-6}		0.3			1			0.6			1.98×10^{-7}	224.8
9	BLEVE	$(ff_3)(a)(e)$	Continuous (10 mm Hole)	1.20×10^{-5}	0.7								0.5		4.20×10^{-6}	112.8

Note: The index j in failure (ff_j) is as follows,

1. j = 1 for instantaneous release of entire inventory of the storage vessel
2. j = 2 for continuous release of entire inventory within 10 minutes
3. j = 3 for continuous release through a 10mm hole in the vessel

Table H.5 - Fatalities (N) vs Accident Frequency (f) for API RP 581 Failure Frequencies

SCENARIO/ EVENT			TYPE OF RELEASE	FAILURE FREQUENCY	PROBABILITY OF DIRECT IGNITION	PROBABILTY OF DIRECT IGNITION **NOT** OCCURING	PROBABILITY A BLEVE WILL OCCUR	PROBABILITY A BLEVE WILL **NOT** OCCUR	PROBABILITY OF DELAYED IGNITION	PROBABILITY OF DELAYED IGNITION **NOT** OCCURING	PROBABILITY OF FLAME FRONT PROPAGATION	PROBABILITY OF FLAME FRONT PROPAGATION **NOT** OCCURING	PROBABILITY OF JET FIRE IMPINGING ON VESSEL	PROBABILITY OF JET FIRE **NOT** IMPINGING ON VESSEL	ACCIDENT FREQUENCY	NUMBER OF FATALITIES
FINAL CONSEQUENCE		SEQUENCE OF EVENTS LEADING TO FINAL CONSEQUENCE		ff_j	a	a^1	b	b^1	d	d^1	c	c^1	e	e^1	f	N
1	BLEVE	$(ff_1)(a)(b)$	Instantaneous	6.00×10^{-7}	0.7	-	0.7	-	-	-	-	-			2.94×10^{-7}	112.8
2	VCE	$(ff_1)(a)(b^1)(c)$	Instantaneous	6.00×10^{-7}	0.7			0.3			0.4				5.04×10^{-8}	2.4
3	FLASH FIRE	$(ff_1)(a)(b^1)(c^1)$	Instantaneous	6.00×10^{-7}	0.7			0.3				0.6			7.56×10^{-8}	47.4
4	VCE	$(ff_1)(a^1)(d)(c)$	Instantaneous	6.00×10^{-7}		0.3			1		0.4				7.20×10^{-8}	50.7
5	FLASH FIRE	$(ff_1)(a^1)(d)(c^1)$	Instantaneous	6.00×10^{-7}		0.3			1			0.6			1.08×10^{-7}	284.6
6	BLEVE	$(ff_2)(a)(e)$	Continuous (Within 10 minutes)	2.00×10^{-6}	0.7								0.5		7.00×10^{-7}	112.8
7	VCE	$(ff_2)(a^1)(d)(c)$	Continuous (Within 10 minutes)	2.00×10^{-6}		0.3			1		0.4				2.40×10^{-7}	36.4
8	FLASH FIRE	$(ff_2)(a^1)(d)(c^1)$	Continuous (Within 10 minutes)	2.00×10^{-6}		0.3			1			0.6			3.60×10^{-7}	224.8
9	BLEVE	$(ff_3)(a)(e)$	Continuous (10 mm Hole)	2.00×10^{-5}	0.7								0.5		7.00×10^{-6}	112.8

Note: The index j in failure (ff_j) is as follows,

1. j = 1 for instantaneous release of entire inventory of the storage vessel
2. j = 2 for continuous release of entire inventory within 10 minutes
3. j = 3 for continuous release through a 10mm hole in the vessel

Appendix – I: Accident Frequencies (f) and Fatalities (N) for Generic Failure Frequency with Safety Barriers

Table I.1 –Fatalities (N) vs Accident Frequency (f) for the Upper Bound Failure Frequency Data Set after inclusion of Safety Barriers

SCENARIO/ EVENT			TYPE OF RELEASE	FAILURE FREQUENCY	PROBABILITY OF DIRECT IGNITION	PROBABILTY OF DIRECT IGNITION **NOT** OCCURING	PROBABILITY OF ACTIVATION OF GAS DETECTION AND EMERGENCY RESPONSE	PROBABILITY OF GAS DETECTION AND EMERGENCY RESPONSE **NOT** BEING ACTIVATED	PROBABILITY A BLEVE WILL OCCUR	PROBABILITY A BLEVE WILL **NOT** OCCUR	PROBABILITY OF DELAYED IGNITION	PROBABILITY OF DELAYED IGNITION **NOT** OCCURING	PROBABILITY OF FLAME FRONT PROPAGATION	PROBABILITY OF FLAME FRONT PROPAGATION **NOT** OCCURING	PROBABILITY OF JET FIRE IMPINGING ON VESSEL	PROBABILITY OF JET FIRE **NOT** IMPINGING ON VESSEL	PROBABILITY OF SUCCESS OF FIREPROOFING	PROBABILITY OF FAILURE OF FIRE PROOFING	ACCIDENT FREQUENCY	NUMBER OF FATALITIES
FINAL CONSEQUENCE		SEQUENCE OF EVENTS LEADING TO FINAL CONSEQUENCE		ff_j	a	a^1	g	g^1	b	b^1	d	d^1	c	c^1	e	e^1	i	i^1	f	N
1	BLEVE	$(ff_1)(a)(b)$	Instantaneous	5.00 x 10^{-7}	0.7	-			0.7	-	-	-	-	-					4.90 x 10^{-8}	112.8
2	VCE	$(ff_1)(a)(b^1)(c)$	Instantaneous	5.00 x 10^{-7}	0.7					0.3			0.4						8.40 x 10^{-9}	2.4
3	FLASH FIRE	$(ff_1)(a)(b^1)(c^1)$	Instantaneous	5.00 x 10^{-7}	0.7					0.3				0.6					1.26 x 10^{-8}	47.4
4	VCE	$(ff_1)(a^1)(g^1)(d)(c)$	Instantaneous	5.00 x 10^{-7}		0.3		0.01			1		0.4						1.20 x 10^{-10}	50.7
5	FLASH FIRE	$(ff_1)(a^1)(g^1)(d)(c^1)$	Instantaneous	5.00 x 10^{-7}		0.3		0.01			1			0.6					1.80 x 10^{-10}	284.6
6	BLEVE	$(ff_2)(a)(e)(i^1)$	Continuous (Within 10 minutes)	5.00 x 10^{-7}	0.7										0.5			0.01	1.05 x 10^{-6}	112.8
7	VCE	$(ff_2)(a^1)(g^1)(d)(c)$	Continuous (Within 10 minutes)	5.00 x 10^{-7}		0.3		0.01			1		0.4						3.60 x 10^{-7}	36.4
8	FLASH FIRE	$(ff_2)(a^1)(g^1)(d)(c^1)$	Continuous (Within 10 minutes)	5.00 x 10^{-7}		0.3		0.01			1			0.6					5.40 x 10^{-7}	224.8
9	BLEVE	$(ff_3)(a)(e)(i^1)$	Continuous (10 mm Hole)	1.00 x 10^{-5}	0.7										0.5			0.01	2.80 x 10^{-6}	112.8

Note: The index j in failure frequency (ff_j) is as follows,

1. j = 1 for instantaneous release of entire inventory of the storage vessel
2. j = 2 for continuous release of entire inventory within 10 minutes
3. j = 3 for continuous release through a 10mm hole in the vessel

Appendix – J: Theoretical Basis for the “Relative Risk Reduction Factor (RRRF)

The RRRF is based on the premise that the area bounded by the boundaries defined by the following functions is a measure of the level of risk posed by a system,

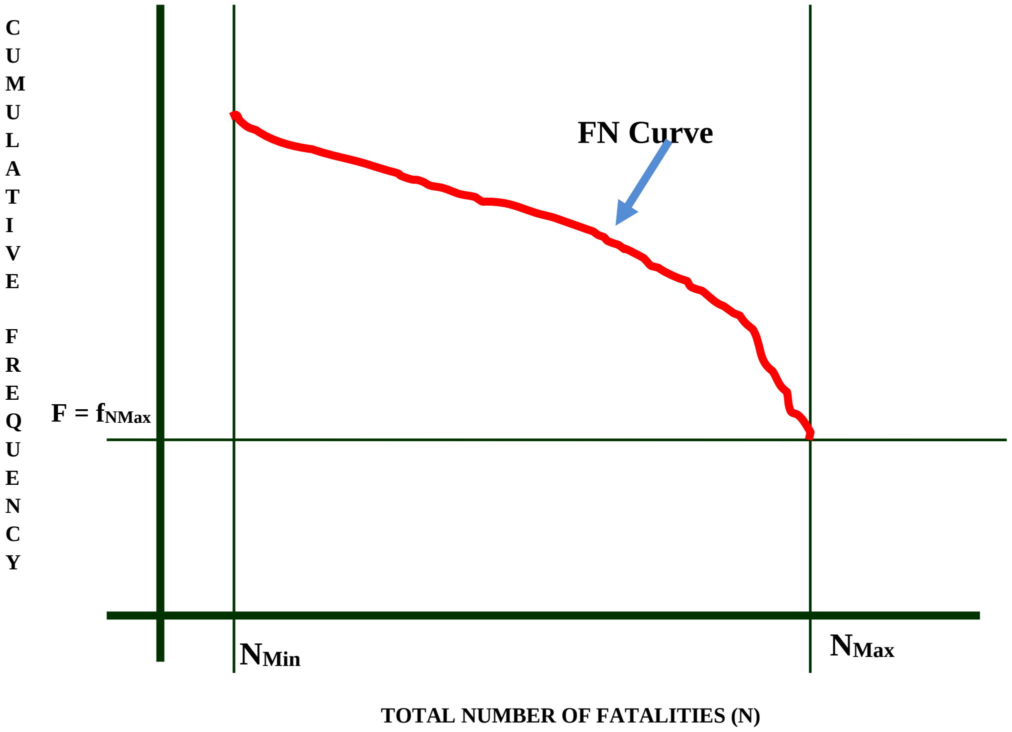


Figure J.1 – Bounded area used for the Calculation of “Level of Risk”

It can indeed be proved that the area under the FN Curve is a weighted average of the possible values taken by N corresponding to the frequency of occurrence f (N). It can be shown as given below (Ravindran, Philips & Solberg, 1987; Ross, 2014),

$$Ex = \int_0^\infty P(X > t)dt = \int_0^\infty F'(t)dt = \int_0^\infty tf(t)dt$$

$$F(t) = P(X \leq t),\ F'(t) = 1 - F(t)$$

Where,

Ex - Expectation

X – Non negative random variable

F (t) – Cumulative Density Function (CDF), $F'(t)$ - Complementary Cumulative Density Function (CCDF)

The aforementioned relationship can be applied to the FN Curve as given below,

Ex (X) = $\int_0^\infty P(X > N)dN$ = $\int_0^\infty F'(N)dN$ = $\int_0^\infty Nf(N)dN$

Where,

N - Number of Fatalities

f (N) – Probability density function (p.d.f) for the occurrence of N fatalities

The integral $\int_0^\infty F'(N)dN$, is in fact the area (A) under the FN Curve; since it is a weighted average and is a measure of the expectation it can be considered as a measure of the overall risk from a particular system. Weighted expectation for assessing land use planning proposals has been studied in detail by Francis et al (Francis, Edwards, Espiner, Haswell, Bilo & Carter, 1999).

Consider an FN curve yielding an area of A1 larger than an FN curve yielding an area A2, such that A1>A2. Hence, the FN curve corresponding to A1 will pose a higher level of risk than the one corresponding to A2. This is essentially the theoretical basis upon which the "Relative Risk Reduction Factor (RRRF)" is based on.