HAZARDS IDENTIFICATION AND RISK ASSESSMENT IN OFFSHORE PLATFORM

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
CHEMICAL ENGINEERING
(With Specialization in Industrial Safety and Hazards Management)

By
WANKHEDE SAGAR GANGARAM

DEPARTMENT OF CHEMICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)
JUNE, 2008

CANDIDATES' DECLARATION

I hereby certify that the work which is being presented in this dissertation entitled **"HAZARDS IDENTIFICATION AND RISK ASSESSMENT IN OFFSHORE PLATFORM"**, in the partial fulfillment of the requirements for the award of the degree of "**Master of Technology**" in **CHEMICAL ENGINEERING** with specialization in "**Industrial Safety and Hazards Management**", submitted in the Department of CHEMICAL ENGINEERING, Indian Institute of Technology Roorkee, under the supervision of **Dr. V. K. AGARWAL**, Professor, Department of Chemical Engineering, Indian Institute of Technology Roorkee.

I have not submitted the matter, embodied in this dissertation for the award of any other degree.

Date: 27-06-08
Place: IIT Roorkee

Wankhede Sagar Gangaram

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

Dr. V.K. AGARWAL
Professor
Department of Chemical Engineering
IIT Roorkee

ACKNOWLEDGEMENT

I first of all like to express my deepest gratitude to my supervisor Dr. V. K.AGRAWAL for his esteemed guidance and support throughout this work. He has always been concerned, kind and understanding and from him I learned many new ideas.

I am grateful to Prof. Shri Chand, Head of the Department, Department of Chemical Engineering, IIT Roorkee, who has let me use their facilities for conducting most of my dissertation work.

I am thankful to Siraz Alam, Research Scholar, Department of Chemical Engineering, IIT Roorkee. I also would like to express my gratitude to all my teachers at Department of Chemical Engineering, IIT Roorkee, who have taught me how to learn, think, decide, and have a stance in life, and who have motivated me during my M Tech course.

I also thank all the non teaching staff of the Department for their help and support and everything else during my work in the laboratory.

My dear laboratory mates Allwyn Abraham, and Rashid Mamoon, whom I see as part of this study, also deserve deep appreciation for everything we have shared. I have lived through the happiness of overcoming the challenges and stresses of the study environment with them and I hope I will have such colleagues in the future.

I would like to thank my friends Manu Agarwal, Vivek S. Khaire, Nilesh Bhosale, Sunil Bagade and Yogesh Dadheech for their help and for being there when I needed, for showing me the meaning of real friendship.

Finally, I am grateful to my mother Vatsalatai Wankhede and my father Gangaram Wankhede and all My family Members who have much contributed to my achievements, for their endless love and support in every single moment of my life.

(WANKHEDE SAGAR GANGARAM)

ABSTRACT

Offshore oil and gas platforms are well-known for their compact geometry, high degree of congestion, limited ventilation and difficult escape routes. The level of risk in such conditions, while operating in a remote and harsh marine environment, is very high. A small mishap under such conditions can quickly escalate into a catastrophe. Among all the accidental process related events occurring offshore, fire is the most frequently reported. It is therefore necessary to study the behavior of fires and quantity the hazards posed by them in order to complete a detailed quantitative risk assessment.

The focus of this work is to use Quantitative Risk Assessment Methodology for estimating the risk levels and assessing their significance in accident prevention. Here this methodology is used for the predefining the accident scenario. It is used as a design basis for fire protection and emergency evacuation equipment, or for emergency planning and training. Fire Consequence models have been developed offshore Quantitative Risk Assessment.

This work signifies the prediction of human error probabilities during the process of emergency musters on offshore oil and gas production platforms by using the expert judgment technique called as Success Likelihood Index Methodology (SLIM). Three muster scenario of varying severity (man overboard, gas release, and fire and explosion) are studied in detailed.

SCAP methodology has been introduced for the risk-based process safety decision making for Offshore Oil Gas activities. This methodology is applied to various offshore process units, that is, the compressor, separators, flash drum and driers of an Offshore Oil Gas platform. Based on the risk potential, appropriate safety measures are designed for each unit. This paper also illustrates that implementation of the designed safety measures reduces the high Fatal accident rate (FAR) values to an acceptable level.

Keywords: Fire modeling, Quantitative risk assessment, Offshore risk modeling, Human Factors, Risk Assessment, Emergency Response

List of Figures

LIST OF TABLES

Nomenclature

β_1	Angle between the normal to the fire surface and the line joining the fire and the receiving element (degrees)
β_2	Angle between the normal to the target surface and the line joining the fire and the receiving element (degrees)
θ	Angle of tilt (degrees)
τ	Atmospheric transmissivity
σ	Stefan-Boltzmann constant ($5.669*10^{-8}$ W/m^2K^4)
A	Surface area of the flame (m^2)
b	Flame liftoff (m)
BHEP	Base Human Error Probability
C	Critical (consequence severity level)
CRT	Core Review Team
d	Distance from the receiver point to the flame center (m)
D	Pool diameter (m)
erf	Error function
EEP	Elevated Exposure Phase (of muster)
ERT	Elicitation Review Team
F&E	Fire & Explosion (muster scenario)
GR	Gas Release (muster scenario)
H	High (consequence severity level)
HEP	Human Error Probability
HEPI	Human Error Probability Index
HRA	Human Reliability Assessment
HTA	Hierarchical Task Analysis
i	Action (subscript)
k	Gray gas absorption coefficient (m^{-1})
k_m	Extinction coefficient (m^{-1})
L	Length of the pool fire (m)

L_c	Clear layer length (m)
n	Moles of combustion gases (mol)
m	Arithmetic mean (subscript)
M	Medium (consequence severity level)
MO	Man Overboard (muster scenario)
OIM	Offshore Installation Manager
ORA	Optimal Risk Analysis
P	Percentage damage (%)
P_o	Overpressure (N/m^2)
Pr	Probit number
POB	Personnel On Board
POS	Probability of Success
PSF	Performance Shaping Factor
q	Radiation heat flux (kW/m^2)
Q	Net heat released by combustion (kW)
QRA	Quantitative Risk Assessment
R	Gas constant (8.314 J/mol·K)
R_L	Length of the frustum (m)
RRM	Risk Reduction Measure
SEP	Average surface emissive power (kW/m^2)
SEP_∞	Maximum surface emissive power (kW/m^2)
SEP_L	Surface emissive power from clear lower layer (kW/m^2)
SEP_S	Surface emissive power of smoke (kW/m^2)
SEP_U	Surface emissive power from smoky upper layer (kW/m^2)
SLI	Success Likelihood Index
SLIM	Success Likelihood Index Methodology
SRK	Skill, Rule, Knowledge
t	Time of exposure (s)
T_{cc}	Temperature at one end of the compartment (K)
T_o	Initial compartment temperature (15° C)
T_{flame}	Flame temperature (K)

T_{gases}	Average gas temperature (K)
u_j	Velocity of the jet (m/s)
U_R	Unobscured ratio
U_x	Wind velocity in the downwind direction (m/s)
U_z	Wind velocity in the crosswind direction (m/s)
U_{xz}	Wind velocity vector (m/s)
VF	Geometric view factor
V_{room}	Volume of the compartment under study (m^3)
W_1	Width of frustum base (m)
W_2	Width of frustum tip (m)

CHAPTER 1

INTRODUCTION

Offshore oil and gas platforms are well-known for their compact geometry, high degree of congestion, limited ventilation and difficult escape routes. A small mishap under such conditions can quickly escalate into a catastrophe. Among all the accidental process related events occurring offshore, fire is the most frequently reported. It is therefore necessary to study the behavior of fires and quantity the hazards posed by them in order to complete a detailed quantitative risk assessment. While there are many consequence models available to predict fire hazards varying from point source models to highly complex computational fluid dynamic models only a few have been validated for the unique conditions found offshore. This study was structure, conduct and performance of the risk assessment and safety management of offshore drilling and production operation, had main four objectives: (1) Risk Assessment of offshore drilling and production platform (2) Safety Climate and Safety Management Practice in offshore environments (3) Identifying Root Causes of Offshore accidents (4) Investigate the Safety and Situation Awareness of offshore crews. Risk can not be avoided especially for complex projects like offshore drilling and production platform. The risk events of drilling and production platforms were ranked according to their occurrence and impact. The principal elements required to manage and mitigate higher risks are generally considered by :

- To eliminate or minimize the hazards by design (e.g. inherently safety, separating the person from the hazard);
- To prevent realization of the hazard (e.g. good inspection, maintenance,); To prevent escalation of the hazard (e.g. blow down);
- To control the hazard (e.g. provision of active or passive fire protection);
- To ensure that personnel can reach a place of safety for any credible event (e.g. adequate evacuation, escape, and rescue) followed to As Low As Reasonable Principle(ALARP).

Safety Climate Assessment Toolkit', an assessment technique, based on the use of multiple methods, was developed for assess the safety climate and safety management practice in offshore environments and seeks to build on current industry initiatives, such as the cross industry leadership initiative, general safety behavior, appreciation of risk etc. Offshore accident investigation techniques and reporting systems identify what type of accidents occur and how they occurred. Accident root causes tracing model (ARCTM) proposes that accidents occur due to three root causes like, failing to identify an unsafe condition that existed before an activity was started or that developed after an activity was started; deciding to proceed with a work activity after the worker identifies an existing unsafe condition; and deciding to act unsafe regardless of initial conditions of the work environment. Research finding showed that unsafe conditions are due to four main causes as Management actions/inactions; unsafe acts of worker or coworker; non-human-related event(s); an unsafe condition that is a natural part of the initial operation site conditions.

An offshore oil and gas platform is usually divided into a number of modules for operations such as separation, water injection, high-pressure compression, and seawater de-aeration, as well as local and main electrical rooms and an accommodations block. Most of these modules are highly congested with the presence of obstacles in the form of pipelines and other equipment necessary for process operations. The level of risk in such conditions, while operating in a remote and harsh marine environment, is very high.

A study by the UK Health and Safety Executive showed that process and structural failure incidents account for almost 80 % of the risk to personnel offshore. Potential risks offshore include: blowouts, riser and process leaks, fires, explosions, vessel collisions, helicopter accidents, dropped objects, structural failures, and capsizing. An examination of incidents such as Piper Alpha in the North Sea and the P-36 production semi-submersible off Brazil reveals that most offshore incidents are in fact process-related.

An offshore development can never be completely safe, but the degree of inherent safety can be increased by selecting the optimum design in terms of the installation/field configuration, layout, and operation. This is done in an attempt to reduce the risk to a level that is As Low As Reasonably Practicable (ALARP) without resorting to costly protective systems. This requires the identification and assessment of major risk contributors, which could be accomplished using Quantitative Risk Assessment (QRA) techniques early in the project life cycle. If a structured approach of identification and assessment is not carried out early in the project, it is possible that the engineering judgment approach will fail to identify all of the major risks, and that loss prevention expenditures will be targeted in areas where there is little benefit. This may result in expensive remedial actions later during the life of the project .

Quantitative risk assessment involves four main steps: hazard identification, consequence assessment, probability calculation, and finally risk quantification. Consequence assessment, which is central to QRA, involves quantification of the likely loss/damage due to any possible eventuality. Among the various possible loss-producing events in offshore production facilities, fire is the most frequently reported process-related incident. A fire may result in anything from no damage/loss, up to catastrophic damage/loss, depending upon the fire characteristics (type of fire, mode of occurrence and potential of escalation). Therefore, fire consequence modeling is a key element of consequence analysis in quantitative risk assessment. Even though mathematical models to study the characteristics of process-related fires in offshore process facilities are reported in the literature, only a few have been validated for offshore conditions.

1.1 RISK ANALYSIS IN THE CHEMICAL PROCESS INDUSTRY AND OFFSHORE INDUSTRY

Risk is defined as a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the injury, damage, or loss (CCPS, 2000). Risk analysis involves the development of an overall estimation of risk by gathering and integrating information about scenarios, frequencies and consequences, and it is one major component of the whole risk management process of a particular enterprise. In the process of risk analysis, both qualitative and quantitative techniques can be used, as shown in Figure 1.1

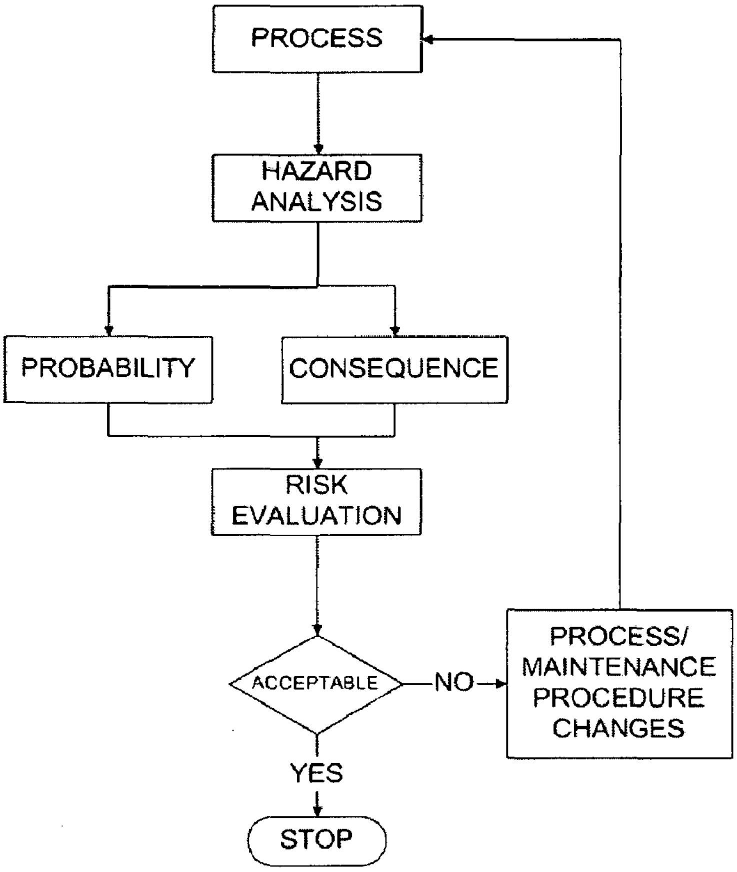


Figure 1.1 The process of risk analysis

1.2 RISK ANALYSIS - WHY?

Along with the rapid progress of industrialization, the risk of incidents (such as fire, explosion, and chemical release) is increasing as well. It became increasingly recognized that there was a worldwide trend for losses due to accidents to rise more rapidly than gross national product (Lees, 1996). The results of a major offshore platform accidents such as the explosion and fire on the Piper Alpha platform, which cost the lives of 167 persons was the world's worst offshore accident and fire on the Bombay High North (BHN) Platform which cost the lives of atleast 12 persons. The results of a major industrial accident can be devastating, such as the Flixborough, England accident, which cost the lives of 28 people, the whole plant and many injuries (Crowl & Louvar, 2002); a massive explosion in Pasadena, Texas on Oct. 23, 1989, resulted in 23 fatalities, 314 injuries, and capital loss of over $715 million (Lees, 1996). These are extreme cases of major accidents in the process industry, but minor incidents are very common in the process industry, occurring on a day to day basis, resulting in many occupational injuries, illnesses, and costing the society billions of dollars every year.

Bhopal, India accident, which killed more than 2000 civilians and injured 20,000 more (Crowl & Louvar, 2002); a massive explosion in Pasadena, Texas on Oct. 23, 1989, resulted in 23 fatalities, 314 injuries, and capital loss of over $715 million (Lees, 1996). These are extreme cases of major accidents in the process industry, but minor incidents are very common in the process industry, occurring on a day to day basis, resulting in many occupational injuries, illnesses, and costing the society billions of dollars every year.

1.3 RISK ASSESSMENT TECHNIQUES

- **Checklist:** A checklist is a list of questions about plant organization, operation, maintenance and other areas of concern to verify that various requirements have been fulfilled and nothing is neglected or overlooked
- **HAZOP:** HAZOP is a simple structured methodology for hazard identification and assessment, PI&D's, PFD, material flow diagrams, and operating manuals are examined to identify causes and consequences for all possible deviations from normal operation that could arise.
- **Fault Tree Analysis:** It is a deductive reasoning technique to determine the occurrence of an undesired event analysis. Having known component failure data and human reliability data it enable determination of the frequency of occurrence of an accidental event.
- **Failure Mode Effect Analysis:** It is an examination of individual component such as pumps, vessels, valves, etc. to identify the likely failures which may have undesired effects on system operation
- **What if analysis:** This technique involves asking a series of questions beginning with "what if" as a means of identifying hazards.
- **Hazard Indices:** Technique to identify and rank hazards quantitatively
    - Dow indices
    - Mond indices
    - HIRA index

- SWeHI
- IFAL index

1.4 RISK ASSESSMENT METHODOLOGIES:

There are four types of Risk Assessment Methodologies. They can be listed as follows .

1 WHO methodology

1. Identification of Hazards
    a. Checklist
    b. Matrix diagram of interaction
2. Assessment of Hazards
    a. Accident sequence analysis
    b. Failure effect analysis
3. Accident Consequence Analysis

2] ISGRA methodology

1.Hazard identification
2.Consequence analysis
3.Quantification of risk

3] Quantitative Risk Analysis

1. Hazard identification
2. Frequency estimation
3. Consequence Analysis
4. Measure of Risk

4] Optimal Risk Analysis

1. Hazard Identification with HIRA (Hazard Identification and Ranking Analysis).
2. Qualitative hazard assessment (QHA).
3. Consequence analysis
4. Optimal analysis

1.5 AIMS AND OBJECTIVES

- To present a comprehensive literature review on risk assessment in offshore industry.
- To assess the risk posed by offshore facilities with focus on the process units and the inventory using QRA Methodology.
- To develop the Fire Consequence Models for Offshore Quantitative Risk Assessment.
- To determine the human error probabilities for offshore platform musters.
- To suggest risk reduction measures if needed.
- To critically examine the results obtained.

1.6 DEFINITION OF THE PROBLEM

To perform the Quantitative Risk Assessment studies, a Oil and Natural Gas Corporation oil-drilling platform at Bombay High, India's biggest offshore oilfield off Mumbai coast, is considered for the analysis. A Russian and Indian oil exploration team that was mapping the Gulf of Cambay in 1965 in a seismic exploration vessel called Academic Arkhangelsky discovered the Bombay High oilfield. ONGC geophysicist M Krishnamurthy headed the Indian team. According to Krishnamurthy, in those days they used explosives as source and used a 24 channel analog instrument without any magnetic record for mapping for oil fields. While they were mapping the regional line from across the Gulf of Cambay, they came across the first line where the exploration team decided to drill for oil.

It is India's largest offshore oil field. Situated some 161 km north of the Mumbai coast, Bombay High has a string of oil and gas rigs in the sea that pumps oil to the coast. It produces 14 per cent of India's oil requirements and accounts for 38 per cent of all domestic production. The whole of Bombay High rigs have the production capacity of approximately 260,000 barrels of oil every day. ONGC has dug multiple wells over several kilometers in the Bombay High oilfield as the oil reservoirs typically extend over a large area. There are also exploratory wells probing new finds, and pipelines all over Bombay High to transport the oil.

Any accident in this industry may trigger the dominos effects. In the present work, Quantitative Risk Assessment study was performed on oil platform with the aims and objectives described earlier. The platform projected is an unmanned, remotely controlled one-leg design. During operation, personnel will be present only for short periods for the purpose of inspection, start-up or maintenance. The probability and consequences of the accidents are assessed based on a combination of general experience, statistical models and engineering judgments.

To a very great extent the safety analysis was performed according to the guidelines of the Norwegian Petroleum Directorate (NPD) and Ministry of Petroleum, Govt. of India. In essence, these guidelines give a check as to whether the conceptual design is up to modern standards. The check is made by imposing different types of accidents on the platform. The consequences are evaluated with respect to environment, human lives or loss of a platform. The probabilities of the accidents are analyzed taking into account the past experience with due respect to actual conditions and new design. If the probability falls below 10~* per year the accident is not analyzed further.

In this thesis work the author has studied the Quantitative Risk Assessment for the offshore industry and Fire consequence models for the offshore QRA has been developed. The focus is also given on the determination of Human error probabilities for offshore platform musters.

CHAPTER 2

LITERATURE RIVIEW

Risk assessment is a process where the magnitude of a specific risk is characterized so that decision makers can conclude whether the potential hazard is sufficiently great that it needs to be managed or regulated, reduced or removed. A number of studies have been carried out in the field of risk assessment.

Cave (1974) whose work on risk assessment methods for vapour-cloud explosions included identification of potential sources of hazard, determination of consequence distance relationships for internal explosions, toxic and explosive releases, estimation of accident probabilities using the Failure Effects and Modes (F.E.M.) analysis and discussion on acceptance of risk. It was concluded that the methods then used by the industry to assess the consequences of vapour-cloud explosions were of an empirical nature and to carry out a detailed risk assessment in which the complete spectrum of possible initiating events and possible consequences were considered using existing practices, would have been extremely expensive and time-consuming. He suggested a development of a more fundamental approach in order to improve the accuracy of assessment of the hazard to the public.

Earlier studies were based mainly with an aim of preventing equipment failures. How ever with betterment of technology and realization that industry was a low frequency high impact accident industry scope of risk assessment was widened to cover risks hazards to the workers and property in and around the plant. This led to risk assessment becoming a powerful tool in loss prevention.

B. Kirwan in 1987, Studied that an offshore platform depressurization (blowdown) system was designed such that control in emergencies necessitated operator actions over a short space of time. The system design for these operations was analyzed using a simple and pragmatic human reliability approach, embedded within a comprehensive risk assessment. The human reliability analysis identified several ways in which human actions could lead to system failure (flare overload), and in the total risk analysis these errors were found to dominate the risk picture. The causes of the human error related primarily to the design of the interface and co-ordination/communication problems previously unaddressed by the design process. Recommendations were made to reduce error potential based on the causes and mechanisms of error identified in the analysis, and several of these recommendations were included in the final design of the system.

Lave (1990) discussed the importance of risk assessment to quantify the benefits of solutions being given for environmental problems in order to make them effective and efficient and also to meet government regulations. He presented Risk assessment as a means of finding what the most important issues were and which uncertainties have to be resolved. It was concluded that though a powerful tool the methods of risk assessment and analysis were still in infancy and highly uncertain. He predicted that the greatest progress would result not from somewhat arbitrary characterizations of the risks of compounds, but from greater understanding that serves to reduce uncertainty and make the risk assessment methods more powerful.

Arendt (1990) discussed growing concern about the risk of major chemical accidents. It was pointed out that as new process technologies are developed and deployed, less of the historical experience base remained pertinent to safety assurance giving example of space industry and novel processes in CPI. Focus was on differentiating it from other methods which were deterministic where as QRA for CPI was mainly probabilistic in nature. Further there is a discussion on risk management and risk perspective. A number of misconceptions relating to data acquisition, accuracy etc were discussed. Its concluded that Quantitative Risk Assessment is an important tool for the CPI and when used judiciously, the advantages of QRA can outweigh the associated problems and costs.

Tweeddale (1992) retrieved the importance of the „Rapid ranking" that had been used for several years as a method of determining the priority that should be given to formal investigation of the wide range of hazards and risks present on major process industry sites. They discussed some historical, recent applications and the nature of the developments which they resulted in. Particular topics discussed include: development of the method such that it can be used by operating managers rather than specialists; use to raise risk consciousness; adaptation for use as an aid to hazard identification; use to define both which risks should be studied and which risks, even if low, should be incorporated in routine monitoring and periodic auditing programme; use as a basis for comparison of the relative risks presented by a variety of different industrial installations; use for a range of different types of risk: and extension beyond ranking to include short listing" i.e., deciding which risks to include in a study programme and which to leave out. Philosophical difficulties including the danger of omitting a risk, from detailed study, which was erroneously shown as low and the uncertainty of the absolute level of the ranked risks and the approaches to minimize these problems were discussed.

Linda J. Bellamy (1994) discusses the applications of human factors science in the offshore process industry in terms of what can be done, why and how. Illustrative examples are given. An explanation is given of the meaning of 'human factors', and the use of human factors science before and after the Piper Alpha disaster is outlined. The influence of approaches developed after the nuclear Three Mile Island accident is discussed briefly. The need for human factors review of offshore installations in design, construction and operation is highlighted by providing quantitative information on underlying causes of loss-of-containment accidents. Human factors review should be part of the safety management system, which is described in terms of a set of control and monitoring loops; the control and monitoring requirements for optimizing human performance are outlined briefly. Using the concept design stage of an installation as an example, the use of human factors review in safety decision-making is exemplified by indicating which areas should be targeted for review and how this would influence safety. Key human factors review methods are identified and an example is given of one approach, a 'walk-through' of design and procedures. It is concluded that identification of causes of accidents has prompted the development of human factor applications, but that there is still room for much more comprehensive and long-term human factors programmer in the offshore industry, with considerable potential for risk reduction.

Rhona Flin et al, (1996) explains the first investigation of risk perception by workers on offshore oil and gas installations on the UK Continental Shelf, following changes in offshore safety legislation in the wake of the Piper Alpha disaster in 1988. The Offshore Safety Case regulations (Health and Safety Executive, 1992, A Guide to the Offshore installations (safety Case) Regulations) put the onus on the operator to identify the major hazards and to reduce the risks to As Low As is Reasonably Practicable (ALARP). The regulations specifically state that Quantitative Risk Assessments (QRA) must be used when preparing the Safety Case. However, people do not use QRA when making everyday judgments about risk; they make subjective judgments known as risk perceptions, which are influenced by a number of different factors. This study was designed to complement the extensive QRA calculations that have already been carried out in the development of Safety Cases. The aim was to measure subjective risk perception in offshore personnel and examine how this relates to the more objective risk data available, namely accident records and QRA calculations. This paper describes the Offshore Risk Perception Questionnaire developed to collect the data and reports on UK offshore workers' perceptions of the risks associated with major and minor hazards, work tasks and other activities aboard production platforms.

D. D. Drysdale and R. Sylvester-Evans (1998), This Paper gives the detail analysis of the Piper Alpha platform accident. On 6 July 1988, at about 22.00, an explosion occurred on the Piper Alpha platform, an oil and gas production facility in the North Sea. Within seconds a major un-stabilized crude-oil fire developed and all but the wellhead area and the lower parts of the platform were engulfed in smoke. The subsequent fire escalation was swift and dramatic with the first of three gas risers failing catastrophically after 20 min. In the disaster 167 persons lost their lives in what was the world's worst offshore accident. The background to the investigation and the sources of evidence are reviewed. The available evidence is examined to explain the rapid fire escalation following the initial explosion. There follows a commentary on the way fire and fire dynamics are now being considered in the design and operation of UK offshore installations.

Mercx et al, (2000) discussed the various models available for the vapour cloud explosion blast modeling. They presented the fundamental objections in applying the TNT Equivalency method for vapour cloud explosion blast modeling. They also discussed the other types of models which do not have the fundamental objections like TNO Multi-Energy method that is increasingly accepted as a more reasonable alternative to be used as a simple and practical method. Computer codes based on computational fluid dynamics (CFD) like Auto Rea Gas, developed by

TNO and Century Dynamics, could be used in case a more rigorous analysis was required. They stressed that a CFD approach, in which the actual situation is modeled, supplies case-specific results. An overview of the key aspects relevant to the application of the Multi-Energy method and CFD modeling were also provided and demonstrated with an example problem involving the calculation of the explosion blast load on a structure at some distance from the explosion in an offshore platform complex..

Andreas Falck (2000) describes the use of QRA in the design of a modern offshore platform. This paper also addresses the work methodology, selection of tools and data, organization of QRA with other activities. The main objective for the QRA and the associated engineering studies was to provide decision support to achieve a cost effective and safe design. In practice this has been accomplished through Reduction of the platform risk level, with cost effective measures. Establishment of design requirements for several systems Some examples of specific design changes, as a direct result of the QRA. The main benefits from this approach have been to obtain cost optimization of safety measures with the end result a safe platform design. In addition to cost optimization, it is realistic to assume that significant savings have been made by making the right decisions at the right time. A wealth of experience shows that risk assessments carried out too late on existing or frozen design. result in excessive costs for modifications and changes, or reveals solutions where unsafe designs cannot be satisfactorily resolved or mitigated.

Daryl Attwood, Faisal Khan (2000) Occupational accidents constitute an area of significant and continuing risk for the oil and gas industry. The statistical data [1] show that fatalities are more likely to be caused by occupational accidents than by more catastrophic events, such as explosions or air transport incidents. The situation is consistent with that observed in the general workplace, where it has been reported [2] that over a third of all major injuries reported each year result from a slip or trip, this being the single most common cause of injuries at work. While workplace safety is regulated under national legislative schemes, analysis is not as rigorous for occupational accidents as for major event hazards. In order to suggest a more quantitative approach to the occupational accident issue than currently exists, the authors have developed a model has been developed to predict the frequency and associated costs of occupational accidents in the offshore oil and gas industry. Model inputs include: (i) direct factors, such as quality of personal protective equipment; (ii) corporate factors, such as training program effectiveness; and (iii) external factors, such as royalty regime. Three applications of the model are described, two for projects in eastern Canada and one for the Gulf of Mexico drilling sector. Published accident data are used to calibrate the model and validate results. The model is shown to predict actual results well, especially considering the subjective nature of the activity. The model's versatility is demonstrated through its application to different types of accident statistics and regions, and its use in generating performance measures for operators.

One particular methodology is the optimum risk analysis (ORA) methodology suggested by **Khan & Abbasi (2001).** They have gone ahead and applied it on a chemical plant sulfolane manufacturing unit and enumerated the advantages of this technique. ORA aims to identify and assess hazards and to estimate the risk factors due to any mishap/accident in the chemical process industry. The ORA framework enables modeling of probable accidents based on the chemical and process characteristics, evaluation of mode of occurrence of these accidents, estimation of detailed consequences and finally prediction of risk factors. This has normal steps like risk identification, ranking, estimation and assessment however the way these are done are a little modified and use various other techniques proposed by the same authors. After assessing the risks to sulfolane unit under consideration the authors made a number of suggestions like instead of one or two large-capacity vessels, several vessels of smaller capacity should be used for storage. Adequate space should be kept between the storage vessels and buffers provided between them so that adverse consequences of failure in one of them do not cause second or higher order A thorough emergency preparedness strategy should always be kept in position, fortified by periodic drills or 'dry runs' so that the damage is contained if an accident does occur. According to authors the methodology optimal risk analysis is swift, less expensive to implement, less time-consuming, and is as (or possibly more) accurate and precise, as existing methodologies.

In the last two decades there has been a dramatic increase of human contribution to accident development, reaching levels of percentages of as high as 70%–80%, independently of the technological domain of application. There are two main reasons for such relevant increase, namely:

- The very high reliability and refinement of mechanical and electronic components;
- The complexity of the system and the role assigned to human operator in the control loop

Realization of this has also led to various changes and additions in the way a risk assessment is performed. Various modules like task analysis, Hierarchal task analysis, HIMI, THERP, SHERPA etc have been developed.

Audun Brandsaeter (2000) describes the implementation and use of risk assessment in the offshore industry in relation to safety aspects safety to people's life and health, as well as environment and property. Although risk assessments may be based on both qualitative and quantitative methods, the main focus here is on quantitative risk assessments (QRA).

Faisal I. Khan, S. A. Abbasi(2002) The importance of inherently safer design (ISD) as a strategy to minimize risk of accidents in chemical process industries is being repeatedly stressed in recent years. The increasing number, frequency, and extents of damage caused by such accidents across the world have contributed to this thinking. However even as the need for ISD is being underscored, there are very few reports on precise methods to implement this concept. Significant recent reports are by Berge (1993, 1995) who has suggested a scenario based design procedure in which construction of accident scenarios in a structured manner is made the basis of ISD.

Faisal I. Khan, Paul R Amyotte (2002) Inherent safety is a proactive approach for hazard/risk management during process plant design and operation. It has been proven that, considering the lifetime costs of a process and its operation, an inherently safer approach is a cost-optimal option. Inherent safety can be incorporated at any stage of design and operation; however, its application at the earliest possible stages of process design (such as process selection and conceptual design) yields the best results. The inherent safety approach is the best option for hazard/risk management in offshore oil and gas activities. In the past, it has been applied to several aspects of offshore process design and operation. However, its use is still limited. This article attempts to present a complete picture of inherent safety application in offshore oil and gas activities. It discuses the use of available technology for implementation of inherent safety principles in various offshore activities, both current and planned for the future.

Apostolakis (2004) who discusses the use of quantitative risk assessment (QRA) in decision making regarding the safety of complex technological systems. The insights gained by QRA are compared with those from traditional safety methods and it is argued that the two approaches complement each other. It is argued that peer review is an essential part of the QRA process. The importance of risk-informed rather than risk based decision making is emphasized. Engineering insights derived from QRAs are always used in combination with traditional safety requirements and it is in this context that they should be reviewed and critiqued. Examples from applications in nuclear power, space systems, and an incinerator of chemical agents are given to demonstrate the practical benefits of QRA.

Ravichandra Pulaa, Faisal I. Khana, Brian Veitcha, Paul R. Amyotte (2005) Offshore oil and gas platforms are well known for their compact geometry, high degree of congestion, limited ventilation and difficult escape routes. A small mishap under such conditions can quickly escalate into a catastrophe. In this paper, we have considered fire consequence modeling as a suite of sub-models such as individual fire models, radiation model, overpressure model, smoke and toxicity models and human impact models. This comprehensive suite of models was then revised by making the following modifications: (i) fire models: existing fire models have been reviewed and the ones most suitable for offshore conditions were selected; (ii) overpressure impact model: a model has been developed to quantify the overpressure effects from fires to investigate the possible damage from the hot combustion gases released in highly confined compartments; (iii) radiation model: instead of a point/area model, a multipoint grid-based model has been adopted for better modeling and analysis of radiation heat flux consequences .

2.1 CONCLUSIONS FROM THE LITERATURE REVIEW

Following conclusions were derived from the above literature survey:

- Risk is a subjective concept which varies with respect to the context and the depth of study..
- Cost benefit analysis is a crucial factor in risk assessment.
- Risk assessment can be qualitative as well as quantitative. Quantitative methods are being given more stress since they allow for a better comparison of risk levels and reduce subjectivity in decision making process.
- The major accidents in the history of the offshore platforms revealed that they originated from the inventories.
- There is no possibility of eliminating risk but we can put efforts to bring it under the acceptable region.

Table 2.1: Summary of literature review

Sl. No.	Name of the paper	Authors and	Journal	Conclusions Drawn
1.	Risk Assessment Methods for Vapour Cloud Explosions	Cave L 1974	Prog. Energy Combust Science	Methods used were of an empirical nature and to carry out a detailed risk assessment was extremely expensive and time-consuming. Suggested development of a more fundamental approach to assess the problem of vapour clouds
2.	Human reliability analysis of an offshore emergency blowdown system	B. Kirwan, 1987,	Applied Ergonomics	The causes of the human error related primarily to the design of th interface and co-ordination/communication problems previousl unaddressed by the design process. Recommendations were made t reduce error potential based on the causes and mechanisms of erro identified in the analysis, and several of these recommendations wer included in the final design of the system.
3.	Risk Analysis And Management	Lave F.B (1990)	The Science of the Total Environment	Though a powerful tool the results of risk assessment and analysis w highly uncertain. Predicted that the greatest progress in reduction uncertainty and make the risk assessment methods more powerful
4.	Using Quantitative Risk Assessment in the Chemical Process Industry	Arendt, J. S. (1990)	Reliability Engineering and System Safety	Importance of QRA in the Chemical Process Industry. Basic elements risk assessment management. Misunderstanding regarding QRA

Sl. No.	Name of the paper	Authors and	Journal	Conclusions Drawn
5.	Some experiences in hazard identification *and risk short listing*	Tweeddale, H.M., Cameron, R.F., *Sylvester,S.S(1992)*	Journal of Loss Prevention in the *Process Industries*	Importance of risk ranking, short listing and the development of method that can be used by the managers rather than specialists.
6.	The influence of human factors science on safety in the offshore industry	Linda J. Bellamy (1994)	J. Loss Prev. Process Ind., 1994, Volume 7, Number 4	This paper aims to clarify applications of human factors science in th offshore process industry in terms of what can be done, why and how Illustrative examples are given. An explanation is given of the meanin of 'human factors', and the use of human factors science before and afte the Piper Alpha disaster is outlined.
7.	Risk Perception By Offshore Workers On UK Oil And Gas Platforms	Rhona F, Kathtyn Mearns, Rachael Gordon, Mark Fleming(1996)	Safety Science, Vol. 22, No. 1-3,	This paper describes the Offshore Risk Perception Questionnaire developed to collect the data and reports on UK offshore workers' perceptions of the risks associated with major and minor hazards, work tasks and other activities aboard production platforms.
8.	The explosion and fire on the Piper Alpha platform, 6 July 1988. A case study	D. D. Drysdale and R. Sylvester-Evans (1998)	The Royal Society TEX Paper	This Paper gives the detail analysis of the Piper Alpha platform accident.

Sl No.	Name of the paper	Authors and Year of Publication	Journal	Conclusions Drawn
9.	Use of QRA for decision support in the design of an Offshore oil production installation.	Andreas Falck, Erik Skramstad, Magne Berg 2000	Journal of Hazardous Materials	This paper describes use of QRA in the design of a modern offsh platform. It also addresses work methodology, selection of tools and da organization of QRA with other activities.
10	Human Factors On Risks Analysis Of Complex Systems	Cacciabue P.C 2000	Journal Of Hazardous Materials	Human reliability assessment concerns The dynamic nature of human machine interaction
11.	Developments in vapour cloud explosion blast modeling	Mercx, W.P.M. et al.., (2000)	Journal of Hazardous Materials	Available models on vapour cloud explosion modeling and the recent developments in the earlier models.
12	Validation of an Offshore Occupational Accident Frequency Prediction Model A Practical Demonstration Using Case Studies	Daryl Attwood, Faisal Khan, and Brian Veitch (2000)	Process Safety Progress	A model has been developed to predict the frequency and associated costs of occupational accidents in the offshore oil and gas industry.

Sl. No.	Name of the paper	Authors and Year of Publication	Journal	Conclusions Drawn
13.	Offshore Safety Assessment and Safety-Based Decision-Making The Current Status and Future Aspects	J. Wang, O. Kieran (2000)	Journal of Offshore mechanics And Arctic Engineering	The current status of offshore safety regulation in the UK, several offshore safety assessment frameworks are presented. These include top-down, bottom-up, probabilistic, and subjective approaches. Probabilistic safety-based decision-making and subjective safety-based decision-making are then studied.
14.	Risk analysis of a typical chemical industry using ORA procedure	Khan, F.I., Abbasi, S.A. (2001)	Journal of Loss Prevention in the Process Industries	The need of elaborate safety arrangements to reactor and storage units as they are highly vulnerable to accidents.
15.	Risk assessment in the offshore industry	Audun Brandsaeter (2002)	Safety Science (2002) 231–269	This paper describes the implementation and use of risk assessment in the offshore industry in relation to safety aspects safety to people's life and health, as well as environment and property. Although risk assessments may be based on both qualitative and quantitative methods, the main focus here will be on quantitative risk assessments (QRA).
16	Inherently safer design based on rapid risk analysis	Faisal I. Khan, S. A. Abbasi (2002)	Journal of Loss Prevention in the Process Industries 11	The importance of inherently safer design (ISD) as a strategy to minimize risk of accidents in chemical process industries is studied.

Sl. No.	Name of the paper	Authors of and year of Publication	Journal	Conclusions Drawn
17.	Inherent safety in offshore oil and gas activities: a review of the present status	Faisal I. Khan Paul R. Amyotte (2002)	Journal of Loss Prevention in the Process Industries	It discuses the use of available technology for implementation of inherent safety principles in various offshore activities, both current and planned for the future. The inherent safety approach is the best option for hazard/risk management in offshore oil and gas activities.
18.	Risk-based emergency decision support.	Jens Korte (2003)	Reliability Engineering and System Safety	This paper discusses how to assist critical decisions taken under comple contingent circumstances, with a high degree of uncertainty and short tim A method called 'contingent risk and decision analysis' is presented, t provide decision support for decisions under variable circumstances ar short available time scales.
19.	How Useful Is Quantitative Risk Assessment	Apostolakis G.E 2004	Risk Analysis	This article discusses the use of Quantitative Risk Assessment (QRA) in decision-making regarding the safety of complex technological systems. The insights gained by QRA are compared with those from traditional safety methods and it is argued that the two approaches complement each other.
20	Revised fire consequence models for offshore quantitative risk assessment	Ravichandra Pulaa, Faisal I. Khana, Brian Veitcha, Paul R. Amyotte (2005)	Journal of Loss Prevention in the Process Industries 18 (2005)	This paper explains the fire consequence modeling as a suite of sub-models such as individual fire models, radiation model, overpressure model, smoke and toxicity models and human impact models.

CHAPTER 3

A GENERAL APPROCH FOR RISK ASSESSMENT

Risk assessment is defined as any analysis or investigation that contributes to understanding of any or all aspects of the risk of major accidents, including their Causes, Likelihood, Consequences, Means of control, Risk evaluation. The Risk assessment should ensure a comprehensive and detailed understanding of all aspects for all major accidents and their causes and should be a component of the demonstration of adequacy required in the safety report e.g. by evaluating the effects of a range of control measures and provide a basis for selection/rejection of measures .

On completion of the risk assessment, recommendations are made so that enough precautions are taken during the job execution to prevent harm and injury and bring down the risk to tolerable level. No fixed rules are prescribed for undertaking a risk assessment and the assessment will depend on the nature of the undertaking and the type and extent of the hazards and risks. Above all the process needs to be practical and it should involve management, whether or not advisers or consultants assist with the detail. It should be ensured that those involved take all reasonable care in carrying out the risk assessment although the assessment would not be expected to cover risks which were not reasonably foreseeable. A general risk assessment procedure is outlined now. It has the following steps

1. Assemble a team
2. Define the scope
3. Conduct hazard identification
4. Carry out Risk analysis
5. Suggest controls
6. Document the results

First step is the assembling of a team. A risk assessment team generally consists of (CCPS, 1992) :

- Plant safety representative (PSR), the concerned activity supervisors and operator or the technician or contractor's representative as the case may be shall be the team member for risk assessment.
- If a new chemical is used or new equipment is used for the first time or any activity which is one time job and which will continue for more than one day safety officer shall also be involved in the risk assessment.
- External experts shall also be involved based on the job requirement e.g. material handling of heavy equipment.
- Contractor's supervisor (in charge of the activity) shall also be a team member, if the job is to be done involving contractors employees

The next step should involve a discussion about the system, project or topic being reviewed through risk assessment process. The purpose of this step is to ensure that all team members have an adequate understanding of the system and the boundaries of the system before starting to identify hazards.

Depending on the Risk Identification tool and the exercise complexity this step may involve one or more of the following

- Reviewing existing system drawing (map, P & ID), etc.
- Detailed techniques like FTA, FMEA, etc.

Identification of hazards is the next step and an extremely important one. The Scope may provide a Hazard Inventory Table to the team. This table would outline the hazard types and clarify any uncertainties about any specific hazard. If any hazard is unclear that uncertainty must either be clarified or the facilitator must define the uncertainty and gather information from the team to document the assumptions made about the hazard. Failure to clarify assumptions about the nature or magnitude of a hazard can lead to inadequate controls and the assumption of unacceptable risk.

Next potential unwanted events are identified. Methods like PHA, HAZOP, FTA, FMEA, ETA, LOPA are used in a combination for as complete evaluation as possible (Lees 1996; CCPS,1992). Each example method is intended to address different desired deliverables and each method varies in the way it prompts the identification of unwanted events.

Analysing the risk follows the above step. Sometimes this is not a part of the exercise. For example, Job Safety or Hazard Analysis, and HAZOP, do not usually involve formal Risk Analysis. In JSA and HAZOP, unwanted events are identified and then controls or barriers are discussed. If this applies the facilitator should skip the next two sections. In most cases some form of Risk Analysis is applied, whether it be qualitative, semi-quantitative or quantitative.

Next in line is deciding on risk acceptability criteria. The selected Risk Analysis method for the team exercise may indicate risk acceptability levels as part of design. Often Risk Analysis methods are included corporate procedures for Risk Management or Risk Assessment. Therefore, the facilitator should know the relevant risk acceptability criteria before the exercise and, subsequently, ensure that the team understands the information.

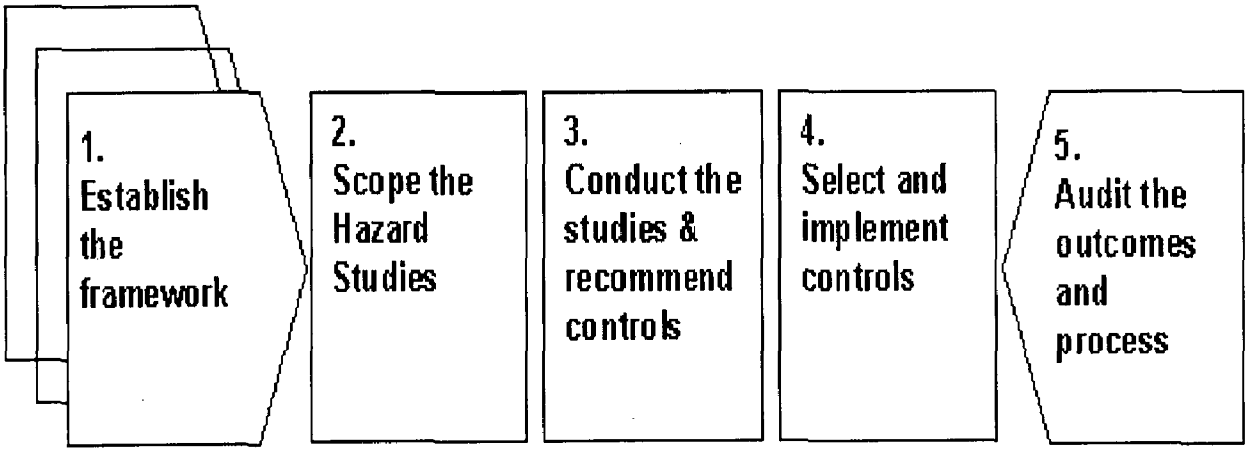


Fig 3.1 General Steps of Risk Assessment

3.1 RISK EVALUATION

Risk evaluation can be undertaken using qualitative and/or quantitative approaches

Risk comprises two categories - frequency and consequence

- Qualitative methodologies that can be used are
  - Risk matrix
  - Risk nomograms

  Qualitative Risk Analysis (Qual RA) is used to very roughly discuss and group risks

- Semi – quantitative techniques
  - Layers of protection analysis
  - Risk matrix

Semi – Quantitative Risk Analysis (SQRA) is used to identify rough priorities for the profile, often where exposure is a key factor to focus on priorities, further study and analysis.

- Quantitative - quantitative techniques

Quantitative Risk Analysis (QRA) is used to more accurately establish the probability of unwanted events to mathematically manipulate and/or consider acceptability.

Acceptability criteria may be illustrated in the method by a "green" or specific low risk rank level. In this case the acceptability criteria simply identify the lowest priority risks.

Normally, qualitative and semi-qualitative methods are not used to determine acceptability but rather to focus discussion on higher priority risks.

A general overview of quantitative method of risk assessment methodology is as follows

- A set of undesirable end states (adverse consequences) is defined, e.g., in terms of risk to the public, loss of crew, and loss of the system.
- For each end state, a set of disturbances to normal operation is developed which, if uncontained or unmitigated, can lead to the end state.
- These are called initiating events (IE's).

- Event and fault trees or other logic diagrams are employed to identify sequences of events that start with an IE and end at an end state.
- Accident scenarios are generated.
- These scenarios include hardware failures, human errors, fires, and natural phenomena.
- The dependencies among failures of systems and redundant components (common-cause failures) receive particular attention.
- The probabilities of these scenarios are evaluated using all available evidence, primarily past experience and expert judgment.
- The accident scenarios are ranked according to their expected frequency of Occurrence and represented on a risk matrix.

Should the risk assessment require quantitative consideration of different events, consequences can be quantified by establishing a common unit for all of the potential losses, such as rupees. Depending on the circumstances, this may require establishing the value of human life. The accuracy of probabilistic data is sometimes challenged, especially when the numbers are multiplied, potentially exacerbating any inaccuracies. Obviously the accuracy of the data is determined by the validity of the source.

Finally after risks have been identified and analyzed output is presented in various forms. A popular format for qualitative analysis is a risk matrix based on severity and frequency of risk scenarios. Here the risks are rated according to analysis results on basis of guidelines adopted by the firm. A typical risk matrix is shown below.

Quantitative results are shown with help of cut sets, plots, contours, frequencies and probabilities (CCPS, 1992). On basis of results of above steps the management takes decisions related to risks and decides whether risk is acceptable or not and what further steps need to be taken.

3.2 RISK ASSESSMENT MATRIX

CONSEQUENCES						**LIKELIHOOD**				
	PEOPLE	**ASSETS**	**ENVIRONMENT**	**REPUTATION**	**GENERATION/ FINANCIAL**	**A**	**B**	**C**	**D**	**E**
						Practically impossible	Not likely to occur	Could occur or I've heard of it happening	It is known to occur or "it has happened"	Common or occurs frequently
1	First Aid Injury	Slight Damage (<$10k)	Slight effect	Slight impact	Slight impact on revenue/ finances (<$10k)	Low	Low	Medium	Medium	High
2	Medical treatment Injury	Component level replacement/ repair ($10k-$100k)	Minor effect	Limited impact	Partial output reduction or equivalent ($10k-$100k)	Low	Medium	Medium	High	Extreme
3	Lost Time Injury less than 7 days	Equipment level replacement/ repair ($100k-$5m)	Localised effect	Local area impact	Unit off line <4hrs or equivalent ($100k-$5m)	Medium	Medium	High	Extreme	Extreme
4	Lost Time Injury more than 7 days or fatality	Unit level damage ($5m-$50m)	Major effect	State wide impact	Unit off line >4hrs or equivalent ($5m-$50m)	Medium	High	Extreme	Extreme	Extreme
5	Multiple Fatalities	Multiple unit capability damage (>$50m)	Massive effect	National impact	Multiple units off line (>$50m)	High	High	Extreme	Extreme	Extreme

www.truenergy.com.au/downloads/RISK_ASSESSMENT_MATRIX_31May04.doc

*PTD = Permanent Total Disability

Harm/Consequence = Potential consequence of an incident/injury given current level of controls.
Likelihood = What is the potential of an incident or injury occurring given the current level of controls.

The intersection of the chosen column with the chosen row is the Risk classification.

RISK SCORE

Key: ☐ **LOW – Tolerable** - Monitor and Manage

☐ **MEDIUM** - Monitor and maintain strict control measures ALARP

☐ **HIGH** - Review and introduce additional controls to mitigate to ALARP

☐ **EXTREME** - Intolerable Stop Work and immediately introduce further control measures

3.3 RISK TOLERANCE

After the risk is calculated, the results must be compared to either governmental or company criteria to determine if the risk is tolerable. This means that the risk is at a level people are generally willing to accept. If it is, then additional fire protection is not required and the level of fire protection (mitigation) used in the risk calculation is adequate. If the level of risk does not meet the "acceptable" risk criteria, then additional mitigation may be required. The options for reducing the risk are selected and the analysis recalculated to determine the impact on the risk. In some cases, the options provide significant risk reduction, whereas others have little impact on the risk. Risk acceptance criteria are based on current international practices in certain developed countries. Hence Health and Safety Executive (HSE) proposed criterion for Individual

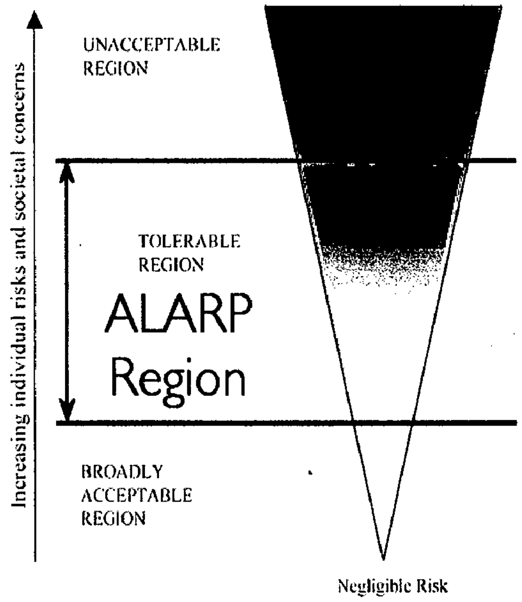


Figure 3.3 As low as reasonably practicable (ALARP)-principle.

Risk is adopted as: 10^{-5} per year for Intolerable risk. Lower than 10^{-6} per year for negligible risk. One concept that is being used extensively is as low as reasonable practical. Figure 3.1 shows the ALARP concept. This concept suggests that, at some point, the cost to mitigate a hazard is so high that it is no longer practical to implement the option. Cost-benefit analysis can be used to determine if ALARP has been achieved.

CHAPTER 4

QUANTITATIVE RISK ASSESSMENT FOR OFFSHORE INDUSTRY

4.1 INTRODUCTION TO QRA

QRA is a mathematical approach to engineers to predict the risks of accidents and give guidance on appropriate means of minimizing them. Nevertheless, while it uses scientific methods and verifiable data, QRA is a rather immature and highly judgmental technique, and its results have a large degree of uncertainty. Despite this, many branches of engineering have found that QRA can give useful guidance. However, QRA should not be the only input to decision-making about safety, as other techniques based on experience and judgment may be appropriate as well. Risk assessment does not have to be quantitative, and adequate guidance on minor hazards can often be obtained using a qualitative approach.

4.2 THE KEY COMPONENTS OF QRA

Figure on next page illustrates the classical structure of a risk assessment. It is a very flexible structure, and has been used to guide the application of risk assessment to many different hazardous activities. With minor changes to the wording, the structure can be used for qualitative risk assessment as well as for QRA.

The first stage is **system** definition, defining the installation or the activity whose risks are to be analyzed. The scope of work for the QRA should define the boundaries for the study, identifying which activities are included and which are excluded, and which phases of the installation's life are to be addressed.

4.2.1 HAZARD IDENTIFICATION

Then hazard identification consists of a qualitative review of possible accidents that may occur, based on previous accident experience or judgment where necessary. There are several formal techniques for this, which are useful in their own right to give a qualitative appreciation of the range and magnitude of hazards and indicate appropriate mitigation measures. This qualitative evaluation is described in this guide as 'hazard assessment'. In a QRA, hazard identification uses similar techniques, but has a more precise purpose - selecting a list of possible failure cases that are suitable for quantitative modeling.

4.2.2 FREQUENCY ANALYSIS

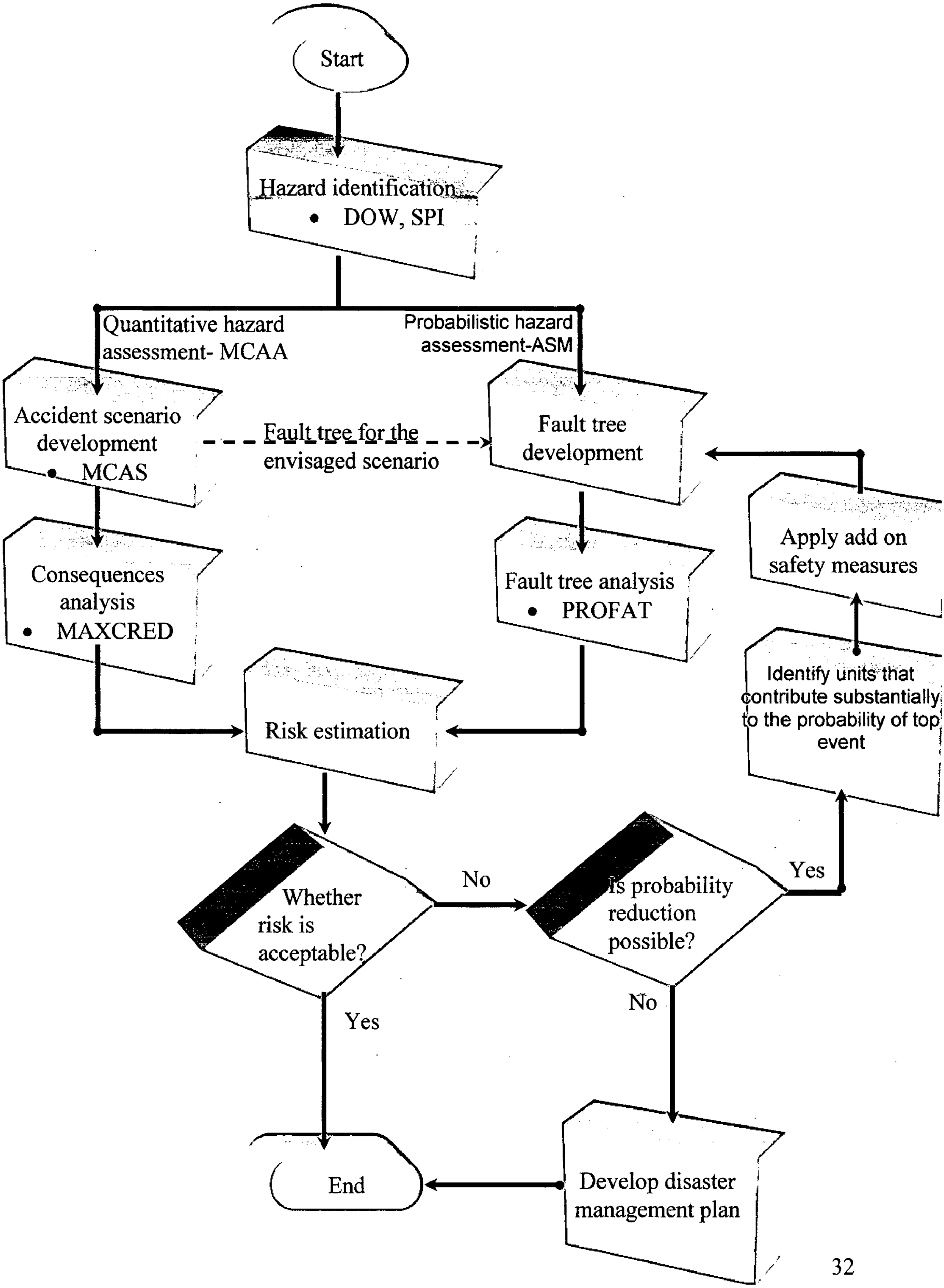
Once the hazards have been identified, frequency analysis estimates how likely it is for the accidents to occur. The frequencies are usually obtained from analysis of previous accident experience, or by some form of theoretical modeling.

In parallel with the frequency analysis, consequence modeling evaluates the resulting effects if the accidents occur, and their impact on personnel, equipment and structures, the environment or business. Estimation of the consequences of each possible event often requires some form of computer modeling, but may be based on accident experience or judgments if appropriate.

When the frequencies and consequences of each modeled event have been estimated, they can be combined to form measures of overall risk. Various forms of risk presentation may be used. Risk to life is often expressed in two complementary forms:

1. Individual risk - the risk experienced by an individual person.
2. Group (or societal) risk - the risk experienced by the whole group of people exposed to the hazard.

Up to this point, the process has been purely technical, and is known as risk analysis. The next stage is to introduce criteria, which are yardsticks to indicate whether the risks are acceptable, or to make some other judgment about their significance. This step begins to introduce non-technical issues of risk acceptability and decision-making, and the process is then known as risk assessment. In order to make the risks acceptable, risk reduction measures may be necessary. The benefits from these measures can be evaluated by repeating the QRA with them in place, thus introducing an iterative loop into the process. The economic costs of the measures can be compared with their risk benefits using cost-benefit analysis. The results of QRA are some form of input to the design or ongoing safety management of the installation, depending on the objectives of the study.



4.3 QRA AS PART OF RISK MANAGEMENT

QRA is primarily an analytical process, estimating risk levels, and evaluating whether various measures are effective at reducing them. This is a part of risk management, which consists of the on-going actions to minimize risks as part of the safety management system of the activity.

There has been a tendency for QRA to be treated as an isolated analytical exercise, with only a loose link to other risk management activities. In order to correct this, QRA can be seen as an integrated part of the risk management process, consisting of the following iterative steps (see figure on next page):

- Identifying hazards that are present.
- Setting acceptance standards for the risks.
- Evaluating the likelihoods and consequences and risks of possible events.
- Devising or confirming arrangements to prevent or mitigate the events, and respond to them if they do occur, and checking that the residual risks are acceptable.
- Establishing performance standards to verify that the arrangements are working satisfactorily.
- Continuously monitoring, reviewing and auditing the arrangements.

There are many points of linkage between QRA and risk management, particularly in the area of decision- making about risk acceptability and reduction measures. Significant research is going on this topic, one may find many research application in open literature.

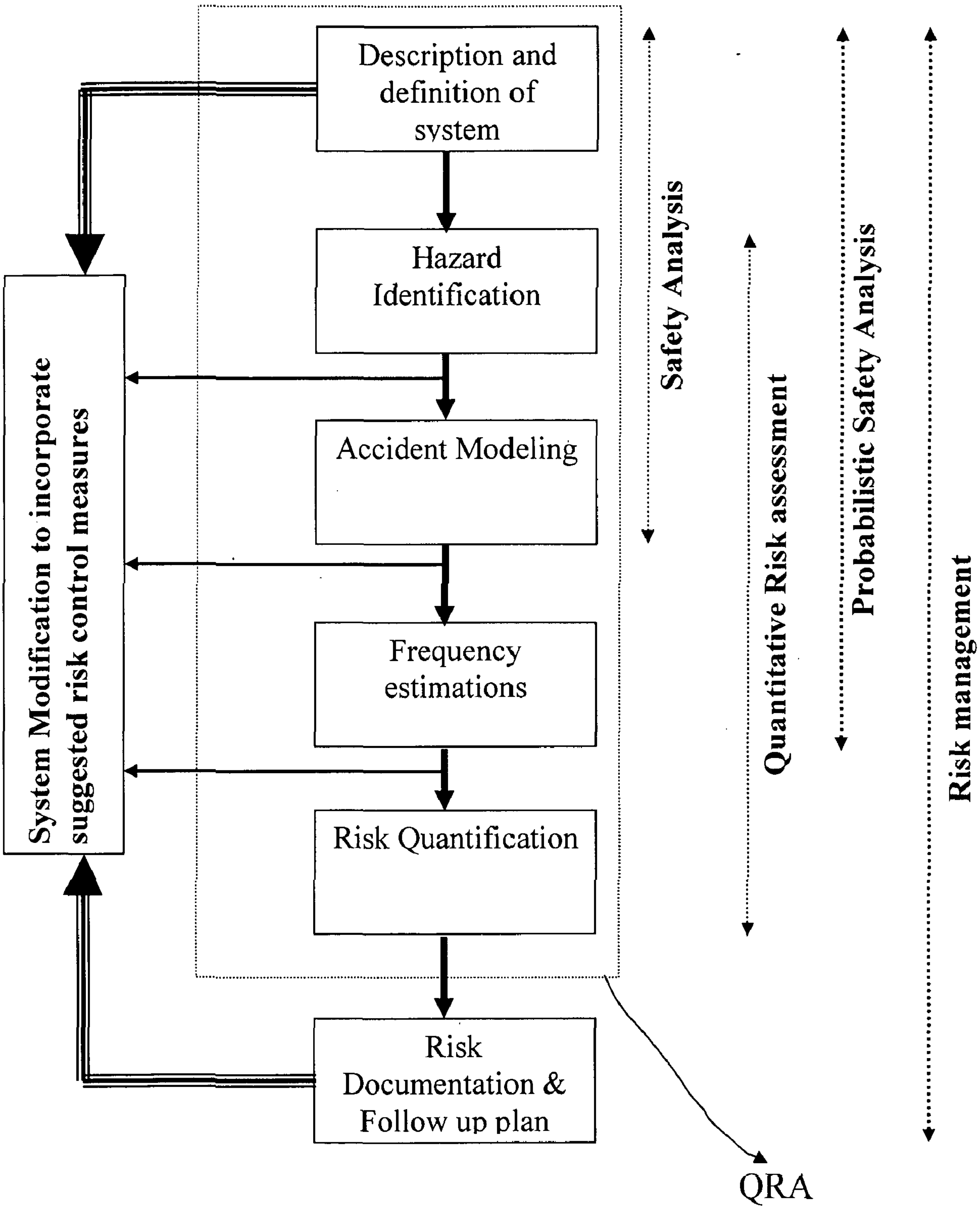


Figure 4.2 QRA and other risk assessment methodologies as part of risk management process

4.4 THE OBJECTIVES OF A QRA MAY INCLUDE:

- Estimating risk levels and assessing their significance. This helps decide whether or not the risks need to be reduced.
- Identifying the main contributors to the risk. This helps understanding of the nature of the hazards and suggests possible targets for risk reduction measures.
- Defining design accident scenarios. These can be used as a design basis for fire protection and emergency evacuation equipment, or for emergency planning and training.
- Comparing design options. This gives input on risk issues for the selection of a concept design.
- Evaluating risk reduction measures. QRA can be linked to a cost benefit analysis, to help choose the most cost-effective ways of reducing the risk.
- Demonstrating acceptability to regulators and the workforce. QRA can show whether the risks have been made ALARP.
- Identifying safety-critical procedures and equipment. These are critical for minimizing risks, and need close attention during operation.
- Identifying accident precursors, which may be monitored during operation to provide warning of adverse trends in incidents.

4.5 SCOPE OF A QRA

The types of risk that a QRA may evaluate include:

1. Loss Of Life : This is usually the only measure of harm to people, since sickness a define and predict.
2. Impairment Of Safety Functions: This is the likelihood of key safety functions lifeboats, temporary refuge etc., being made ineffective by an accident. This risk me: as a simple alternative to the risk of loss of life.

3 Property Damage: This consists of the cost of clean-up and property replacement, re-drilling wells if necessary.

4. Business Interruption: This includes the cost of delays in production or drilling.

5. Environmental Pollution: This may be measured as quantities of oil spilled onto the shore, or as likelihoods of defined categories of environmental impact.

The choice of appropriate types of risk will depend on the objectives of the QRA and criteria that are to be used. Many offshore QRAs consider only loss of life or impairment of safety functions, but a comprehensive evaluation of acceptability and cost-benefit should address all the above types of risk.

4.6 PHASES OF PLATFORM LIFE

In principle, a QRA should address risks over the entire life of the platform, from the drilling to the final abandonment of the field or scrapping of the rig. In practice, most phases where the risks are high and the potential for risk reduction is greatest.

Most QRAs of production platforms have only addressed the main drilling and hydrocarbons. Other phases have mainly been addressed qualitatively QRA to cover all phases of the platform life and may include:

- Onshore construction
- Inshore outfitting and mating
- Towing operations
- Offshore installation
- Offshore hook-up and commissioning
- Development drilling
- Simultaneous drilling and production
- Production
- Workovers
- Major modifications (e.g. addition of gas compression)
- Abandonment at the end of the platform's life

4.7 BOUNDARIES OF THE QRA

The boundaries of the QRA should be defined clearly, identifying which activities, hazards and personnel are included. An offshore installation has relatively clear boundaries, but several issues require definition. These include:

- Accidents involving attendant vessels such as supply vessels, stand-by vessels, etc. It might be expected that all activities and personnel involved in routine operations of the platform would be included in the QRA, but in practice attendant vessels are often neglected except where they damage the platform in a collision. If they were included, this would require risk estimates for them while on-station and in-transit to shore, and introduce a new issue of defining the boundary in their port.
- Accidents involving passing merchant ships. Most platform QRAs include the risk of passing ships damaging the platform but not the risk of fatalities or damage this may cause on the ship. Since this is the main area where the platform may be the cause of third party fatalities, the UK Marine Safety Agency has argued that it should be included in the QRA of the platform.
- Accidents involving helicopter transport to and from the platform. Most platform QRAs include accidents in helicopter travel. Some have excluded risks to the helicopter crew, on the grounds that their safety is the responsibility of the helicopter company and the civil aviation authorities not
- the offshore operator. Where crew boats are used, these are normally included in the QRA.
- Accidents involving road transport to and from the heliport. These are not normally covered, except where different concept designs involve different amounts of road transport from a well-defined base.
- Accidents originating in pipelines between the platform and the shore and/or other platforms. This boundary is important if pollution or business interruption risks are to be evaluated.

The installation's safety zone may form its legal boundary, and this may be used to define the boundary of a QRA.

4.8 QRA IN THE LIFE OF AN INSTALLATION

To obtain the **full** benefit from the study, QRA should be an on-going process throughout the life of an installation, as an integral part of its risk management. Ideally, one QRA should be prepared and evolve through the installation's life. Typical stages when a QRA or an update are required are:

- Feasibility studies and concept selection stage. Here, a simple QRA is appropriate due to the absence of design detail. The QRA should compare the risk implications of the various possible concepts, and verify that the chosen one has the potential to be acceptably safe.
- Concept design. This is one of the most fruitful stages for a QRA, since information is available to allow a reasonably detailed study, while the design is still flexible enough to be influenced substantially by the QRA conclusions. QRAs at this stage have often been known as Concept Safety Evaluations, but full fatality risk analyses are also possible. The QRA should evaluate major risk reduction measures such as layout changes, lifeboat numbers, etc.
- Detailed design. During detailed design a Total Risk Assessment may be appropriate, although some companies restrict it to fatalities. The QRA may
- use several supporting studies. It should be in sufficient detail to evaluate
- specific risk reduction measures such as life boat locations, fire protection, etc. and should be able to provide guidance for developing operating and emergency procedures.
- Operation. The full QRA of the final design should be revised to take account of the 'as built' state of the platform typically every 3-5 years or after significant changes to the installation or to QRA methodology. The QRA should reflect operational experience of leaks, shipping movements, manning levels and emergency exercises. It should be used in decision-making as part of the on-going safety management system on the installation.

4.9 WHICH CALCULATION ENVIRONMENT TO USE

Manual calculations are based on written documentation, typically supported by hand-held calculators. Early QRAs were performed in this way, but the approach is suitable only for very simple QRAs or for checks of more sophisticated work. Its strengths are flexibility and economy of effort in simple work. Its weaknesses are difficulty in handling large numbers of events and updating after changing inputs, and the variable quality documentation from different analysts.

Computer spreadsheets have been used extensively in recent QRA studies. At the most basic level, they can be used to combine some of the function of hand-held calculators and word-processors, performing simple calculations, adding the results of each failure case, and presenting the risk in tabular and graphical format. They are also widely used as a computing environment for simple consequence models. Some spreadsheets are controlled by macro commands, allowing them to function like complete computer programs for offshore QRA. The strengths of spreadsheets are their low cost, flexibility of calculation and presentation, minimal training requirements, and easy portability from one study to the next. Their weaknesses are that they are prone to errors by the analyst and very difficult to check; the macro programming language is particularly difficult to understand and check; they require relatively simple modeling; and they tend to be very personal to the analyst and so difficult to update without errors. As a result, they require very careful quality assurance.

Computer programs are mainly used in QRA as single-issue stand-alone models for consequence calculation, fault-tree analysis, and theoretical frequency models for specific events. In this form, they can be combined with manual calculations, spreadsheets or more comprehensive software to produce overall risk results.

Comprehensive offshore QRA software has been developed to combine event frequencies with consequence models, and produce documentation. Although these have been developed in spreadsheet form, the main examples are in more advanced operating environments. The Offshore Hazard and Risk Analysis (OHRA) Toolkit is a graphical tool for structuring an offshore risk analysis. It provides a set of consequence and frequency models (i.e. single-issue computer programs), event trees and frequency data, and allows the user to combine them using an intuitive graphical interface and a restricted spreadsheet capability. The toolkit automatically transfers data between the models, and keeps a record of the input values that were used, thus allowing ready updating of the results. Its strengths are the inclusion of many computer models in a common environment, the ability to link them flexibly, to audit the calculations and readily update them. Its weaknesses are the high initial cost of learning to use the technology efficiently, the difficulty of modeling the impact of consequence zones on a 3-dimensional platform population, and the relatively early stage of development of this approach.

PLATO is a software system for offshore risk analysis which performs the entire risk calculation from definition of the platform's equipment and initiating events to production of the risk results. It is based on 'object-orientated' programming, involving a 3-D model of the platform geometry and emergency control systems. Individual events can be generated automatically and the various possible escalation paths can be simulated according to pre-defined rules, replacing traditional event-tree modeling under the analyst's control. Risk results can then be computed automatically.

4.10 STRENGTHS AND LIMITATIONS OF QRA

4.10.1 STRENGTHS

The main strength of QRA is that it is one of the few techniques able to provide guidance to designers and operators on how best to minimize the risks of accidents. QRA combines previous experience with structured judgments to help anticipate accidents before they occur. QRA is most effective when applied to *major* accidents. These are difficult to address subjectively, because they lie outside the experience of most designers, operators and regulators. The chances of such accidents occurring are low, but their consequences can be catastrophic, involving the potential for massive loss of life, damage to the environment, financial loss, and on occasions leading to the failure of the company or major changes to the entire industry. Thus there is a moral and practical incentive to use the best-available methods to minimize these risks.

QRA is readily applied to activities where there is plenty of operating experience to provide a statistical base for the analysis (e.g. semi-submersible drilling rigs). However, safety in these areas can be managed reasonably well on the basis of accident experience.

The added value of a QRA is usually greatest in relatively novel applications (e.g. early concrete platforms, floating production systems, tension leg platforms etc) with little operating experience, especially where standard technology is applied in novel environments. Here, identify and assess accidents that have never happened in these applications, on the basic elsewhere. An example of this is provided by QRAs in the Norwegian Sector which explicitly identified the need for measures to minimize the risks of gas riser fires several years before the *Piper Alpha* accident.

Because offshore QRA has developed largely from techniques used by the onshore process industries, it is most highly developed in the area of hydrocarbon release forming fires and explosions and hence is most effective at predicting risk of process or pipeline operations. Its prediction in other areas (e.g. structural failures, capsize of floating units) are relatively simplistic at present.

4.10.1 LIMITATIONS OF QRA

QRA is a relatively new technique. In general, there is a lack of agreed approaches and poor circulation of data, resulting in wide variations in study quality. In some areas, accident data has not been collected or analyzed, and no theoretical models are available, so risk estimates are inevitably very crude. In other areas, availability of data and analytical techniques is developing rapidly, and the risk estimates tend to fluctuate as a result. Because it is quantitative, QRA appears to be objective, but in reality it is very judgmental. These judgments may be explicit in areas where data is unavailable, but there are also many implicit judgments in the analysis and application of data that is available, and these are often unrecognized. Overlooking the significance of these judgments may lead to false precision in the risk estimates. Over-emphasis on the judgmental nature of a QRA, on the other hand, may lead to its potential benefits being overlooked.

QRA only provides one input to decision-making about safety issues, and most of its advocates recognize that it cannot make the decision itself. There are some aspects, such as public dread of particular sources of risk, which QRAs do not take into account at present. Decision-making about hazardous activities is legitimately influenced by many other economic, social and political factors besides risk, and these must be considered independently in the decision-making process.

DETERMINATION OF HUMAN ERROR PROBABILITIES FOR OFFSHORE PLATFORM MUSTERS

The focus of this chapter is on prediction of human error probabilities during the process of emergency musters on offshore oil and gas production platforms. Due to a lack of human error databases, and in particular human error data for offshore platform musters, an expert judgment technique, the Success Likelihood Index Methodology (SLIM), was adopted as a vehicle to predict human error probabilities. Three muster scenarios of varying severity (man overboard, gas release, and fire and explosion) were studied in detail. Offshore platform musters have significant potential for severe ramifications and present a challenging scenario for human error prediction and reduction. Due to the relatively slow progress in the field of quantification of human reliability, there is a need to advance this area of research and provide techniques that could link human factors with quantitative risk assessment (QRA).

A primary issue is the concept of human error and how it has entered the safety vocabulary as a catchall phrase with a lack of consistent definition and application. The result is an inadequate understanding of how human error identification may be applied in a useful preemptive manner in high-risk scenarios. A better understanding of human error and its consequences can be achieved through the application of human error identification models. To accomplish this, human error must first be removed from the emotional domain of blame and punishment and placed in a systems perspective.

5.1 AIM OF THIS STUDY IS

- To advance the field of human error identification for offshore platform musters in a unique manner.
- To promote and enhance safety in platform musters through the recognition and quantification of human error.

- To provide an accessible human reliability assessment tool yielding a meaningful and useful result.
- To provide risk reduction recommendations to mitigate the potential for human error during platform musters.

5.2 HUMAN ERROR PROBABILITY DATA ELICITATION AND ANALYSIS

The current work concerns itself with the actions beginning at the time of muster initiation (t_I) and ending with the tasks performed in the temporary safe refuge (TSR) before standing down or moving on to the abandonment phase (Figure 5.1). Each phase of the muster has an associated elapsed time (i.e. t_A, t_{Ev}, t_{Eg}, t_R) that collectively make up the total time of muster (t_M). This study therefore focuses on the muster phases that precede evacuation and for which there is significant risk to personnel.

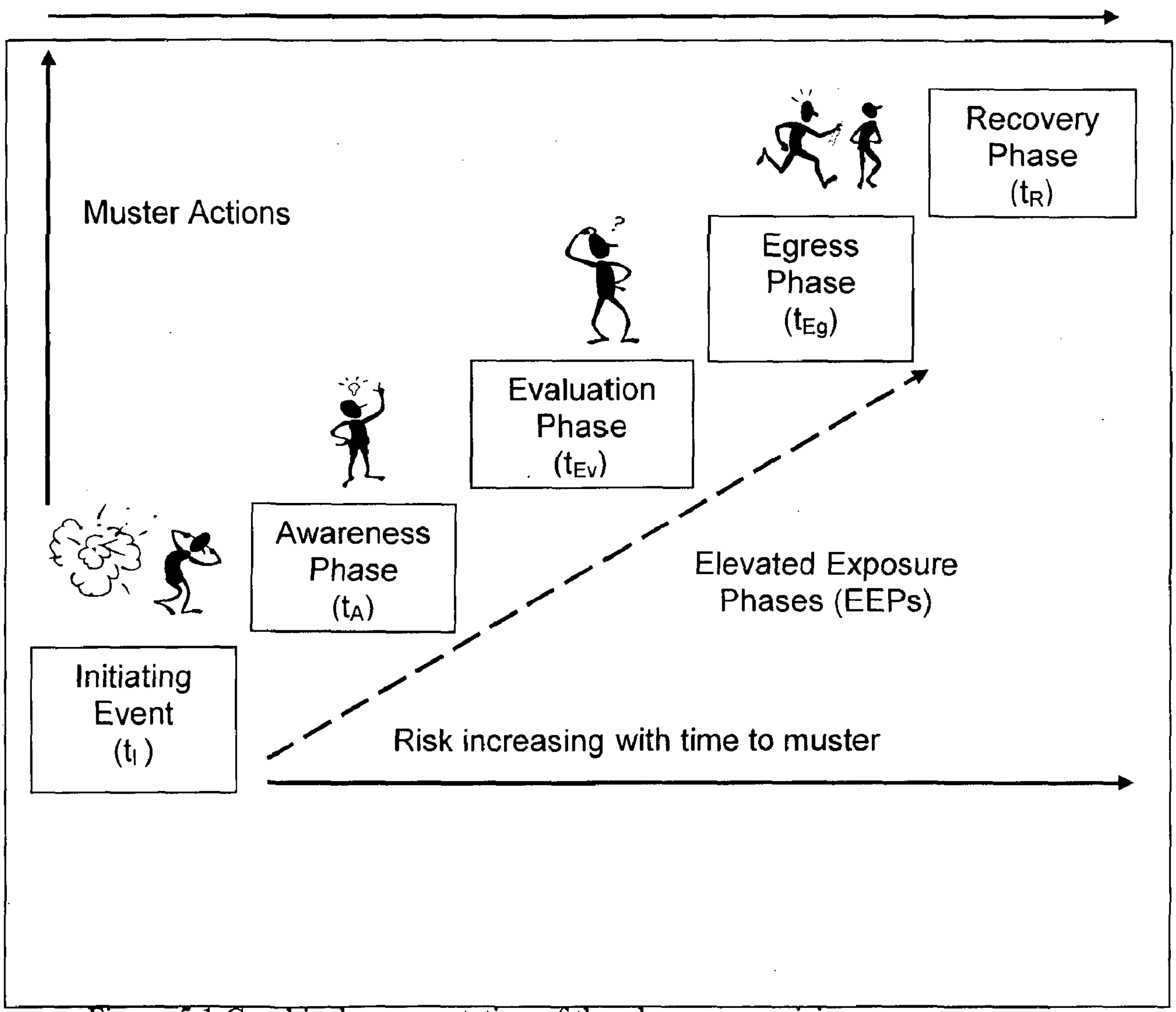


Figure 5.1 Graphical representation of the phases comprising a muster sequence.

The first three phases of muster (awareness, evaluation and egress) are brief compared to the total time of muster. They are typically 10 to 30 % of t_M. It is during these phases that individuals have the greatest exposure to the effects of the muster initiator (e.g. heat, smoke, pressure) and to high levels of physiological and psychological stress; these phases are identified as elevated exposure phases (EEPs). During the EEPs an individual's local egress route and surrounding environment can rapidly degrade. The quality of the egress path and the surrounding environment is referred to as tenability a concept that is well-established in the modeling of human behavior during fires and that lends itself well to muster scenarios as a factor influencing the success of muster tasks.

5.2.1 Core and Elicitation Review Teams

The lack of HEP data for platform musters was the motivation for employing an expert judgment technique in this work. As previously mentioned the technique adopted here was SLIM Success Likelihood Index Methodology. Several researchers have reviewed the usefulness of SLIM in relation to other available HRA techniques .

In essence, the use of an expert judgment technique involves people making subjective decisions in as objective a manner as possible. A critical first step, therefore, was the formation of the team of judges who were to generate the relevant data (selection, weighting and rating of PSFs) for this research project. A grouping of five judges, known as the core review team (CRT), was selected for the initial tasks of deciding on the muster scenarios, the specific muster actions, and the set of performance shaping factors to be used. The following selection criteria were used for the CRT:

- Actively involved in offshore activities as a member of a producing company or regulator.
- Actively participated in platform musters or involved in the design or evaluation of platform safety systems.
- Participated or led risk assessments in offshore related activities.
- Minimum of 10 years of industrial experience in hydrocarbon processing.
- Capable of dedicating the required time to perform evaluations and committed to participate as required.
- Does not work directly for any other member of the CRT or with any member of the CRT on a daily basis.

- Available to meet in person during work hours.

In addition to the set-up work described above, the CRT assisted in the development of questionnaires used in the elicitation of PSF weights and ratings which were subsequently used in the HEP calculations. This data generation phase of the project was conducted by the elicitation review team (ERT), consisting of the five members of the CRT and an additional 19 judges. As shown in Table 5.1, the ERT was thus composed of 24 judges whose primary job functions were: engineering (14 members), operations (6), health and safety (3), and administrative (1).

Table 5.1 ERT judges and relevant backgrounds.

Judge	Classification
A*	Engineer, Facility Engineer (author DGD)
B*	Engineer, Regulatory Engineer
C*	Operations, Control Room Operator
D*	Operations (supervisory background)
E*	Health and Safety (operations background)
F	Engineer, Facility Engineer
G	Engineer, Facility Engineer
H	Engineer, Facility Engineer
I	Engineer, Facility Engineer
J	Engineer, Facility Engineer
K	Administrative
L	Engineer, Facility Engineer
M	Health and Safety (operations background)
N	Engineer, Contract Process Engineer
O	Engineer, Facility Engineer
P	Operations (survival training background)
Q	Operations, Maintenance Planner
R	Engineer, Facility Engineer
S	Engineer, Reservoir Engineer
T	Operations, Trainer

U	Engineer, Materials Engineer
V	Health and Safety (operations background)
W	Operations (supervisory background)
X	Engineer, Contract Instrumentation and Control Engineer

*CRT member

5.2.2 Muster Scenarios

Three muster scenarios were established by the CRT to encompass the widest possible range of credible muster initiators. The following criteria were used in the establishment of these scenarios:

- Credible muster scenarios that can occur on an offshore platform.
- Muster scenarios that provide a wide range of risk.
- At least one scenario that has a close relationship to empirical data.
- At least one severe scenario that can be referenced through known offshore incidents.
- At least one scenario that has been experienced by the majority of the CRT.

The scenarios thus selected were man overboard (MO), gas release (GR), and fire and explosion (F&E). The specific details of each muster scenario were further developed by the CRT in the process of establishing the PSF rating questionnaires.

5.2.3 Muster Hierarchical Task Analysis

The next step for the CRT was to conduct a hierarchical task analysis (HTA) for a generic muster scenario. The goal in this stage was to develop a series of muster steps (or actions) that were independent of the muster initiator (MO, GR or F&E). A preliminary HTA of a muster sequence was developed by Judge A (table 5.1), and provided to the other members of the CRT for review and comment. The result of this review of the original HTA is shown in Table 5.2 and also graphically in Figure 5.2. The muster sequence begins subsequent to the initiating event and does not concern itself with why the event occurred. The sequence ends with the completion of the muster actions in the TSR before standing down (i.e. returning to normal activities) or commencing evacuation actions.

5.2.4 Performance Shaping Factors

Performance shaping factors (PSFs) are those parameters influencing the ability of a human being to complete a given task. Similar to the muster HTA previously described, a draft list of nine PSFs was developed by Judge A (Table 1), and provided to the other members of the CRT for review and comment. The CRT review resulted in a set of 11 PSFs which was reduced to the final set of six (Table 5.3) by means of a pair-wise comparison to determine the most relevant PSFs.

Table 5.2 Muster actions broken down by muster phase.

Awareness Phase	
1	Detect alarm
2	Identify alarm
3	Act accordingly
Evaluation Phase	
4	Ascertain if danger is imminent
5	Muster if in imminent danger
6	Return process equipment to safe state
7	Make workplace as safe as possible in limited time
Egress Phase	
8	Listen and follow PA announcements
9	Evaluate potential egress paths and choose route
10	Move along egress route
11	Assess quality of egress route while moving to TSR
12	Choose alternate route if egress path is not tenable
13	Collect personal survival suit if in accommodations at time of muster
14	Assist others if needed or as directed
Recovery Phase	
15	Register at TSR
16	Provide pertinent feedback attained while enroute to TSR
17	Don personal or TSR survival suit if instructed to abandon
18	Follow OIM's instructions

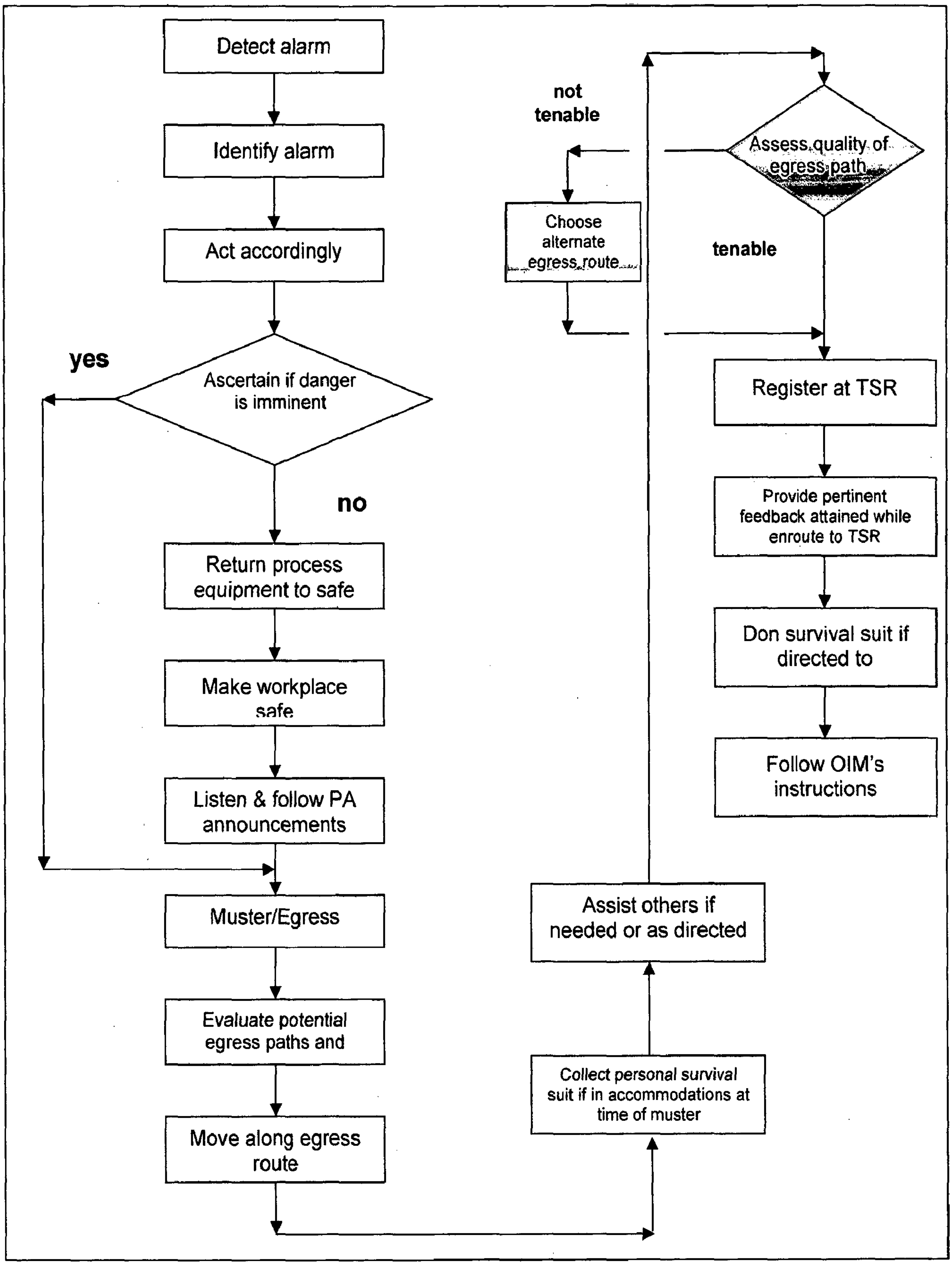


Figure 5.2 Muster sequence.

5.2.5 Performance Shaping Factor Weights

The weight of a performance shaping factor is the relative importance of that PSF in comparison to the PSF judged to be *the* most important. PSF weights range from 0 to 100, with a value of 100 being assigned to the most important PSF (i.e. the PSF most critical to the successful completion of a given action). Here, the weight was determined for each of the six PSFs (Table 5.3) for each of the 18 muster actions (Table 5.2), for each of the three muster scenarios (MO, GR and F&E). This procedure was completed by each of the 24 members of the ERT using questionnaires that had been developed by the CRT.

Table 5.3 Descriptions of performance shaping factors.

PSF	Description
ess	PSF affecting the completion of actions as quickly as possible to effectively muster in a safe manner. This is essentially the effect from the muster initiator on the consequences of not completing the task.
mplexity	PSF that affects the likelihood of a task being completed successfully because of the intricacy of the action and its sub-actions. This, combined with a high level of stress, can make actions that are normally simplistic in nature complicated or cumbersome. This PSF can cause individuals to take shortcuts (violations) to perform a task as quickly as possible or not to complete the task.
aining	PSF that directly relates to an individual's ability to most effectively identify the muster alarm and perform the necessary actions to complete the muster effectively. Training under simulation can provide a complacency factor as a highly trained individual may lack a sense of urgency because of training's inherent repetitiveness.
perience	PSF related to real muster experience. An individual may not be as highly trained as other individuals but may have experienced real musters and the stressors that accompany real events. Strong biases may be formed through these experiences.
vent factors	PSF that is a direct result from the muster initiator and the location of the individual with respect to the initiating event. Distractions that can affect the successful completion of a muster include smoke, heat, fire, pressure wave and noise.
tmospheric factors	PSF that influences actions due to weather. High winds, rain, snow or sleet can affect manual dexterity and make egress paths hazardous when traversing slippery sections. Extremely high winds negatively impact hearing and flexibility of movement.

An illustration of the mean PSF weights (mean of the 24 judges) thus obtained is given in Figure 5.4 for the MO scenario. Focusing on one PSF shown in Figure 5.4 will permit a better understanding of the meaning of the term *weight* when applied to performance shaping factors. For example, stress weights display a generally increasing trend throughout the muster sequence from the awareness phase (actions 1-3 as per Table 5.2) through to the recovery phase (actions 15-18) in the TSR. The importance of low stress levels in completing the muster tasks increases as the muster progresses and the evaluation phase (actions 4-7) ends. Stress weights throughout most of the egress phase (actions 8-4) do not vary significantly because muster conditions were seen by the judges not to be deteriorating under this scenario. There is, however, a notable increase in stress weight at the end of the egress phase at action 14 (assist others). This action is rarely practiced during muster drills and can slow progress to the TSR; the increased weight is thus a reflection of the importance of remaining calm to assist others effectively. There is a notable drop in stress weight in the recovery phase at action 15 (register at TSR). This action requires little skill to complete and no decision making is associated with this relatively simple act. Stress weights increase through the final three recovery actions as lower levels of stress will improve a person's ability to provide feedback and prepare for potential evacuation from the facility.

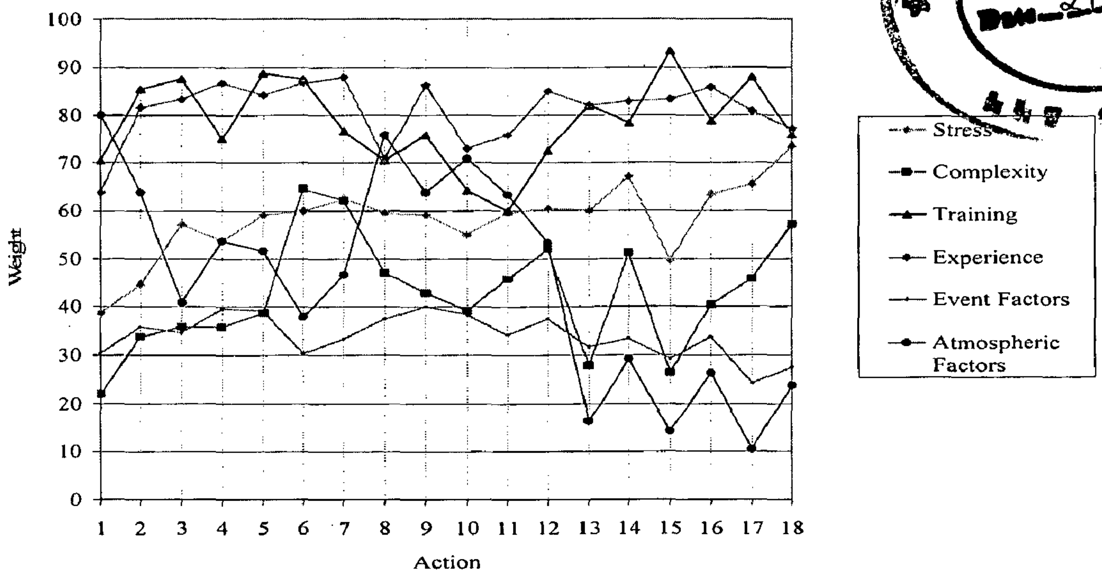
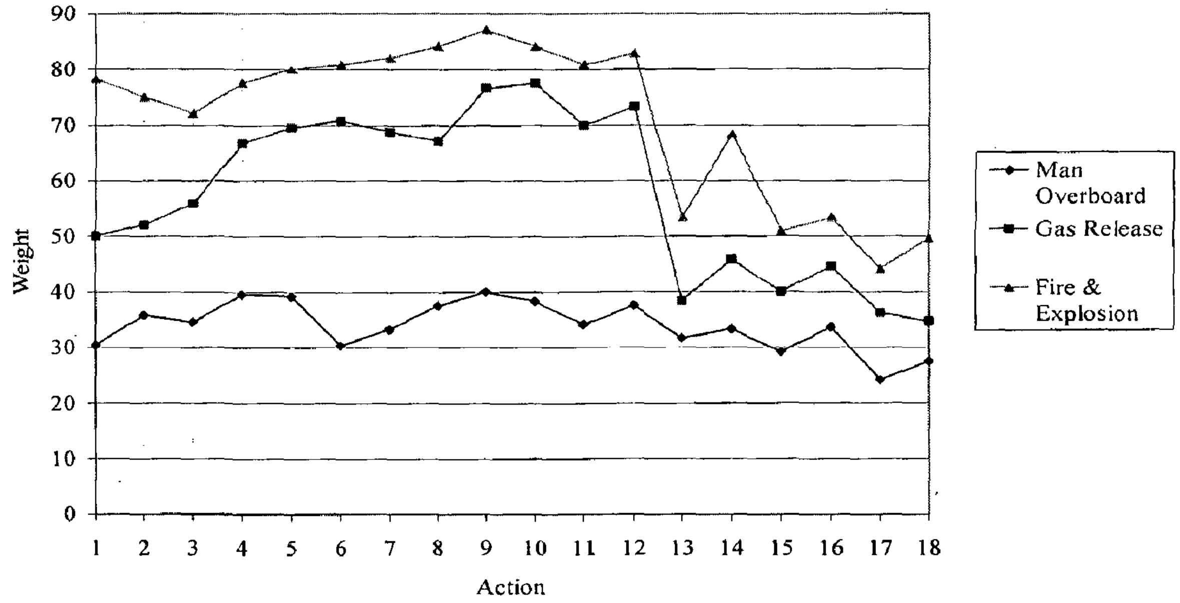


Figure 5.3 PSF weights for man overboard scenario.

A second illustration of the mean PSFs elicited from the ERT judges is given in Figure 5. Here, the weights for one PSF (event factors) across all 18 muster actions are shown for the three muster scenarios. The event factors PSF shows the widest range in weights between scenarios among all six PSFs. The largest gap occurs in the awareness, evaluation and egress phases; there is then a narrowing of the range in the final recovery stage. Gas release and fire and explosion weights are more closely weighted and follow the same trends, showing a step change in importance from the more benign man overboard event. The man overboard scenario resembles the least severe form of muster a drill, where event factors have little effect on the successful completion of tasks.

Figures 5.4 and 5.5 are part of the test of applied to the elicited PSF weight data. The data were plotted and examined from various perspectives: by muster scenario for all actions and PSFs (e.g. Figure 5.4), by PSF for all actions and muster scenarios (e.g. Figure 5.5), and by ERT subgroup. This work was undertaken to verify that the data made sense and could be explained by reasoned argument. Additionally, the PSF weight data were subjected to statistical analysis to test various null hypotheses aimed at determining whether, for example, the muster scenarios affected the judges' PSF weights for each muster action.



Figures 5.4 Comparison of weights for event factors PSF for all three muster initiators

The conclusion reached is that the elicited PSF weight data are rationally explainable and show no significant biases arising from the team of judges that provided the data (e.g. due to sample size, background qualifications, etc.).

5.2.6 Performance Shaping Factor Ratings

The rating of a performance shaping factor is a measure of the quality of that PSF. PSF ratings range from 0 to 100, with a value of 100 being optimal. Here, the rating was determined for each of the six PSFs (Table 5.3) for each of 17 muster actions (Table 5.2, excluding action 13 gather personal survival suit if in accommodations at time of muster), for each of the three muster scenarios (MO, GR and F&E). PSF ratings were not elicited for action 13 because, as described below, the muster scenarios were set up with the mustering individual outside the accommodations module at the time of muster initiation. Similar to the PSF weights, the rating elicitation procedure was completed by each of the 24 members of the ERT using questionnaires that had been developed by the CRT. As previously mentioned, the process of establishing the PSF rating questionnaires required the CRT to further develop the specific details of each muster scenario. These details are given in Table 4 which clearly illustrates the philosophy of the musters being of varying severity. The MO scenario was set up so that the muster sequence provided as few obstacles as possible during the event. In the GR scenario, all six PSFs are of lower quality than in the MO scenario, while the F&E scenario represents the most severe combination of events. Taking one PSF as an example, one can see a degradation in the experience PSF from 15 years offshore experience (MO) to three years (GR), to six months (F&E).

Using the rating scales shown in Table 5 as a guide, the ERT judges were directed to rate the PSFs according to the muster actions for each scenario (from 0 to 100, in increments of 10). An illustration of the mean PSF ratings (mean of the 24 judges) thus obtained is given in Figure 5.6 for the MO scenario. Similar to the PSF weights, focusing on one PSF shown in Figure 5.6 will permit a better understanding of the meaning of the term *rating* when applied to performance shaping factors. For example, ratings for experience (and other PSFs) are high throughout the entire muster sequence. This means the ERT felt that the operator's 15 years of offshore experience was a positive factor in completing all muster actions (particularly action 15 of registering at the TSR). This may be contrasted with Figure 5.7, which illustrates the relationship among the three reference scenarios for the experience PSF ratings. Although the trends throughout the sequences of actions are generally the same, the experience ratings are clearly lowest (i.e. least optimal) for the F&E scenario. This illustrates the poor quality of this PSF in the most severe of the muster scenarios.

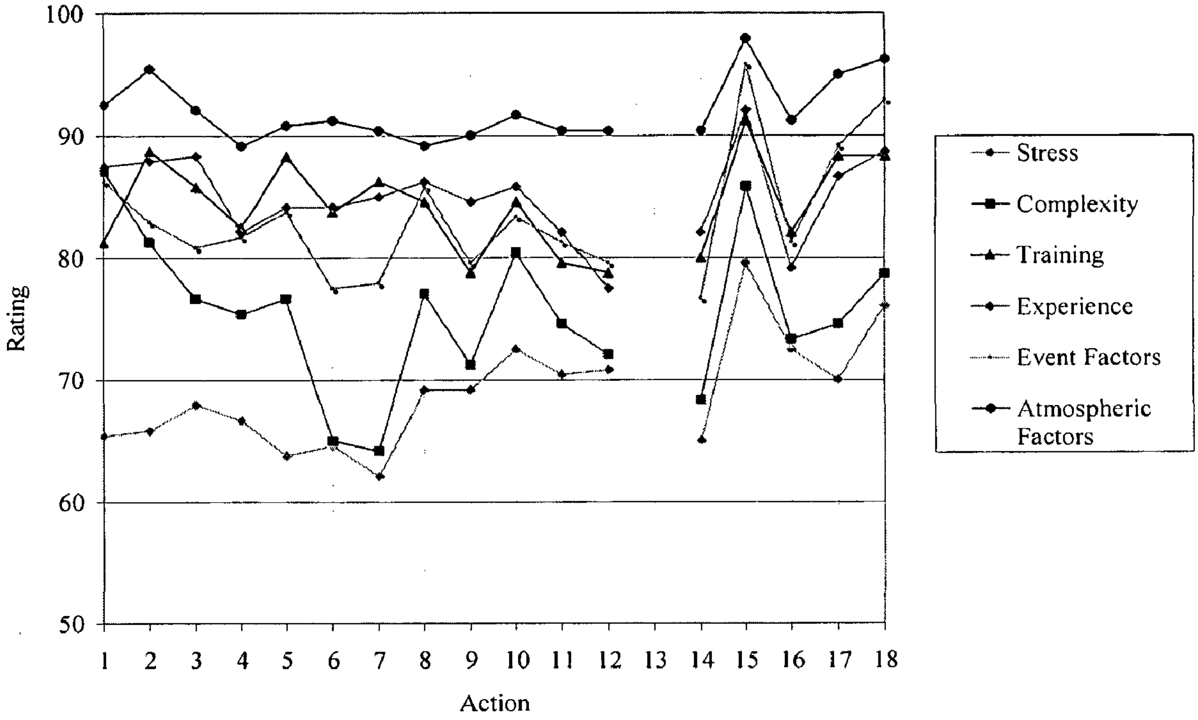


Figure 5.5 PSF ratings for man overboard scenario.

As with the PSF weights, the elicited rating data were subjected to extensive reasonableness and statistical testing. The conclusion from these tests is that the rating data, similar to the weight data, are rationally explainable and show no significant biases arising from the team of judges that provided the data (e.g. due to sample size, background qualifications, etc.). These are important conclusions, because it is the PSF weight and rating data that form the basis of the human error probabilities calculated in this work.

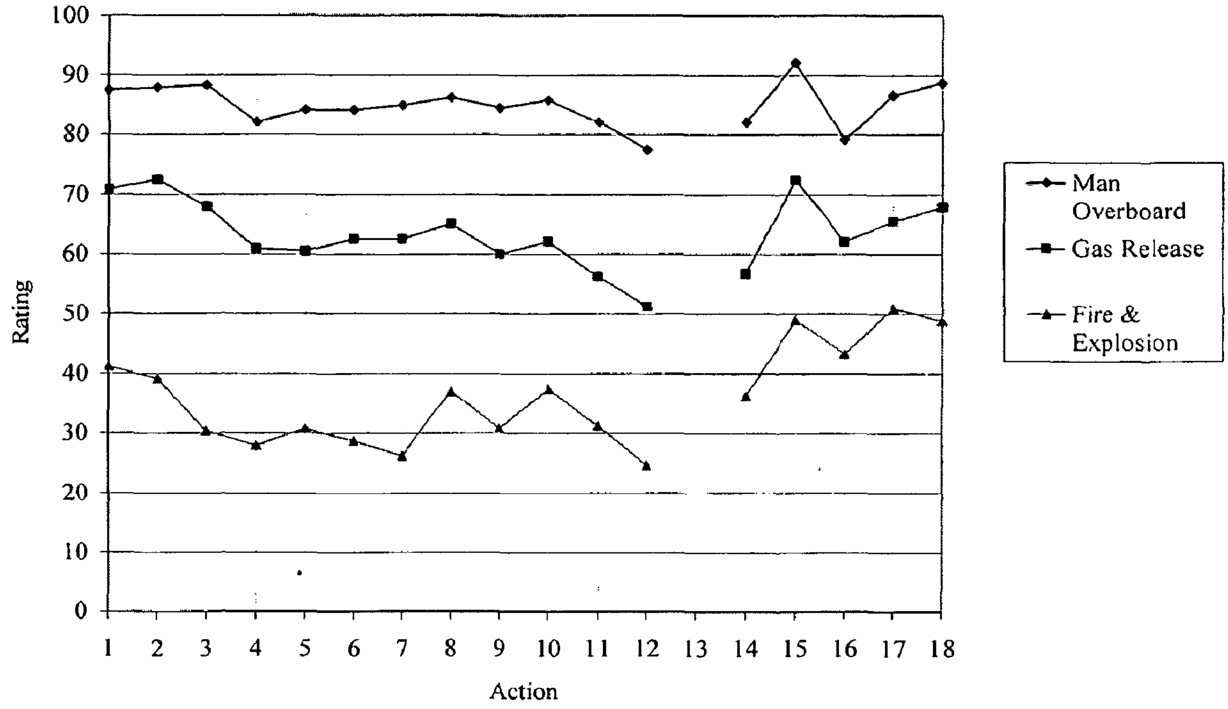


Figure 5.6 Comparison of ratings for experience PSF for all three muster initiators

5.2.7 Human Error Probabilities

The final step in this phase of the research was the actual determination of human error probabilities following the SLIM protocol. For a given muster action, the weight of each PSF is normalized by dividing the weight by the sum of all PSF weights for that action. The resulting quotient is termed the PSF n-weight. Again for a given action, the product of the n-weight and the rating yields the success likelihood index (SLI) for a given PSF. The SLI values for all six PSFs are then summed to yield the total SLI (or simply the SLI) for a given action. The higher the SLI value, the greater the probability of successfully completing a particular muster action.

The results of these calculations are shown in Figure 5.8 in terms of the mean SLI values (mean of the 24 ERT judges). It can be seen that the F&E scenario actions are predicted to have the least likelihood of success among the three reference muster sequences. The likelihood of success is lower through the high risk phases (awareness, evaluation and egress) for both the GR and F&E series, while the MO sequence maintains a similar SLI through all four muster phases. Having established the validity of the SLI data, it was then possible to determine the HEP values for a given action by means of the logarithmic relationship of Pontecorvo (1965), which is a foundational aspect of SLIM:

$$\log(POS_i) = a(SLI_{i,m}) + b \qquad [5.1]$$

where POS_i = Probability of Success for action i = 1 HEP_i

$SLI_{i,m}$ = arithmetic mean of Success Likelihood Index values (from ERT data) for action i

a, b = constants

Determination of the constants *a* and *b* requires an evaluation of the HEPs for the actions having the lowest and highest SLI values. These base HEPs (BHEPs) permit the solution of *a* and *b* via equation [5.1] which is simply the equation of a straight line – and then subsequent calculation of the HEPs for the remaining 16 muster actions (again via equation [5.1]). In accordance with Figure 5.8, action 15 (register at TSR) was selected as having the maximum SLI for all three reference scenarios. The minimum SLI actions were then specified as action 14 (assist others if needed or as directed) for the MO scenario and action 12 (choose alternate route if egress path is not tenable) for both the GR and F&E scenarios. Three approaches were then used to complete the base action analysis by which the constants *a* and *b* were determined:

- Empirical BHEPs from limited available muster data,
- Elicited BHEPs from a randomly selected subset of the ERT, and
- Estimated BHEPs from limited THERP data of Swain & Guttmann (1983) and data of Kirwan (1994).

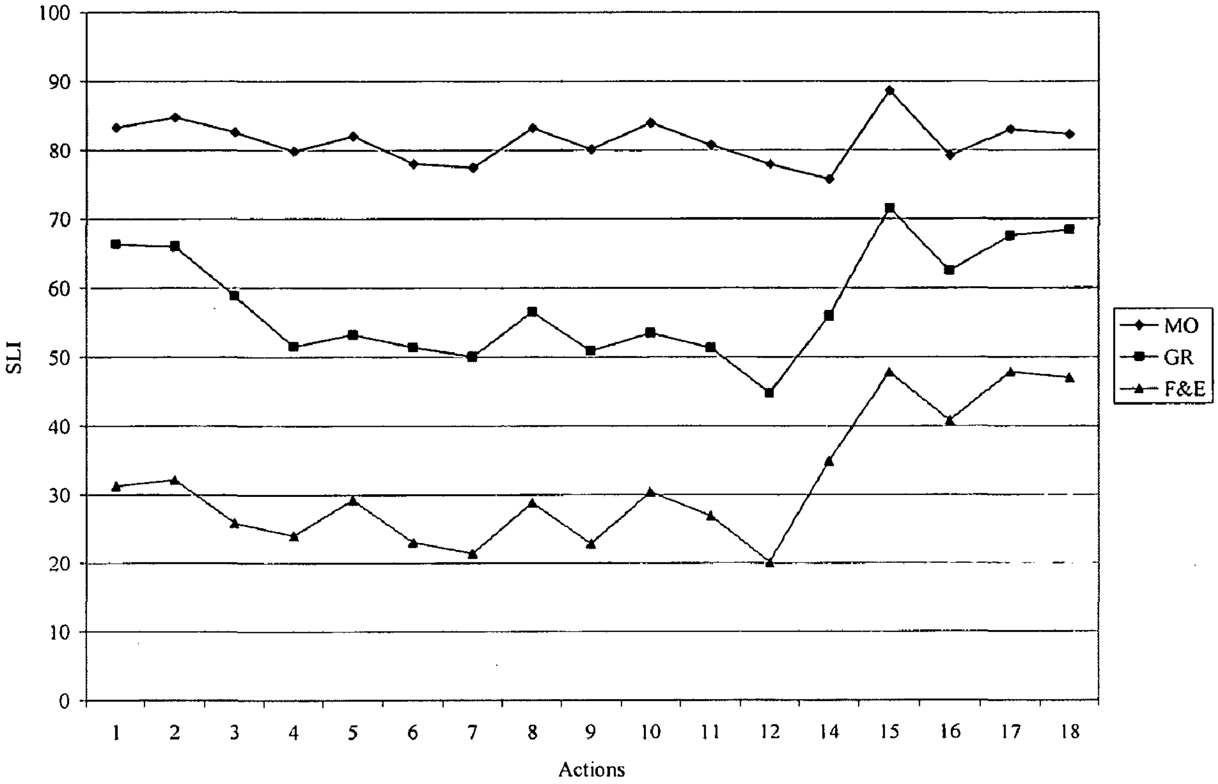


Figure 5.7 SLI values for each action and muster scenario

The last approach mentioned above provided adequate rigor to permit its adoption as the basis for calculating the remaining HEPs for each muster scenario according to equation [5.1]. Table 5.6 gives a summary of the human error probabilities predicted in this manner, along with a list of possible failure modes (loss of defences). In essence, Table 5.6 represents the culmination of the work of the Elicitation Review Team and the endpoint of the Success Likelihood Index Methodology.

Table 5.4 Summary of predicted human error probabilities.

	Action	HEP			Phase	Loss of Defences
		MO	GR	F&E		
1	Detect alarm	0.00499	0.0308	0.396	Awareness	Do not hear alarm. Do not properly identify alarm. Do not maintain composure (panic).
2	Identify alarm	0.00398	0.0293	0.386		
3	Act accordingly	0.00547	0.0535	0.448		
4	Ascertain if danger is imminent	0.00741	0.0765	0.465	Evaluation	Misinterpret muster initiator seriousness and fail to muster in a timely fashion. Do not return process to safe state. Leave workplace in a condition that escalates initiator or impedes others egress.
5	Muster if in imminent danger	0.00589	0.0706	0.416		
6	Return process equipment to safe state	0.00866	0.0782	0.474		
7	Make workplace as safe as possible in limited time	0.00903	0.0835	0.489		
8	Listen and follow PA announcements	0.00507	0.0605	0.420	Egress	Misinterpret or do not hear PA announcements. Misinterpret tenability of egress path. Fail to follow a path which leads to TSR; decide to follow a different egress path with lower tenability. Fail to assist others. Provide incorrect assistance which delays or prevents egress.
9	Evaluate potential egress paths and choose route	0.00718	0.0805	0.476		
10	Move along egress route	0.00453	0.0726	0.405		
11	Assess quality of egress route while moving to TSR	0.00677	0.0788	0.439		
12	Choose alternate route if egress path is not tenable	0.00869	0.1000	0.500		
14	Assist others if needed or as directed	0.01010	0.0649	0.358		
15	Register at TSR	0.00126	0.0100	0.200	Recovery	Fail to register while in the TSR. Fail to provide pertinent feedback. Provide incorrect feedback. Do not don personal survival suit in an adequate time for evacuation. Misinterpret OIM's instructions or do not follow OIM's instructions.
16	Provide pertinent feedback attained while enroute to TSR	0.00781	0.0413	0.289		
17	Don personal survival suit or TSR survival suit if instructed to abandon	0.00517	0.0260	0.199		
18	Follow OIM's instructions	0.00570	0.0208	0.210		

5.3 APPLICATION OF HUMAN ERROR PROBABILITY DATA TO RISK ASSESSMENT

The human error probability data in Table 6 are useful in and of themselves. They present a quantitative measure of the likelihood component of risk due to human error during offshore platform musters of varying severity. Confidence in the predicted HEP values arises due to the rigorous and scientifically validated process of data elicitation and analysis afforded by the Success Likelihood Index Methodology.

The applicability of these data can be extended in the following ways:

- By generalization of the human error probabilities to muster scenarios other than the three scenarios (MO, GR and F&E) investigated via SLIM, and
- Through incorporation of consequence severity into the analysis to enable the full assessment of risk from human error during platform musters (i.e. consideration of *both* likelihood *and* consequences).

The ultimate aim of our further work is to present the aforementioned Human Error Probability Index (HEPI) as a risk assessment tool in both manual and electronic formats. Ideally, this tool will provide a generalized procedure by which any credible muster scenario can be assessed for the likelihood of human error arising in the completion of the various muster tasks. Use of the human error probabilities thus predicted, in conjunction with a consequence table specific to the act of mustering, will enable estimation of the risk for each muster action. The provision of suggested risk reduction measures (RRMs) will allow a re-ranking of risk in an effort to determine an acceptable level.

Tables 5.7, 5.8 and 5.9 demonstrate our current thinking on some of the points in the above paragraph. Table 5.7 gives possible human error consequences according to four receptor categories; the potential consequences range from simple time delays to loss of life. Use of Table 5.7 (or a similar compilation) would involve assigning a severity level to each of the four consequence categories for each muster action (Table 5.2).

Table 5.5 Consequence table for offshore platform musters.

Severity	Egressability	Other POB	Muster Initiator	Health
Critical (C)	Can no longer reach TSR or any other safe refuge. Can no longer have a dry evacuation.	Prevents one or more persons from reaching TSR or any safe refuge. Prevents others from having a dry evacuation.	Raises muster initiator severity to a level where muster is no longer possible.	Results in loss of life.
High (H)	Can no longer reach TSR or complete actions in TSR.	Prevents one or more persons from reaching TSR or prevents others from completing actions in TSR.	Raises muster initiator severity to a level where muster is in jeopardy.	Results in significant physical injury.
Medium(M)	Moderate to significant delay in arriving at TSR. Moderate to significant delay in completing TSR actions.	Moderately to significantly delays others from reaching TSR or their actions in TSR.	Raises muster initiator severity to a level that produces moderate to long delays in reaching TSR.	Potential for minor to moderate injuries.
Low (L)	Minor delay in reaching TSR or in performing actions in TSR.	Minor delay for others reaching TSR, or on others completing actions in TSR.	Is not likely to raise muster initiator severity and does not affect time to muster to any significant level.	No injuries likely.

This could be done via empirical data from muster drills, expert judgment elicitation (similar to that used for the PSF weights and ratings), or simply agreement of knowledgeable individuals. Bringing together such a consequence table with HEP data to determine the level of risk would best be accomplished via the well-accepted industry practice of a risk matrix. The HEP data in Table 6 are suggestive of three likelihood categories covering ranges separated by an order of magnitude (i.e. 0.001 – 0.01, 0.01 – 0.1, and 0.1 – 1.0).

Table 5.6 Human error mechanisms (adapted from Kennedy, 1993).

Error Mechanism	Error Form	Muster Example
ortcut invoked	A wrong intention is formed based on familiar cues that activate a shortcut or inappropriate rule.	The workplace is not made safe before starting egress to the TSR.
ilure to consider special cumstances	A task is similar to others but special circumstances prevail which are ignored and the task is carried out inappropriately.	An egress path is chosen without considering its proximity to a gas release.
ed for information not mpted	There is a failure of internal or external cues to prompt the need to search for information.	A malfunction of the muster alarm system prevents important messages from reaching personnel.
reotype overrule	Due to a strong habit, actions are diverted along a familiar but incorrect pathway.	An egress route taken during muster drills is chosen during a gas release despite the path's close proximity to the muster initiator.
sumption	Response is based, inappropriately, on data supplied through recall or guesses which do not correlate with available external information.	Prior to opening a door, no checks are performed on surface temperature despite a known fire in the local area.
isinterpretation	Response is based on incorrect interpretation of data or the misunderstanding of a verbal message command or request.	A PA announcement is misinterpreted and an egress path of low tenability is taken.
istake among ernatives	Several options are available, of which the incorrect one is chosen.	The muster process offers alternative modes of egress and the incorrect path is chosen.
sing one's place	The correct position in the sequence of actions is misidentified as being later than actual.	Once in the TSR, an individual does not register, generating a missing person scenario.
otor variability	There is a lack of manual precision, or incorrect force is applied.	An individual does not effectively close a valve while making the workplace safe.
nic	There is a lack of composure, and the result is disorientation, incoherence and possibly static movement.	Upon hearing the muster alarm or witnessing the muster initiator, a person becomes incapacitated.
emory slip	Performance of an action or some component of the action is forgotten.	Mustering individuals forget which direction the TSR is from their current location.
atial orientation adequate	Despite an individual's correct intention and recall of identification markings, an action is performed in the wrong place or on the incorrect object.	An individual chooses a similar but incorrect valve while in haste to make the workplace safe before starting egress to the TSR.

Table 5.7 Possible risk mitigation measures for action 1.

Action	Training	Procedures and Management Systems	Equipment
tect alarm	1. Familiarization of personnel with alarms 2. Muster training at infrequent intervals 3. Enlisting feedback after training exercises on alarm effectiveness 4. Behavioural studies to determine panic potential 5. Training of control room operators to limit and remove inhibits as soon as possible 6. Training of experienced personnel to assist others as identified	1. Regular preventative maintenance of alarm system 2. Regular testing of alarm system 3. Survey of alarm effectiveness in severe weather conditions 4. Limiting number of alarm types that can be enunciated to lessen potential confusion 5. Identification of new personnel with different coloured clothing 6. Buddy system for new personnel 7. Location board in control room identifying work locations and personnel 8. Equipping all personnel in process units with two-way radios 9. Pushbuttons in strategic process locations	1. Strategic placement of alarm systems to ensure coverage in all areas 2. Alarm redundancy through both audio and visual enunciation 3. Review of alarm system and comparison with advances in technology 4. Review of applicable regulations and standards

Risk reduction and re-ranking can be addressed by first adapting the general human error literature to the specific tasks of mustering offshore, as illustrated by the examples in Table 5.8. By identifying *human errors*, one is then in a better position to suggest risk reduction measures that crossover into the field of *human factors*. Examples of potential RRMs in various categories are given in Table 5.9 for the first muster action of detecting the alarm. Given the close link between human factors and inherent safety identification of RRMs based on the principles of inherent safety would be highly beneficial. Such work is underway within our research group in addition to the other considerations mentioned in this section.

CHAPTER 6

REVISED FIRE CONSEQUENCE MODELS FOR OFFSHORE QUANTITATIVE RISK ASSESSMENT

Considering the importance of fire modeling in offshore QRA and the available knowledge gap, the current work was undertaken with the objective of revising available fire models for offshore operations. The work is ongoing and has been planned to enhance existing knowledge of fire consequence modeling through the following advancements:

- *Fire characteristics*: Available fire models have been reviewed and the most appropriate ones selected and revised by incorporating wind and confinement effects which are unique to offshore process platforms.
- *Overpressure impact:* The importance of overpressure caused due to fire in a confined or semi-confined space has been highlighted by Wighus. However, there appears to have been no attempt to quantify this phenomenon. In the present work, a model has therefore been developed to study the overpressure impact. This model is embedded in the basic fire consequence modeling methodology described herein.
- *Radiation modeling:* Instead of point/area modeling, a grid-based approach has been employed to enable better modeling and analysis of radiation impact at different locations, the impact of obstacles, and the effects of flame impingement.

6. CURRENT STATUS OF FIRE CONSEQUENCE MODELING

There are many predictive models available for the assessment of fire consequence hazards varying from point source techniques to more complex computational fluid dynamic (CFD) calculations. Such predictive models can be categorized as follows into: semi-empirical models, field models, integral models and zone models.

6.1. Semi-Empirical Models

6.1.1 Point source models

Point source models do not predict the flame geometry, but rather assume that the source of thermal radiation is a single point in the flame and that a selected fraction of the heat of combustion is emitted as radiation. These models generally over-predict the heat flux for near-field conditions; however, they can be used reliably beyond approximately five pool diameters from the flame. The use of point source models within offshore structures is limited.

6.1.2 Solid flame models

Solid flame surface emitter models assume a fire to be a solid flame with heat being radiated from the surface of the flame. They rely mainly on correlations for flame geometry estimation, average surface emissive power (SEP) of the flame, atmospheric transmissivity and view factors. The various surface emitter models differ in their methods of assessing atmospheric attenuation of the heat flux, view factors, and the SEP. Well-validated solid flame models provide a better prediction of flame geometry and external thermal radiation for offshore fires than is possible with point source models.

In general, semi-empirical models are task specific, are designed to address specific hazard consequences, and incorporate correlations fitted to large-scale experimental data. These models are mathematically simple and can be easily computer programmed with short run times.

6.2 FIELD MODELS

Field models are CFD models based on numerical solutions of the Navier-Stokes equations of fluid flow i.e. a description of the conservation of mass, momentum and scalar quantities in flowing fluid, by means of a set of partial differential equations. To predict fire behavior, these models incorporate various sub-models to account for the physical and chemical processes occurring in a fire. All such models require validation against experimental data before using them as predictive tools to estimate the hazards of open or compartment fires. Limiting factors in the applicability of these models are related to high CPU demands and user expertise.

6.3 INTEGRAL MODELS

Integral models are a compromise between semi-empirical and field models, and are formulated mathematically in a manner similar to field models. Thus, integral models also solve the conservation of mass and momentum equations and contain sub-models for combustion and heat transfer. The mathematical treatment is simpler than in field models, thus reducing computer run times. Some integral models that have been validated against laboratory-scale experimental data are available.

6.4 ZONE MODELS

Zone models divide a module or a compartment into a number of zones that are assumed physically distinct, but coupled by empirical heat and mass transfer equations. Even though this is a traditional approach to model compartment fires, very few zone models have been validated quantitatively for offshore applications. Zone models have wide applicability and validity for the purposes for which they are designed, i.e. buildings with reasonably small rooms and predominantly small vertical vents. However, they encounter severe limitations in modeling large offshore compartments. Further research in this area of modeling would be beneficial.

Provided they are used within their range of applicability, validated semi-empirical solid flame models are well-suited for the prediction of heat fluxes to objects outside the flame. These models have been successfully used for fire consequence analysis and further, for QRA. However, they are not directly applicable to the study of fire characteristics in offshore facilities without revision by incorporation of sub-models as described in the current work.

6.5 CHARACTERISTICS OF OFFSHORE FIRES

The characteristics of a fire depend on factors such as the type of fuel, release conditions, local geometry, ventilation, and air access. Potential fuels handled offshore include crude oil, natural gas, and gas containing condensate and water all of which are continuously produced, processed, separated, dried and stored. These fuels pose a significant amount of risk to personnel, equipment and the environment.

Fires on process plants onshore differ from offshore mainly in the level of confinement. The harsh marine environment offshore dictates the need for process areas to be enclosed and shielded against the weather. It is well-established that a fire inside a confined volume develops differently from an open fire. The restriction in air supply is often the limiting factor with respect to fire size, and a severely under-ventilated fire environment can develop. Burning of hydrocarbons under such conditions may be more intense than in open fires, as the mixture of air and fuel may be closer to an ideal stoichiometric mixture. Additionally, heat losses from the fire to the surroundings are reduced, leading to higher flame temperatures.

Major hazards associated with compartment fires include those normally associated with open fires, such as external thermal radiation and direct flame impingement on objects. In addition, other hazards exist due to the effect of confinement. Some of these additional hazards to personnel are impaired visibility along escape routes due to excess smoke, toxicity from the release of carbon monoxide due to incomplete combustion, and overpressure impacts from the hot combustion gases.

Consideration of smoke and carbon monoxide generation requires detailed chemistry calculations which are outside the scope of the current paper. An important aspect mentioned above, and often neglected in fire modeling, is overpressure due to fires in confined spaces. With only small openings in a compartment, the highly energized combustion products released from these fires can generate pressures greater than ambient. This condition may further lead to an explosion creating blast wave and missile effects. Therefore, overpressure effects have to be taken into account when analyzing the hazards from offshore fires. In the present work we have developed a set of equations for overpressure quantification, which are discussed in detail in the following section.

6.6 REVISED FIRE MODELS

Leakage or spillage of flammable material can lead to a fire that is triggered by any number of potential ignition sources (sparks, open flames, etc.). These fires are broadly classified into four types, namely pool fires, jet fires, fireballs and flash fires, irrespective of offshore or onshore conditions. The available models for each of the four fire types are now reviewed, and the ones most suitable for offshore environments are identified. Model revisions are also discussed.

6.6.1 Pool fires

A **pool fire** is a turbulent diffusion fire burning above a pool of vaporizing hydrocarbon fuel where the fuel vapor has negligible initial momentum.The probability of occurrence of pool fires on offshore platforms is high due to continuous handling of heavy hydrocarbons onboard. Liquid fuel released accidentally during overfilling of storage tanks, rupture of pipes and tanks etc., forms a pool on the surface, vaporizes, and upon ignition, results in a pool fire.

Consequence models for pool fires in open spaces have been well-documented over the past few years. Although there has also been significant work done on compartment fires, most of these efforts deal with CFD modeling. There are also a few physically based zone models that have been developed for compartment fires.

Using a solid flame approach, a pool fire is modeled as a sheared elliptical cylinder which is assumed to radiate in two layers – a high emissive power, clean burning zone at the base, with a smoky obscured layer above as shown in Figure 5.1. The radiation heat flux received by a target depends on the atmospheric transmissivity, geometric view factor and surface emissive power of the fire. The correlation used to quantify heat flux, q, is as follows:

$$q = q_L + q_U = \tau_L * VF_L * SEP_L + \tau_U * VF_U * SEP_U \qquad (6.1)$$

where τ is atmospheric transmissivity, VF is the geometric view factor and SEP is the average surface emissive power. The subscripts L and U refer to values calculated for the clear lower layer and smoky upper layer of the model flame shape, respectively.

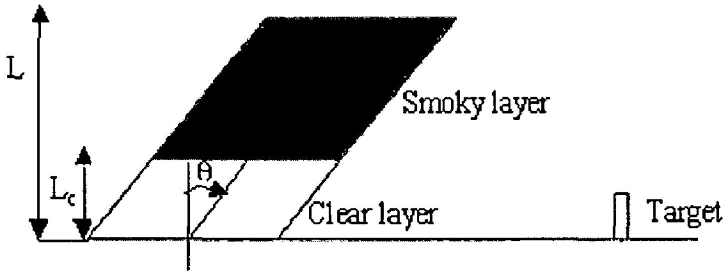


Figure 6.1 Flame geometry for a tilted pool fire.

Atmospheric transmissivity is calculated using an algorithm developed by Wayne. This calculation is based on the assumptions that the flame is a black body source at 1500 K, with CO_2 and H_2O vapor being the only molecules that absorb radiation in the pathway between the fire and the target.

The view factor (Davis & Bagster, 1989) represents the fraction of the overall heat output that strikes the target, and is dependent upon the geometry of both the flame and the target. For radiation from a finite flame to a differential receiving element, the view factor is given by the integral over the flame surface:

$$VF = \int_s \frac{\cos\beta_1 \cos\beta_2}{\pi d^2} \tag{6.2}$$

where β_1 and β_2 are the angles between the normal to the fire surface and the receiving element, respectively, and d is the distance from the receiver point to the flame center.

The surface emissive powers for the clear lower layer and the smoky upper layer are correlated separately as follows:

$$SEP_U = U_R \times SEP_L + (1 - U_R) SEP_S \tag{6.3}$$

$$SEP_L = SEP_\infty \left(1 - e^{-k_m D}\right) \tag{6.4}$$

where U_R is the un-obscured ratio, SEP_S is the surface emissive power of smoke, SEP_∞ is the maximum surface emissive power of a fuel, k_m is the extinction coefficient, and D is the pool diameter.

Overpressure calculation

The model described so far predicts only the radiation heat flux received by a target object. A model for the estimation of overpressures generated by highly energized combustion gases in a compartment is given by a combination of the ideal gas law and radiative heat transfer equations with the following assumptions:

a) negligible convective heat transfer,
b) ideal gas behavior of the combustion gases,
c) small compartment openings, and
d) linear distribution of temperature variation within the defined space.

The algorithm for overpressure calculation is as follows:

1. Calculate the flame temperature, T_{flame}, using the surface emissive power estimated from the radiation model described earlier:

$$Q_{rad} = \sigma \left(T_{flame}^4 - T_o^4\right) \qquad (6.5)$$

2. Similarly calculate the temperature at one corner of the compartment, T_{cc}, and using assumption d) above, estimate the average temperature of the gases, T_{gases}:

$$T_{gases} = \frac{T_{flame} + T_{cc}}{2} \qquad (6.6)$$

3. Finally, use the ideal gas law to estimate an approximate value of the overpressure, P_o, generated by the gases in the compartment:

$$P_o = \frac{nRT_{gases}}{V_{room}} \qquad (6.7)$$

where Q_{rad} is the heat emitted by the flame per unit area, σ is the Stefan-Boltzmann constant ($5.669 * 10^{-8}$ W/m^{2}K^4), T_o is the initial compartment temperature, n is the moles of combustion gases in the compartment, R is the gas constant, and V_{room} is the volume of the compartment under study.

This overpressure impact model is embedded in the pool fire radiation model as well as in the other fire models described in subsequent sections.

6.6.2 Jet fires

A **jet fire** is a turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction. Jet fires represent a significant element of risk associated with major incidents on offshore installations, with the fuels ranging from light flammable gases to two-phase crude oil releases. Between horizontal and vertical jet fires, the former is the most dangerous because of the high probability of impingement on objects downwind. This can lead to structural, storage vessel, and pipe-work failures, and can cause further escalation of the event (i.e. domino effect). The heat fluxes released from these fires are very high, ranging from 200 – 400 kW/m^2 depending on the type of fuel. Almost all the fuels handled offshore can form jet fires provided that the release occurs under conditions such that the fluid has some initial momentum (such as a leak from a pressurized gas line). Vertical jet fire models are commonly used to assess the hazards from flares. The model of Chamberlain has been extended to horizontal jet fires by Johnson et al. (1994). This model was developed with offshore conditions in mind, and was therefore chosen as the base jet fire model in the current work. A brief description of the selected radiation model follows. A horizontal jet fire is modeled as the truncated frustum of a cone, which emits thermal radiation from its surface as shown in Figure 5.2 . For horizontal releases, the buoyancy of the flame dominates over wind momentum, causing the flame to rise above the horizontal plane. Because objects in the direction of the release receive radiation from emitting paths roughly equal to the flame length (which is much larger than the flame width), a different surface emissive power is assigned to the ends of the solid flame from the SEP used for the sides of the flame. Thus, the thermal radiative flux at a target object is given as:

$$q = \left(VF_{side} * SEP_{side} + VF_{end} * SEP_{end}\right) * \tau \qquad (6.8)$$

where the subscripts *side* and *end* refer to values calculated for the side and end of the model flame shape.

View factors and atmospheric transmissivity are calculated as per the formulation for pool fires. The surface emissive powers for the side and end of the model flame are given as follows:

$$SEP_{side} = SEP_{\infty}\left(1 - e^{-kW_2}\right) \tag{6.9}$$

$$SEP_{end} = SEP_{\infty}\left(1 - e^{-kR_L}\right) \tag{6.10}$$

where $SEP_{\infty} = \dfrac{F_{s\infty}Q}{A}$, is the maximum surface emissive power, and

$F_{s\infty} = 0.21e^{-0.00323u_j} + 0.14$, is the fraction of the overall heat emitted as radiation.

The factor k is the gray gas absorption coefficient, W_2 is the maximum width of the flame, R_L is the length of the frustum, Q is the net heat released by combustion, A is the surface area of the flame, and u_j is the velocity of the jet.

This radiation consequence model, with the inclusion of the overpressure impact model described in the previous section on pool fires, enables prediction of the characteristics of horizontal jet fires on offshore platforms.

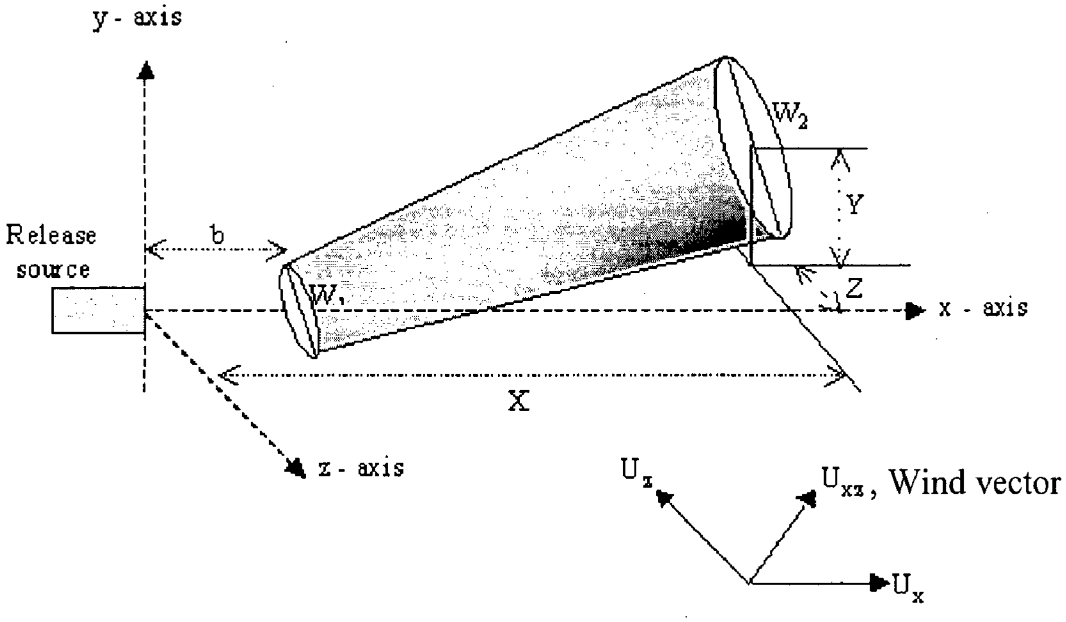


Figure 6.2 Flame geometry for a horizontal jet fire.

6.6.3 Fireballs

A **fireball** is a rapid turbulent combustion of fuel, usually in the form of a rising and expanding radiant ball of flame. When a fire such as a pool or jet fire impinges on a vessel containing pressure-liquefied gas, the pressure in the vessel rises and the vessel wall weakens. This can eventually lead to catastrophic failure of the vessel with the release of the entire inventory. This phenomenon is known as a boiling liquid expanding vapor explosion (BLEVE). In such releases, the liquefied gas released to the atmosphere flashes due to the sudden pressure drop. If the released material is flammable, it will ignite; in addition to missile and blast hazards, there is thus a thermal radiation hazard from the fireball produced. It is this thermal radiation which dominates in the near field. Although the duration of the heat pulse from a fireball is typically of the order of 10 - 20 s, the damage potential is high due to the fireball's massive surface emissive power. Large-scale experiments carried out by Roberts et al. with propane as the fuel, measured a maximum average surface emissive power ranging from 270 – 333 kW/m^2 up/downwind and 278 – 413 kW/m^2 crosswind. Due to the high turbulence involved, a fireball can also be expected to cause significant overpressures. Alternative scenarios for fireballs to the one described in the previous paragraph, e.g. fireballs from delayed ignition of continuous jet releases, have also been dealt with by Cracknell & Carsley . For the present study, the model of Roberts et al. (2000) was selected as the base fireball model. In this approach Roberts et al., a fireball is modeled as a sphere as shown in Figure 6.3. The radiation heat flux incident on a target is evaluated using a solid flame model as the product of atmospheric transmissivity, geometric view factor and the surface emissive power:

$$q = \tau * VF * SEP \qquad \textbf{(6.11)}$$

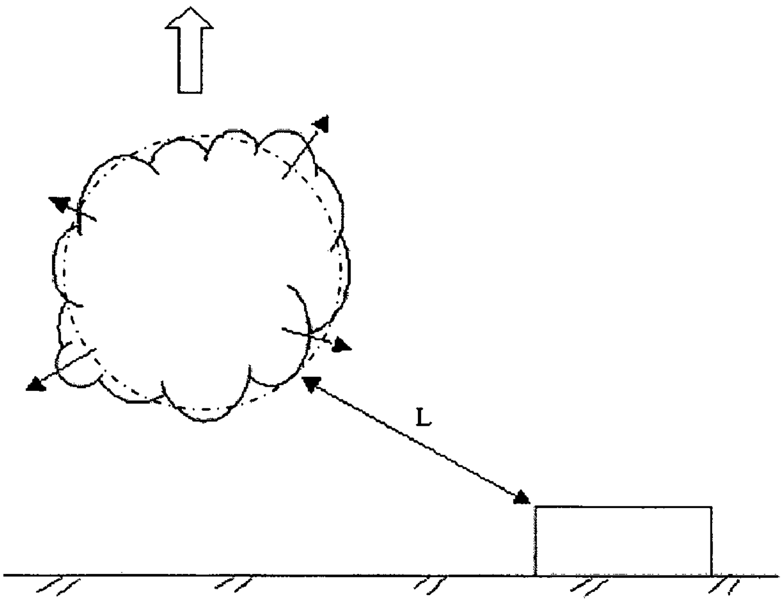


Figure 6.3 Flame geometry for an expanding, rising fireball.

Surface emissive powers measured experimentally by Roberts et al. (2000) are used, while view factors and transmissivity are evaluated using the correlations described in the previous section on pool fires. Because a fireball is a transient event, the heat flux varies with time initially increasing, and then falling off after reaching a maximum value (e.g. Figure 6.4). This is because the fireball size grows in the initial stages, reaches a maximum, and then reduces as the fireball rises

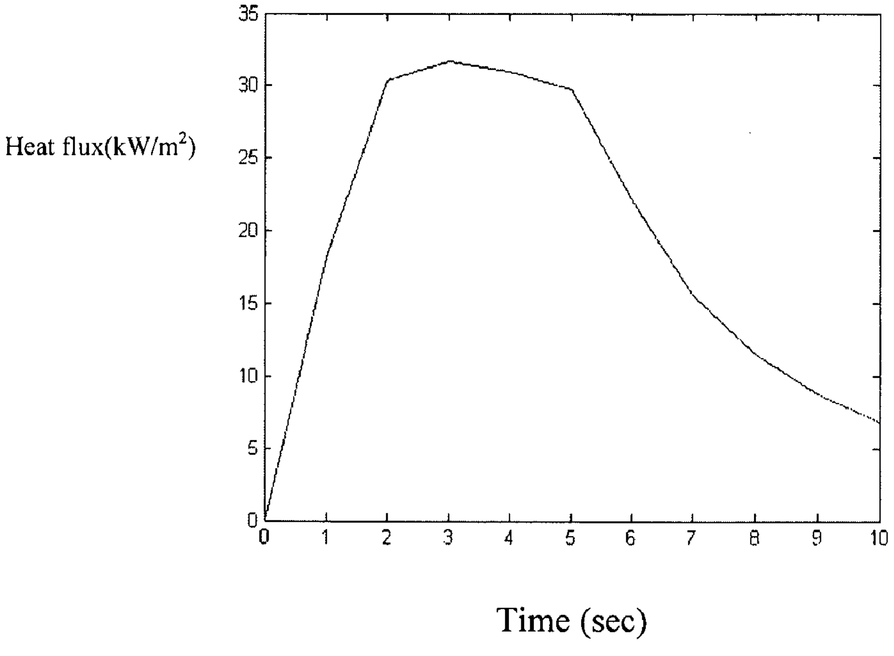


Figure 6.4 Time dependent heat flux for a fireball.

6.6.4 Flash fires

A **flash fire** is a transient fire resulting from the ignition of a gas or vapor cloud, where a delay between the release of flammable material and subsequent ignition has allowed a cloud of flammable material to build up and spread out from its release point.

A flash fire is usually characterized by a "wall of flame" progressing out from the point of ignition at a moderate velocity until the whole flammable cloud has burned. Similar to fireballs, flash fires can occur either by ignition of a flammable vapor cloud formed from an instantaneous release, or by delayed ignition of a cloud from a continuous release, provided the turbulence in the cloud is low enough that a fireball does not occur. The instantaneous or continuous releases considered in risk studies would physically correspond to a spreading transient puff or a long steady-state plume.

When the cloud ignites, the initial damage will be caused primarily by thermal radiation. However, flash fires may generate more damaging "knock-on" events, especially if they burn back to the source. The knock-on events can be a pool fire, jet fire, BLEVE etc. Further, the presence of obstacles along the pathway and the high degree of congestion on offshore platforms can lead to significant flame acceleration. Such increases in flame speed can in turn lead to significant overpressures and ultimately a partially confined or confined vapor cloud explosion. The effects of these escalation events are likely to be more severe than the flash fire itself.

Consequence modeling of a cloud fire in an un-congested/unconfined environment where overpressure is not a principal hazard has been well-documented. These flash fire models are based on gas dispersion modeling coupled with the probability of ignition, where the boundary of the fire is defined by the un-ignited cloud's downwind and crosswind dimensions at flammable limit concentrations (usually the lower flammable limit, LFL, of the cloud). This stage of the modeling work is ongoing within our research group.

6.7 DAMAGE EFFECT CALCULATIONS

The consequence models discussed so far provide estimates of the radiation heat flux at a target object and the overpressure in a confined area. These are, of course, important parameters to know, but they must be translated into anticipated harm to personnel onboard. Dose response evaluation is therefore needed to quantify the damage (fatality) from thermal radiation and overpressure. To facilitate this analysis, personnel harm is expressed in terms of probit functions, which relate the percentage of people affected in a bounded region of interest by a normal distribution function.

The probit function, Pr, for heat radiation lethality is given as:

$$Pr = -36.38 + 2.56 * ln(t * q^{4/3}) \tag{6.12}$$

where q is the radiation heat flux and t is the time of exposure.

The probit function for likelihood of death due to overpressure (lung rupture) is given as:

$$Pr = -77.1 + 6.91 * ln(P_o) \tag{6.13}$$

where P_o is the overpressure.

Finally the probability P, of damage is quantified using the formula (CCPS,):

$$P = 50\left[1 + \frac{Pr-5}{|Pr-5|} erf\left(\frac{|Pr-5|}{\sqrt{2}}\right)\right] \tag{6.14}$$

where erf is the error function.

A grid-based approach has been adopted to facilitate modeling and analysis of radiation impact at different locations in a predefined area. In this approach, the area under study is divided into smaller grids, and the heat flux and radiation damage are estimated at each grid point with the results plotted as contours.

CHAPTER 7

RESULTS AND DISCUSSION

In this section, we will first discuss how the revised pool fire, jet fire and fireball models are simulated under specific scenarios for radiation heat fluxes and overpressures for n offshore platform. The simulation results for each of the fires are presented graphically in three different ways: radiation flux contours, radiation damage contours and the variation of radiation damage along the centerline.

7.1 SIMULATION RESULTS FOR REVISED FIRE MODELS

7.1.1 Scenario 1 – Pool Fire: A crude oil storage tank of 4-m diameter and 100-kg capacity on an offshore platform catches fire, leading to a ***pool fire***. The mass burning rate of the crude oil is 0.0507 kg/s. Wind speed is 5 m/s in an easterly direction.

Simulation Results:

Height of pool fire = 5.5 m

Angle of tilt from vertical = 56 degrees

SEP of lower clear flame = 112 kW/m^2

SEP of upper smoky flame = 25 kW/m^2

Assuming the pool has formed in the center of a 50 m * 50 m room, the radiation heat flux in that space can be represented by the contours shown in Figure 7.1. Similarly, lethality (radiation damage) contours in a 100 m * 100 m area are represented in Figure7.2, while the thermal radiation damage along the centerline is shown in Figure 7.3. As the pool fire is tilted 56 degrees from the vertical toward the downwind direction, the radiation and hence the damage must be higher downwind than upwind. This is evident from the contours in Figures 7.1 and 7.2 Figure 7.3 shows that 100% lethality is expected up to a distance of ~30 m and minor damages up to a distance of ~50 m downwind from the center of the pool. Distances greater than 50 m downwind and 45 m upwind are identified as safer zones.

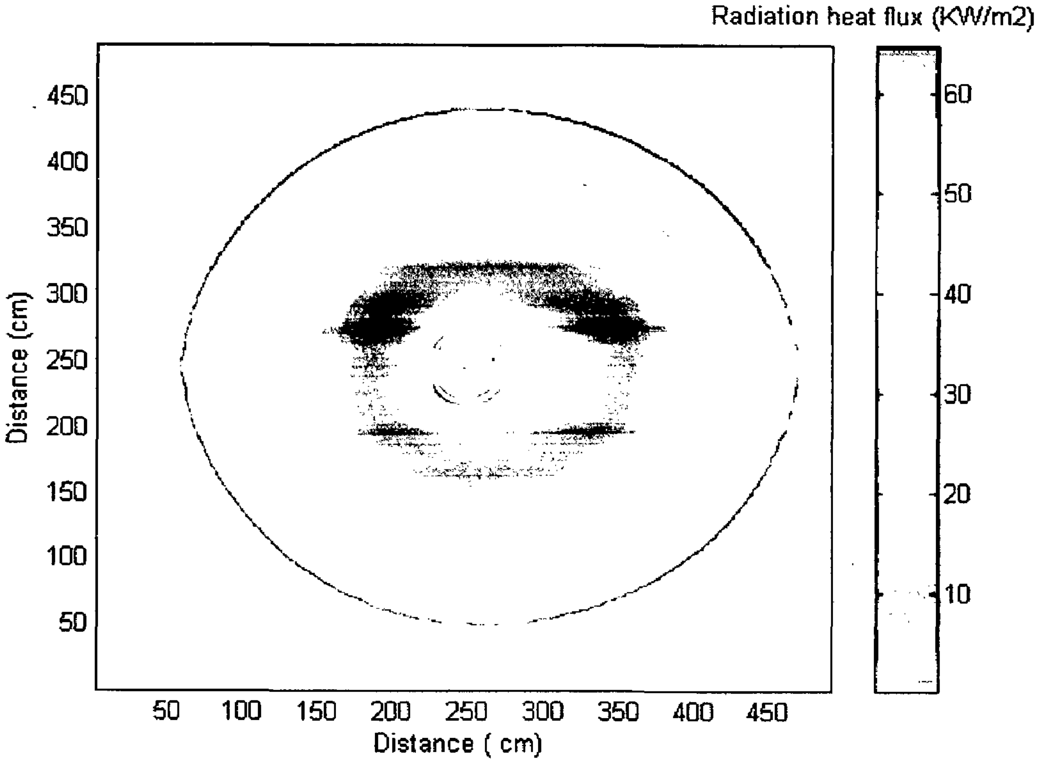


Figure 7.1 Radiation contours from revised pool fire model.

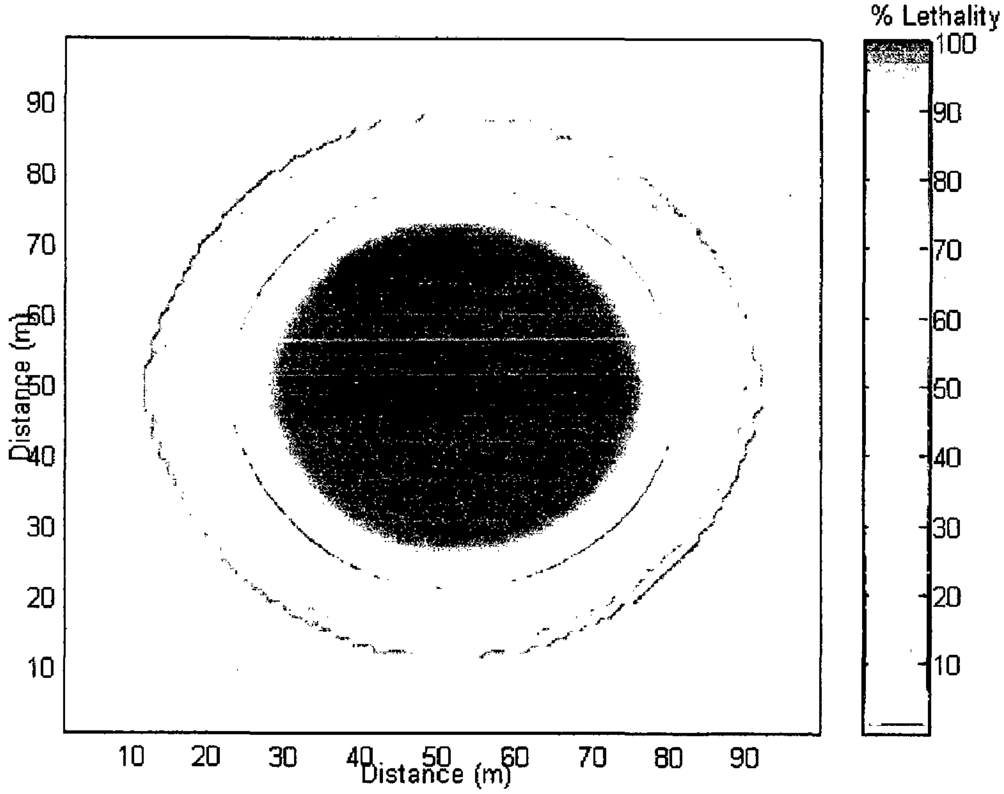


Figure 7.2 Percentage lethality (thermal radiation) contours from revised pool fire model.

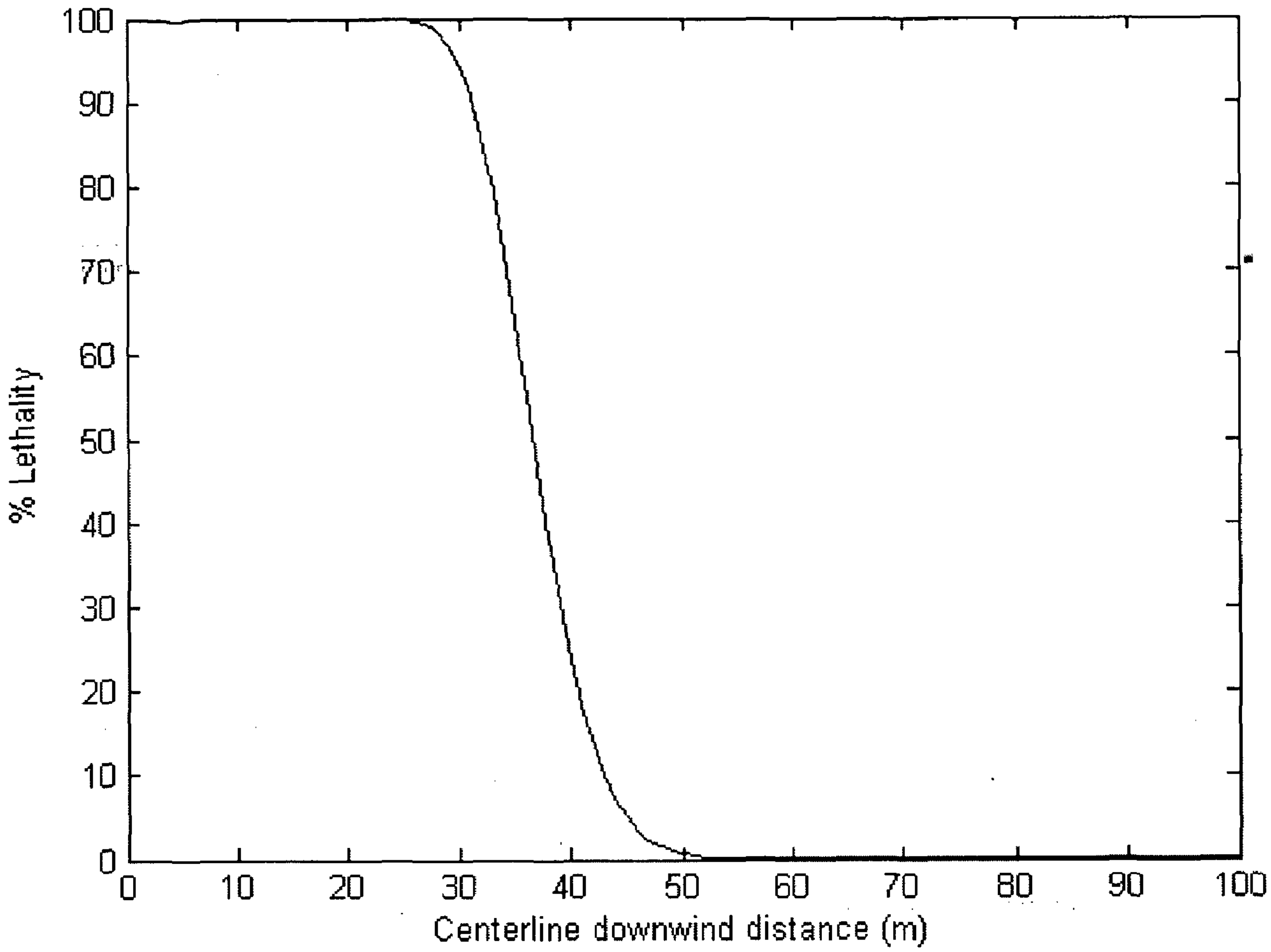


Figure 7.3 Percentage lethality (thermal radiation) vs. distance plot from revised pool fire model.

Overpressure from the pool fire in a 50 m x 50 m x10 m compartment was calculated as 0.25 kPa, which has negligible impact. It must be remembered, though, that this result is for a fuel loading of 100 kg. Larger fuel inventories, such as are routinely found on offshore installations, would generate higher overpressures (as demonstrated in the next scenario).

7.1.2 Scenario 2 – Jet Fire: A leak of 0.152 m in a pressurized natural gas storage tank causes the inventory to exit as a horizontal jet at a rate of 11.2 kg/s. The fuel ignites immediately after release and results in a *horizontal jet fire* lasting for approximately 30 minutes.

Simulation Results:

Length of flame = 38 m

Frustum length = 26 m

Angle of tilt from vertical = 80 degrees

SEP from sides of flame = 223 kW/m^2

SEP from end of flame = 242 kW/m^2

Assuming the fuel release occurs from one end of a 60 m * 60 m room, the radiation heat flux in that space is represented by the contours in Figure 7.4. Since the flame length is 38 m, the amount of damage is expected to be very high. Thus, the lethality (radiation damage) contours are represented in a 240 m * 240 m area as shown in Figure 7.5, while the thermal radiation damage along the centerline is shown in Figure 7.6

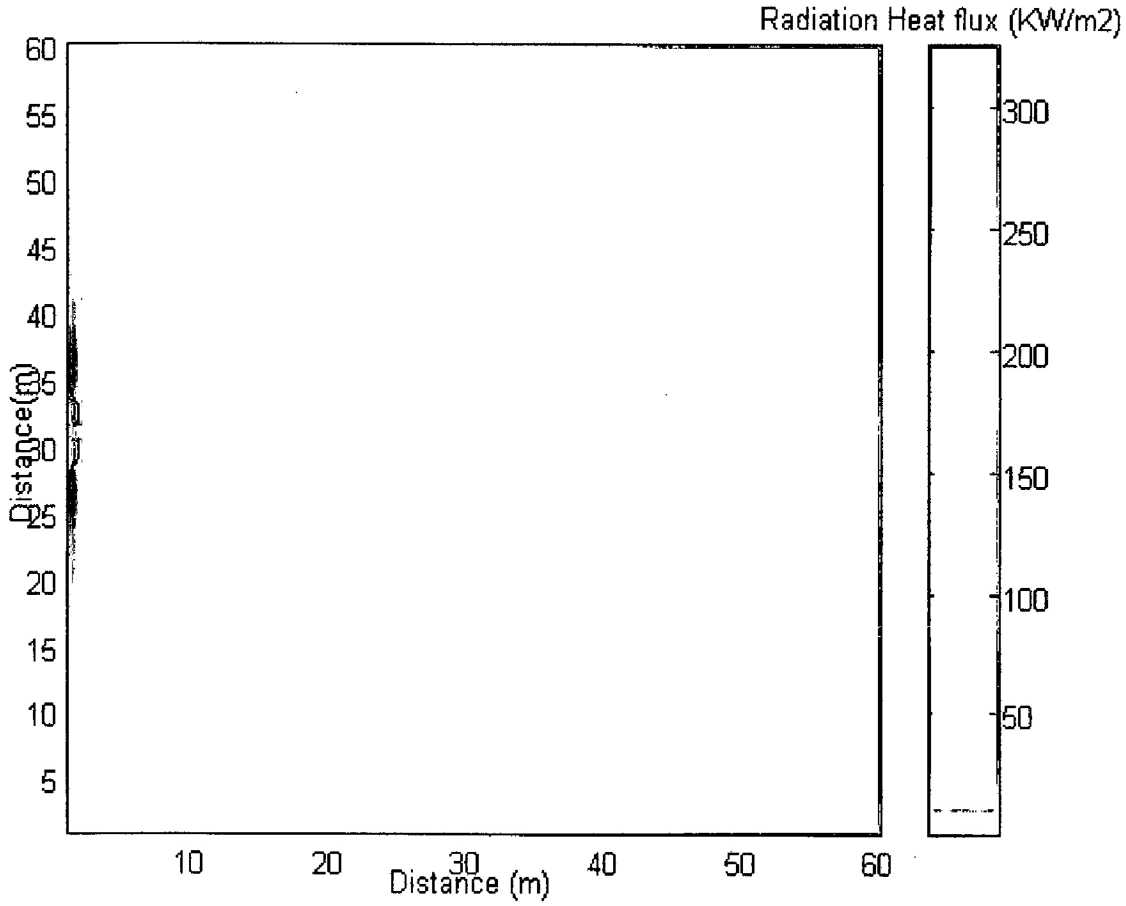


Figure 7.4 Radiation contours from revised horizontal jet fire model.

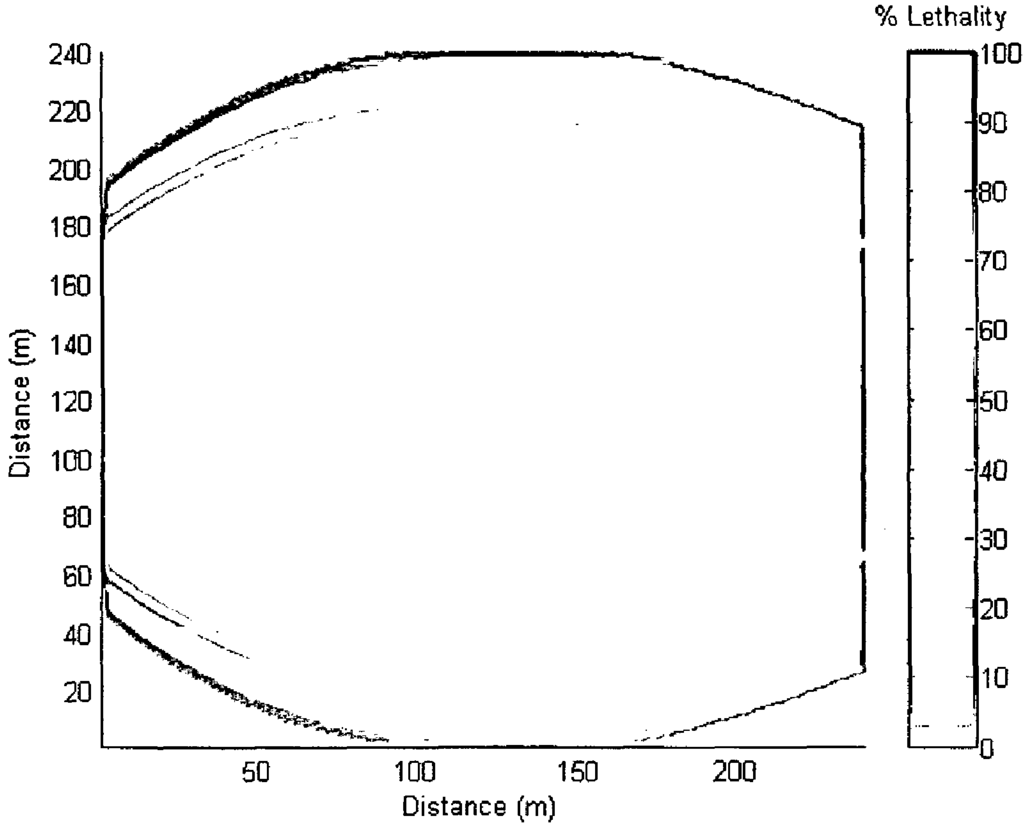


Figure 7.5 Percentage lethality (thermal radiation) contours from revised horizontal jet fire model.

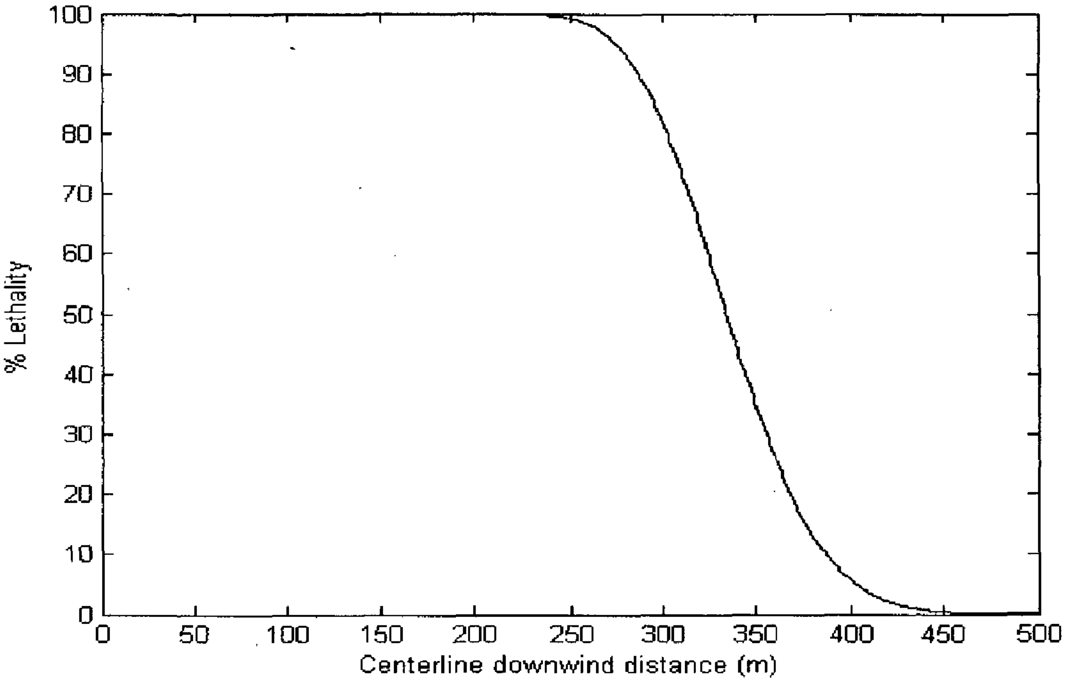


Figure 7.6 Percentage lethality (thermal radiation) vs. distance plot from revised horizontal jet fire model.

The contours shown in Figures 7.4 and 7.5 are elliptical, as is expected from the initial and boundary conditions that define the physical scenario. This confirmation facilitates the reliable prediction of consequences, which in turn provides an opportunity to identify safer zones for escape when an unwanted event occurs. For example, Figure 7.6 illustrates that 100% lethality is predicted for distances up to 250 m downwind, whereas minor damage exists up to a distance of about 500 m. Safer zones in all directions are apparent from the lethality contours in Figure 7.5.

For this scenario, the overpressure generated by the combustion gases in a 60 m x 60 m x 10 m compartment was calculated to be 236 kPa i.e. significantly higher than atmospheric pressure due to the fact that the flame jet occupies a relatively large portion of the enclosure volume. This clearly highlights the necessity of overpressure considerations for the congested plant found on offshore oil and gas platforms.

7.1.3 Scenario 3 – Fireball: Fire impingement on a propane gas storage tank causes a pressure rise inside the tank and eventually leads to a BLEVE. A fuel mass of 1272 kg is released and ignited, resulting in a fireball.

Simulation Results:

Diameter of fireball = 66 m

Time of existence of fireball = 7.9 s

Height of fireball center above ground = 49.5 m

SEP from the fireball = 320 kW/m2

The fireball is assumed to occur at the center of a 50 m x 50 m room and the radiation contours are given in Figure 7.7. Radiation damage contours are presented for a 100 m x 100 m area as shown in Figure 12. Figure 13 shows the radiation damage variation along the centerline. Although the fireball lasts for only about 8 s, the large amount of fuel released results in ~90 % lethality close to the fireball with minor damage persisting until a distance of 50 m from the epicenter. Distances greater than this 50-m radius are therefore safer for escape in the event of such a fireball.

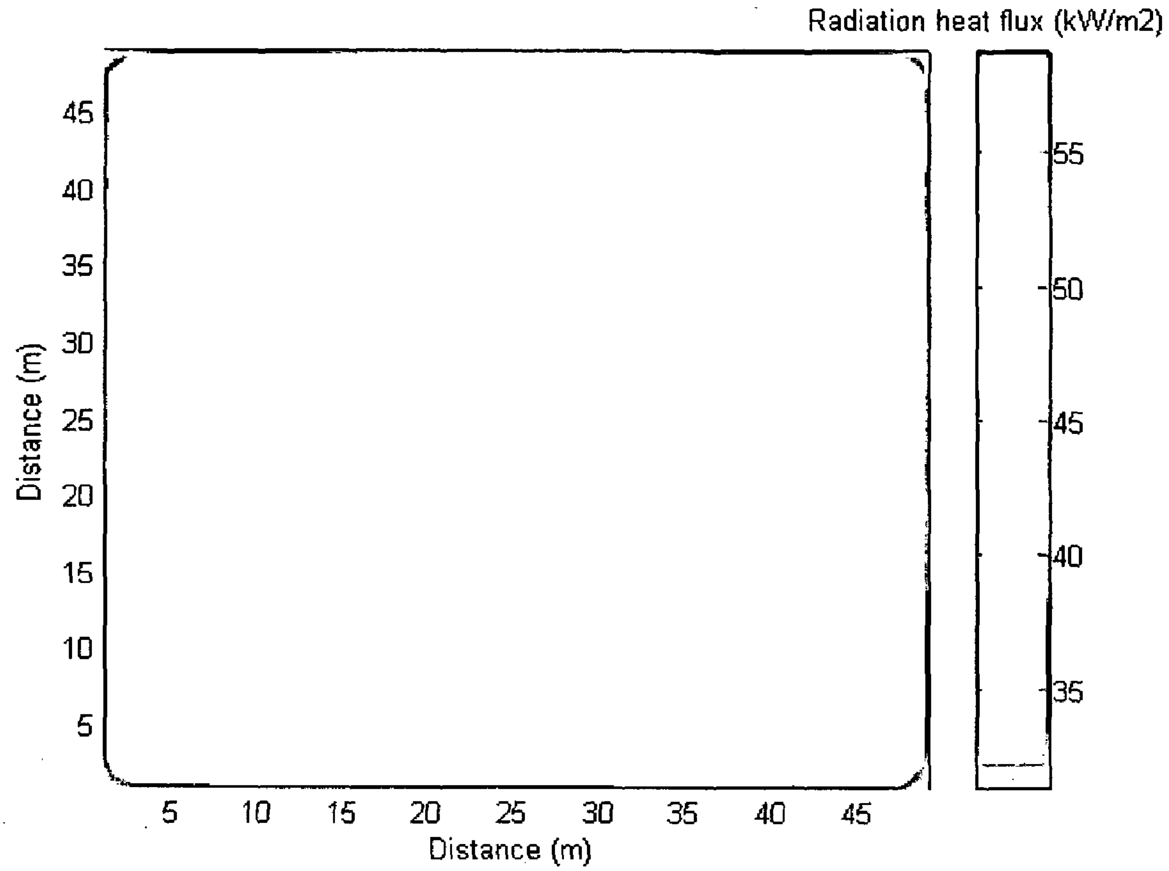


Figure 7.7 Radiation contours from revised fireball model.

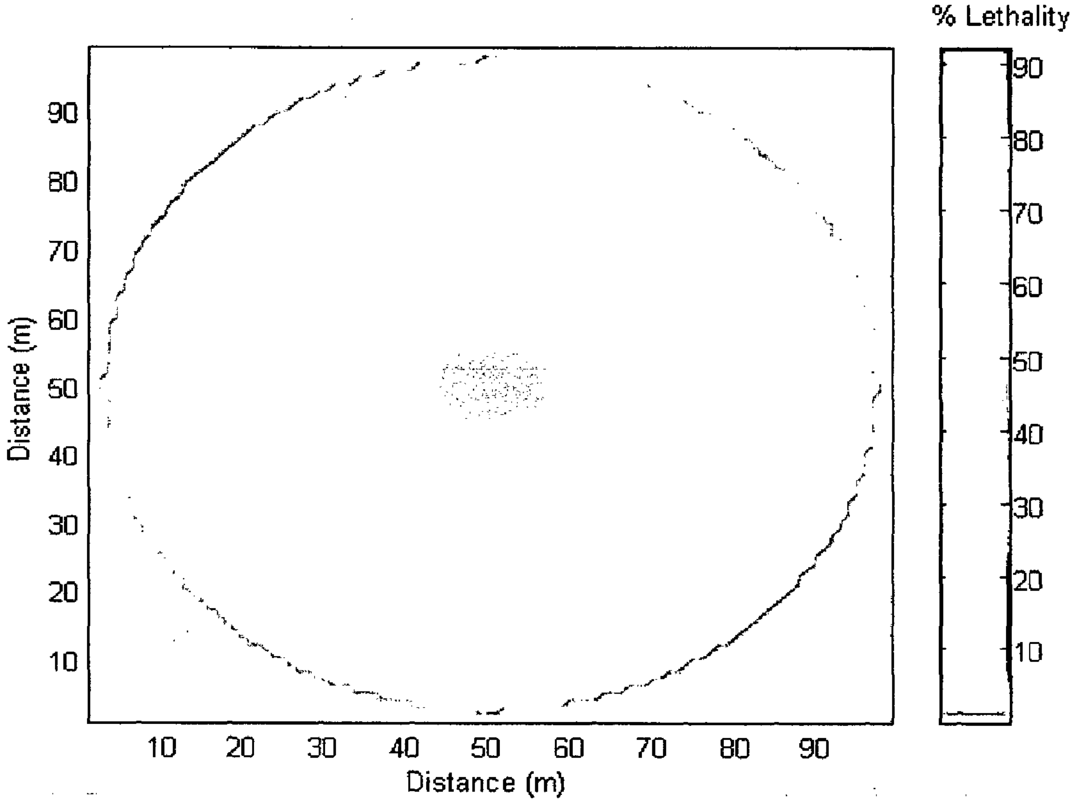


Figure 7.8 Percentage lethality (thermal radiation) contours from revised fireball model.

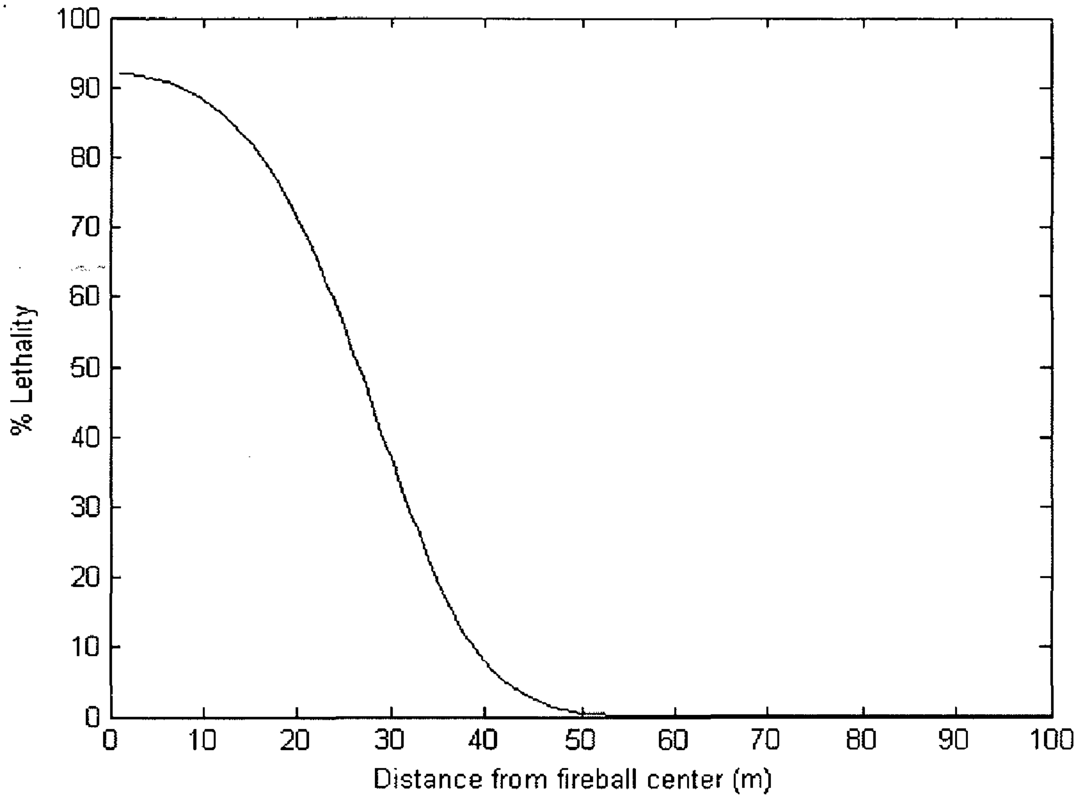


Figure 7.9 Percentage lethality (thermal radiation) vs. distance plot from revised fireball model.

The overpressure created by the fireball in a 50 m * 50 m * 10 m compartment was calculated as 2.4 kPa, a value which is approaching the point at which personnel mobility is affected. The fact that the fireball overpressure is higher than that predicted for the pool fire (scenario 1) is explainable in part by the much higher mass of fuel released in the fireball scenario which in turn is significantly less than the total fuel mass burned in the jet fire (scenario 2), which has the highest overpressure of the three scenarios studied.

7.2 COMPARISON OF MODELS

In this section, the results of the revised pool fire and jet fire models are compared with those from the commercial software PLATO, a well-known package for simulating hydrocarbon leakage and ignition on offshore installations. A description of the modeling approaches for pool fires, jet fires and fireballs that are embedded in this package are given by Jones & Irvine (1997). The fire model equations in PLATO indicate the use of a point source approach. These pool fire and jet fire point source models were simulated for the same data and specifications as in scenarios 1 and 2 in the previous section. The results are represented as radiation contours and radiation damage contours in Figures 7.6 - 7.9

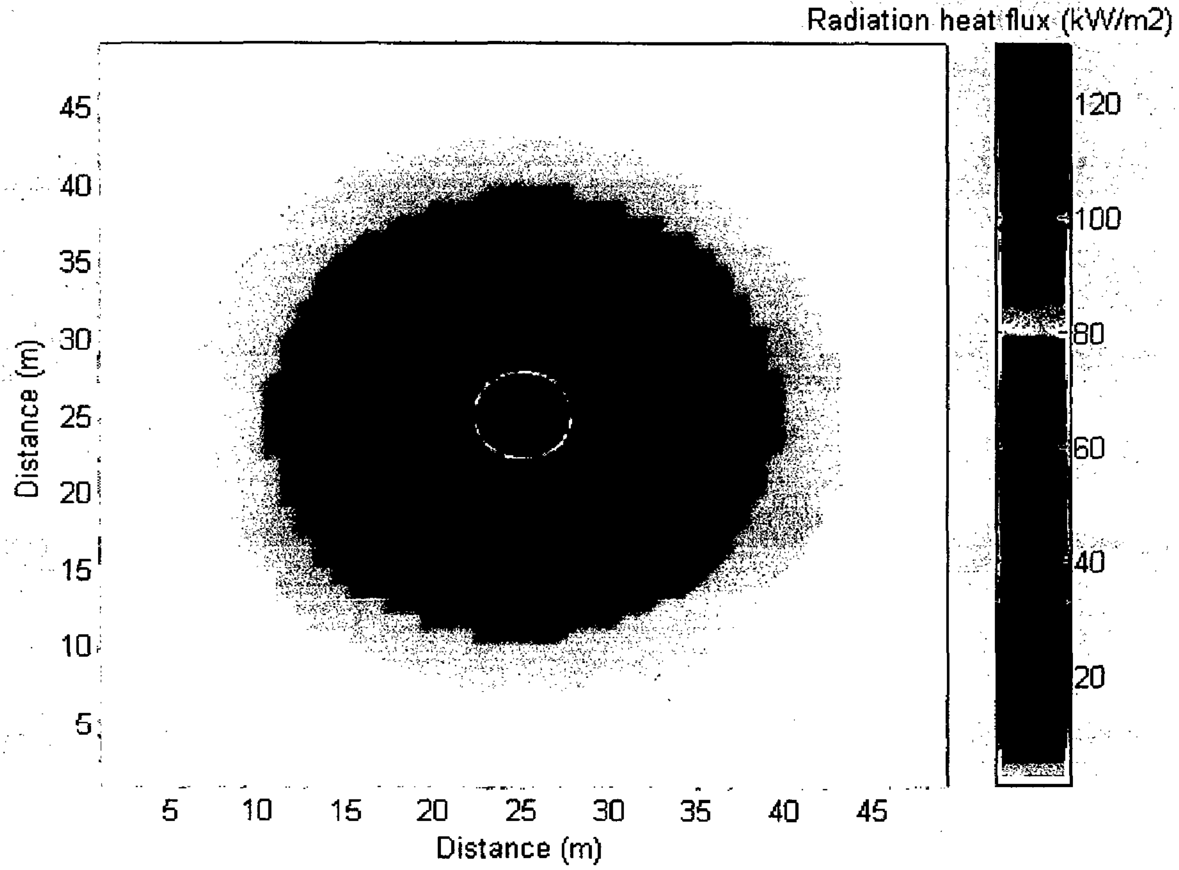


Figure 7.10 Radiation contours from PLATO pool fire model.

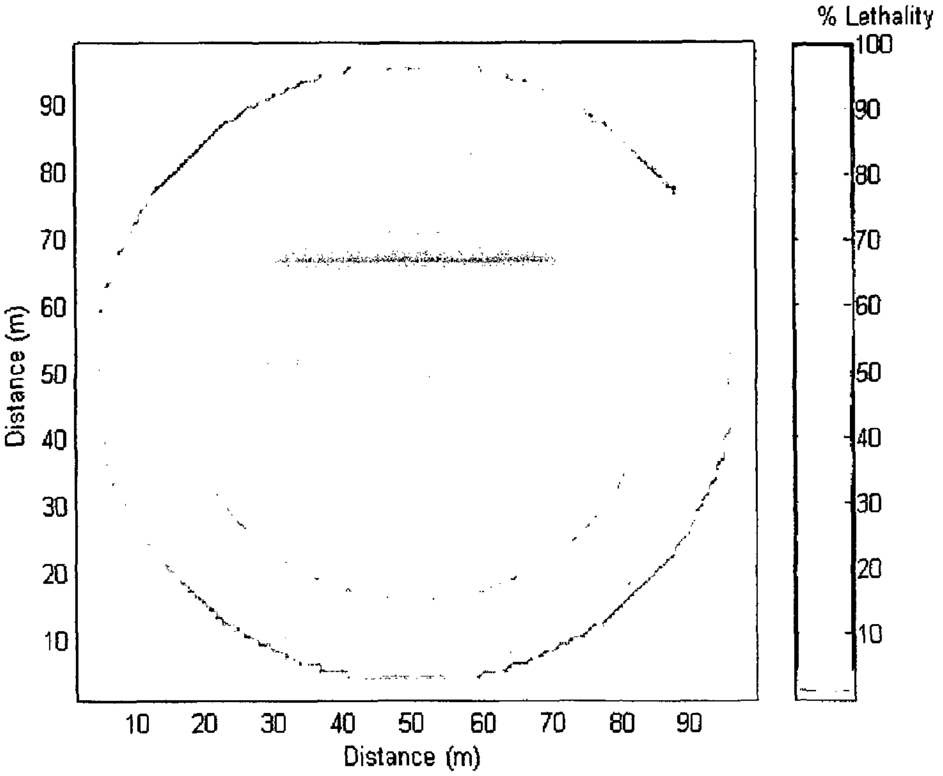


Figure 7.11 Percentage lethality (thermal radiation) contours from PLATO pool fire model.

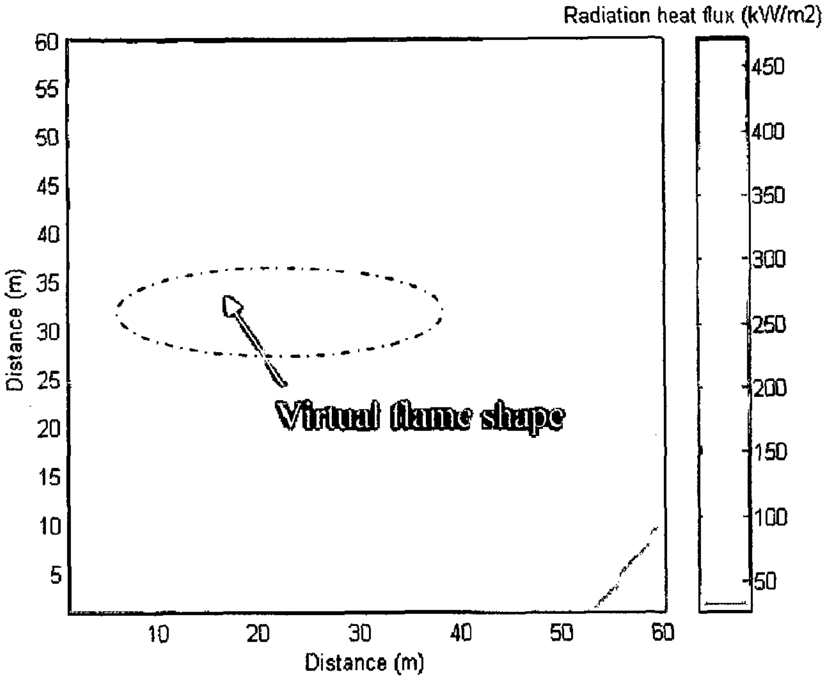


Figure 7.12 Radiation contours from PLATO jet fire model.

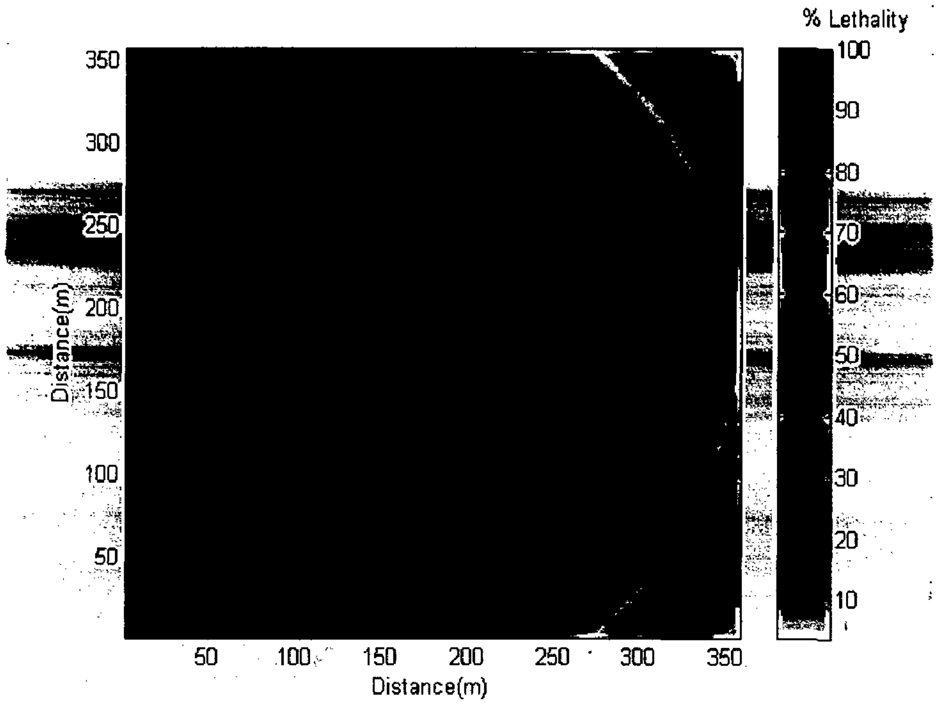


Figure 7.13 Percentage lethality (thermal radiation) contours from PLATO jet fire model.

7.2.1 POOL FIRE RESULTS COMPARISON (SCENARIO 1)

Comparing the results of the revised pool fire model as shown in Figures 7.1 and 7.2 with those in Figures 7.10 and 7.11 indicates that:

The radiation contours from the PLATO model are circular, whereas the revised model gives elongated contours due to the actual physical mechanism of flame tilt.The PLATO model over-predicts the thermal radiation damage relative to the revised pool fire model. This is to be expected given the point source approach in the former model and the use of a solid flame in the latter.

7.2.2 JET FIRE RESULTS COMPARISON (SCENARIO 2)

Comparing the results of the revised jet fire model as shown in Figures 7.4 and 7.5 with those in Figures 7.12 and 7.13 indicates that:

- The radiation contours predicted by the revised model are elliptical in shape, whereas those from the point source model are co-centric circles.
- The damage contours display the same features as the radiation contours described in the previous point.
- The over-predictions as a result of using a point source model are clear from the damage contour plots.

Although the comparisons above are admittedly limited, it is felt that the ability of the revised pool fire and jet fire models to simulate aspects of physical behavior has been demonstrated. These aspects include pool fire flame tilt due to the prevailing wind direction and the elliptical shape of a horizontal jet fire due to the momentum impulse created in such a scenario. In addition to radiation impact consequences, the revised models enable consideration of the overpressure impact caused by hot expanding combustion gases and unburned fuel gases.

7.3 DISCUSSION FOR THE QRA METHODOLOGY APPLIED ON OFFSHORE PLATFORM :

The QRA methodology been applied to decide on the safety measures for various process units on an offshore platform.

The process plant on an offshore platform generally has three main parts: (i) the wellhead, (ii) separators, and (iii) gas compression.

7.3.1 MAXIMUM CREDIBLE ACCIDENT SCENARIO DEVELOPMENT :

A number of accident scenarios has been envisaged for each unit. The most credible scenario for each unit is presented here. The credibility of an accident scenario is assessed considering the damage potential and the likelihood of occurrence.

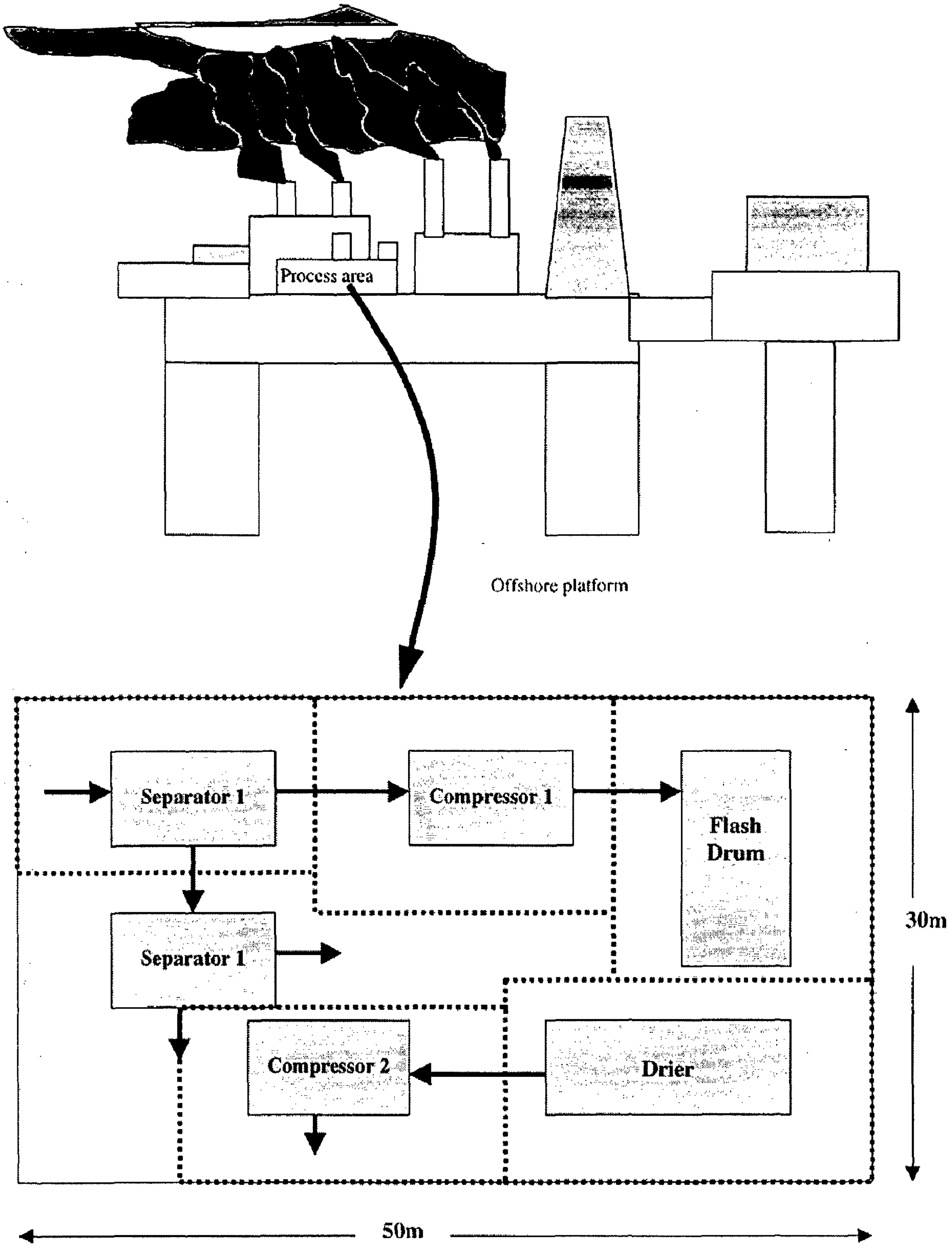


Figure 7.14 Layout of process plant on offshore platform.

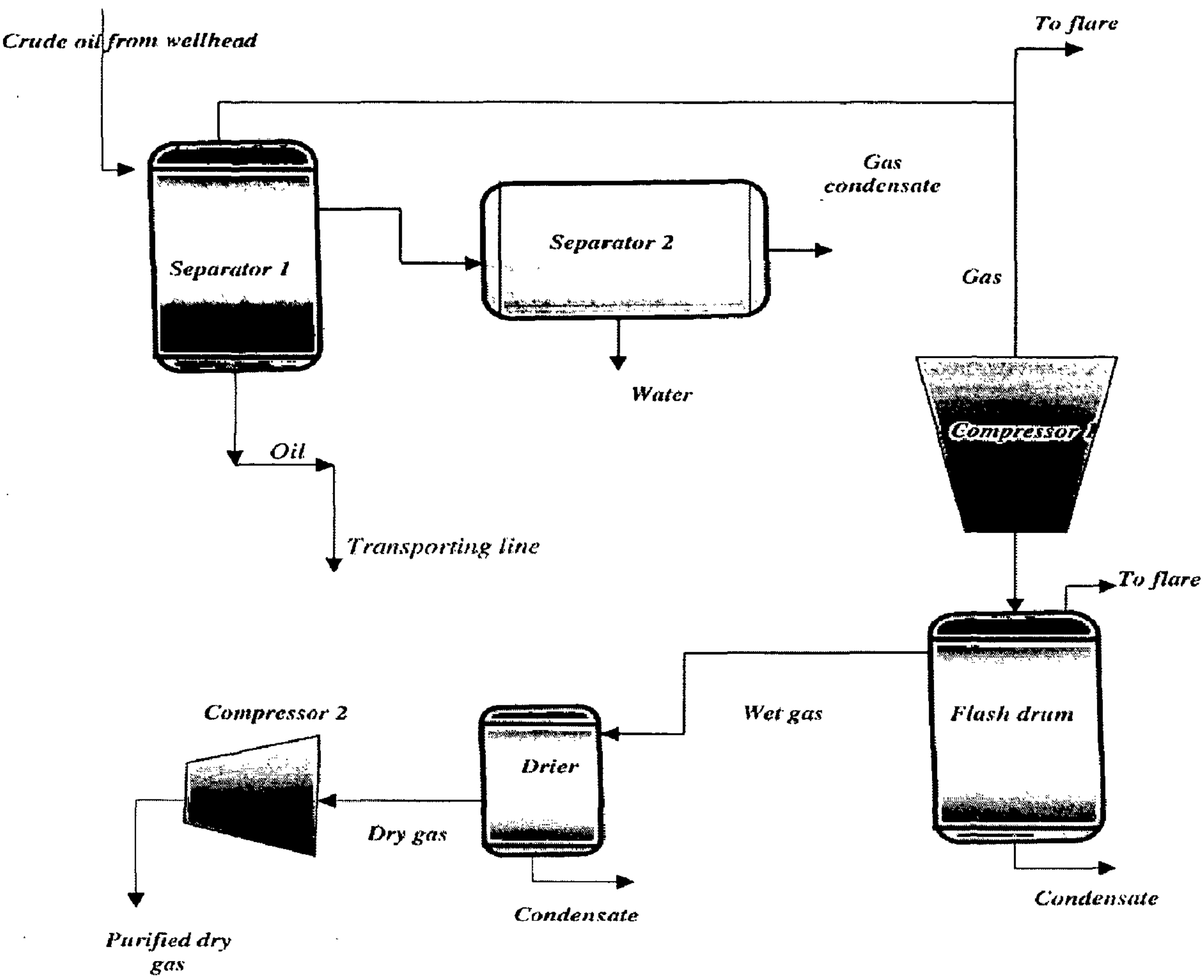


Figure 7.15 Process flow diagram of separation and compression operation on offshore production platform.

7.3.1.1 Oil Separator (Boiling Liquid Expanding Vapor Explosion (BLEVE) Followed By Fire (Scenario 1)):

High-pressure development in the separator causes the unit to fail as BLEVE. The vapor cloud formed due to BLEVE on ignition would cause a fireball. The cumulative effect of overpressure and heat load may cause the release of a chemical from other units, which on ignition would cause a fire.

7.3.1.2 Condensate Separator (Vapor Cloud Explosion (VCE) Followed By Fire (Scenario 2)):

The instantaneous or continuous release of a chemical from the condensate separator would form a vapor cloud. On ignition the vapor cloud would cause VCE. Unreleased liquid in the unit would burn as a pool fire.

Table 7.1

Results of consequence analysis for scenario 1; accident in separator 1

Parameters	**Values**
Unit: separator 1	
Scenario: BLEVE followed by fireball and pool fire	
Explosion: BLEVE	
Total energy released (kJ)	2.2E+08
Peak overpressure (kPa)	600
Variation of overpressure in air (kPa/s)	482
Shock velocity of air (m/s)	753
Duration of shock wave (ms)	64
Missile characteristics	
Initial velocity (m/s)	137
Kinetic energy of fragment (kJ)	4.65E+04
Fragment velocity at study point (m/s)	134
Penetration ability at study point (based on empirical models)	
Concrete structure (m)	0.0529
Brick structure (m)	0.0676
Steel structure (m)	0.0136
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	61
DR for 100% fatality or 50% complete damage (m)	93
DR for 50% fatality or 25% complete damage (m)	138

Fire: fireball	
Radius of fireball (m)	92
Duration of fireball (s)	38
Energy released by fireball (kJ)	5.87E+08
Radiation heat flux (kJ/m2)	22449
DR due to thermal load	
DR for 100% fatality/damage (m)	144
DR for 50% fatality/damage (m)	181
DR for 100% third degree of burn (m)	209
DR for 50% third degree of burn (m)	268
Fire: pool fire	
Radius of pool fire (m)	5
Burning area (m2)	79
Burning rate (kg/s)	8
Heat flux (kJ/m2)	57283
DR due to thermal load	
DR for 100% fatality/damage (m)	230
DR for 50% fatality/damage (m)	288
DR for 100% third degree of burn (m)	333
DR for 50% third degree of burn (m)	428

Table 7.2

Results of consequence analysis for scenario 2; accident in separator 2

Parameters	**Values**
Unit: separator 2	
Scenario: VCE followed by pool fire	
Explosion: VCE	
Total energy released by explosion (kJ)	1.23E+07
Peak overpressure (kPa)	320
Variation of overpressure in air (kPa/s)	345
Shock velocity of air (m/s)	353
Duration of shock wave (ms)	8
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	53
DR for 100% fatality or 50% complete damage (m)	74
DR for 50% fatality or 25% complete damage (m)	86
Fire: pool fire	
Burning area (m2)	265
Burning rate (kg/s)	10
Heat flux (kJ/m2)	2654
DR due to thermal load	
DR for 100% fatality/damage (m)	34
DR for 50% fatality/damage (m)	55
DR for 100% third degree of burn (m)	69
DR for 50% third degree of burn (m)	78

7.3.1.3 Compressor 1 (Jet Fire (Scenario 3)):

The continuous release of flammable gas from compressor 1 on ignition would cause a jet fire.

7.3.1.4 Compressor 2 (Jet Fire (Scenario 4)):

The continuous release of flammable gas from compressor 2 on ignition would cause a jet fire.

Table 7.3 Results of consequence analysis for scenarios 3 and 4; accident in compressor units

Parameters	**Values**
Unit: compressor units Scenario: jet fire Fire: jet fire	
Flame length (m)	5.45
Burning area (m2)	792
Burning rate (kg/s)	10
Heat flux (kJ/m2)	1493
DR due to thermal load	
DR for 100% fatality/damage (m)	24
DR for 50% fatality/damage (m)	35
DR for 100% third degree of burn (m)	44
DR for 50% third degree of burn (m)	57

7.3.1.5 Flash Drum (VCE Followed By Fire (Scenario 5)):

Flammable gas released from the flash drum would form a highly flammable vapor cloud which on ignition would burn instantly causing high overpressure. Unreleased condensate in the unit would burn as a pool fire.

7.3.1.6 Drier (BLEVE Followed By Fire (Scenario 6)):

The high-pressure instantaneous release of gas from the drier may cause BLEVE. The released gas on ignition would cause a fireball. The cumulative effect of overpressure and heat may cause other units to fail and result in pool and/or jet fires.

7.3.2 DAMAGE POTENTIAL ESTIMATION

The results for scenario 1 (BLEVE followed by fire) are presented in Table 7.1. BLEVE would generate fatal overpressure over an area of 90 m radius.The vapor cloud generated by the released chemical on ignition causes a fireball, which would generate a heat radiation

Table 7.4 Results of consequence analysis for scenario 5; accident in flash drum

Parameters	**Values**
Unit: separator 2	
Scenario: VCE followed by pool fire	
Explosion: VCE	
Total energy released by explosion (kJ)	7.97E+06
Peak overpressure (kPa)	226
Variation of overpressure in air (kPa/s)	225
Shock velocity of air (m/s)	359
Duration of shock wave (ms)	11
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	23
DR for 100% fatality or 50% complete damage (m)	35
DR for 50% fatality or 25% complete damage (m)	47
Fire: flash fire	
Volume of vapor cloud (m3)	104
Effective time of fire (s)	738624

Effective thermal load (kJ/m2)	1214
DR due to thermal load	
DR for 100% fatality/damage (m)	17
DR for 50% fatality/damage (m)	21
DR for 100% third degree of burn (m)	25
DR for 50% third degree of burn (m)	32
Fire: pool fire	
Burning area (m2)	358
Burning rate (kg/s)	15
Heat flux (kJ/m2)	1579
DR due to thermal load	
DR for 100% fatality/damage (m)	25
DR for 50% fatality/damage (m)	42
DR for 100% third degree of burn (m)	56
DR for 50% third degree of burn (m)	77

Table 7.5 Results of consequence analysis for scenario 6; accident in drier unit

Parameters	**Values**
Unit: drier	
Scenario: BLEVE followed by fireball and pool fire	
Explosion: BLEVE	
Total energy released (kJ)	4.4E+07
Peak overpressure (kPa)	600
Variation of overpressure in air (kPa/s)	363
Shock velocity of air (m/s)	753
Duration of shock wave (ms)	28
Missile characteristics	
Initial velocity (m/s)	61
Kinetic energy of fragment (kJ)	9.30E+03
Fragment velocity at study point (m/s)	61
Penetration ability at study point (based on empirical models)	
Concrete structure (m)	0.0161
Brick structure (m)	0.0205
Steel structure (m)	0.0062
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	36
DR for 100% fatality or 50% complete damage (m)	55
DR for 50% fatality or 25% complete damage (m)	81

Fire: fireball	
Radius of fireball (m)	44
Duration of fireball (s)	18
Energy released by fireball (kJ)	7.33E+07
Radiation heat flux (kJ/m2)	11205
DR due to thermal load	
DR for 100% fatality/damage (m)	51
DR for 50% fatality/damage (m)	64
DR for 100% third degree of burn (m)	74
DR for 50% third degree of burn (m)	95
Fire: pool fire	
Radius of pool fire (m)	5
Burning area (m2)	79
Burning rate (kg/s)	8
Heat flux (kJ/m2)	22912
DR due to thermal load	
DR for 100% fatality/damage (m)	73
DR for 50% fatality/damage (m)	92
DR for 100% third degree of burn (m)	106
DR for 50% third degree of burn (m)	136

It is clear from Table 7.1 that an area of 180 m radius faces a 50% probability of fatality due to heat load. The overpressure and heat radiation effect may cause a fatalities well as second-order accidents by seriously damaging other units such as separator 2, the oil transportation pipeline, and the main pumping station; these consequences would extend far beyond a 250 m radius.

The forecasts based on detailed calculations for scenario 2 are presented in Table 7.2. VCE followed by fire would cause considerable damage. It is evident from Table 7.2 that damage of a high degree of severity due to overpressure and shockwave would be operative over an area of 50 m radius, while moderate damage (50% probability of lethality) would occur over an area of 75 m radius. The unburned chemical in the unit would burn as a pool fire. The heat load generated due to the pool fire would be lethal over an area of 55 m radius. The heat load and shockwave generated by this unit may initiate secondary and a higher order of accidents in the units within close proximity such as condensate and gas pipeline. The forecasts of scenarios 3 and 4 are presented in Table 7.3 It is evident from the results that this scenario would cause moderate damage. There is no likelihood of overpressure development; however, a fire jet of 5 m in length would be operative. The lethal heat load of 50% probability of causing fatality and damage would be operative over an area of 35 m radius. It is likely that the jet flame would cause damage in the neighboring unit either through direct impingement or by external heat load. The units that would become frayed by this accident are the flash drum and the drier.

ble 7.6 Elements of the fault tree developed for a probable accident in separator 1

No in Fig. 6	Elements	Failure frequency(per year)
1	Flow control valve failed	0.0250
2	Level indicator failed	0.0200
3	Excess flow at upstream	0.0800
4	Impurities causing exothermic reaction	0.0030
5	Sudden change in pressure	0.0170
6	Temperature controller failed	0.0200
7	High-pressure upstream line	0.0700
8	Upstream pressure controller failed	0.0250
9	Condensate line choked	0.0021
10	Oil pipeline choked	0.0075
11	Gas pipeline or valve choked	0.0015
12	Safety valve undersize	0.0500
13	Safety/pressure release valve choked or could not function on demand	0.0015
14	External heating	0.0150
15	Exothermic reaction in vessel	0.0030
16	Temperature controller failed	0.0200
17	Pressure controller system of separator failed	0.0200
18	Pressure or safety release inadequate	0.0015
19	Ignition due to explosion energy	0.1500
20	Ignition due to heat from surroundings	0.2000
21	Electric spark as source of ignition	0.2500

Unlike the separators, the flash drum poses fewer hazards. The results of the damage calculation for the most credible accident scenario (scenario 5) in the flash drum are presented in Table 7.4 It is evident from the results that damage causing shockwaves would be effective only to a limited area (35 m radius).

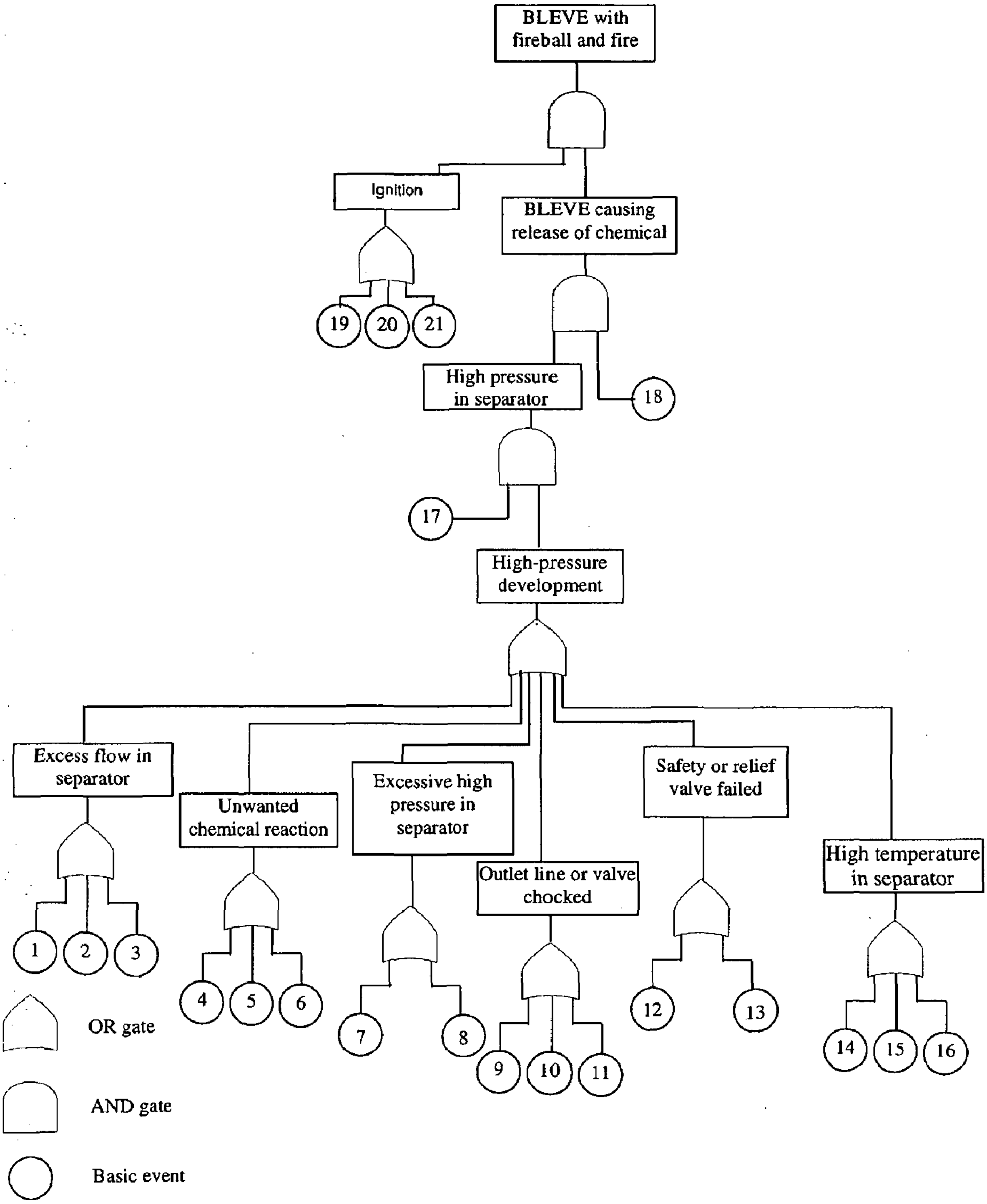


Figure7.16. Fault tree diagram for separator 1; detail of basic events is presented in Table 7.6

Table 7.7

FTA results (output of PROFAT) for separator 1 (scenario 1)

Event not occurring	Probability	Improvement	Improvement index
0	1.066923E−05	0.000000E+00	0.000000
1	9.462237E−06	4.827976E−06	2.514747
2	9.670852E−06	3.993516E−06	2.080101
3	7.554889E−06	1.245737E−05	6.488667
4	1.023710E−05	1.728537E−06	0.900342
5	9.819864E−06	3.397467E−06	1.769638
6	9.670852E−06	3.993516E−06	2.080101
7	7.882713E−06	1.114607E−05	5.805650
8	9.462237E−06	4.827976E−06	2.514747
9	1.029670E−05	1.490117E−06	0.776157
10	1.010299E−05	2.264976E−06	1.179757
11	1.032650E−05	1.370906E−06	0.714063
12	1.014769E−05	2.086166E−06	1.086620
13	1.032650E−05	1.370906E−06	0.714063
14	9.849667E−06	3.278258E−06	1.707545
15	1.023710E−05	1.728537E−06	0.900342
16	1.029670E−05	1.490117E−06	0.776157
17	0.000000E+00	4.267693E−05	22.22911
18	0.000000E+00	4.267693E−05	22.22911
19	7.793307E−06	1.150369E−05	5.991926
20	6.973744E−06	1.478195E−05	7.699469
21	5.945563E−06	1.889467E−05	9.841661

Table 7.8

Elements of the fault tree developed for a probable accident in separator 2

Number in Fig. 7	Elements	Failure frequency (per year)
1	Leak from joints	0.045
2	Leak from main pipeline	0.003
3	Leak from joints	0.045
4	Leak from main pipeline	0.003
5	Leak from vessel	0.0015
6	Leak from fracture, joints or crack	0.0004
7	Leak from the pipe connections	0.0065
8	Leak from safety valve	0.0055
9	Leak from pressure release valve	0.015
10	Leak from control valves	0.025
11	Outlet pipe choked	0.0035
12	High-pressure upstream line	0.17
13	Sudden phase change	0.017
14	External heat absorption causing increase in	0.016
15	Ignition due to explosion energy	0.15
16	Ignition due to external heat from surroundings	0.20
17	Ignition due to electric spark	0.25
18	Release from pipe after explosion	0.10
19	Release from vessel aftermath of explosion	0.05
20	Ignition due to external explosion energy	0.20
21	Ignition due to fire heat load	0.25

evident from the detailed results, this unit does not pose a serious threat and there is less likelihood of a secondary accident.

The drier is another important unit in the process facility as it handles a large quantity of flammable gas at high-pressure. The detailed results of the most credible accident scenario (scenario 6) in the unit is presented in Table 7.5. It is evident from this table that this scenario would cause considerable damage. Lethal overpressure load is enough to cause fatality, and damage would be operative over an area of 55 m radius. The released chemical on ignition would cause a fireball and a pool fire (leftover chemical in the unit), which would generate an excessive heat load. The lethal heat load of 50% probability of causing fatality and damage would engulf an area of ~90 m radius. It is likely that overpressure and heat radiation load may cause other units to fail as secondary accidents. The units which are likely to become frayed are compressors, gas transportation line, and drier.

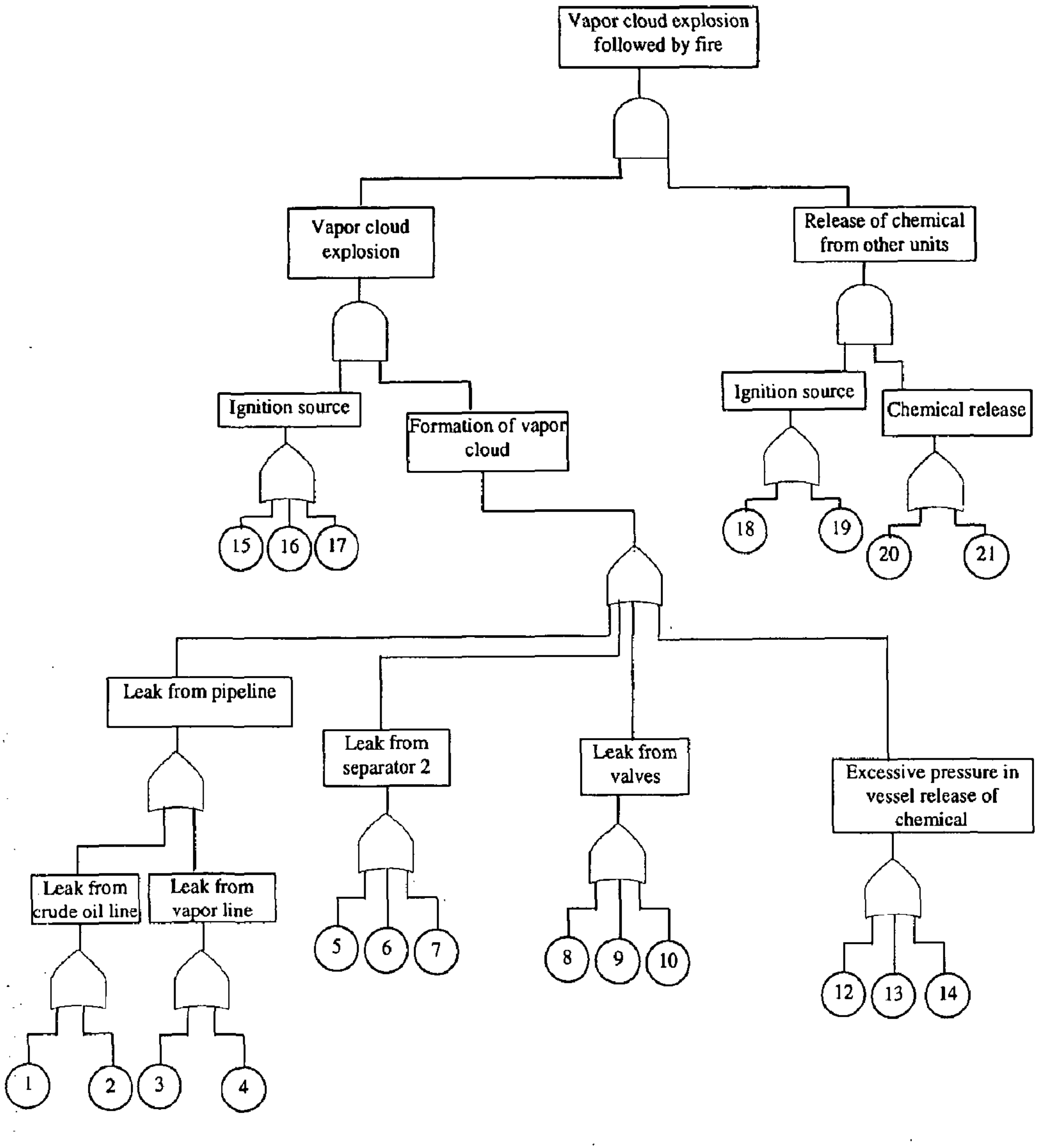


Figure 7.17 Fault tree diagram for separator 2; detail of basic events is presented in Table 7.8.

7.3.3 PROBABILISTIC HAZARD ASSESSMENT (PHA)

PHA has been conducted for all six accidents scenarios identified in the six different units. Most of the failure frequency data is presented in Tables 7.6, 7.8, 7.10, 7.12 and 7.13. This data is derived from World-wide Offshore Accident Databases [44], HSE reports [45,46], and offshore data from E&P forum [47]. Using the data presented in Tables 7.6,7.8, 7.10, 7.12 and 7.13, a FTA has been conducted to estimate the failure probability of each accident scenario.

7.3.3.1 Separator 1

The fault tree has been constructed for the most credible accident scenario in this unit (Fig. 7.16). There are 21 basic events which contribute directly and indirectly to the happening of the accident scenario. These events and their frequencies of failure are given in Table 7.6. The developed fault tree is subsequently analyzed using the ASM algorithm. The result of a FTA (output of PROFAT) is presented in Table 7.7. The total probability of occurrence of the undesired event, when all initiating events occur, is estimated as 1.07E−05 per year. The improvement factor analysis (fifth step in ASM) suggests that events 17 and 18 have the largest contribution (about 22% each) to the probability of the eventual accident. It is further evident from Table 7.7 that events 4, 9, 11, 13, 15 and 16 do not contribute significantly to the occurrence of the accident. This analysis concludes that particular attention must be paid to events 17,18, 21, 20, 3, 7, and 19, as these are the most likely to cause this accident.

7.3.3.2 Separator 2

The most credible accident scenario for this unit is envisaged as VCE followed by a fire. There are 21 basic events that contribute directly and indirectly to the occurrence of this accident (Table 7.8). The likely sequences of events in this accident are depicted in Fig. 7.7. The developed fault tree (Fig. 7.7) was analyzed using PROFAT, and the results are presented in Table 7.9. The overall probability of the occurrence of this accident scenario is computed as

9.474E−04 per year. Table 7.9 indicates that events 18, 20, 12, and 17 contribute 17, 17, 12, and 10%, respectively to causing this accident. Controlling these events would reduce considerably the overall probability of their occurrence.

Table 7.9 FTA results (output of PROFAT) for separator 2 (scenario 2)

Event not occurring	Probability	Improvement	Improvement index
0	9.474457E−04	0.000000E+00	0.000000
1	8.279830E−04	4.778510E−04	3.155792
2	9.397716E−04	3.069656E−05	0.202724
3	8.279830E−04	4.778510E−04	3.155792
4	9.397716E−04	3.069656E−05	0.202724
5	9.436756E−04	1.508045E−05	0.099593
6	9.465664E−04	3.517309E−06	0.023229
7	9.302496E−04	6.878450E−05	0.454262
8	9.329916E−04	5.781649E−05	0.381828
9	9.077042E−04	1.589659E−04	1.049832
10	8.810459E−04	2.655993E−04	1.754053
11	9.383557E−04	3.635992E−05	0.240126
12	4.958510E−04	1.806379E−03	11.92956
13	9023399E-04	1.804231E−04	1.191538
14	9.050069E−04	1.697551E−04	1.121085
15	7.109045E−04	9.461649E−04	6.248599
16	6.318837E−04	1.262248E−03	8.336055
17	5.529077E−04	1.578152E−03	10.42232
18	3.161132E−04	2.525330E−03	16.67761
19	6.318094E-04	1804231E-04	1191538
20	6.318094E-04	2.525270E−03	16.67722
21	6.318094E−04	1.262546E−03	8.338019

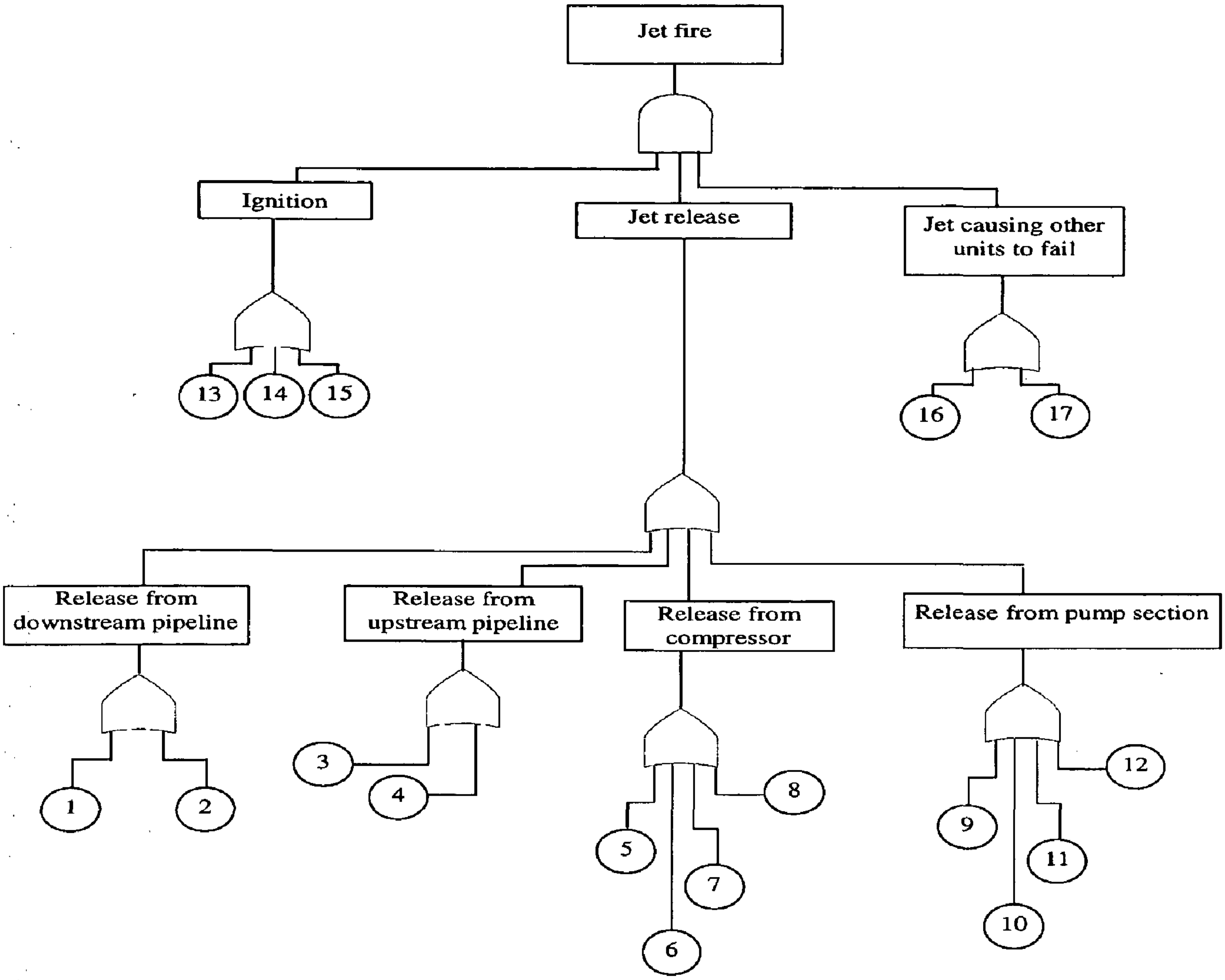


Figure 7.18 Fault tree diagram for compressor unit; details of basic events is presented in Table 7.10.

Table 7.10

Elements of the fault tree developed for a probable accident in compressor units

Number in Fig. 8	Elements	Failure frequency (per year)
1	Leak from compressor downstream pipeline	0.0065
2	Leak from compressor downstream pipeline joints	0.090
3	Leak from compressor upstream pipeline	0.003
4	Leak from joints of compressor upstream pipeline	0.045
5	Release from casing of compressor	0.050
6	Leaking of seal	0.120
7	Release from impeller	0.100
8	Compressor completely failed causing release of chemical	0.070
9	Leak from junction of pump and pipeline	0.010
10	Leak from rotor	0.060
11	Pump failed to operate and caused release of chemical	0.150
12	Leak from casing	0.200
13	Ignition due to explosion energy	0.150
14	Ignition due to external heat from surrounding	0.200
15	Ignition due to electric spark	0.250
16	Fire caused failure of pipeline leading to chemical release	0.010
17	Fire caused vessel to fail and release of chemical from vessel	0.005

7.3.3.3 Compressors 1 And 2

The fault tree comprising of 17 basic events has been developed for the most credible accident scenario in the compressor units (Fig. 7.18). The probabilities of the occurrence of these basic events are presented in Table 11.

Table 7.11 FTA results (output of PROFAT) for compressors (scenarios 3 and 4)

Event not occurring	Probability	Improvement	Improvement index
0	1.364250E−02	0.000000E+00	0.000000
1	1.355903E−02	3.339117E−04	0.205645
2	1.248035E−02	4.648631E−03	2.862933
3	1.360403E−02	1.539034E−04	0.094784
4	1.306202E−02	2.321958E−03	1.430014
5	1.299739E−02	2.580464E−03	1.589220
6	1.209246E−02	6.200195E−03	3.818488
7	1.235117E−02	5.165338E−03	3.181155
8	1.273893E−02	3.614304E−03	2.225926
9	1.286812E−02	3.097529E−03	1.907662
10	1.170394E−02	7.754267E−03	4.775589
11	1.170394E−02	7.754267E−03	4.775589
12	1.105588E−02	1.034648E−02	6.372044
13	7.998807E−03	2.257479E−02	13.90304
14	9.132371E−03	1.804053E−02	11.11054
15	1. .026367E−02	1.351535E−02	8.323643
16	9.132714E−03	1.803916E−02	11.10970
17	4.584522E−03	3.623193E−02	22.31400

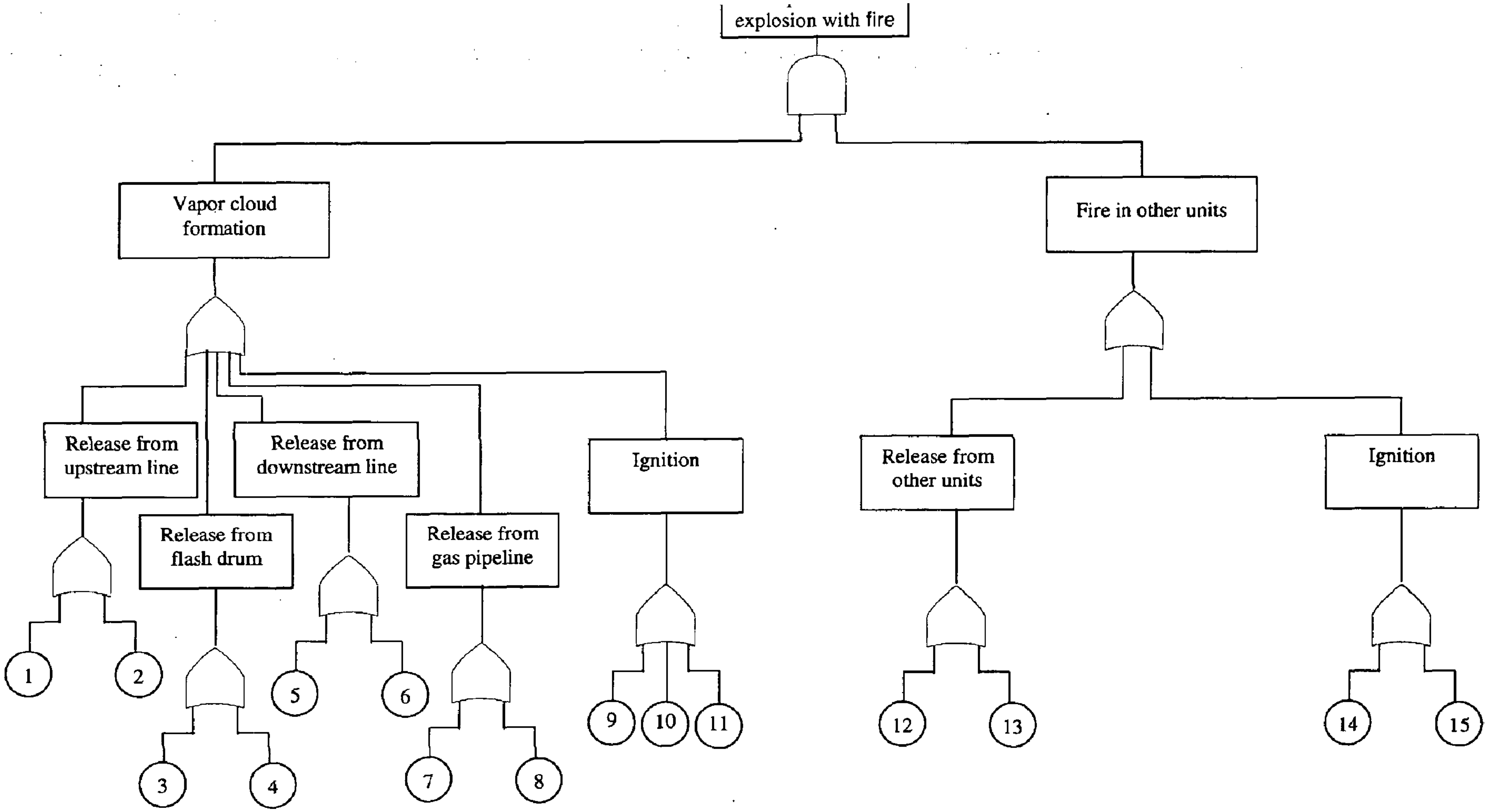


Fig. 9. Fault tree diagram for flash drum; detail of basic events is presented in Table 13.

Figure 7.19 Fault tree diagram for flash drum; detail of basic events is is prevented in Table 7.12

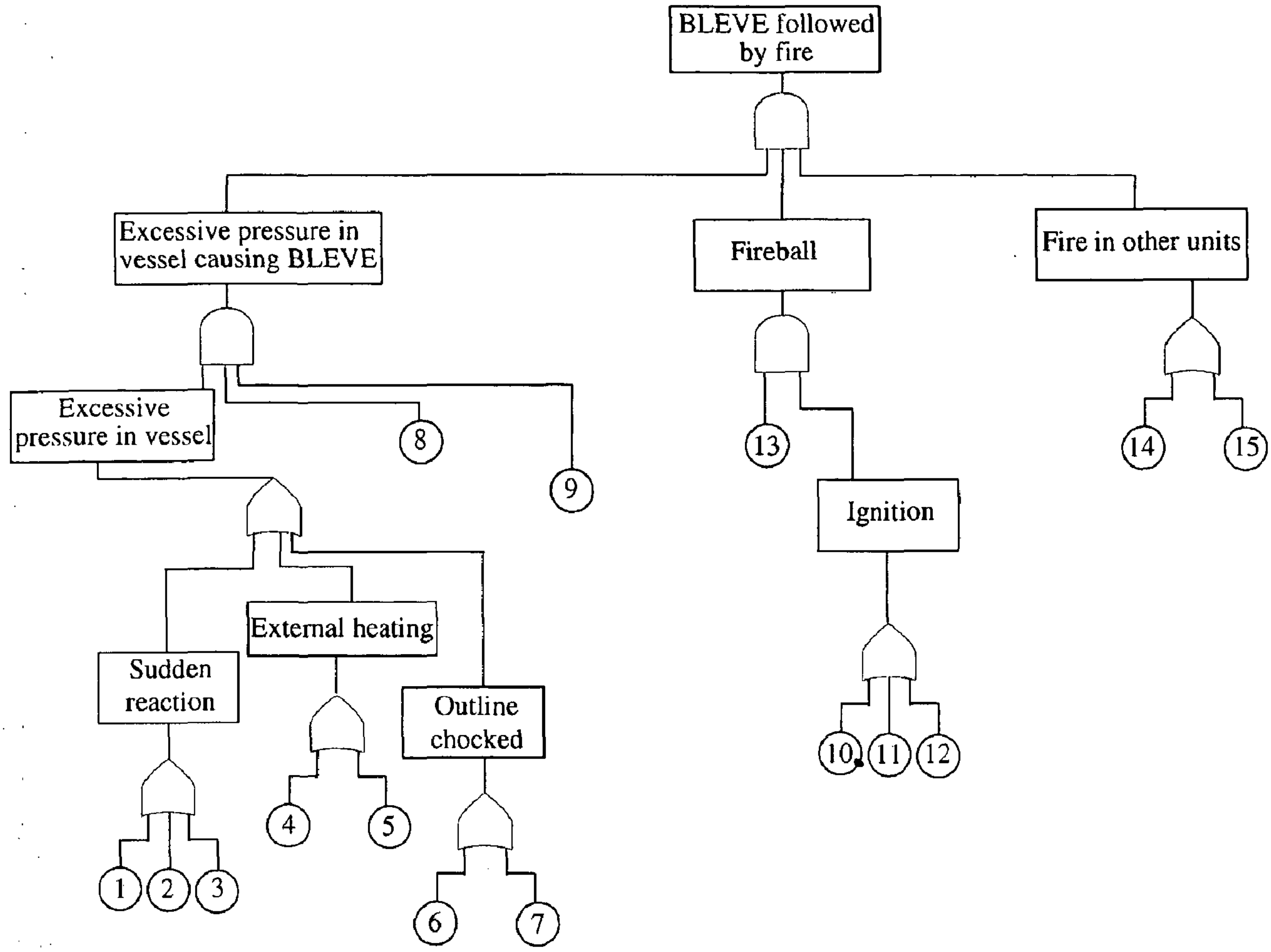


Figure 7.20 Fault tree diagram for drier; detail of basic events is presented in Table 7.13

Table 7.12

Elements of the fault tree developed for a probable accident in flash drum unit

Number in Fig. 9	Elements	Failure frequency(per year)
1	Leak from upstream pipeline	03
2	Leak from upstream pipeline joints	0 .045
3	High-pressure in vessel causing rupture of vessel and release of gas	0.003
4	Leak from joints or flange	0.0075
5	Leak from downstream pipeline	0.00003
6	Leak from joints of downstream pipeline	0.0450
7	Leak from joint of gas pipeline	0.0650
8	Leak from gas pipeline	0.0045
9	Ignition due to explosion energy	0.150
10	Ignition due to external heat from surroundings	0.200
11	Ignition due to electric spark	0.250
12	Ignition due to explosion energy	0.150
13	Ignition due to external heat from surroundings	0.200
14	VCE causes pipeline to fail and release chemical	0.150
15	VCE causes vessel to fail and release chemical	0.050

Table 7.14

FTA results (output of PROFAT) for flash drum (scenario 5)

Event not occurring	Probability	Improvement	Improvement index
0	9.062887E−04	0.000000E+00	0.000000
1	8.906126E−04	6.270446E−05	0.432300
2	6.735921E−04	9.307862E−04	6.417066
3	8.802116E−04	1.043084E−04	0.719127
4	8.672774E−04	1.560454E−04	1.075815
5	9.045153E−04	7.093447E−06	0.048904
6	6.735921E−04	9.307862E−04	6.417066
7	5.701929E−04	1.344383E−03	9.268506
8	8.827745E−04	9.405663E−05	0.648449
9	4.531294E−04	1.812637E−03	12.49676
10	7.250159E−04	7.250910E−04	4.998954
11	6.344170E−04	1.087487E−03	7.497399
12	5.180090E−04	1.553119E−03	10.70758
13	3.883690E−04	2.071679E−03	14.28266
14	3.022254E−04	2.416254E−03	16.65823
15	6.041825E−04	1.208425E−03	8.331176

Table 7.15

FTA result (output of PROFAT) for drier (scenario 6)

Event not occurring	Probability	Improvement	Improvement Index
0	2.831220E−06	0.000000E+00	0.0000000
1	2.875924E−06	1.788148E−07	0.2695430
2	2.607703E−06	8.940692E−07	1.3477080
3	2.533197E−06	1.192093E−06	1.7969460
4	2.607703E−06	8.940692E−07	1.3477080
5	9.685755E−07	7.450580E−06	11.230907
6	2.875924E−06	−1.788148E−07	−0.269543
7	2.786517E−06	1.788130E−07	0.2695400
8	0.000000E+00	1.132488E−05	17.070980
9	0.000000E+00	1.132488E−05	17.070980
10	1.907349E−06	3.695487E−06	5.5705290
11	1.713634E−06	4.470347E−06	6.7385440
12	2.130866E−06	2.801416E−06	4.2228190
13	0.000000E+00	1.132488E−05	17.070980
14	1.981854E−06	3.397464E−06	5.1212930
15	8.940698E−07	7.748602E−06	11.680142

7.3.3.2 Flash Drum And Drier

The fault tree of the flash drum and the drier as illustrated in Figs. 7.19 and 7.20 are comprised of 15 basic events. Although the number of basic events in both cases is the same, their details are different (summarized in Tables 7.12 and 7.13).These fault trees were analyzed using PROFAT. The results for the flash drum as presented in Table 7.14 indicate that the likelihood of this accident occurring is 9.06E−04 per year. Among the 15 basic events, events 14, 13, 9, 7 and 15 contribute almost 50% to the total probability of occurrence. Control of these events would ensure a better design and a safer operation.

The FTA for the drier (Table 7.15) estimates the probability of occurrence of this accident scenario as 2.831E–06 per year. Among the various basic events 9, 13, 5, and 15 control the total probability of occurrence. A check on these basic events would ensure a safer design and operation.

7.3.4 RISK QUANTIFICATION

Using the results of the previous steps, risks are computed for all six units under study. Interesting results are observed. Though the compressor units are moderate in damage causing capabilities, they were found to be the most risky. This is because of their high probability of failure. The unit observed to be the most disastrous in damage calculation separator 1 was found to be comparatively less risky, due to its low probability of failure. Fig. 7.21 presents a summary of the average individual risk factors caused by different units along with ALARP criteria. Analysis of these results reveals that the compressor units followed by separator 2, flash drum and separator 1 pose a high individual risk. Their risk and FAR values exceed the ALARP acceptance criteria. These units need attention in order to bring these high risks to an acceptable level.

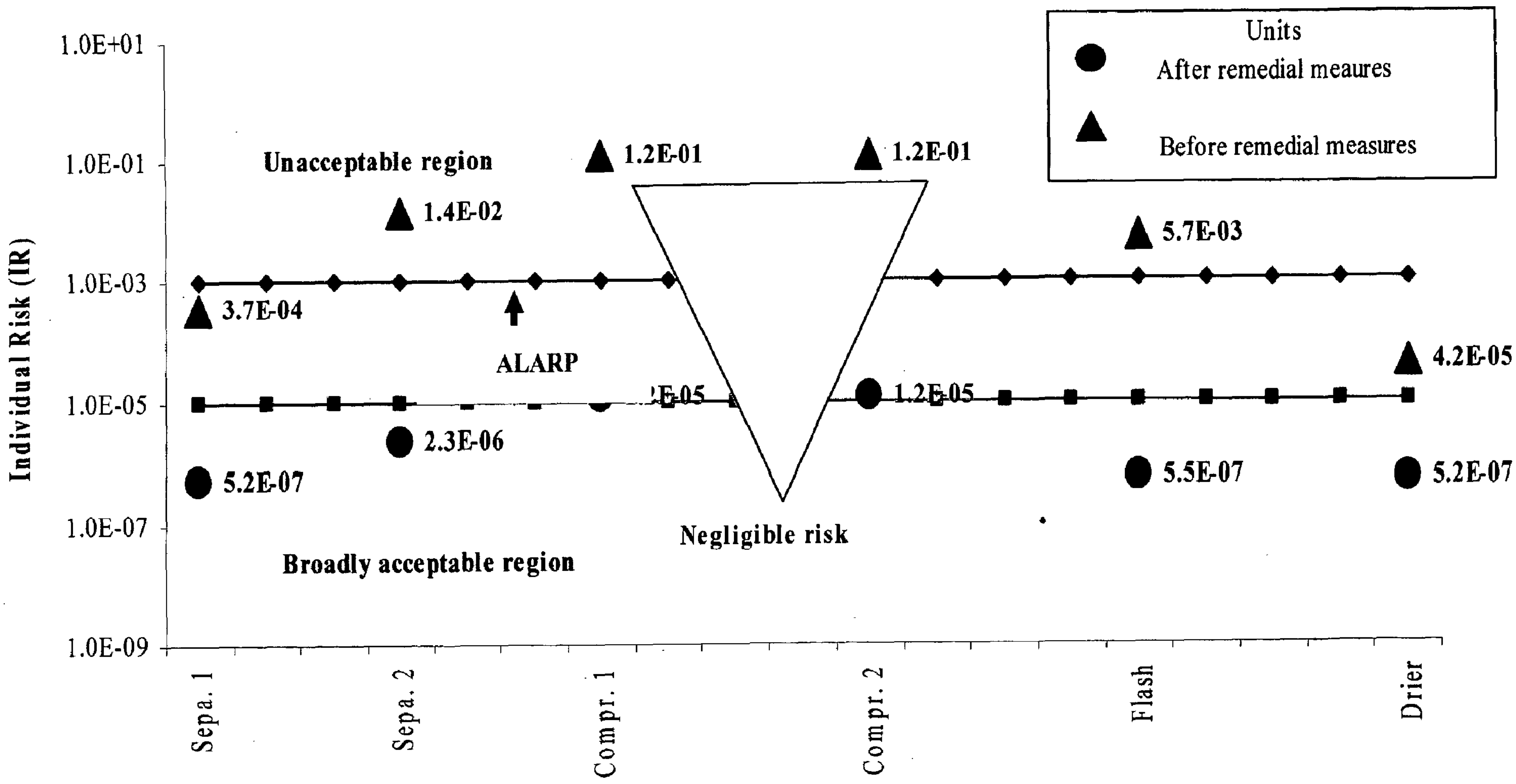


Figure 11. Comparision of individual risk factors with ALARP criteria

Figure 7.21 Comparison of individual risk factor with ALARP criteria

Table 7.16

Control measures implemented over different units to reduce the risk

Control measures	Frequency of failure (per year)
Flame arrester	0.040
Water sprinkling system	0.045
Flammable gas detector	0.065
Advanced control mechanism, (i.e. feed forward, cascade control, neural network based control, DDC)	0.005
Advanced final control element (digital controller)	0.002
Installation of emergency relief system against over pressurization of separators, flash drum, and drier	0.050
Check valve with relief provision to flare	0.030
Installation of bypass line	0.004
Preventive maintenance of pumps	0.100
Preventive maintenance of compressors	0.150
Preventive maintenance of pipeline	0.070
Leak detector in compressor and pumping section	0.057
Installation of safe venting system on pipeline	0.010
Installation of blast barriers	0.030
Installation of external cooling system for separators, and drier	0 .045
Installation of inert gas purging system to prevent flammable gas cloud formation	0.065

7.3.6 RISK REDUCTION THROUGH SAFETY MEASURES MCCA-PFTA CONTROLLER SYSTEM

A risk reduction exercise was conducted by incorporating various safety measures and add-on control measures. Possible control options to reduce the risk are given in Table 7.16, and from these, various combinations of control measures were selected to re- duce the risk potential of a unit. When these measures are taken into account, the unit fault tree is modified, as shown in Fig. 12 (compressor unit). On analyzing the new fault tree (Fig. 7.22), the frequency of occurrence of the top event (envisaged accident) is reduced to 1.311E−06, which is about 10,373 times lower than the previous value. The individual risk and FAR value after the implementation of control measures for this unit come well within the acceptable range (Fig. 11). The FAR value was reduced from 11127 to 1.

After deciding the safety measures (Table 7.16), the fault tree for separator 2 is modified, as shown in Fig. 7.23, and processed through PROFAT for probability estimation. The results reveal that after implementing the safety measures, the probability of occurrence decreases to 1.555E−08. Using the revised value of the probability of occurrence, the average individual risk decreases to 1.55E−07 and FAR reduces from an original value of 1291–0.01. These values lie within the acceptable zone of ALARP criteria The incorporation of safety measures on separator 1, the flash drum and the drier reduces the probability of occurrence to 1.79E−08, 7.86E−08, and 3.47E−08, respectively. The average individual risk and FAR values for these units after implementing the safety measures fall well within the ALARP acceptable region (Fig. 7.21).

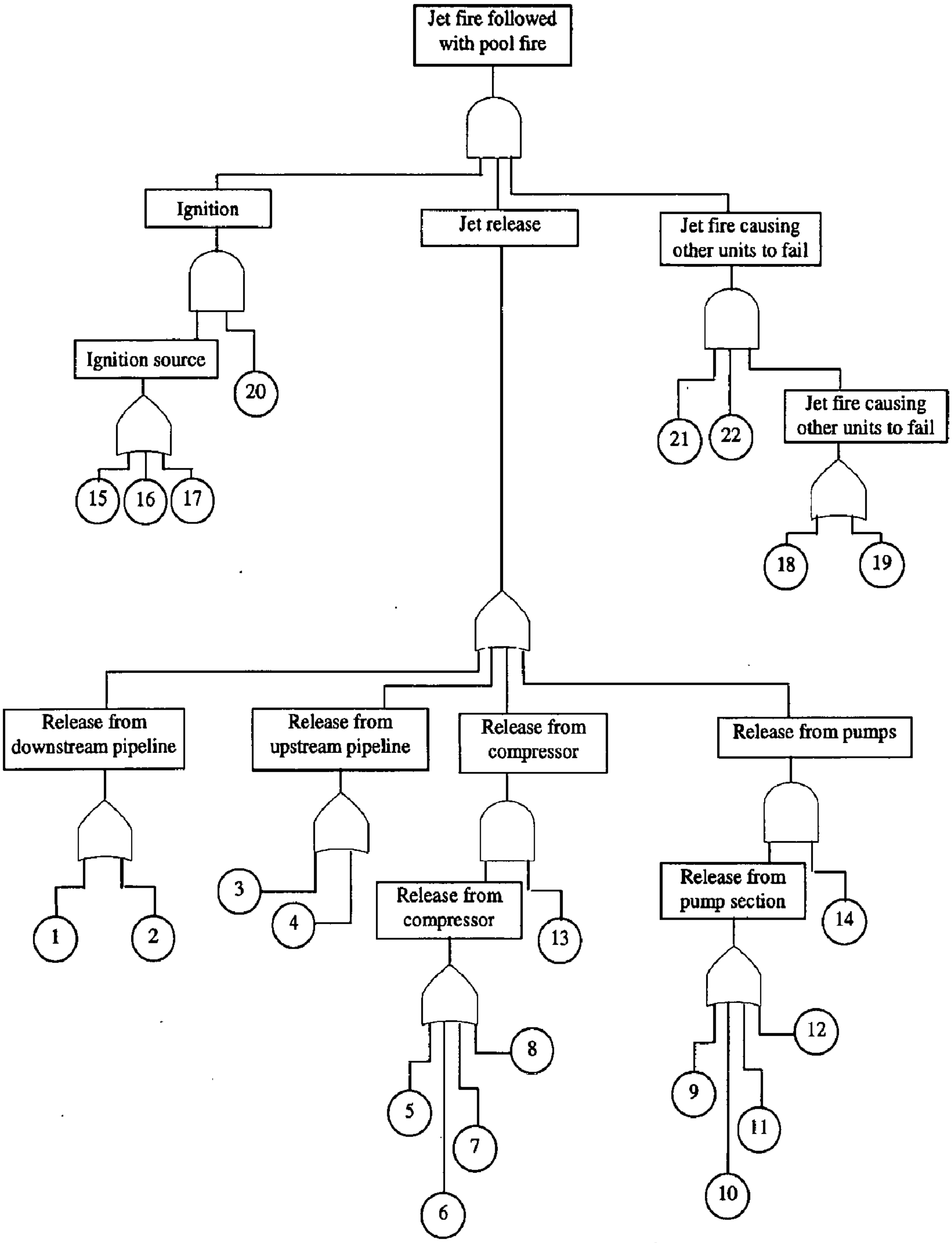


Figure 7.22 Modified fault tree diagram for compressor unit after implementing safety measures.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

It was indicated before that the role played by QRA in contributing to a demonstration that offshore major accident risks are ALARP depends on the approach taken for the QRA, in relation to how probabilities are interpreted. It depends on whether a QRA relies on a classical/relative frequency interpretation of probability (where probability is given an objective status) or on a subjective interpretation (where probability is a degree of belief).

This work discusses a revised version of the recently proposed SCAP methodology for risk-based safety management for offshore process activities through a quantitative feed back system of probabilistic risk assessment. It illustrates the application of the discussed methodology to a typical offshore process.

The advantage of using this methodology has been demonstrated by applying it to a typical offshore process facility. From the initial phase of the case study, it was observed that compressor units inherit maximum risk due to their higher probability of failure. This methodology is useful due to following reasons.

1. It is a step-by-step straightforward approach with structured techniques and computer- automated tools available at each step.

2. It does not require much data like other detailed QRA methodologies. This makes its application easy at the early design stage of the process units.
3. It recommends the latest reliable techniques and models for each step, such as revised HIRA, MCAA with MCAS, and ASM.

Revised Fire consequence models for Offshore Quantitative Risk Assessment i.e pool fires, jet fires and fireballs have been simulated and the results presented as contours by using a grid-based approach. The radiation and damage (lethality) contours for pool fires show that these consequences are concentrated more toward the downwind direction due to flame tilt caused by the wind.

The results for horizontal jet fires demonstrate the expected behavior of lethality contours that are elliptical in shape, rather than circular as obtained from point source models. Thus, the solid flame models employed in the current work more closely match the physical characteristics of fire scenarios that arise on offshore installations.

The damage contours obtained by adopting a grid-based approach permit the development of a clear picture of potential impact zones. This can facilitate proper selection and specification of safe separation distances to prevent injury to people and damage to nearby equipment. Overpressure generation from fires has also been shown to be a critical consideration in developing the impact zone map for an offshore facility.

CHAPTER 9

REFERENCES

Adam, W..B., On the Mechanical Condition of Railway working to prevent Tire Wear and risk., *J. Franklin Inst.*, (1865), 19-29.

Falck, A., Erik, S., Berg, M., Use of QRA for decision support in the design of an offshore oil production installation., *J. Hazardous Materials* 71, (2000), 179–192

Apostolakais, G. E., How useful is Quatitative Risk Assessment, *Risk Analysis,* 24, (2004), 515-525.

Arendt, J. S., Using Quantitative Risk Assessment in the Chemical Process Industry, *Reliability Engineering and System Safety, 44,* (1990), *22-35.*

Brandsaeter, A., Risk assessment in the offshore industry, *Safety Science*, 40, (2002), 231–269.

Aven, T., Kristensen, V., Perspectives on Risk: Review and Discussion of the basis for Establishing a unified and Holistic Approach, *Reliability Engg. And System Safety,* 90, (2005), 1-14.

Kirwan, B., Human reliability analysis of an offshore emergency blowdown system , *Applied Ergonomics* 18, (1987), 23- 33.

Cacciabue P.C, Human Factors On Risks Analysis of Complex Systems, *Journal Of Hazardous Materials,* 34, (2000), 118-125.

Cave, L., Risk Assessment Methods for Vapour Cloud Explosions, Prog. Energy Combust Science, 23, (1974), 344 – 355

Drysdale1, D. D., R. Sylvester-Evans, (1988) The explosion and _re on the Piper Alpha platform, 6 July 1988. A case study *Phil. Trans. R. Soc. Lond.,* 356, 2929- 2951

Attwooda, D., Khanb, Faisal, Veitch, B., Offshore oil and gas occupational accidents—What is important?, *Journal of Loss Prevention in the Process Industries,* 19, (2006), 386–398.

Attwood, D., Khan, F., Veitch, B., Validation of an Offshore Occupational Accident Frequency Prediction Model—A Practical Demonstration Using Case Studies, *Process Safety Progress*, 25, (2006), 160-171.

Borse, E., Design basis and accident analysis with particular reference to offshore platforms, *Journal of Occupational Accidents,* 2, (1979), 227-243.

Faisal I. Khan A, Paul R. Amyotte, (2002), Inherent safety in offshore oil and gas activities: a review of the present status and future directions, *Journal of Loss Prevention in the Process Industries*, 15, 279–289.

Khan, F. I., Abbasi, S. A., (1998), Inherently safer design based on rapid risk analysis *Journal of Loss Prevention in the Process Industries,* 11, 361–372.

Khan, F. I., Sadiq, R., Husain, T., Risk-based process safety assessment and control measures design for offshore process facilities, *Journal of Hazardous Materials* 94, (2002), 1–36

Wang, J., Kieran, O., Offshore Safety Assessment and Safety-Based Decision-Making—The Current Status and Future Aspects, *Journal of Offshore Mechanics and Arctic Engineering,* 122, (2000), 93-99.

Kharbanda, O. M., Stallwerty, E. A., Planning for the Emergencies Lessons from the Chemical Industries, *Long range planning,* 22, (1989), 83-89.

Kirchsteiger, C., On the use of Probabilistic and Deterministic methods in Risk Analysis, *J. Loss Prevention in the Process Industries,* 12, (1999), 399-419.

Lave, F. B., Risk analysis And Management, *the science of total Environment* , 99, (1994), 235-242.

Bellamy, L. J., The influence of human factors science on safety in the offshore industry *Journal of Loss Prevention in Process Industries., 7,* (1990), *370 – 375.*

Lipto, J., Gilllett, J. W., Uncertainity in the risk assessment: Exceedence Freqencies, Aceptable Risk and Risk based Decision making, *Regulatory Toxicology and Pharmacology*, 15, (1992), 51-61.

Mercx, W.P.M. et al., Developments in vapour cloud explosion blast modeling, *Journal of Hazardous Materials*, 34, (2000), 245-254.

Pulaa, R., Khan, F. J., Veitcha, B. , Amyotte, R. P., Revised fire consequence models for offshore quantitative risk assessment, *Journal of Loss Prevention in the Process Industries* 18, (2005), 443–454.

Rhona, F., Mearns, K., Gordon, R., Fleming, M., Perception by offshore workers on UK oil and gas platforms, *Safety Science*, 22, (1996), 131-145.

Schauer, F. P., Shinozuka, M., Environmental-Structural Considerations In Nuclear Facility Risk Assessment, *Nuclear Engg., And Design*, 32, (!975), 410-420.

Starr, C., Social Benefit Versus Technological Risk, *Science*, 165, (1972), 1232- 1238.

Tweedale, H. N., Balancing quatitative and nonquatitative Risk Assessment, *Inst Of Chem. Engr.*, (2005), 70-76.

Tweeddale, H.M., Cameron, R.F., Sylvester, S.S., Some experiences in hazard identification and risk short listing, *Journal of Loss Prevention in the Process Industries*, 85, (1992), 87-95.

Ziegler, A., Chemical Risk Assessment- A tool for Disaster Prevention, *J. Hazardous Materials*, 31, (1992), 233-239.

Chamberlain, G.A., Hazards posed by large-scale pool fires in offshore platforms, *Process Safety and Environmental Protection*, **74**, (1996), 81-87.

Chamberlain, G.A., & Persaud, M.A.. A model for predicting the hazards from large-scale compartment jet fires. *IChemE Symposium Series No. 141*, (1997), 163-174.

HSE (1996). Offshore accident/incident statistics reports. OTO96.954, Health and Safety Executive, London, UK.

Khan, F.I., & Amyotte, P.R. Inherent safety in offshore oil and gas activities: a review of the present status and future directions, *Journal of Loss Prevention in the Process Industries*, **15**, (2002), 279-289.

Khan, F.I., Sadiq, R., & Husain, T. Risk based process safety assessment and control measures design for offshore process facilities, *Journal of Hazardous Materials*, **94**, (2002)., 1-36.

Vinnem, J.E. Evaluation of methodologies for QRA in offshore operations. *Reliability Engineering and System Safety*, **61**, (1998), 39.

Cracknell, R.F., & Carsley, A.J. Cloud fires – a methodology for hazard consequence modeling. *IChemE Symposium Series No. 141*, (1997). 139-150.

Bellamy, L.J..The influence of human factors science on safety in the offshore industry. *Journal of Loss Prevention in the Process Industries*, 7(4), (1994). 370-375.

Pontecorvo, A.B., A method of predicting human reliability. Annals of Reliability and Maintainability, **4**, (1965), 337-342.