FIRE HAZARDS & RISK ASSESSMENT IN OFFSHORE PETROLEUM FACILITIES

By

AHMAD HASSAN

17852

Dissertation submitted in partial fulfilment

of the requirement for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

JANUARY 2016

Universiti Teknologi PETRONAS

32160 Bandar Seri Iskandar

Perak Darul Ridzuan

Malaysia

CERTIFICATION OF APPROVAL

FIRE HAZARDS & RISK ASSESSMENT IN OFFSHORE PETROLEUM FACILITIES

By

AHMAD HASSAN

17852

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfilment of the requirement for

the BACHELOR OF ENGINEERING

(Hons) (MECHANICAL)

Approved by,

____

(Dr. Mohammad Shakir Nasif)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

January 2016

CERTIFICATION OF ORIGINALITY

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

AHMAD HASSAN

ABSTRACT

This project highlights the methods to analyze and determine Fire Hazards & Risk Assessment in Offshore Petroleum Facilities. A comprehensive risk assessment study is conducted to find the best and effective method or techniques for determining the fire risk in offshore petroleum facilities. The project is based on Quantitative risk assessment and Qualitative Risk Assessment Techniques. A comparison between qualitative and quantitative risk assessment techniques is done for specifying the best methodology to effectuate the objects of the project. An offshore structure is a mammoth platform with facilities to drill wells, to extract and process oil and natural gas or to temporarily store products until they can be brought on the shore for refining and marketing. As the natures of the operations are hostile it may encounter extreme pressure and dangerous environments. Risks, accidents and tragedies can occur spontaneously. Process operations are the most hazardous activity. A small miss-happening in the Oil & Gas offshore platform process operations can escalate to catastrophe. By engaging Quantitative techniques Monte Carlo Simulation, Probabilistic Fault Trees and Probabilistic Bow Tie diagrams are made to calculate and evaluate the Fire Risk present in an offshore petroleum facility. Implementation of Quantitative techniques derived the fire risk by incorporating HAZOP work sheet and time based risk matrix. After conducting the whole project the preeminent risk assessment method and techniques are Quantitative Risk Assessment Techniques.

Keywords: *Offshore Petroleum Facilities; Risk Assessment; Fire Hazards; Qualitative & Quantitative techniques; FTA; HAZOP; Monte Carlo Simulations.*

ACKNOWLEDGEMENT

First and foremost, I would like thank the Almighty Allah for his countless blessing and the support HE endured in me to complete this project successfully. Then I would like to express my deepest gratitude towards my supervisor Dr. Mohammad Shakir Nasif. He has not only imparted technical knowledge, but has also facilitated and guided me towards completing my final year project. Secondly, I'd like to thank Dr. Masdi Muhammad for his continued assistance and guidance. I'd also like to thank and express my deepest respect to my parents (Mrs. & Mr. Major Nabeel Hassan) for their continued support both financially and emotionally. Without them, I would never have had the opportunity to experience any of this, and none of this would have been possible.

Furthermore, I'd also like to thank Dr. Majid Majeed Akbar, Awais, Atika, M.H.K, Usama and to all those who I have not mentioned, and have directly or indirectly contributed to the completion of my project and undergraduate studies.

Table of Contents

LIST OF FIGURES:

List of Tables

Nomenclature

$R_{(S)}$	**Reliability of the system.**
λ	**Constant failure rate.**
t_f	**Time period in hours , months, years or cycles.**
Exp	**Exponential function.**
CDF	**Cumulative Density Function .**
F(t)	**Failure Rate.**
RBD	**Reliability Block Diagram.**
POF	**Probability OF Failure.**

CHAPTER ONE

INTRODUCTION

1.0 INTRODUCTION

1.1 Background of Study

An offshore structure is a huge structure with facilities to drill wells, to extract and process oil and natural gas or to temporarily store products until they can be brought on the shore for refining and marketing. Depending on the circumstances the platform can be fixed or floating. As the nature of the operations is hostile it may encounter extreme pressure and dangerous environments. Risks, accidents and tragedies can occur spontaneously. Process operations are the most hazardous activity. A small miss-happening in the Oil & Gas offshore platform process operations can escalate to catastrophe. Due to limited space and compact geometry on the process area, less ventilation and difficult escape routes the chances of fire accidents and hazards are very high.

Fire is the rapid oxidation of a material in the exothermic chemical process of combustion, releasing heat, light, and various reaction products. Fire is the most frequent phenomenon among the offshore accidents. The burning of hydrocarbons possesses a high level threat to the personnel, equipment and environment. Products of hydrocarbon fire accidents have both chronic and acute health effects. Fire can wreak on an offshore rig and serve as a constant reminder of the importance of having fully trained staff and maintaining fully functioning fire safety systems to detect and stop fires. Fire occurs when sufficient heat is produced to cause combustion. Factors influencing resultant combustion from a given ignition source are temperature, exposure time and energy. Ignition sources which are present in offshore platforms are chemical reactions, fuel operations, electric sparks, hot surfaces and hydrocarbon flaring. Eventualities in Oil & Gas platforms and process operations can be avoided through incorporating appropriate control measures. Early detection of fire hazards is essential if fire damage to be minimized.

Hazard identification is equally important as consequences analysis in order to estimate the risk of the system. In offshore industry "Hazard" is defined as potential threat to assets and property. Hazard is also explained as potential source of harm, while harm is further defined as "physical injury or damage to the health of people, or damage to the property or environment. Since millions of revenues and resources accompanying precious human lives are being involved in an offshore facility 'Hazard Identification' is one of the core component of risk assessment. Offshore platforms and facilities possess a great amount of various kinds of risks.

Risk is defined as a "combination of the probability of an event and its consequences". Risk is the expression of probability for and consequences of one and several accidental events relative to the occurrence of harm and severity of harm.

Risk management in an offshore industry is comprised of 'Risk Assessment' and 'Hazard Identification'. Risk management plays a key role in the safety of human beings, assets and equipment in offshore platforms. Usually risk assessment and hazard identification are employed in the early stage of platform designing. There are several methods for risk assessment on offshore facilities such as 'Qualitative', 'Quantitative' and 'Hybrid' risk analysis. Although risk assessment can be based on both qualitative and quantitative analysis.

Qualitative analysis refers to a non-numerical representation and explanation based on attributes of graphics, flow diagrams, graphs and sources of data. The most significant qualitative methods and models are HAZOP, HAZID and Major Hazard Analysis (MHZ). The well-established and widely used qualitative hazard identification method is the Hazard and Operability Analysis (HAZOP). The HAZOP is well-established and accepted method which is used to identify and evaluate process hazards as well as to identify operability problems.

Quantitate analysis employs numerical approach. Quantitative analysis provides a realistic numerical estimate for better understanding and informed decision making. A quantitative risk assessment is a key tool applied in safety management and risk control throughout the design, construction, and operation and decommissioning of any industrial activity in order to achieve safe operation and major hazard control. The famous quantitative methods are Optimal Risk Analysis (ORA) and Quantitative Risk Analysis (QRA). The QRA methodology involves four major steps: (1) hazard identification, (2) hazard assessment, (3) consequences analysis, and (4) risk estimation.

By comparing both techniques 'Quantitative Analysis' and 'Qualitative Analysis' a comprehensive study can be done which can be useful in reducing fire related and other accidents at offshore petroleum platforms and facilities.

1.2 Problem Statement

A Comparison between Qualitative Risk Assessment & Quantitative Risk Assessment Techniques.

Risk assessment is the process of gathering data and synthesizing information to develop an understanding of the risk of a particular enterprise. Offshore production of oil and gas involves different threats and dangers which need to be identified and analyzed. The identification of hazards and risk assessment provides a way to deal with these potential threats and to minimize them. Using risk assessment techniques the risk can be mitigated thus providing a safe working environment. With the development of advanced risk assessments techniques fire hazards and risk can be minimized to possible low thresholds. Qualitative Risk Assessment & Quantitative Risk Assessment Techniques provides a systematic explanation of hazards and their identification. It also acts as a guide in minimizing the dangers and improves occupation safety to the highest possible levels. It enables implementation of inherent safety principles.

Use of process safety concepts in industrial practice started with the occurrence of major accidents between 1960 and 1990. Qualitative analysis involves process hazards and risk assessments methods such as HAZOP, FEMA, FTA and ETA. Where Quantitative analysis method involve the use of simulation for modeling **fire, explosion and release**. One of the major emerging techniques is to do the comparison between both methods and then implement inherent safety design and strategies for better occupational safety and working environment.

1.3 Objectives

I. To conduct an effective study for identifying major “Fire Hazards & Risk” in offshore petroleum facilities.

II. To evaluate the importance of risk management and risk assessment.

III. To compare the results obtained from qualitative and quantitative risk analysis.

IV. To simulate and evaluate the applicability of Quantitate analysis in offshore risk assessment

1.4 Scope of Study

I. Determining the method to assess the maximum levels of safety at offshore platforms or structures. Identifying the major risks and hazards at offshore petroleum facilities. The approach will be developed by conducting qualitative or quantitative risk assessments. The method is determined form selected existing literatures, which in turn can be used for risk based analysis if successful.

II. Comparison between qualitative and quantitative risk analysis and choosing the most appropriate method which will provide effective and efficient risk analysis and hazard identification..

CHAPTER TWO

LITERATURE REVIEW

2.0 LITERATURE REVIEW

2.1 Literature Review

Risk assessment describes systematic procedures or guidelines for accomplishing or approaching a development related to process safety and risk management. Models cover mathematical, analytical, empirical, probabilistic, and computational methods. These are classified into four different types: (1) qualitative, (2) semi-quantitative, (3) quantitative, and (4) hybrid.

Khan and Abbasi (1999a) conducted a comprehensive study on major process accidents that occurred during 1926–1977 and recommended the need for accident forecasting, consequence assessment, and development of emergency management plans. The report of Marsh Energy Practices listed 100 largest property damage losses that have occurred in hydrocarbon processing industries from 1970 to2011 (Marsh, 2012). Accident occurrences and their consequences show a non-uniform fluctuation. The non-uniform trend confirms the uncertain and unpredictable behavior of accidents and their consequence and reinforces the need of efficient and effective process safety and risk management to implement preventive and mitigating safety measures to reduce both the likelihood and severity of industrial accidents (Tauseef et al., 2011).

Ramzanet al. (2007) developed the Extended HAZOP which was supported by dynamic simulation. Extended HAZOP adopted the concept of risk and included the following additional features which standard HAZOP cannot produce. These were: dynamic simulation, consequences classification, frequency classification, risk-based result documentation, and risk-based hazard ranking. For highly complex dynamic systems, the methodology by integration of the mathematical model and HAZOP was presented by Labovsk´y et al. (2007). This methodology helps to decrease the possibility of overlooking hazards and to increase the efficiency of the hazard identification process. A systematic hazard identification method was introduced to perform along with HAZOP which enhanced the hazard identification process by providing an opportunity to identify the major sources of potentially critical accidents and their consequences beyond the boundaries of the premises (Laskova and Tabas, 2008). This method can also be used for scheduling and maintenance activities of plant operations.

A new process hazard analysis methodology called Major Hazards Analysis (MHA) was proposed by Baybutt (2003), with the sole purpose of identifying major hazards such as fire, explosion and toxic release. This method provided an efficient and complete identification of major hazard scenarios using a categorization scheme and brainstorming of initiating events that can lead to major accidents. A computer aided hazard identification method, called HAZID was developed.

Sklet (2006) discussed the event scenarios that lead to release of hydrocarbon at an offshore oil and gas production platform. Subsequently, safety barriers and their functions in preventing a particular release scenario were outlined. Later, Kujath et al. (2010) developed a conceptual accident prevention model which highlights the vulnerabilities of an oil and gas operation and provides appropriate guidelines to minimize the hazards and to prevent accidents. The safety barriers were identified to prevent, control or mitigate the accident process due to hydrocarbon release.

Risk assessment approaches. Instead of a detailed quantitative risk assessment (QRA), a simple risk index was proposed starting with a fundamental definition of the risk, which was the product of the probability of occurrence and the severity of the consequences, for an extended definition (Al-Sharrah et al., 2007). Unlike standard risk assessment, the proposed risk index was comprised of four elements: frequency/probability of accident, hazardous effects of the accident inventory of the chemical released, and the size of the plant. Rather than developing complex mathematical equations to assess consequences of chlorine and ammonia release, a simple and transparent model was developed based on the fatality index (Brockhoffet al., 1992). The fatality index was estimated using historical accident data and consequences were determined for three different population density classes: rural, semi-urban and urban. Exposure risk assessment is performed using methods such as dangerous dose (DD), LD_{10} and significant likelihood of death (SLOD). Based on a weighted multiple threshold approach, a method called total risk of death (TROD) was pro-posed by Rushton and Carter (2008).

A systematic framework for quantitative risk assessment called optimal risk analysis (ORA) was proposed by Khan and Abbasi (1998a). The ORA methodology involves four main steps: (1) hazard identification, (2) hazard assessment, (3) consequence analysis, and (4) risk estimation. Each step used unique techniques and tools which were previously developed by Khan and Abbasi for conducting the optimal risk analysis. The HIRA technique was used for hazard identification which produced the damage radius and the areas with high probability of lethal impacts. The dynamic risk assessment methodology was developed using accident precursor data and the Bayesian updating mechanism by Kalantarnia et al. (2009). In their method, an event tree was used to identify the potential accident scenario and then estimate the end-state probability based on the available failure data.

Cockshott (2005) combined rapid risk ranking (RRR) which was a simple qualitative method based on the risk matrix that is used to estimate the likelihood and consequences sever-ity for an unwanted incident to assess the risk level with traditional BT diagrams, and the Probability Bow–Tie (PBT)was proposed. Cockshott (2005) further described a frame-work for constructing PBT and a mathematical background and computer aided program based on a spreadsheet to perform quantification. Khakzad et al. (2012) discussed the application of Bayes' theorem for probability updating. In their method, the two stages Bayesian updating was used: (1) basic event failure probability updating of the FTA and (2) safety barrier failure probability updating of the event tree. Subsequently, end event probabilities were re-calculated based on posterior or updated probabilities. The likelihood probability distributions used for both updating processes were connected to plant dynamics; thus the BT model produced dynamic results with the system variation.

Dynamic Bayesian Network (DBN) is more suitable than classical Bayesian Network (Murphy, 2002). Application of the DBN to model the decision criteria of a safety monitoring system was presented by Kohda and Cui (2007). DBN modeled the entire behavior of the system including the safety monitoring system. The logic of DBN was dynamically modified based on the sensor output data that was monitored at regular intervals from the control system. This method helped to prevent or minimize the expected loss caused by failure of the safety monitoring system due to failed-dangerous or/and failed-safe events. The safety barrier diagram is another popular method in risk modeling and assessment. Itis simple and helpful in communicating with non-experts as it depicts the accident process as a failure of safety measures. The definition, syntax and principles of constructing safety barrier diagrams were introduced by Duijm (2008).

From the literature review, the following are disclosed:

- Although there is no universal agreement on the most adequate failure analysis, hazard identification and risk assessment methods. Compassion between both techniques Qualitative and Quantitative risk assessments will provide a better strategy to overcome accidents and assessment of risks.

- Optimization of previous work done in the relative filed will provide basic necessary data and framework. Complex theoretical models can be simplified by following mathematical approach or by creating simulations.
- Analysis of qualitative analysis methods and quantitative analysis methods combined are known as hybrid techniques. Hybrid methods are the most emerging technology. Fire hazards and risk assessment based on Hybrid methods (qualitative and quantitate) techniques are more comprehensive and employ all possible situation for risk management and assessment and mitigation.

CHAPTER THREE

METHODOLOGY AND PROJECT ACTIVITIES

3.0 RESEARCH METHODOLOGY

3.1 Project Flow Chart

Figure 4.0 below highlights the steps that are needed in order to achieve the project objectives. The literatures for the project were found using OpenAthens and Science Direct which provides access to numerous subscriptions for academic journals and e-books. It should be noted that the theoretical/numerical analysis to obtain and effective risk assessment based study will only be done if adequate knowledge is attained and there is sufficient time.

The project flow is shown below:

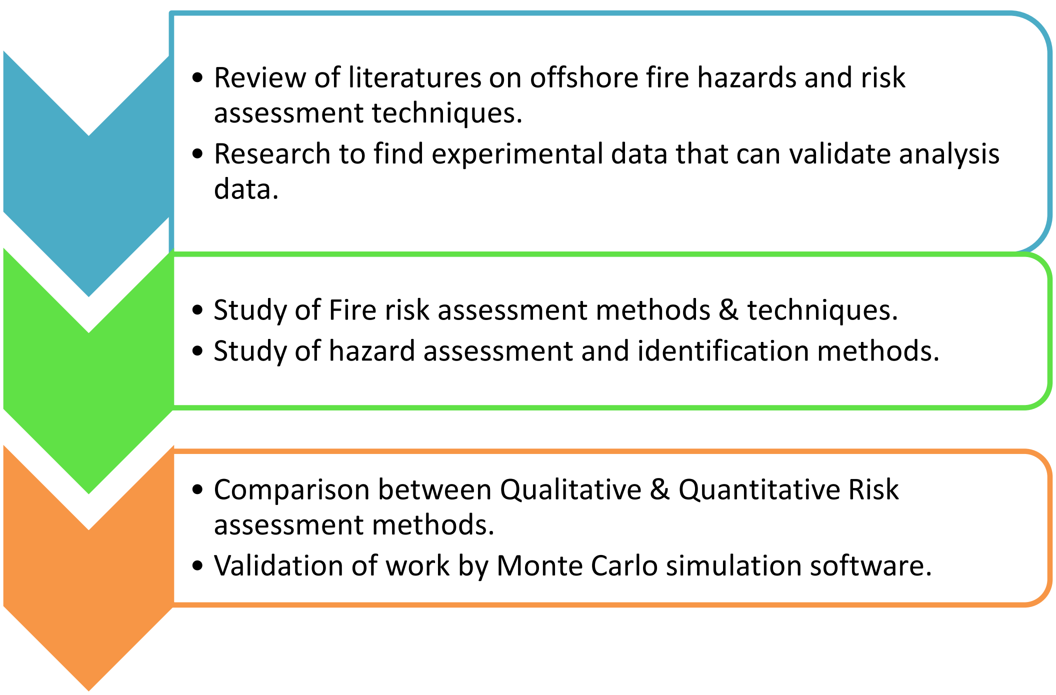


Figure 1: Research Process Flow.

3.2 RESEARCH METHODOLOGY

The research methodology is based on the following flow as shown below:

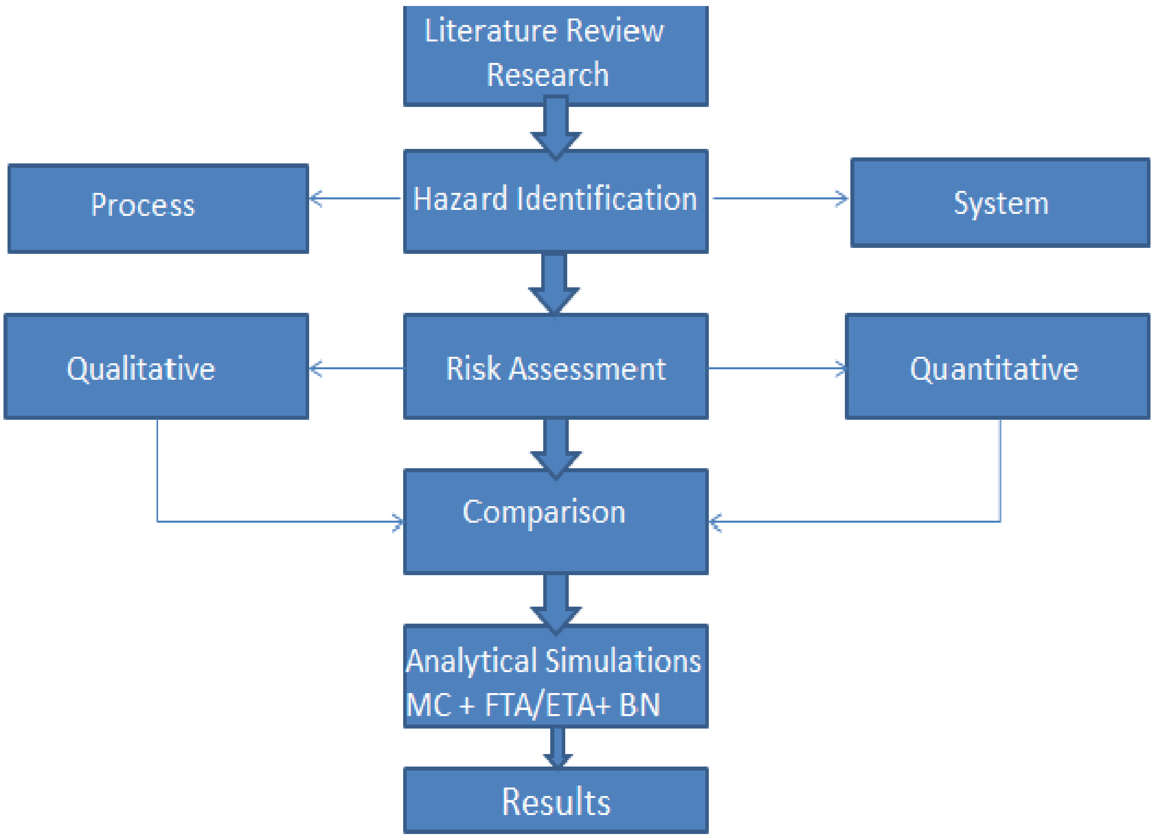


Figure 2: Methodology Flow Chart.

3.3 Equipment and Software Required

The only required software for the entire duration of the final year project is Monte Carlo Simulation software, Microsoft Excel and SPSS statistical software . All other information that is required can be acquired from literatures and other sources. Hence, there is no need for any physical testing to obtain the required risk assessments, which in turn means that there is no requirement for any sort of equipment.

3.4 Gantt Chart and Key Milestones

Table 3.0 – Gantt Chart for FYP I & FYP II

FYP I

No	Activity/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review		25.10.15			14.11.15							18/12/15	Final Exam	
2	Research to find literatures with experimental data.			6.11.15					21.11.15						
3	Study on Offshore Fire Hazards & Risks										3.11 .15		1		
4	Extended Proposal							15.11.15							
5	Proposal defense									30.11.15					
6	Interim report												18.12.15		
7	Analysis on Fire Hazards & Risk.										5.11. 15		2		
8	Risk Assessment & Mitigation												16.12.15		

FYP II

No	Activity/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review	21.1.16												Final Exam	
2	Qualitative & Quantitative Study						12.2.16			3					
3	Simulation, Fire Risk assessment / prevention							19.2. 16			4				

Key Milestones   Process

Table 3.1 – Key Milestones

Table 1: Key Milestones.

Key Milestone 1	**Completion of study** on **Offshore Fire Hazards and Risk Assessment.**
Key Milestone 2	**Completion of analysis on Fire Hazards and Risk Assessment.**
Key Milestone 3	**Completion of comparison between Qualitative and Quantitative Studies.**
Key Milestone 4	**Simulation of Fire Risk assessment / prevention. Methods to mitigate and overcome fire risk and hazards.**

14.12.2015	**Key Milestone 1**
16.12.2015	**Key Milestone 2**
22.02.2016	**Key Milestone 3**
08.03.2016	**Key Milestone 4**

The Gantt chart and key milestones are as shown in table 3.0 and 3.1. By following the set activities and completing them as per required in the Gantt chart, the project can completed within the allocated time period.

3.5 Basic Modeling & Simulations Outline

This project report covers the validation of the study done by Khan et al (2001) on Risk Based Process Safety and Assessment of offshore process facilities. Khan et al only used probabilistic method in their study. The FAILURE RATE data used for modeling and simulation is extracted from Khan et al study.

The simulations shown in this report are done by following Monte Carlo Technique. Monte Carlo simulation is a computerized mathematical technique that allows determining risk in quantitative analysis and helps in decision making process. Monte Carlo simulation performs risk analysis by building models of possible results by substituting a range of values (Random Numbers) for any factor that has inherent uncertainty. It then calculates results over and over, each time using a different set of random values from the probability functions. Depending upon the number of uncertainties and the ranges specified.. Monte Carlo simulation produces distributions of possible outcome values.

Process operations is the most hazardous and dangerous activity in an offshore Oil & Gas platform. Past experiences had shown that a slight miss-happening can lead to catastrophic events. An offshore facility involves, drilling rig , structures, process plant, transportation, workers offices & accommodation and utility facilities.

The process plant of a fully manned production facility typically includes a number of stages of oil, gas and water separation, gas compression and dehydration processes. The risk present is the process pant is very high. Process plant can be a potential site for ‘Fire & Explosion. The risk due to fire and explosion in the process facility consist of more than 50% of the total risk of the overall installations.

The process plant consists of many types of equipment and processes such as (Separators , Compressors, Pumps, Pipelines and etc.). For this project I choose the “Separator Section” for determining the amount and level of hazards and risks present, which can be a potential factor for fire and explosion.

3.6 Process Description

Separator: It is a type of pressure vessel which is designed to divide a combined liquid- gas system into individual components, that are relatively free for each other for subsequent process and disposition.

The well fluid (oil, gas and water) passes through the separators where it is separated into three major components i.e. Oil Gas and Water. Oil is pumped through the main oil line to the desired facility. Gas is compressed and dehydrated for storage and other required processes. Water is treated or discarded.

- A simplified 'Reliability Block Diagram' of the separator facility is shown below:
- Arrows show the process flow. Dotted line **(…)** show pipelines (oil/gas)

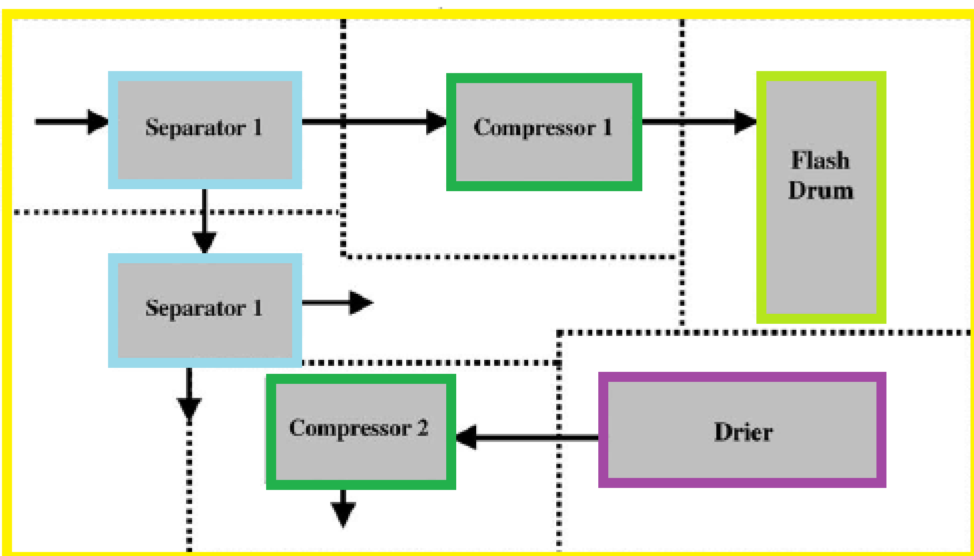


Figure 3 Reliability Block Diagram.

3.7 Hazards Identification

It is evident form the reliability block diagram shown above that separators , compressors, driers and flash drums are highly dangerous and hazardous. While Oil and Gas pipelines and pumps are moderately hazardous.

Following are some of the most potential hazards identified which can cause instant ‘Fire and Explosion’

1. Electric spark as a source of ignition.
2. Ignition due to heat from the surrounding.
3. Oil or Gas pipeline chocked.
4. Temperature controller failed.
5. Excess flow at upstream.
6. Safety valve undersized.
7. Safety / pressure valve failed.
8. Pressure controller system of the separator failed.
9. Flow control valve failed.
10. Level indicator failed.

CHAPTER FOUR

SIMULATIONS

4.0 SIMULATIONS

For simulations, assume a scenario in which fire and explosion can take place due to “Electric spark as source of ignition” which further combines with the leaking gas from the separator system to cause fire**.** Electric sparks can be produced by fault electrical equipment or by hot working condition nearby. Hot work is any work that involves burning, welding, using fire – or spark producing tools. Welding and cutting operations are very common in servicing or maintenance of separators.

For simulation reliability of the system is to be found. The reliability of the system relates to the percentage; it is the probability that system/component/equipment will perform its required function for a stated period of time (without failure) under stated conditions. Then the reliability can be plotted in form of distribution. By using probability distributions, variables can have different probabilities of different outcomes occurring. Probability distributions are a much more realistic way of describing uncertainty in variables of a risk analysis

The general expression used for simulation is based on **exponential distribution**. It is considered that the systems and its components have a constant failure rate of 1.0 per year.
The failure rate is defined by **lambda"λ”.** The value of Lambda is taken as **0.25 per year.** The data values are extracted for the study on Risk Assessment conducted by Khan et al (2001).

Failure Type	Failure Rate / per year
Electric spark as a source of ignition	0.25 per year

The Reliability of the system is given by equation which is as following:

$$R(_S) = \exp[-\ \lambda\ t_f\ ]\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where,
$R(_S)$ is the Reliability of the system.
Lambda λ is the constant failure rate.
t_f is the time period in hours , months, years or cycles.
Exp is the exponential function.

The Cumulative Density Function is give as CDF = **F(t)**

⇨ $$F(t) = 1 - R(_s)\ \ldots\ldots\ldots\ldots\ldots\ldots..\ (2)$$

The value of Lambda is already available. The value for (F(t)) would be a random number between **(0-1)**. Random number is required for Monte Carlo technique. The value of the t_f is to be found out by developing a standard equation.

⇨ $$F(t) = 1 - R(_s)\ldots\ldots\ldots\ldots\ldots......(2)$$

⇨ Putting value of $R(_s)$ in equation………(2)

⇨ $$F(t) = 1 - \exp[-\ \lambda\ t_f\ ]$$

⇨ $$\exp[-\ \lambda\ t_f\ ] = 1 - F(t)$$

⇨ By taking "ln" on both sides, the exponential function "exp" is omitted.

⇨ $$\ln\{\ \exp[-\ \lambda\ t_f\ ]\ \} = \ln[1 - F(t)]$$

⇨ $$\lambda\ t_f = \ln\,[1 - F(t)]$$

⇨ $$t_f = \lambda\ \ln \frac{1}{(1 - F(t))} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The value for (F(t)) would be a random number between (0-1)

CHAPTER FIVE

RESULTS AND DISCUSSION

5.0 RESULTS AND DISCUSSION

The results are divided into two parts. The below mentioned two stage approach is followed to determine the fire risk in separator unit of an offshore process plant.

1- Quantitative Risk Assessment.
2- Qualitative Risk Assessment.

1- Quantitative Risk Assessment:

Quantitate analysis employs numerical approach. Quantitative analysis provides a realistic numerical estimate for better understanding and informed decision making. A quantitative risk assessment is a key tool applied in safety management and risk control throughout the design, construction, and operation and decommissioning of any industrial activity in order to achieve safe operation and major hazard control. The famous quantitative method used for this project are as following:

- Monte Carlo Simulations
- Probabilistic Fault Tree Analysis.
- Probabilistic Bow Tie Diagram

2- Qualitative Risk Assessment.

Qualitative analysis refers to a non-numerical representation and explanation based on attributes of graphics, flow diagrams, graphs and sources of data. The most significant qualitative methods and models are HAZOP, HAZID and Major Hazard Analysis (MHZ). The well-established and widely used qualitative hazard identification method is the Hazard and Operability Analysis (HAZOP). The HAZOP is well-established and accepted method which is used to identify and

evaluate process hazards as well as to identify operability problems.
The qualitative technique used for this project is as following:

- HAZOP Work Sheet
- Risk Matrix

5.1 Monte Carlo Simulations.

Monte Carlo simulations are used to determine the uncertainty in a process. These simulations are also used to check the randomness of a process. This process is largely used in determining the randomness of a process. Since fire is also taken as a random occasion which can occur in the process industry due to two main sources which are enlisted as below:

A. Leakage of flammable fluid (hydrocarbons).
B. Ignition sources present.

For determining the fire risk accident scenarios are developed. The accident scenarios are based on two potential causes of fire as mentioned above. The separator system shown above in Figure 3 consist of following main sub systems

I. Separator Unit.
II. Compressor unit.
III. Flash Drum Unit.
IV. Dryers Unit.

These system and subsystems carry a high potential fire risk upon the leakage of flammable hydrocarbons and a source of ignition present. For determining the fire risk using 'Monte Carlo Simulations' accidents scenarios are developed. The accident scenarios are based on two hazardous events i.e. leakage of flammable hydrocarbons and ignition sources present.
The events are determined on the basis of high failure rate and are selected from the literature and research conducted previously.

5.2 Probabilistic Fault Tree Analysis:

Fault Tree Analysis is top down deduction based approach in determining the risk of an event occurring or the causes of failures. It employees Boolean logic to determine the top event probability of occurrence/ risk.

The FTA technique is used to determine the POF at the specified time and then relating it to Monte Carlo Simulations to determine the level of fire risk in separator process unit at certain time per year.

To express the fire risk by following the above mentioned techniques four accident scenarios are generated in four different sub systems of a separator process system which are listed as following:

i. Accident Scenario 1 for Separator Units.
ii. Accident Scenario 2 for Compressor Units.
iii. Accident Scenario 3 for Flash Drum Units.
iv. Accident Scenario 4 for Drier Units.

5.3 Probabilistic Bow Tie Diagram:

Bow tie diagram is quantitative risk assessment technique. It is used to quantify the value of risk. Bow tie technique is based on three phases which are as following:

1- Causes
2- Event
3- Effects

Each above mentioned phase is determined carefully. The probabilities of the causes and events are calculated following induction or deduction based methods and employing Boolean logic depending on the situation. Bow tie method is very effective in terms of risk assessment and as well as risk representation. It also enables the participant to employ appropriate preventive and mitigation measures. These preventive and mitigation measures helps in making the system safe.

The fire risk can be calculated by calculating the probabilities of the causes that may ignite fire in a separator system of an offshore petroleum facility.

5.4 HAZOP Work Sheet:

HAZOP stands for Hazard and Operability study. HAZOP is a structured and systematic examination of a process or operation. It is used to identify and evaluate process deviations and risks to equipment or personnel. It is also used to prevent efficient operations. HAZOP is a qualitative risk assessment technique. It enables to stimulates the imagination of participants to identify potential hazards, risk and operability problems.

5.5 Risk Matrix:

A risk matrix is a matrix that is used for risk assessment and for defining various levels of risk associated with processes, equipment, systems or operations. Risk matrix are used to identify and assess different levels of risk as the product of the harm probability categories and harm severity categories. This is a simple mechanism to increase visibility of risks and assist management decision making.

5.6 Accident Scenarios Fire Risk Representation By Monte Carlo Simulations:

Taking separator unit into consideration it must be noted here that the separator unit is the first unit to which the hydrocarbon pipeline is connected firstly from the well. All crude containing pipelines are connected straight from the well to this system. Any mishap can turn into catastrophe relating to fire risks.

High-pressure development in the separator causes the unit to fail. If there is high pressure development there can be leakages from pipelines going through the separator unit. Any leakage and a source of ignition present can cause a huge fire.

Excess flow can also be determined as a cause of leakage from the pipelines. The excess and high velocity flow can damage not only the pipelines but also the separator system and can also be one of the major cause of fire or system failure.

Another dangerous situation can be the failure of level indicator in this case there could be excess of high pressure flammable hydrocarbon flowing through the separator unit.

The events mentioned above are interrelated to each other and if any of the situation happens there could be fire in the separator unit provided there is an ignition source present.

Following are the three most potential leakage sources:

1- Leakage due to excess flow at upstream pipeline.
2- Leakage due to high pressure in the pipelines.
3- Level indicator failure and leakage from the main pipeline.

If these leakage sources are present they could combine with ignition sources to create fire. Most potential ignition sources are mention below:

1- Electric spark as a source of ignition.
2- Ignition due to heat from the surroundings .
3- Ignition due to explosion energy.

Since the separator section is consist of separator units, compressors , pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions

5.6.1 Monte Carlo Simulations for the above mentioned fire risk for separator unit:

- **Leakage due to excess flow at upstream pipelines:**

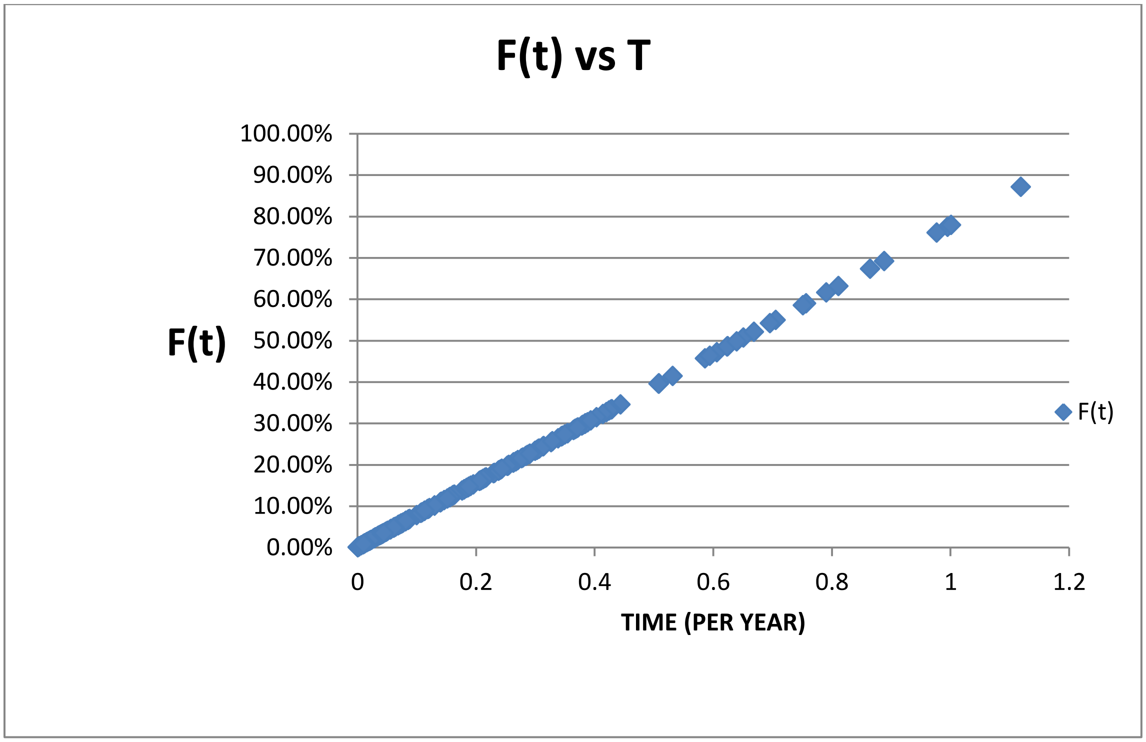


Figure 4: Leakage due to excess flow at upstream pipeline

The graph illustrated in Figure 4 shows Cumulative Density Function (CDF) of the failure '**leakage due to excess flow at upstream pipeline**. The graph is plotted between failure rate F(t) vs Time. It specifies the failure rate according to time. According to the graph shown above at about time (t) = 1 (per year) the failure rate is about 80% which is actually very high. This graph also communicates that at t=1(per year) about 80% of the equipment has failed since we are accounting the fire risk due to leakage so it means that at the specified time t=1 there is about 80% chances of fire provided if there is an ignition source present. This is a random estimation using Monte Carlo technique.

- **Leakage due to high pressure in pipelines:**

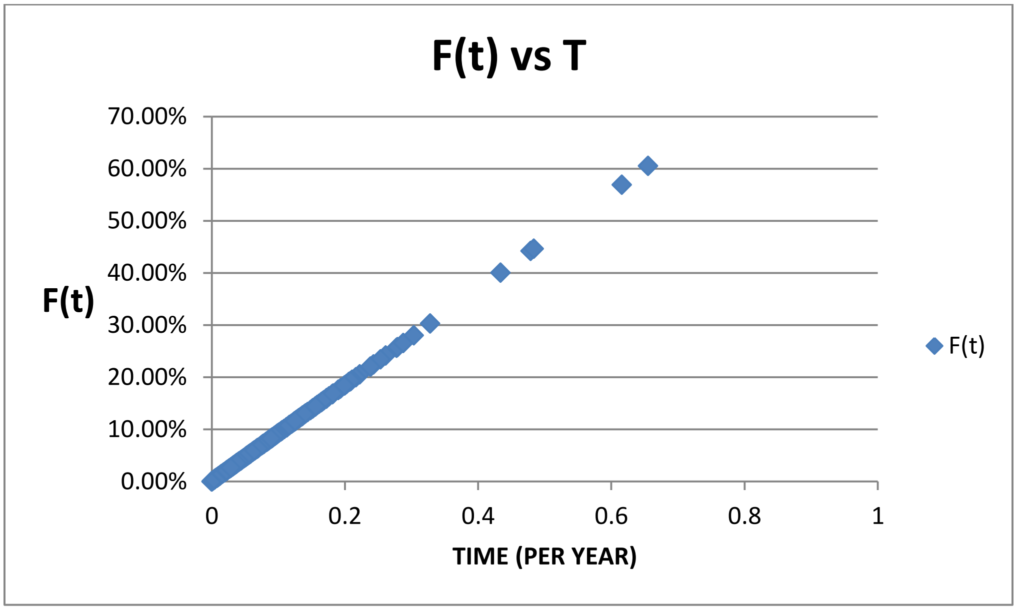


Figure 5: Leakage due to high pressure in pipelines.

The graph illustrated in Figure 5 shows Cumulative Density Function (CDF) of the failure '**leakage due to high pressure in pipelines**. The graph is plotted between failure rate F(t) vs Time. It specifies the failure rate according to time. According to the graph shown above at about time (t) = 0.7 (per year) the failure rate is about 60% which is actually high. This graph also communicates that at t= 0.7 (per year) about 60% of the equipment has failed since we are accounting the fire risk due to leakage. if there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique.

- **Level indicator failure and leakage from the main pipeline**

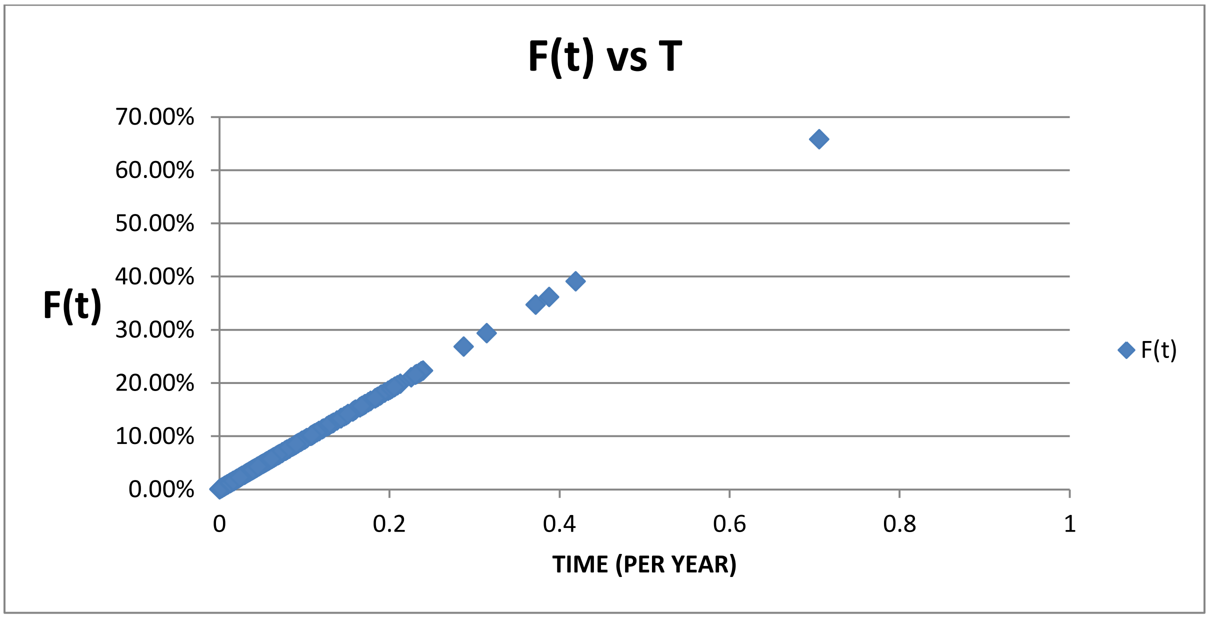


Figure 6: Level indicator failure and leakage from main pipeline.

The graph illustrated in Figure 6 shows Cumulative Density Function (CDF) of the failure '**leakage due to high pressure in pipelines**. The graph is plotted between failure rate F(t) vs Time. It specifies the failure rate according to time. According to the graph shown above at about time (t) = 0.75 (per year) the failure rate is about 68% which is actually high. This graph also communicates that at t= 0.75 (per year) about 68% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it means at about 68% there is a high risk of leakage of hydrocarbons from the main pipeline. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique.

5.6.2 Fault Tree Analysis For The Above Mentioned Leakage and Ignition cases:

FTA are done to calculate the exact probability of fire at the specified time. The values of POF at specified times can be found by following the FTA method. As the project is to find the fire risk in the offshore facilities. Fire is usually a result of two factors combining together which are as following:

1- Leakage of hydrocarbons.
2- Ignition sources.

On an offshore petroleum process facility if the above mentioned two sources are not controlled there could be fire and other fire related hazardous accidents. The FTA is top bottom deduction based failure analysis technique, in which an undesired state of system is analyzed using Boolean logic.

For the fire risk assessment, fire in the separator unit is an undesired top event which is being followed by leakage sources and ignition sources. There are three basic leakage sources identified along with three basic ignition sources. These sources are obtained by performing hazard identification study. The probabilities of leakage and ignitions are calculated.

The probability of the top event "fire in the separator unit" is calculated and shown with respect to time. The probability of top event which is fire in the separator unit gives the overall fire risk. It can be seen in the graph the probability of fire in the separator or the fire risk the separator system increases as the time increases.

FTA gives the insight of an undesired event. It also shows the potential causes that relates to the top event. It is also helpful in mitigation of the potential causes of failure.

The FTA for fire in the 'Separator Unit' is shown below. Since the system is considered to be in series the separator section is consist of separator units, compressors, pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions

FTA SEPARATOR

TIME (PER YEAR)	PROBABILITY
0.1	0.89934136

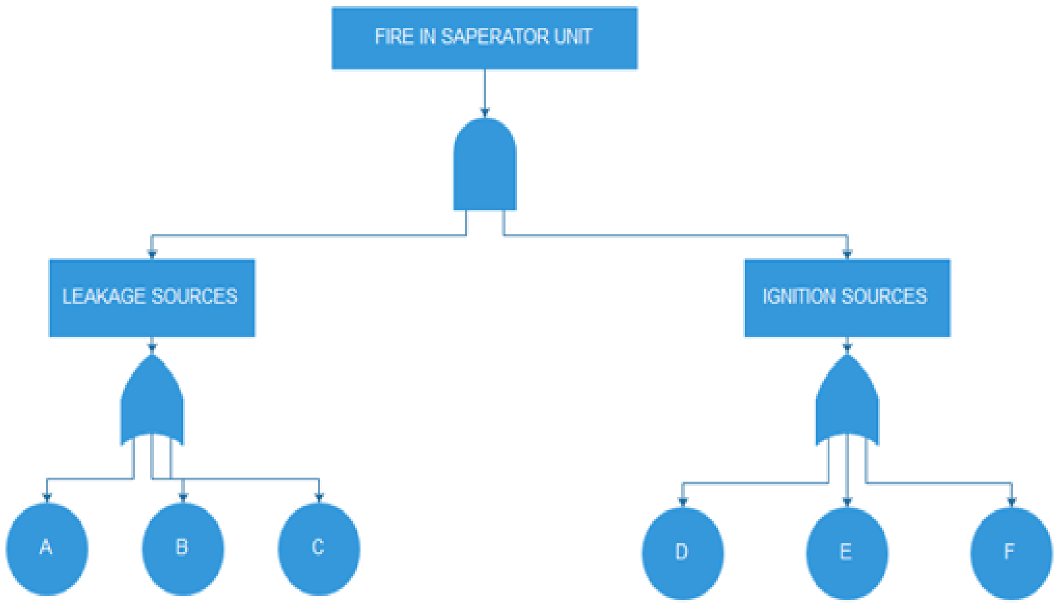


Figure 7 Probabilistic Fault Tree For Separator Unit.

EVENTS	DESCRIPTION
A B C	LEAKAGE SOURCES
D E F	IGNITION SOURCES

Table 2: Fire Risk For Separator Unit

Time (per Year)	Probability of Fire (percent %)
0.1	0.899
0.2	0.918
0.3	0.935
0.4	0.950
0.5	0.963
0.6	0.974
0.7	0.983
0.8	0.990
0.9	0.995
1.0	0.998

- **Probability of Fire versus Time: (Fire Risk Determination)**

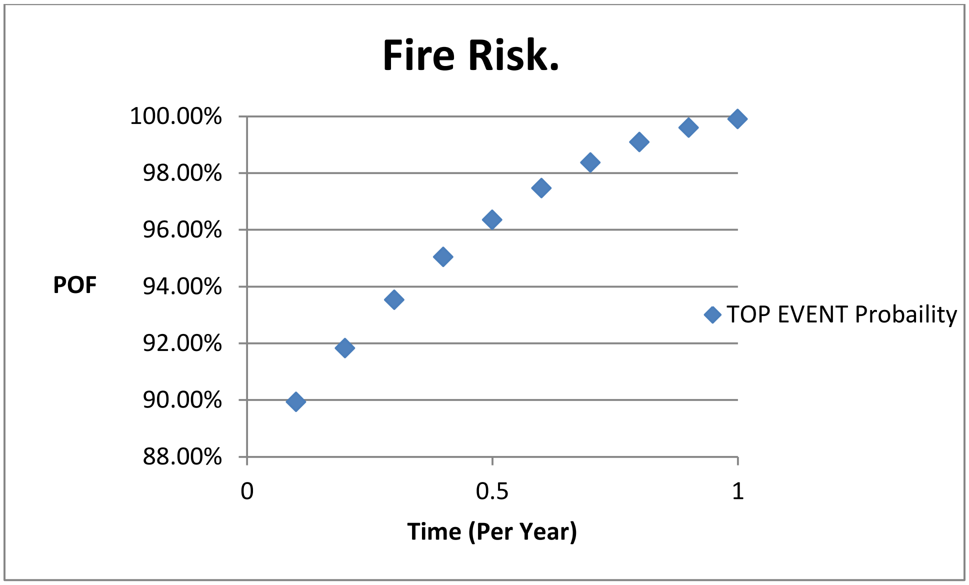


Figure 8 : Probability of Fire w.r.t Time

The graph in Figure 7 shows the **Probability of Fire** with respect to time. It means that the probability of fire in separator unit can be find on a time scale from time 0 per year to 1 per year. At any specified time the probability of fire can be found out if any of the three basic leakage events happen accompanied with any of the three basic mentioned ignition sources present.

For instance from the monte Carlo graphs we can find out that at time 0.9 per year the CDF shows F(t) = 80 % this means that the probability of fire at time 0.9 per year when the equipment is failed at about 80% (leakage) and in presence of ignition sources is approximately **0.99 %.**

Following the above approach the Fire Risk can be determined at any specified time.

5.7 Accident Scenario 2 for Compressor Units:

Taking compressor unit into consideration it must be noted here that this section is used to compress the gas.. All gas containing pipelines are connected straight from the separator to this system. Any mishap can turn into catastrophe relating to fire risks.

Any leakage of gas from this compressor unit can causes the unit to fail. If there is high pressure development there can be leakages from pipelines going through the compressor unit. Any leakage and a source of ignition present can cause a huge fire.

Excess flow of gas can also be determined as a cause of leakage from the pipelines. The excess and high velocity flow can damage not only the pipelines but also the compressor system and can be one of the major cause of fire or system failure.

Another dangerous situation can be the leakage of gas from the seals of the compressor in this case there could be a vapor cloud forming inside the separator unit. this gas that is being leaked is very flammable and can catch fire instantly providing there is a source of ignition or temperature change inside the separator unit.

The events mentioned above are interrelated to each other and if any of the situation happens accompanied with the presence of a ignition source. There could be fire in the compressor unit or separator system

Following are the three most potential leakage sources:

1- Leakage from down - stream pipeline.
2- Leakage from up - stream pipelines.
3- Leakage from the seals of the compressor.

If these leakage sources are present they could combine with ignition sources to create fire. Most potential ignition sources are mention below:

4- Electric spark as a source of ignition.
5- Ignition due to heat from the surroundings .
6- Ignition due to explosion energy.

Since the separator section is consist of separator units, compressors , pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions

5.7.1 Monte Carlo Simulations for the above mentioned fire risk for compressor unit:

- **Leakage from down - stream pipeline.**

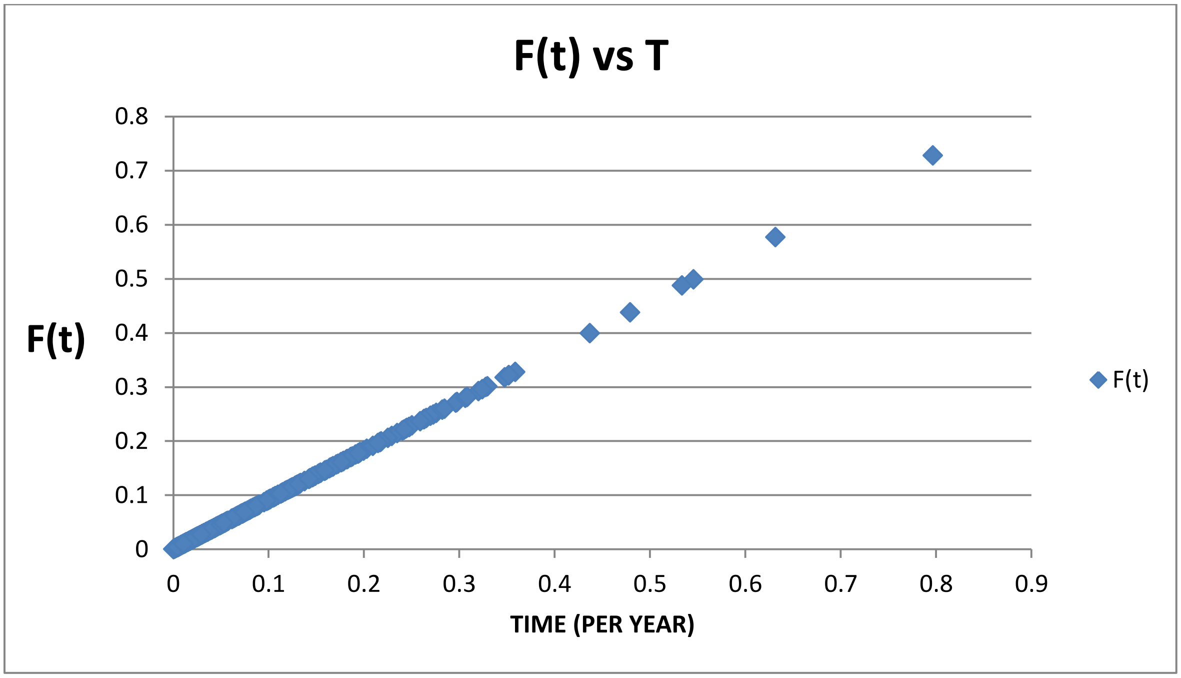


Figure 9: Leakage from down - steam pipeline.

The graph in Figure 8 illustrates Cumulative Density Function (CDF) of the failure '**leakage from down steam pipelines**. The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 0.82 (per year) the POF is about 75% which is actually high. This graph also communicates that at t= 0.82 (per year) about 75% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it means at about 75% there is a high risk of leakage of hydrocarbons from the down - stream pipeline. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique to check the uncertainty in the process.

- **Leakage from up - stream pipelines.**

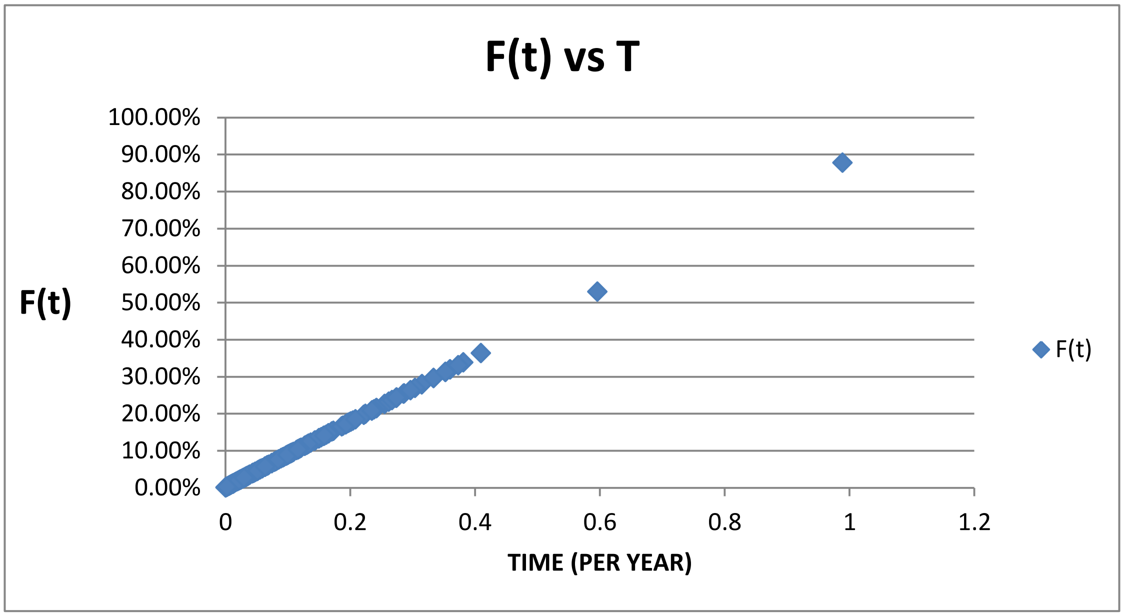


Figure 10 : Leakage from up-stream pipelines.

The graph illustrated in Figure 9 shows Cumulative Density Function (CDF) of the failure '**leakage from upstream pipelines**. The graph is plotted between failure rate F(t) vs Time. It specifies the failure rate according to time. According to the graph shown above at about time (t) = 1.0 (per year) the failure rate is nearly about 90% which is actually high. This graph also communicates that at t= 1.0 (per year) about 90% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it means at about 90% there is a high risk of leakage of hydrocarbons from the down - stream pipeline. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique.

- **Leakage from the seals of the compressor:**

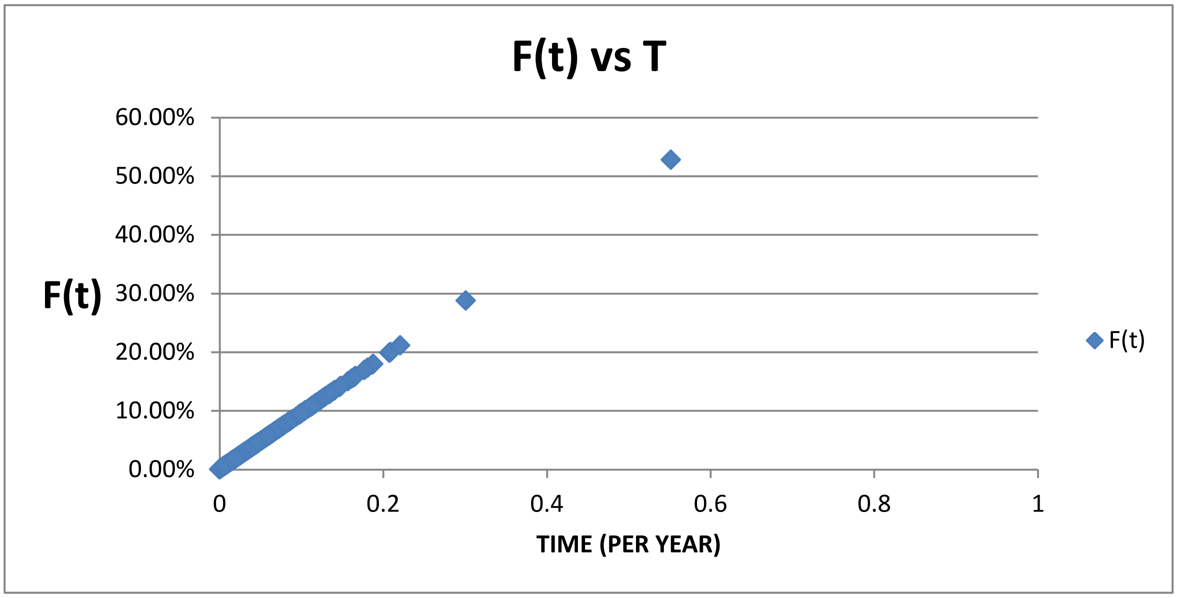


Figure 11 : Leakage from the seals of the compressor:

The graph illustrated in Figure 10 shows Cumulative Density Function (CDF) of the failure '**leakage from the seal of the compressor**.' The graph is plotted between failure rate F(t) vs Time. It specifies the failure rate according to time. According to the graph shown above at about time (t) = 0.58 (per year) the failure rate is nearly about 55% which is actually high. This graph also communicates that at t= 0.58 (per year) about 55% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it means at about 55% there is a high risk of leakage of hydrocarbons from the down - stream pipeline. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique.

5.7.2 Fault Tree Analysis For The Above Mentioned Leakage and Ignition cases:

FTA are done to calculate the exact probability of fire at the specified time. The values of POF at specified times can be found by following the FTA method. As the project is to find the fire risk in the offshore facilities. Fire is usually a result of two factors combining together which are as following:

1- Leakage of hydrocarbons.
2- Ignition sources.

On an offshore petroleum process facility if the above mentioned two sources are not controlled there could be fire and other fire related hazardous accidents. The FTA is top bottom deduction based failure analysis technique, in which an undesired state of system is analyzed using Boolean logic.

For the fire risk assessment, fire in the separator unit is an undesired top event which is being followed by leakage sources and ignition sources. There are three basic leakage sources identified along with three basic ignition sources. These sources are obtained by performing hazard identification study. The probabilities of leakage and ignitions are calculated.

The probability of the top event "fire in the separator unit" is calculated and shown with respect to time. The probability of top event which is fire in the separator unit gives the overall fire risk. It can be seen in the graph the probability of fire in the separator or the fire risk the separator system increases as the time increases.

FTA gives the insight of an undesired event. It also shows the potential causes that relates to the top event. It is also helpful in mitigation of the potential causes of failure.

The FTA for fire in the 'Compressor Unit' is shown below. Since the system is considered to be in series the separator section is consist of separator units, compressors, pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions

FTA COMPRESSOR

TIME (per year)	Probability OF FIRE
0.1	0.8492

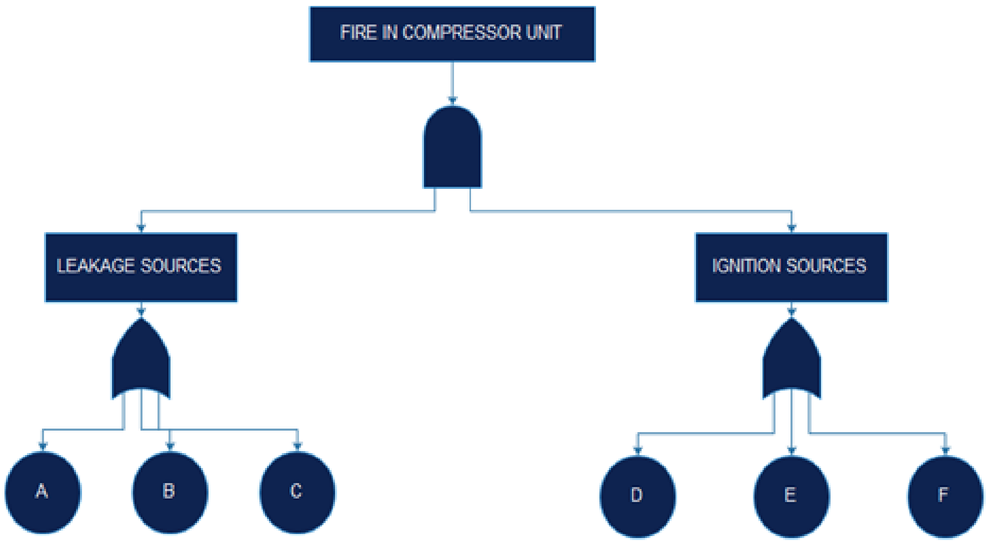


Figure 12: Probabilistic Fault Tree for Compressor Unit.

EVENTS	DESCRIPTION
A B C	LEAKAGE SOURCES
D E F	IGNITION SOURCES

Time (per Year)	Probability of Fire (percent %)
0.1	0.899
0.2	0.877
0.3	0.902
0.4	0.925
0.5	0.945
0.6	0.961
0.7	0.975
0.8	0.986
0.9	0.993
1.0	0.998

Table 3: Fire Risk for Compressor Unit

- **Probability of Fire versus Time: (Fire Risk Determination)**

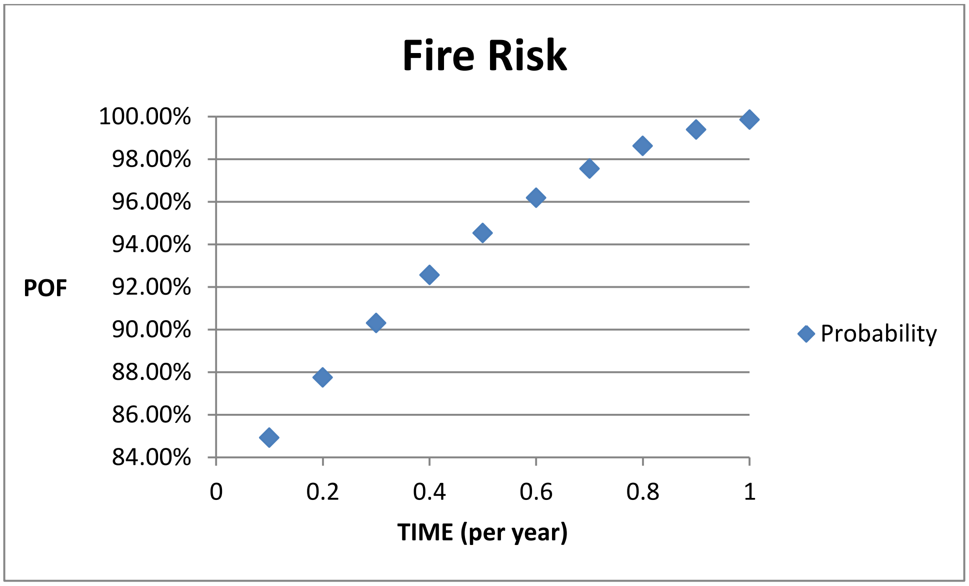


Figure 13: Probability of Fire Vs Time.

The graph in Figure 11 shows the **Probability of Fire** with respect to time. It means that the probability of fire in separator unit can be found on a time scale from time 0 per year to 1 per year. At any specified time the probability of fire can be found out if any of the three basic leakage events happen accompanied with any of the three basic mentioned ignition sources present.

Form the graph it can be seen that the probability of fire increases with the increase in time. For instance from the monte Carlo graphs we can find out that at time 0.9 per year the CDF shows F(t) = 80 % this means that the probability of fire at time 0.9 per year when the equipment is failed at about 80% (leakage) and in presence of ignition sources is approximately **0.99 %.**

Following the above approach the Fire Risk can be determined at any specific point in time. Now with the help of FTA analysis we can determine the exact probability of fire at the give time. As shown above the FTA consist of three leakage sources and three ignition sources. These sources are combined together by using Boolean operators and the combined probability of fire is found which represents the fire risk.

5.8 Accident Scenario 3 for Flash Drum Units:

A flash drum is a vessel which is used to separate vapor – liquid mixture. Considering the flash drum units it must be known, this system contains high amount of flammable vapor-liquid mixture. The vapor – liquid mixture is highly flammable. The vapors travel through the gas outlets at a specified velocity. If there is any kind of leakage, immediately a vapor cloud can be and if not controlled there could be fire and explosions.

Any leakage of gas from the flash drum unit can causes the unit to fail. If there is high pressure development there can be leakages from pipelines going through the unit. Any leakage and a source of ignition present can cause a huge fire.

If the velocity of exiting vapor is not controlled there could be excess of vapor around the system. This will result in the formation of vapor cloud and will ultimately result in explosion or fire if there is any ignition source present in the surrounding or if the temperature changes.

The events mentioned above are interrelated to each other and if any of the situation happens accompanied with the presence of a ignition source. There could be fire in the compressor unit or separator system

Following are the three most potential leakage sources:

1- Leakage from pipelines due to high pressure.
2- Leakage or vapor escape from the joints of pipelines.
3- Leakage from the downstream pipelines.

If these leakage sources are present they could combine with ignition sources to create fire. Most potential ignition sources are mention below:

4- Electric spark as a source of ignition.
5- Ignition due to heat from the surroundings .
6- Ignition due to explosion energy.

The most potential cause of fire in this unit is related to the escape of vapor from the pipeline and formation of a vapor cloud. If the above mentioned sources of leakages and ignitions are present there is a high possibility of fire.

5.8.1 Monte Carlo Simulations for the above mentioned fire risk for compressor unit:

.

- **Leakage from pipelines due to high pressure**

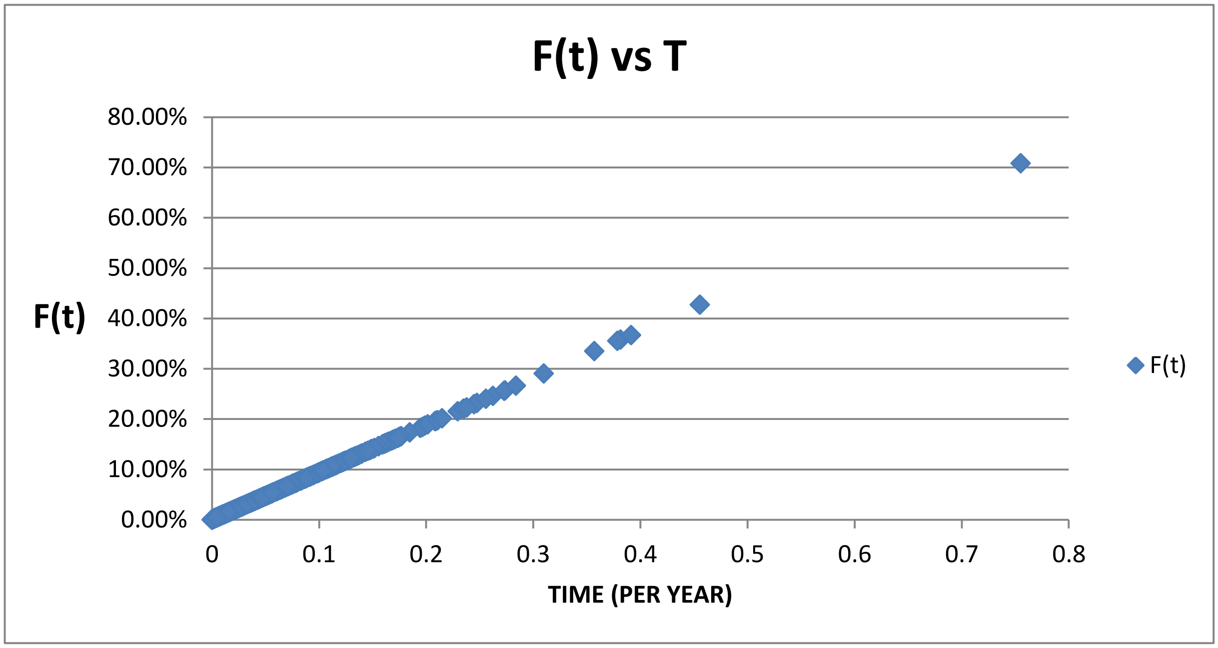


Figure 14: Leakage of gas from pipeline due to high pressure.

The graph in Figure 12 illustrates Cumulative Density Function (CDF) of the failure ' **Leakage from pipelines due to high pressure**. The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 0.76 (per year) the POF is about 70% which is actually high. This graph also communicates that at t= 0.76 (per year) about 70% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it reveals that there are about 70% chances of leakage from the pipeline due to high pressure.. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique to check the uncertainty in the process.

- **Leakage or vapor escape from the joints of pipelines.**

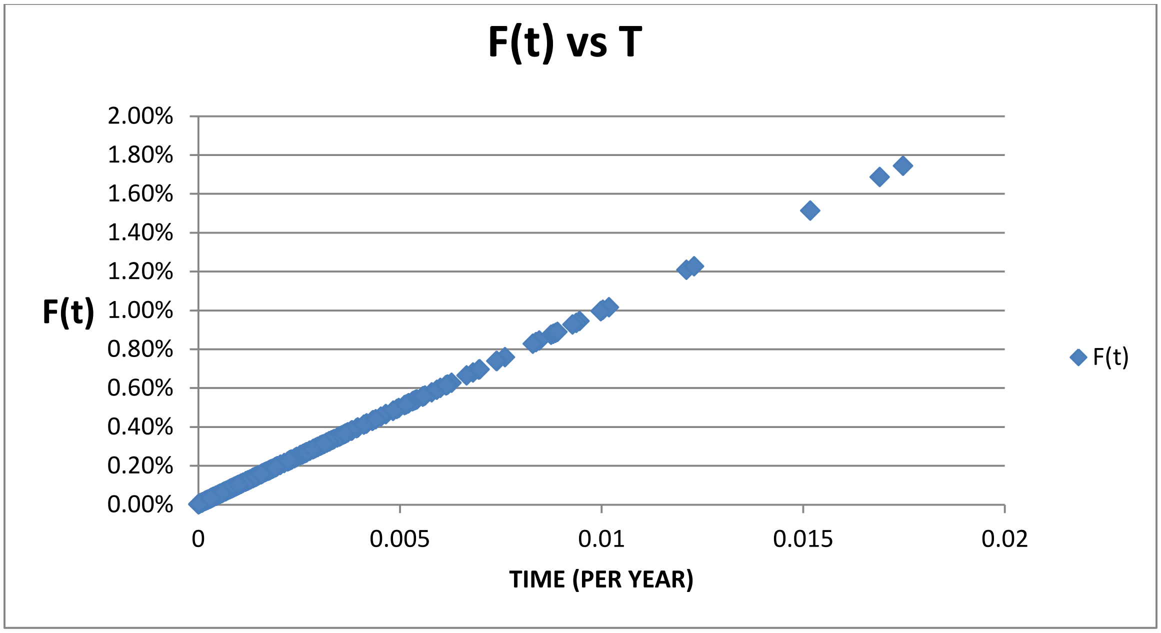


Figure 15: Leakage or vapor escape from the joints of Pipelines.

The graph in Figure 13 illustrates Cumulative Density Function (CDF) of the failure '**Leakage or vapor escape from the joints of pipelines**. The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 0.019(per year) the POF is about 1.80% which is actually very low. This graph also communicates that there is very low possibility of leakage of from the joints. The system is safe and the probability of failure is low. The probability of occurrence of leakage from the joints of pipelines is very low.

- **Leakage from the downstream pipelines.**

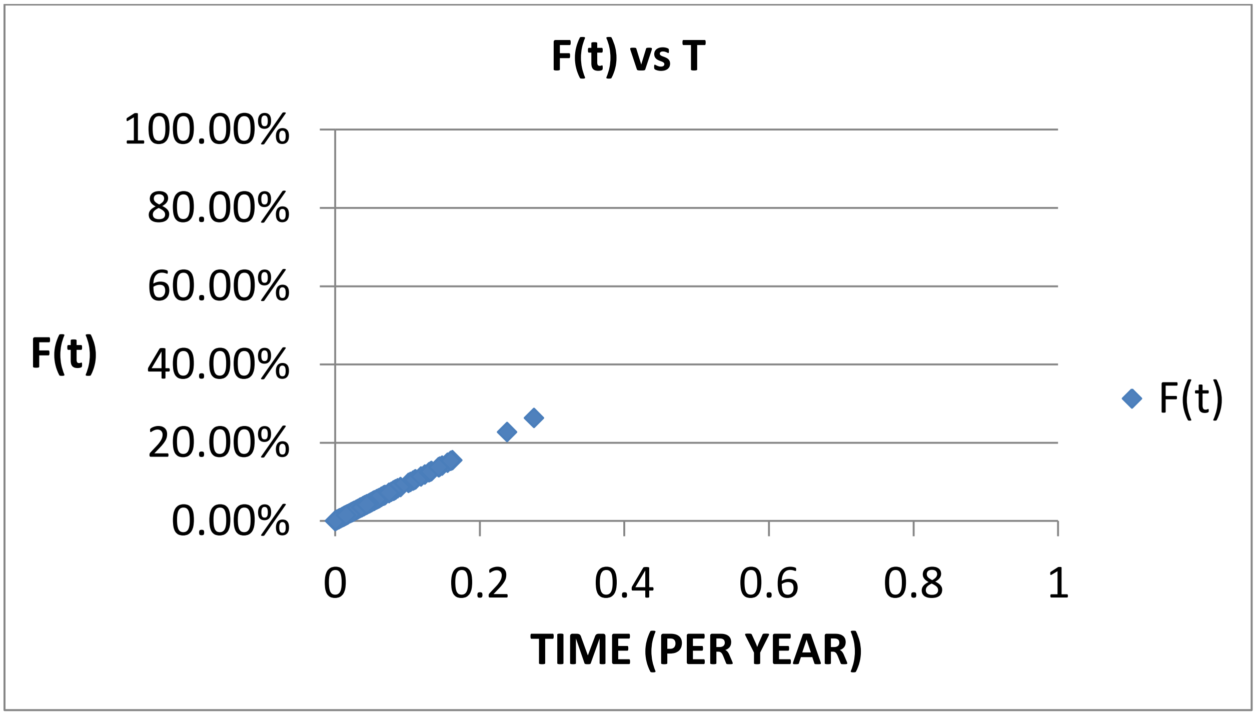


Figure 16: Leakage from Downstream Pipelines.

The graph in Figure 14 illustrates Cumulative Density Function (CDF) of the failure '**Leakage from the downstream pipelines.**. The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 0.3(per year) the POF is about 35% which is actually very low. This graph also communicates that there is very low possibility of leakage of from the downstream pipelines of a flash drum unit thus resulting in low fire risk. The system is safe and the probability of failure is low. The probability of occurrence of leakage from the downstream pipeline of a flash drum unit is very low.

5.8.2 Fault Tree Analysis For The Above Mentioned Leakage and Ignition cases:

FTA is done to calculate the exact probability of fire at the specified time. The values of POF at specified times can be found by following the FTA method. Fire is usually a result of two factors combining together which are as following:

1- Leakage of hydrocarbons.
2- Ignition sources.

On an offshore petroleum process facility if the above mentioned two sources are not controlled there could be fire and other fire related hazardous accidents. The FTA is top bottom deduction based failure analysis technique, in which an undesired state of system is analyzed using Boolean logic.

For the fire risk assessment, fire in the separator unit is an undesired top event which is being followed by leakage sources and ignition sources. There are three basic leakage sources identified along with three basic ignition sources. These sources are obtained by performing hazard identification study. The probabilities of leakage and ignitions are calculated.

The probability of the top event "fire in the separator unit" is calculated and shown with respect to time. The probability of top event which is fire in the separator unit gives the overall fire risk. It can be seen in the graph the probability of fire in the separator or the fire risk the separator system increases as the time increases.

FTA gives the insight of an undesired event. It also shows the potential causes that relates to the top event. It is also helpful in mitigation of the potential causes of failure.

The FTA for fire in the 'Dryer Unit' is shown below. Since the system is considered to be in series the separator section is consist of separator units, compressors, pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions

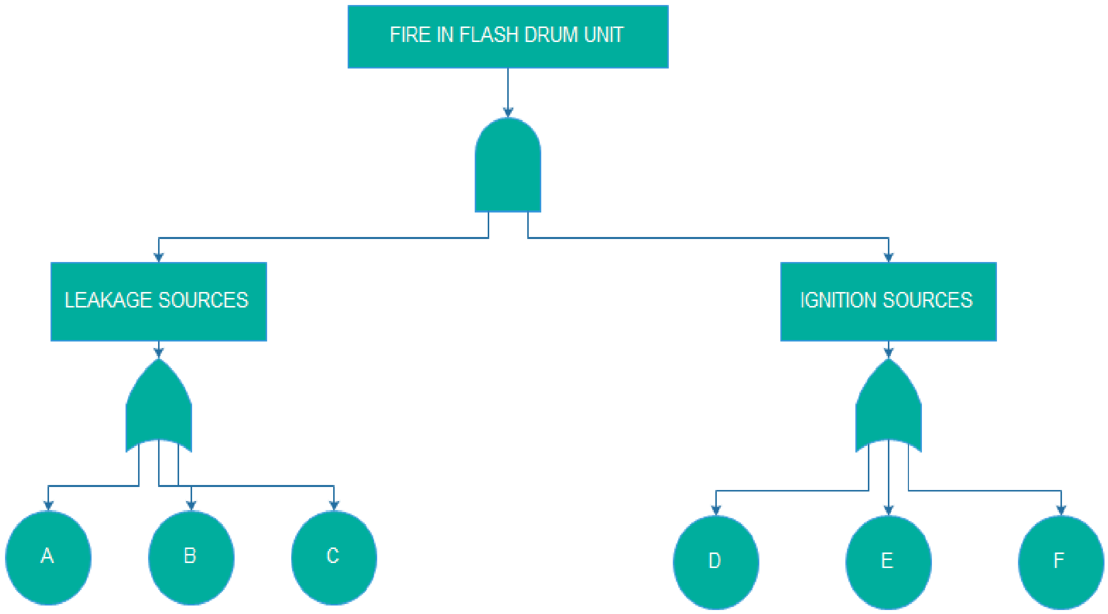


Figure 17: Probabilistic Fault Tree For Flash Drum Unit.

EVENTS	DESCRIPTION
A B C	LEAKAGE SOURCES
D E F	IGNITION SOURCES

Time (per Year)	Probability of Fire (percent %)
0.1	0.933
0.2	0.945
0.3	0.956
0.4	0.966
0.5	0.975
0.6	0.983
0.7	0.989
0.8	0.991
0.9	0.993
1.0	0.997

Table 4: Fire Risk For Flash Drum Unit.

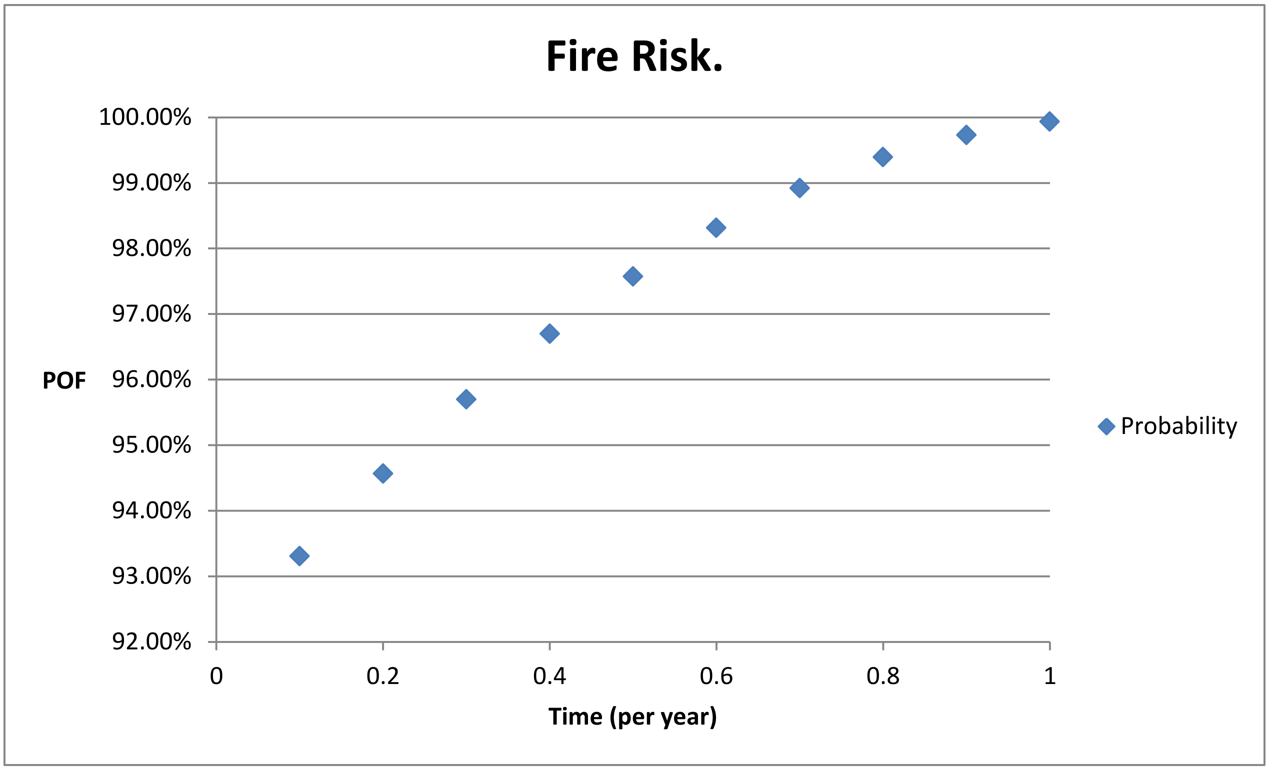


Figure 18 Probability of Fire

The graph in Figure 15 shows the **Probability of Fire** with respect to time. It means that the probability of fire in separator unit can be found on a time scale from time 0 per year to 1 per year. At any specified time the probability of fire can be found out if any of the three basic leakage events happen accompanied with any of the three basic mentioned ignition sources present.

Form the graph it can be seen that the probability of fire increases with the increase in time. For instance from the monte Carlo graphs we can find out that at time 0.9 per year the CDF shows F(t) = 80 % this means that the probability of fire at time 0.9 per year when the equipment is failed at about 80% (leakage) and in presence of ignition sources is approximately **0.99 %.**

Following the above approach the Fire Risk can be determined at any specific point in time. Now with the help of FTA analysis we can determine the exact probability of fire at the give time. As shown above the FTA consist of three leakage sources and three ignition sources. These sources are combined together by using Boolean operators and the combined probability of fire is found which represents the fire ris

5.9 Accident Scenario 4 for dryer Units:

Dryer unit is used to dry the wet gas and process it. The small droplets of water are removed from the gas. Once the wet gas enters the dryers its velocity is changed along with the flow direction to separate the heavier droplets of water from the gas.

Any leakage of gas from this dryer unit can causes the unit to fail. The leakage of gas can also be one of the main reasons of fire in the system. If there is high pressure development there can be leakages from pipelines going through the dryer unit. Any leakage and a source of ignition present can cause a huge fire. Along with the pressure control, temperature is also very critical factor in this process and unit. The dry gas is highly flammable. Any kind of external heat sources or temperature changes can cause ignition, fire and explosion.

Excess flow of gas can also be determined as a cause of leakage from the pipelines. The excess and high velocity flow can damage not only the pipelines but also the dryer system and can be one of the major cause of fire or system failure.

Temperature is one the key factors to control the process as well as accidents. Since the dryer unit is used to separate the droplet of water from the wet gas, a constant temperature is required. Any drastic change in the processing temperature can cause leakages and also fire. Maintaining the temperature is very necessary for the process and also to avoid any fire related accidents. If there is even a small leakage and the temperature is not controlled it could lead to explosion and fire.

The events mentioned above are interrelated to each other and if any of the situation happens accompanied with the presence of a ignition source or temperature change, there could be fire in the dryer unit or separator system

Following are the three most potential leakage sources:

1- Leakage due to pressure relief valve failure.
2- Leakage due to external sources of heat..
3- Leakage due to temperature controller failure.

If these leakage sources are present they could combine with ignition sources to create fire. Most potential ignition sources are mention below:

4- Electric spark as a source of ignition.
5- Ignition due to heat from the surroundings .
6- Ignition due to explosion energy.

Since the separator section is consist of separator units, compressors , pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions.

5.9.1 Monte Carlo Simulations for the above mentioned fire risk for compressor unit:

- **Leakage due to pressure relief valve failure.**

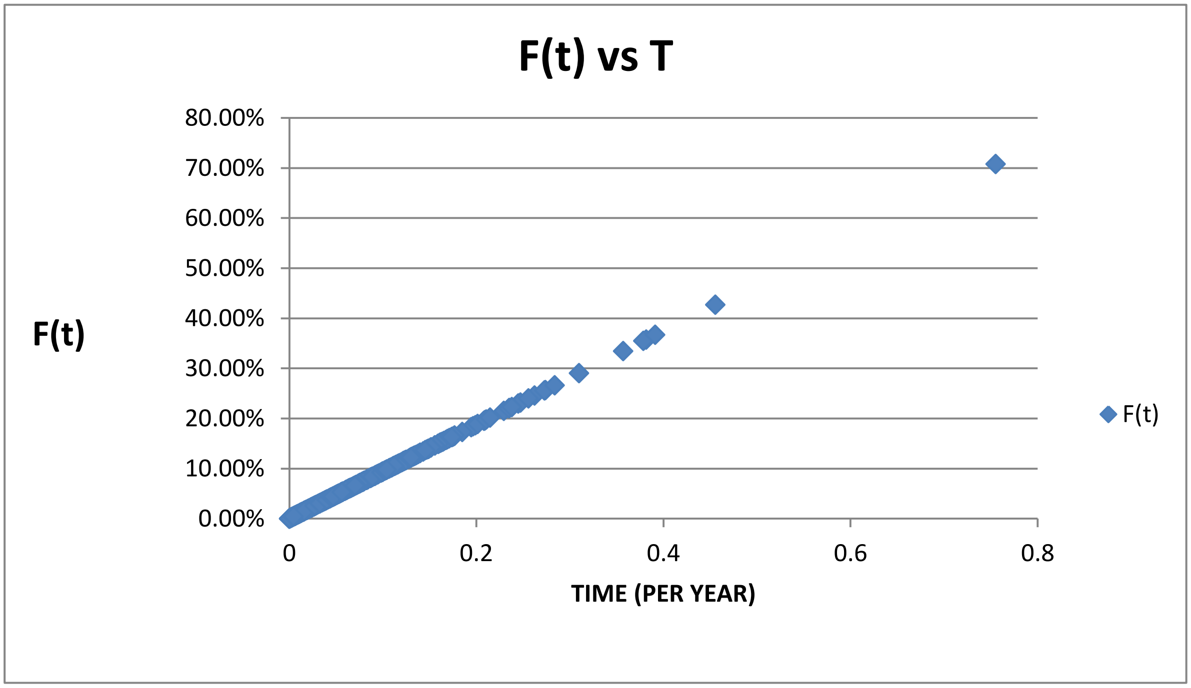
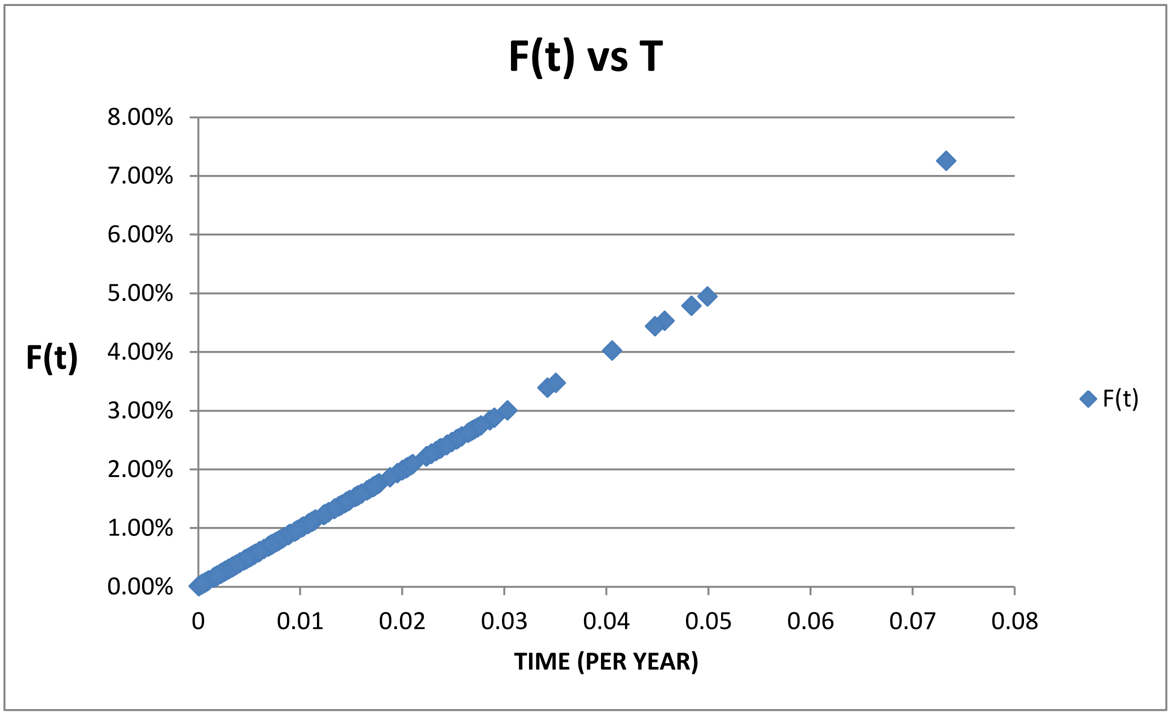


Figure 19: Leakage due to pressure relief valve failure.

The graph in Figure 15 illustrates Cumulative Density Function (CDF) of the failure ‘ **Leakage due to pressure relief valve failure**. The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 0.78 (per year) the POF is about 72% which is actually high. This graph also communicates that at t= 0.78 (per year) about 72% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it reveals that there are about 72% chances of leakage from the pipeline due to high pressure.. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique to check the uncertainty in the process.

- **Leakage due to external sources of heat.**



`Figure 20: Leakage due to external sources of heat.

The graph in Figure 16 illustrates Cumulative Density Function (CDF) of the failure ‘ **Leakage due to external sources of heat**. The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 0.08 (per year) the POF is about 7.5% which is actually high. This graph also communicates that at t= 0.08 (per year) about 7.5% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it reveals that there are about 7.5% chances of leakage from the pipeline due to high pressure.. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique to check the uncertainty in the process. Since all the outside temperatures are kept very controlled so the POF is very low as the failure rate is also low.

- **Leakage due to temperature controller failure.**

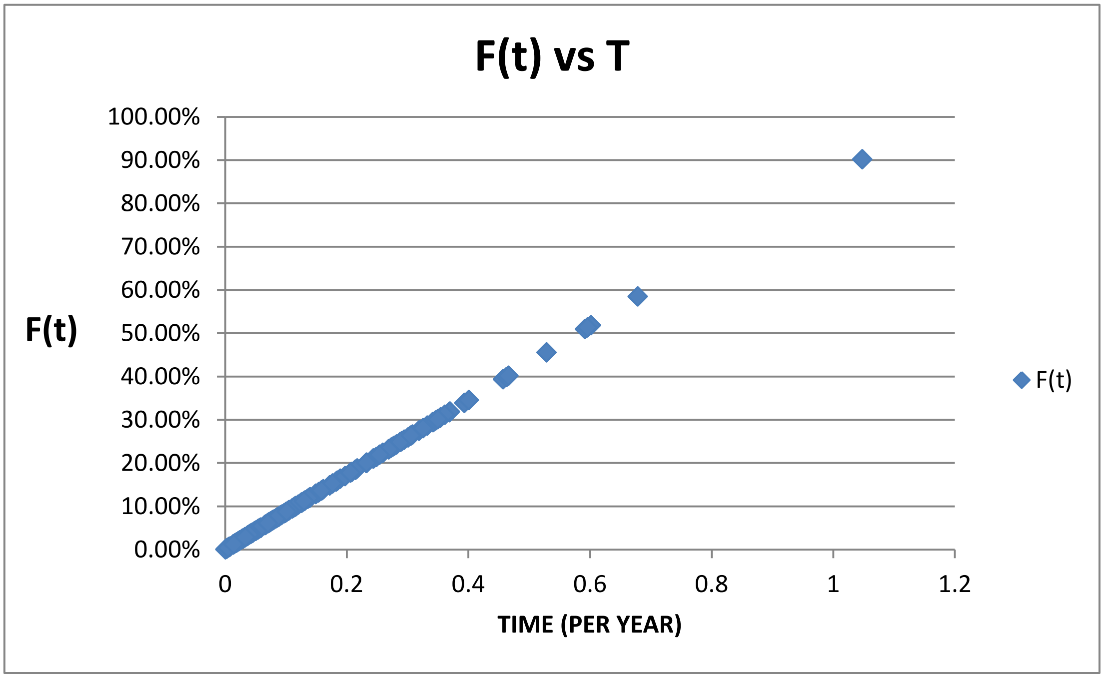


Figure 21: Leakage due to temperature controller failure.

The graph in Figure 17 illustrates Cumulative Density Function (CDF) of the failure ‘ **Leakage due to temperature controller failure’.** The graph is plotted between failure rate F(t) vs Time. It specifies the **Probability of Failure** according to time. According to the graph shown above at about time (t) = 1.0 (per year) the POF is about 90% which is actually high. This graph also communicates that at t= 1.0 (per year) about 90% of the equipment has failed since we are accounting the fire risk due to leakage. In this case it reveals that there are about 90% chances of leakage from the unit or relating pipeline.. If there is an ignition source present there would be an instant fire followed by explosions. This is a random estimation using Monte Carlo technique to check the uncertainty in the process. As already mentioned above temperature is a very critical factor in dryer unit. If the temperature is not maintained and controlled according to the required process there is a high probability of leakage of flammable hydrocarbons form the dryer unit which can cause fire and other hazardous accidents.

5.9.3 Fault Tree Analysis For The Above Mentioned Leakage and Ignition cases:

FTA are done to calculate the exact probability of fire at the specified time. The values of POF at specified times can be found by following the FTA method.. Fire is usually a result of two factors combining together which are as following:

1- Leakage of hydrocarbons.
2- Ignition sources.

On an offshore petroleum process facility if the above mentioned two sources are not controlled there could be fire and other fire related hazardous accidents. The FTA is top bottom deduction based failure analysis technique, in which an undesired state of system is analyzed using Boolean logic.

For the fire risk assessment, fire in the separator unit is an undesired top event which is being followed by leakage sources and ignition sources. There are three basic leakage sources identified along with three basic ignition sources. These sources are obtained by performing hazard identification study. The probabilities of leakage and ignitions are calculated.

The probability of the top event "fire in the separator unit" is calculated and shown with respect to time. The probability of top event which is fire in the separator unit gives the overall fire risk. It can be seen in the graph the probability of fire in the separator or the fire risk the separator system increases as the time increases.

FTA gives the insight of an undesired event. It also shows the potential causes that relates to the top event. It is also helpful in mitigation of the potential causes of failure.

The FTA for fire in the 'Dryer Unit' is shown below. Since the system is considered to be in series the separator section is consist of separator units, compressors, pumps, driers and flash drum. In event of electric spark there would be a fire or leakage among the mentioned units. The high pressure instantaneous leak of gas is highly flammable and can cause flammable vapor cloud. Thus the spark will lighten up this highly flammable gas and will cause a catastrophic event of inter related fires and explosions

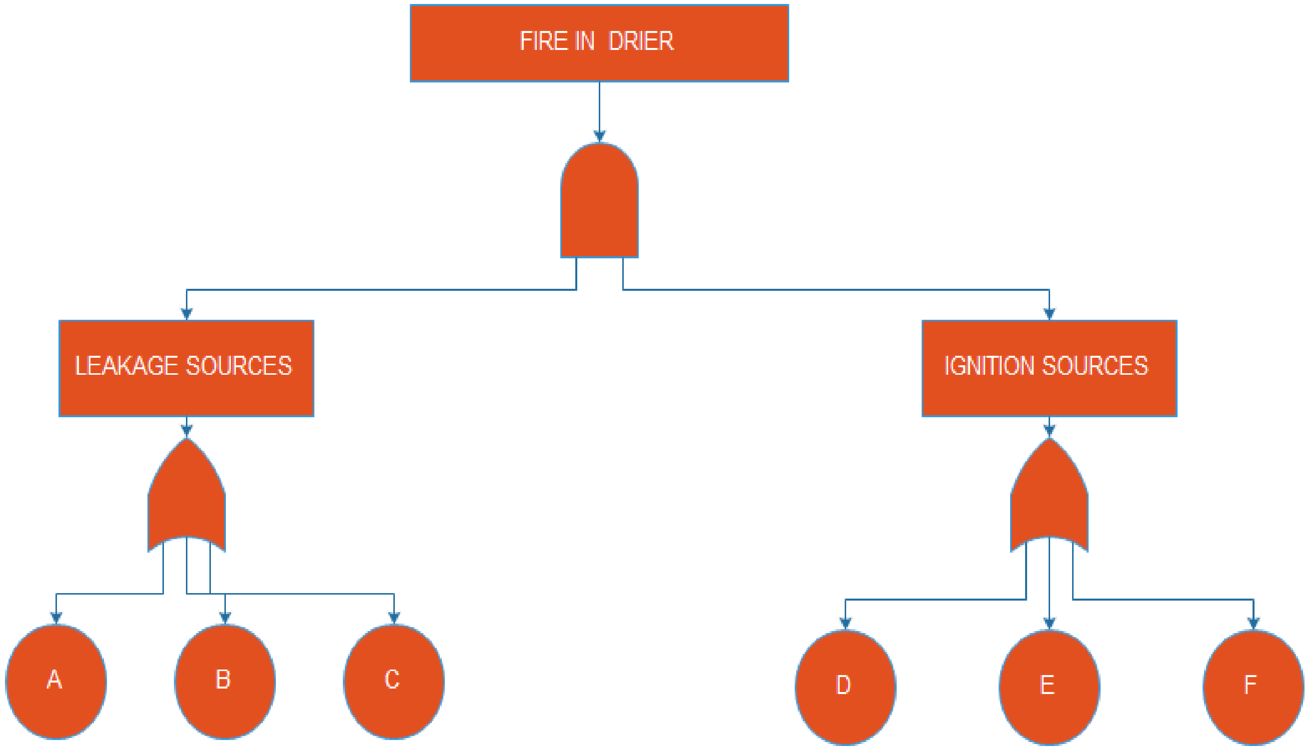


Figure 22: Probabilistic Fault Tree For Dryer Unit.

EVENTS	DESCRIPTION
A B C	LEAKAGE SOURCES
D E F	IGNITION SOURCES

Time (per Year)	Probability of Fire (percent %)
0.1	0.893
0.2	0.913
0.3	0.931
0.4	0.947
0.5	0.961
0.6	0.973
0.7	0.982
0.8	0.990
0.9	0.995
1.0	0.998

Table 5: Fire Risk For Dryer Unit.

- **Probability of Fire versus Time: (Fire Risk Determination)**

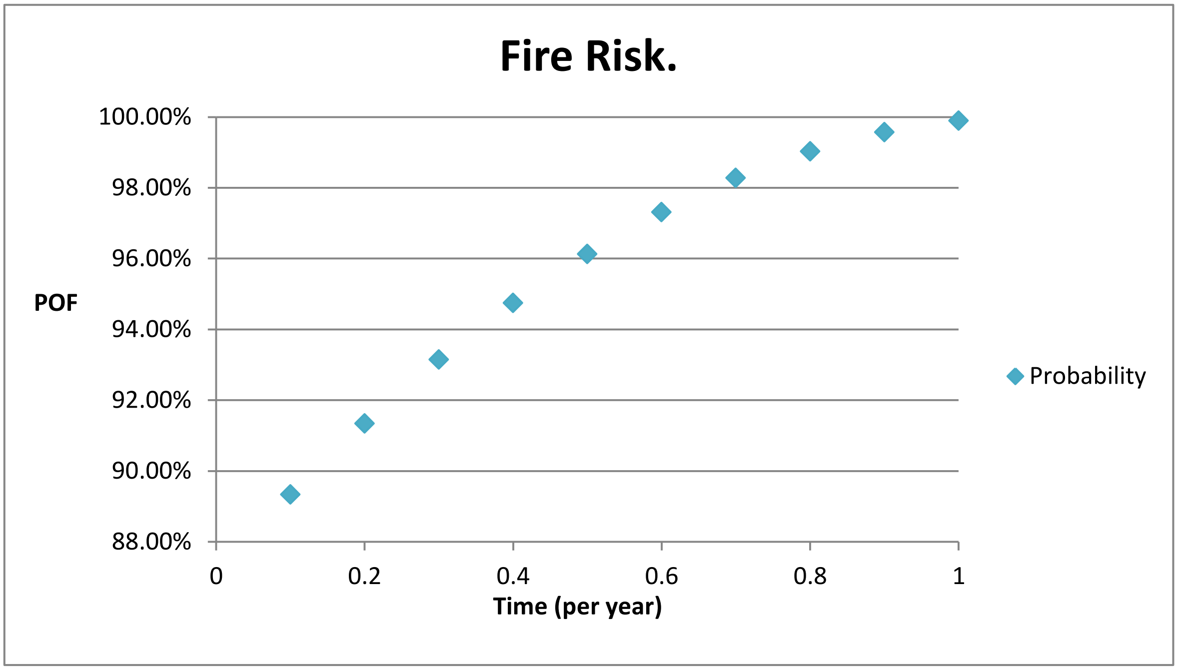


Figure 23: Fire Risk

The graph in Figure 18 shows the **Probability of Fire** with respect to time. It means that the probability of fire in separator unit can be found on a time scale from time 0 per year to 1 per year. At any specified time the probability of fire can be found out if any of the three basic leakage events happen accompanied with any of the three basic mentioned ignition sources present. The graph shows that the at time 1 per year the POF is 100%.

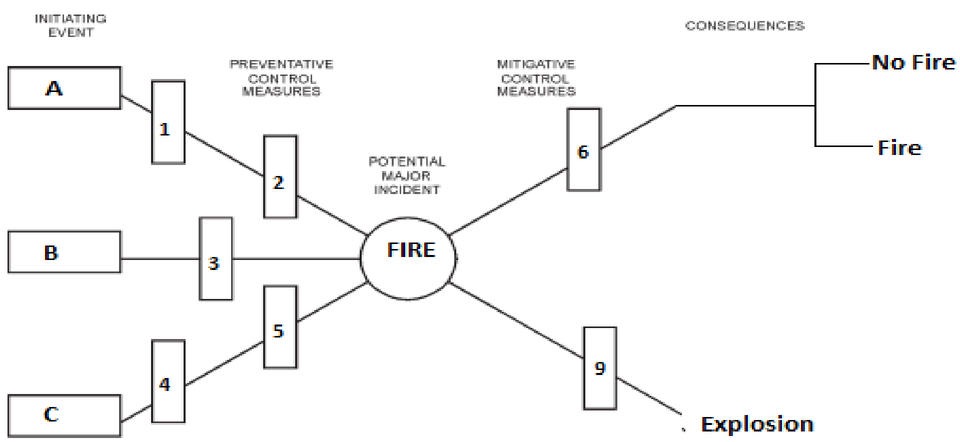
Form the graph it can be seen that the probability of fire increases with the increase in time. For instance from the monte Carlo graphs we can find out that at time 0.9 per year the CDF shows F(t) = 80 % this means that the probability of fire at time 0.9 per year when the equipment is failed at about 80% (leakage) and in presence of ignition sources is approximately **0.99 %.** Combing the sources of leakage and ignition and calculating the probabilities the fire risk can be estimated.

Following the above approach the Fire Risk can be determined at any specific point in time. Now with the help of FTA analysis we can determine the exact probability of fire at the give time. As shown above the FTA consist of three leakage sources and three ignition sources. These sources are combined together by using Boolean operators and the combined probability of fire is found which represents the fire risk.

5.10 Bow Tie Diagram Fire Risk Assessment in Separator Unit:

Bow Tie diagram is risk assessment technique which is frequently used in oil and gas industry. This is a very useful technique as it not only identifies the potential causes of risk but also helps in identifying the after effects or the consequences of the risk. Bow Tie diagram is used to identify the critical or initiating events. It is also used to do consequential analysis (order of magnitude) as well as causal analysis (qualitative).

For identifying the fire risk in the separator system bow tie diagrams helps to identify the potential causes of fire and the after effects of fire in the separator system. Then performing the probabilistic calculation and incorporating Boolean logic the fire risk is determined in the separator system.



Fi figure 24: Bow Tie diagram of Fire in Separator System

A	Leakage Due to Excess flow at upstream
B	Leakage From High Pressure Upstream Line
C	Electric Spark As A source of Ignition

1	Alarm System
2	Leakage Control Valve
3	Leakage Control Valve
4	Alarm System
5	SYSTEM SHUT DOWN
6	halon gas fire ext system
9	System Shutdown

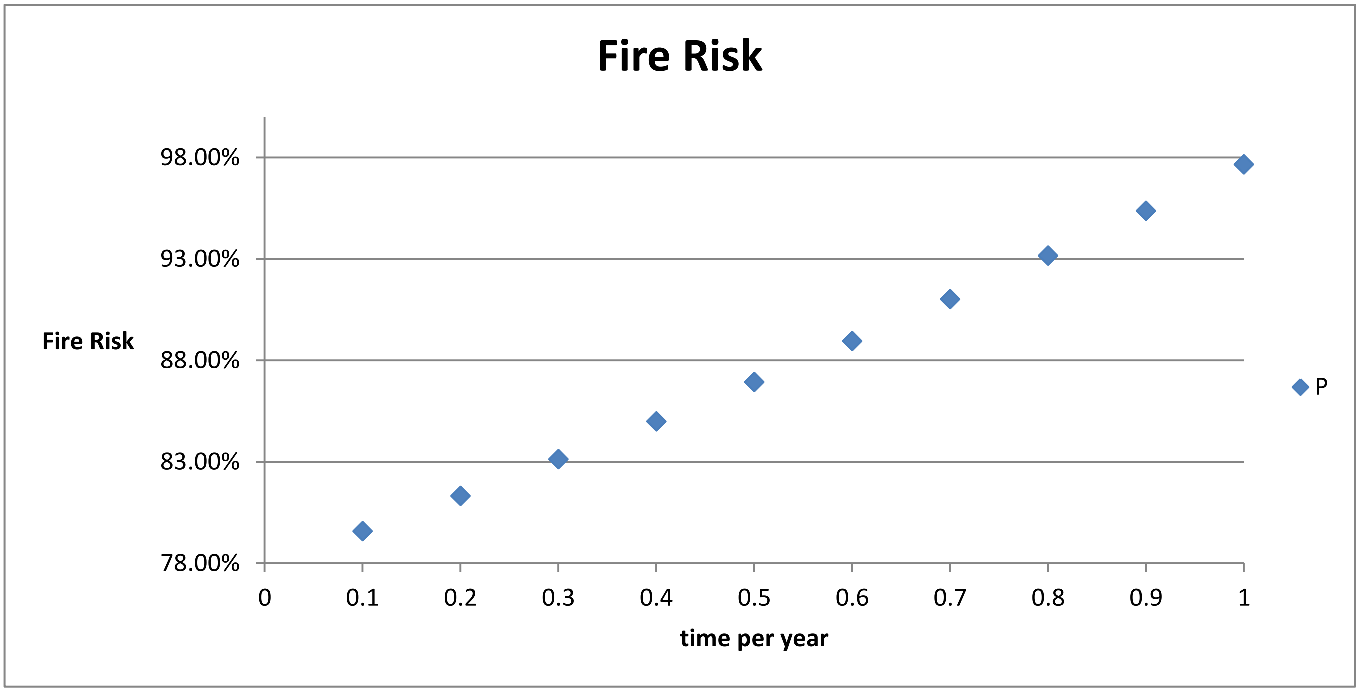


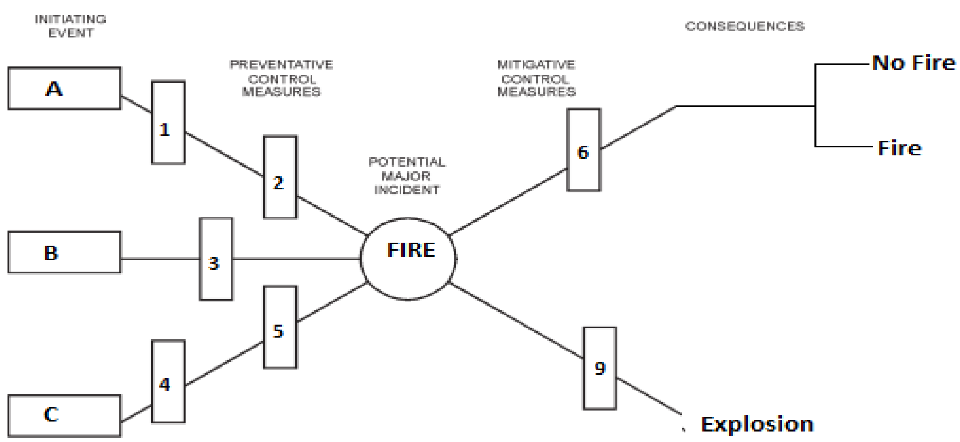
Figure 25: Fire Risk calculation using BT diagram

The figure above shows the fire risk in separator system. The figure illustrates that there are more than 95% chance of fire if the causes are leakage due to excess flow at upstream or leakage from high pressure upstream line combining with electric spark as a source of ignition. The bow tie diagram also shows the consequences of fire. Safety systems are also incorporated. The combined probability is calculated to show the fire risk in the separator system with respect to time.

5.11 Bow Tie Diagram Fire Risk Assessment in Compressor Unit:

Bow Tie diagram is risk assessment technique which is frequently used in oil and gas industry. This is a very useful technique as it not only identifies the potential causes of risk but also helps in identifying the after effects or the consequences of the risk. Bow Tie diagram is used to identify the critical or initiating events. It is also used to do consequential analysis (order of magnitude) as well as causal analysis (qualitative).

For identifying the fire risk in the separator system bow tie diagrams helps to identify the potential causes of fire and the after effects of fire in the separator system. Then performing the probabilistic calculation and incorporating Boolean logic the fire risk is determined in the compressor unit.



A		LEAK From Compressor Downstream Pipeline
B		Leak From Upstream line Pipeline
C		Electric Spark As A source of Ignition

1		Alarm System	
2		Leakage Control Valve	
3		Leakage Control Valve	
4		Alarm System	
5		SYSTEM SHUT DOWN	

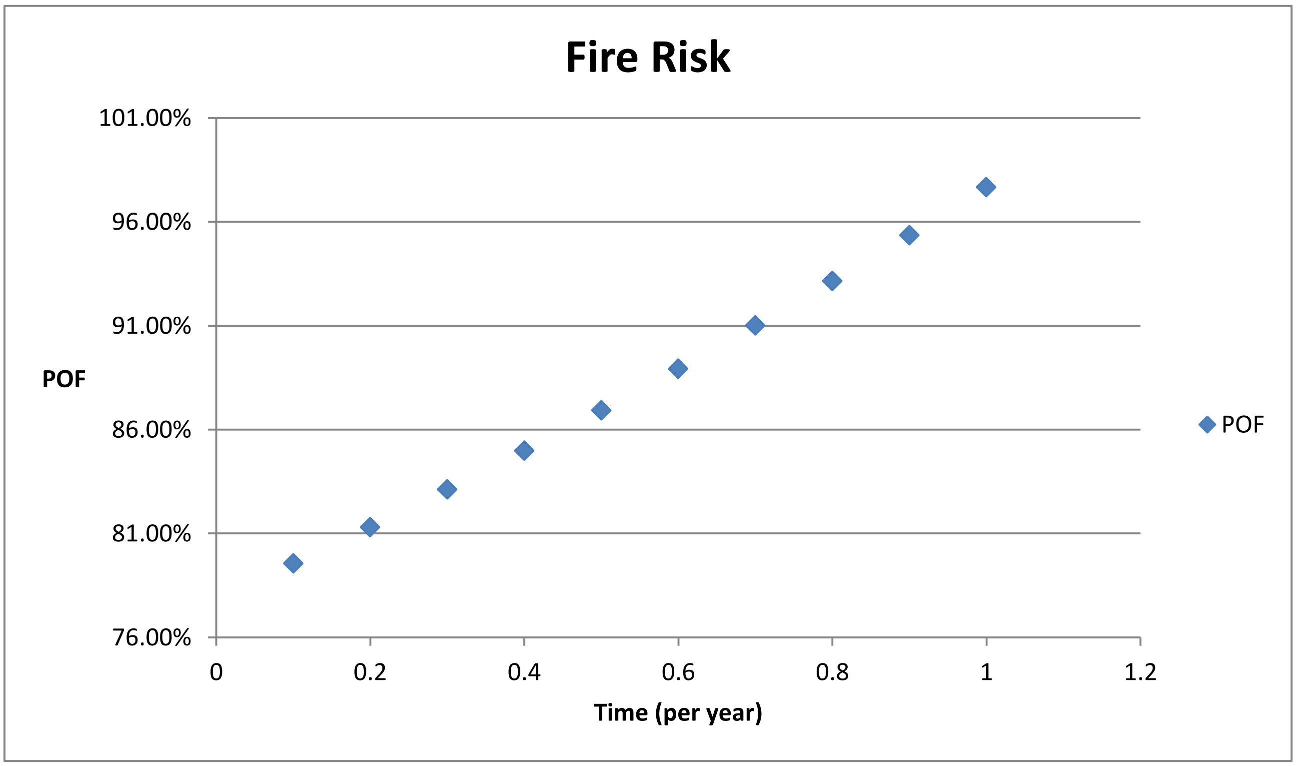


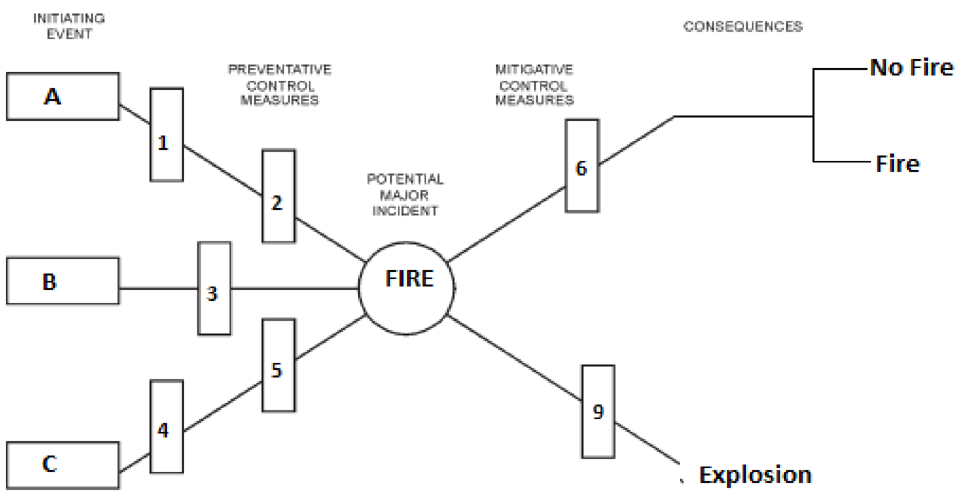
Figure 26: Probability of Fire (Fire Risk)

The figure above shows the fire risk in separator system. The figure illustrates that there are more than 95% chance of fire if the causes are leakage due to excess flow at upstream or leakage from high pressure upstream line combining with electric spark as a source of ignition. The bow tie diagram also shows the consequences of fire. Safety systems are also incorporated. The combined probability is calculated to show the fire risk in the separator system with respect to time.

5.12 Bow Tie Diagram Fire Risk Assessment in Flash Drum Unit:

Bow Tie diagram is risk assessment technique which is frequently used in oil and gas industry. This is a very useful technique as it not only identifies the potential causes of risk but also helps in identifying the after effects or the consequences of the risk. Bow Tie diagram is used to identify the critical or initiating events. It is also used to do consequential analysis (order of magnitude) as well as causal analysis (qualitative).

For identifying the fire risk in the separator system bow tie diagrams helps to identify the potential causes of fire and the after effects of fire in the separator system. Then performing the probabilistic calculation and incorporating Boolean logic the fire risk is determined in the flash drum unit.



A		LEAK as a result of High Pressure from Pipeline
B		Leak from joints of GAS P/Line
C		Electric Spark As A source of Ignition

1		Alarm System		
2		Leakage Control Valve		
3		Leakage Control Valve		
4		Alarm System		
5		SYSTEM SHUT DOWN		
6		halon gas fire ext system		
9		System Shutdown		

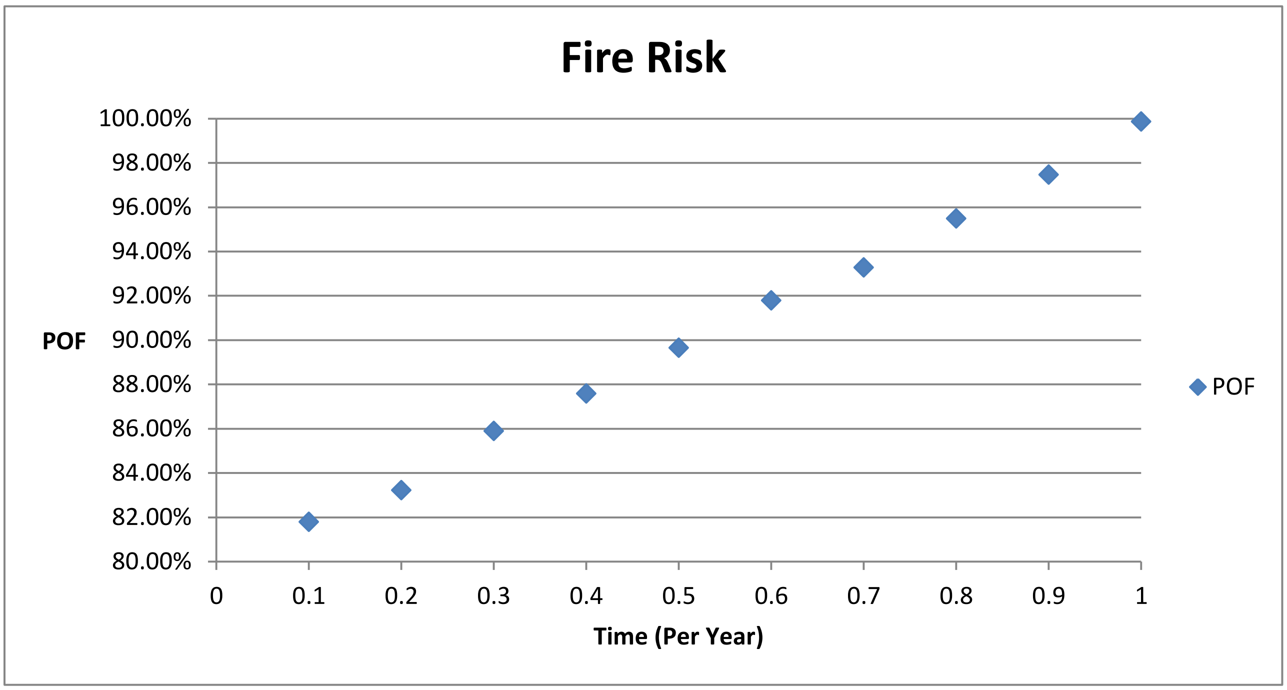


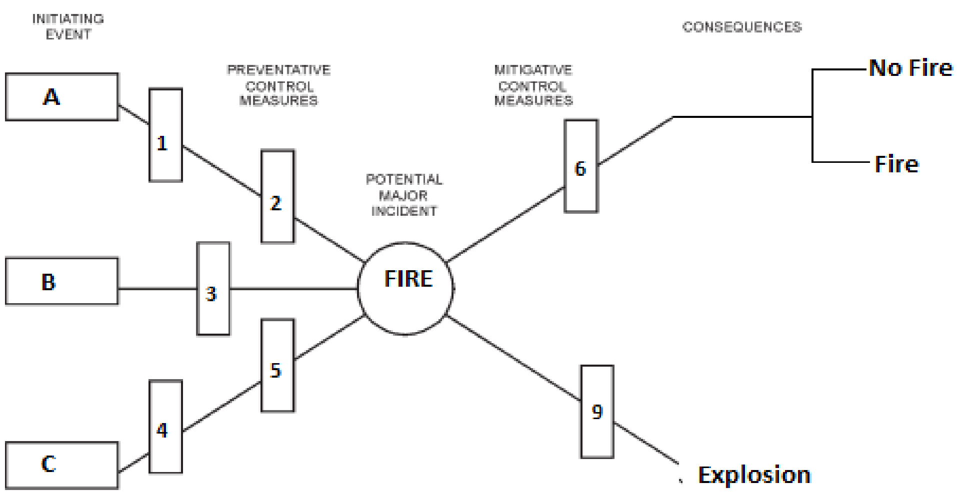
Figure 27: Probability of Fire (Fire Risk).

The figure above shows the fire risk in separator system. The figure illustrates that there are more than 95% chance of fire if the causes are leakage due to excess flow at upstream or leakage from high pressure upstream line combining with electric spark as a source of ignition. The bow tie diagram also shows the consequences of fire. Safety systems are also incorporated. The combined probability is calculated to show the fire risk in the separator system with respect to time.

5.13 Bow Tie Diagram Fire Risk Assessment in Dryer Unit:

Bow Tie diagram is risk assessment technique which is frequently used in oil and gas industry. This is a very useful technique as it not only identifies the potential causes of risk but also helps in identifying the after effects or the consequences of the risk. Bow Tie diagram is used to identify the critical or initiating events. It is also used to do consequential analysis (order of magnitude) as well as causal analysis (qualitative).

For identifying the fire risk in the separator system bow tie diagrams helps to identify the potential causes of fire and the after effects of fire in the separator system. Then performing the probabilistic calculation and incorporating Boolean logic the fire risk is determined in the flash drum unit.



A		Leak due to Pressure Relief Valve Failure
B		Leak due temperature controller failed
C		Electric Spark As A source of Ignition

1		Alarm System		
2		Leakage Control Valve		
3		Leakage Control Valve		
4		Alarm System		
5		SYSTEM SHUT DOWN		

6		halon gas fire ext system		
9		System Shutdown		

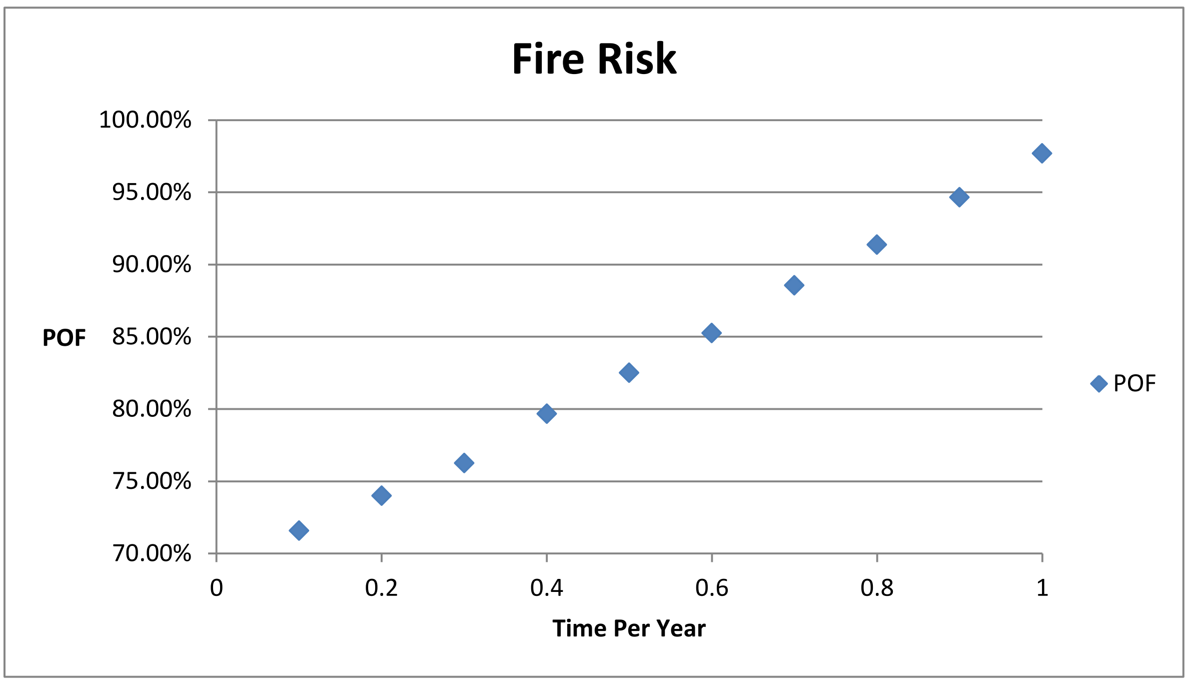


Figure 28: Probability of Fire (Fire Risk).

The figure above shows the fire risk in separator system. The figure illustrates that there are more than 95% chance of fire if the causes are leakage due to excess flow at upstream or leakage from high pressure upstream line combining with electric spark as a source of ignition. The bow tie diagram also shows the consequences of fire. Safety systems are also incorporated. The combined probability is calculated to show the fire risk in the separator system with respect to time.

5.14 Qualitative: HAZOP Work Sheet:

HAZOP stands for Hazard and Operability study. HAZOP is a structured and systematic examination of a process or operation. It is used to identify and evaluate process deviations and risks to equipment or personnel. It is also used to prevent efficient operations. HAZOP is a qualitative risk assessment technique. It enables to stimulates the imagination of participants to identify potential hazards, risk and operability problems.

A HAZOP Work Sheet is developed involving a risk matrix to show the potential fire risk in an offshore petroleum facility. As discussed earlier in the report only the separator system incorporating separator unit, compressor unit , flash drum and dryer units are analyzed for the fire risk assessment.

The HAZOP work sheet is connected with a time based risk matrix which elaborates the fire risk at different operational times. The risk can be only specified in terms of its severity as it is a qualitative technique. There are different parameters mentioned in the HAZOP sheet based on the process of the system under consideration. These parameters are of utter importance. Any deviation in the process or any complications in the operability of the equipment can lead to fire and other fire related hazardous accidents.

The parameters which are chosen for the HAZOP sheet are industrial standards. They are determined after a thorough hazard identification study. The HAZOP work sheet not only represents the risk but also process deviations, preventive measures and mitigation measures. It also represents the person responsible based on the industrial codes and ethics.

By connecting a simple HAZOP sheet with a time based risk matrix the severity of the risk can also be determined. This risk matrix can also help in preventing the situation by preventive maintenance and other risk mitigation measures. The time is obtained by Monte Carlo Simulations and Fault Tree Analysis which can be seen in the earlier part of the report.

The method applies to processes for which design and other failure rates information is given. After determining the risk it can be then decided that whether the safeguards and other preventive actions used are sufficient or not. The guide words used are set industrial codes and practices.

To analyze the fire risk in a separator unit the HAZOP sheet is made using the following parameters:

1- Flow of Hydrocarbons.
2- Pressure
3- Temperature.

Different operability and process conditions are incorporated with the above mentioned parameters. Basing on the severity and likelihood of the events a risk matrix is developed. After the careful study of these parameters and a through a comprehensive literature review on fire risk and accidents in offshore industry risk indexing is developed. According to the likelihood and severity the indexing is done which is further connected to the operational time of equipment.

The HAZOP work sheet incorporating time based risk matrix specially designed for the assessing the fire risk in an offshore separator system can be seen below:

Guidewords	Causes	Consequences	Risk matrix			Safeguards	Recommendations	Responsibilities
			L	S	R			
No flow	FCV is fail to open	Level Decreasing	4	1	4		Install manual valve (HCV) and level switch	Plant builder should check this segment.
	Pipe is blocked	Level Decreasing	3	1	3		Install additional pipe line and level switch	Plant builder should check this segment.
Less flow	Pipe is leaked	Level Decreasing	3	1	3		Install additional pipe line and level switch	Plant builder should check this segment.
More flow	FCV is fail to close	Separator overpressurized , level incleasing	4	2	8	Pressure control valve and liquid control valve are		Plant builder should check this segment.
Reverse flow	PCV is fail to open and separator overpressurized	Separator damaged	4	4	16		Install additional pipe line and flow control valve	Plant builder should install additional pipe line and pressure control valve.
Less temperature	Saperation process effected	No Saperation process. Component Failure	3	1	3	Liquid control valve is already	Install temperature indicator	Plant builder and operator should check on the refrigerator.
More temperature	Saperation Process is Effected	No Saperation process. Component Failure	3	1	3	Pressure control valve is already	Install temperature indicator	Plant builder and operator should check on the refrigerator.
Less pressure	PCV is fail to close	Level falling	4	1	4		Install flow back pipe line and additional pressure control valve	Plant builder should check this segment.
	LCV is fail to close and level falling	Two phase flow	4	2	8	Pressure control valve is already	Install additional pipe line and flow control valve	Plant builder should check this segment.
More pressure	PCV is fail to open	Separator overpressurized and reverse flow occurs	4	3	12		Install additional pipe line and flow control valve	Plant builder should install additional flow control valve and additional pipe line.
	Pipe line is blocked	Separator overpressurized and reverse flow occurs	3	3	9		Install additional pipe line and flow control valve	Plant builder should install additional flow control valve and additional pipe line.
Start-up	Feed gas is not cooled	Efficiency deacrese	3	1	3			
Shut down	Reverse flow occurs at the separator	reverse flow	4	2	8	Flow control valve is already installed		Plant builder should check this segment.
Maintenance	Saperator maintenance	Total system failure	3	1	3			

Time (t) per year	RISK ASSESSMENT MATRIX				
	SEVERITY / PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
0.7-1.0	Frequent (A)	High	High	Serious	Medium
0.5-07	Probable (B)	High	High	Serious	Medium
0.3-0.5	Occasional (C)	High	Serious	Medium	Low
0.1-0.3	Remote (D)	Serious	Medium	Medium	Low
0.1	Improbable (E)	Medium	Medium	Medium	Low
< 0.1	Eliminated (F)	Eliminated			

Figure 29: Time based risk matrix with HAZOP work sheet

The HAZOP sheet and Risk Matrix shows the fire risk level in the separator system. It can be deduced form the risk matrix that with increasing time the risk is also increased. This is because after a certain level of operability time the equipment is more prone to failure. To prevent the accidents from happening and to decrease the level or risk and threat preventive maintenance and inspection are a set standard practice in industries.

The HAZOP sheet specifies different scenarios and their consequences. The events happening in the separator unit are accounted for Fire and other Fire related hazardous accidents. The severity is calculated along with the probability of occurrence. The linkage is developed with HAZOP sheet and risk matrix based on the severity level. The failure time is found in the earlier part of the project. The time is also combined with the HAZOP sheet and Risk Matrix to specify the FIRE RISK more significantly. Figure 19 above shows the time based risk matrix for fire risk assessment based on a HAZOP sheet.

CHAPTER SIX

CONCLUSION

6.0 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Fire accidents are among the most frequently occurring accidents on the offshore facilities. The heat radiations caused by the fire is one of the main reasons for the fatalities and injuries. From the literature it can be seen that “Fire” is one of the most dangerous hazard occurring on the offshore facility, hence it is important to evaluate the risk and hazards. Risk assessment is done to prevent accidents form happening.

Fire accidents if not controlled can cause a mammoth damage. The damage is not restricted to property or equipment only; it can also affect human lives and investors/companies monetarily benefits. Risk and hazards should be assessed and mitigated in order to protect the organization objectives.

The following proposal highlights the literatures that are relevant and important, in order to understand the method to model fire hazards and risk assessment in offshore petroleum facilities. The models and methods described in the literature were categorized into four categories: qualitative, semi-quantitative, quantitative, and hybrid.

The optimum approach for risk analysis is qualitative and quantitative risk assessments. However if ‘Quantitative Risk Assessment” could be done, it would be more beneficial. As QRA implements numerical models and simulations which are more understandable and reliable then just based on theoretical data.

Monte Carlo simulations help in effective decision making and risk analysis. By plotting the graphs and simulations one can determine the failure rate and critical events leading to failure by the skewedness of the graphs. The simulations also help in determining the maintenance activities time schedules and also helps in determining the Preventive Maintenance schedules.

Fault Tree Analysis is a deduction based top-bottom approach used in determining the risk using Boolean logic. Risk can be determined by tracing forward in time. FTA requires a premise of a known hazard.

In this project different Qualitative and Quantitative techniques were used to find out the most effective and efficient method for determining the fire risk. The difference of results can be seen in this report. Quantitative techniques deduced results in a numerical approach where by qualitative techniques just give a range (high/low) of results. By calculating the fire risk in offshore petroleum facilities implementing quantitative and qualitative techniques following difference were found between the two chosen methods.

Qualitative Analysis	Quantitative Analysis
1. Primarily exploratory.	1- Used to quantify the problem by way of generating numerical data or data that can be transformed into useable statistics.
2. Used to gain an understanding of underlying reasons, opinions, and motivations.	2- Helps in selecting preventive, mitigation and safety measures. It is used to quantify attitudes, opinions, behaviors, and other defined variables and generalize results from a larger sample population.
3. Provides insights into the problem or helps to develop ideas or hypotheses for potential quantitative research.	3- uses measurable data to formulate facts and uncover patterns in risk assessment.

In the lieu of this research project conducted it is highly recommended to use Quantitative analysis methods or techniques for effective and efficient risk assessment and better results.

6.2 Recommendations and Future Research:

The recommendations for further studies and research are as following:

I. Validation of various experimental case studies on risk based analysis on offshore facilities. This is of unique values as it ensures the accuracy of the results for the final simulations, which is to test the potential factors that causes fire related hazards in the petroleum facilities. As stated earlier fire is the most hazardous and dangerous event in offshore industry.

II. Use of qualitative techniques in risk assessment and hazard identifications. An effective risk assessment covers both qualitative and quantitative risk assessment.

III. Analysis of failure mode and effect analysis. FEMA is very prudent for determining the probability of failure and reliability of the equipment or system. This method not only helps in hazard identifications and risk analysis but also help in scheduling preventive maintenance and other operations services activities

7.0 REFERENCE

Aven, T., Sklet, S., Vinnem, J.E., 2006. Barrier and operational riskanalysis of hydrocarbon releases (BORA-Release). Part I.Method description. J. Hazard. Mater. 137 (2), 681–691.

Baybutt, P., 2003. Major hazards analysis: an improved methodfor process hazards analysis. Process Saf. Prog. 22 (1), 21–26.

Baybutt, P., 2012. Using risk tolerance criteria to determine safetyintegrity levels for safety instrumented functions. J. Loss Prev.Process Ind. 25 (6), 1000–1009.

Bedford, T., Cooke, R., 2001. Probabilistic Risk AnalysisFoundations and Methods. Cambridge University Press,Cambridge, UK.

Bobbio, A., Portinale, L., Minichino, M., Ciancamerla, E., 2001.Improving the analysis of dependable systems by mappingfault trees into Bayesian networks. Reliab. Eng. Syst. Saf. 71(3), 249–260.

Coolen, F.P.A., 2006. On probabilistic safety assessment in thecase of zero failures. J. Risk Reliab. 220 (2), 105–114.

Covello, V.T., Mumpower, J., 1985. Risk analysis and riskmanagement: an historical perspective. Risk Anal. 5 (2),103–120.

Khakzad, N., Khan, F., Amyotte, P., 2011. Safety analysis inprocess facilities: comparison of fault tree and Bayesiannetwork approaches. Reliab. Eng. Syst. Saf. 96 (8), 925–932.

Khan, F.I., Abbasi, S.A., 1999d. TORAP—a new tool for conductingrapid risk assessment in petroleum refineries andpetrochemical industries. J. Loss Prev. Process Ind. 12 (4),299–313.

Khan, F., Abunada, H., John, D., Benmosbah, T., 2010.Development of risk-based process safety indicators. ProcessSaf. Prog. 29 (2), 133–143.

Khan, F.I., Abbasi, S.A., 1998a. Techniques and methodologies forrisk analysis in chemical process industries. J. Loss Prev.Process Ind. 11 (4), 261–277.

Khan, F.I., Abbasi, S.A., 1999a. Major accidents in processindustries and an analysis of causes and consequences. J.Loss Prev. Process Ind. 12 (5), 361–378.

Marsh, D.W.R., Bearfield, G., 2008. Generalizing event trees usingBayesian networks. J. Risk Reliab. 222 (2), 105–114.

Pasman, H., Rogers, W., 2013. Bayesian networks make LOPAmore effective, QRA more transparent and flexible, and thussafety more definable! J. Loss Prev. Process Ind. 26 (3), 434–442

Pula, R., Khan, F.I., Veitch, B., Amyotte, P.R., 2006. A grid basedapproach for fire and explosion consequence analysis. ProcessSaf. Environ. Prot. 84 (2), 79–91.

Rathnayaka, S., Khan, F., Amyotte, P., 2012. Accident modelingapproach for safety assessment in an LNG processing facility.J. Loss Prev. Process Ind. 25 (2), 414–423.

Rusli, R., Shariff, M.A., 2010. Qualitative assessment forinherently safer design (QAISD) at preliminary design stage. J.Loss Prev. Process Ind. 23 (1), 157–165.

F.P. Lees, Loss Prevention in Process Industries, Vol. 1–3, Butterworths, London, 1996.

H.H. Fawcett, Toxicity versus hazards, in: H.H. Fawcett,W.S.Wood (Eds.), Safety and Accident Prevention Chemical Operations, 2nd Edition, Wiley, NY, 1993.

B.J. Tyler, A.R. Thomas, P. Doran, T.R. Grieg, A toxicity hazard index, Hazards XIII (1994) 351.

F.I. Khan, S.A. Abbasi, A maximum credible accident analysis based quantitative risk assessment study of chemical process industry, Indian Chem. Eng. A39 (2) (1997) 92.

F.I. Khan, S.A. Abbasi, Techniques and methodologies for risk analysis in chemical process industries, J.Loss Prevent. Process Ind. 11 (1998) 261.

CCPS, Guidelines for Chemical Process Quantitative Risk Analysis, American Institution of Chemical Engineers, 3 Park Ave, NY, 1989.

I.L. Hirst, D.A. Carter, A worst-case methodology for risk assessment of major accident installations, ProcessSafety Prog. 19 (2) (2000) 78.

F.I. Khan, Development of maximum credible accident scenarios for realistic and reliable risk assessment,Chem. Eng. Prog. 11 (2001) 56.

D.J. Gardner, G. Hulme, D.J. Hughes, R.F. Evans, P. Brington, in: Proceedings of the IChemE Symposium Series, No. 134, Institution of Chemical Engineers, London, UK, 1995.

M. Finucane, The adoption of performance standards in offshore fire and explosion hazard management, Fire Safety J. 23 (1994) 171.

K.V. Wingerden, Course and strength of accidental explosions on offshore installations, J. Loss Prevent. Process Ind. 7 (4) (1994) 295.

J.C. Jones, P. Irvine, PLATO software for offshore risk assessment: a critique of the combustion features incorporated, J. Loss Prevent. Ind. 10 (4) (1997) 259.

F.I. Khan, S.A. Abbasi, MAXCRED—a new software package for rapid risk assessment in chemical process