A Thesis Report on

DEVELOPMENT OF RISK ASSESSMENT MODEL FOR PETROCHEMICAL STORAGE USING BAYESIAN APPROACH

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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CHEMICAL ENGINEERING

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BANGLADESH UNIVERSITY OF ENGINEERING & TECHNOLOGY

September 7, 2022

CERTIFICATION OF THE DISSERTATION

We, the undersigned, are pleased to certify that **Ifat Sharmin**, a candidate for the Degree of Master of Science in Chemical Engineering has presented the dissertation on the subject **'Development of Risk Assessment Model for Petrochemical Storage Using Bayesian Approach'**. The thesis is acceptable in form and content. The student presented a satisfactory knowledge in the field covered by this thesis in an oral examination held on September 7, 2022.

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CANDIDATE'S DECLARATION

This is to certify that this thesis work has been done as the fulfillment of the requirement of the degree of M.Sc. in Chemical Engineering by Ifat Sharmin under the supervision of Dr. Md. Easir Arafat Khan, Associate Professor of the Department of Chemical Engineering, BUET. Neither this thesis nor any part of it has been submitted elsewhere for the purpose of any other diploma or degree.

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Acknowledgement

I would like to express my gratitude to my thesis supervisor, Dr. Md. Easir Arafat Khan, the person of my inspiration to work in the field of process safety. I would also like to thank him for giving me the opportunity to attend several conferences and submitting conference papers which helped me to improve my communication and presentation skills. He also provided me with the opportunity to visit Omera Petroleum Limited LPG satellite plant, Ghorashal where I explored process units and collected information for my thesis. He helped me in every stage of this thesis work by proposing this research topic, rendering his valuable knowledge, guidance and opinion and encouraging me to carry out this thesis work. I am grateful to him to give me the opportunity to work with him in this area and provide me with all facilities I needed all along this journey.

I would like to acknowledge Omera Petroleum Limited LPG satellite plant family for giving me the opportunity to visit the plant which was very helpful for my study. I would like to thank Walton Group to provide me with important information. Lastly, I would like to express my gratitude to the Almighty, my parents and my partner without who this work would not have been completed.

Abstract

Petrochemical products are inherently hazardous. Accidents related with these products are very frequent these days in Bangladesh. If the storage of this highly flammable and explosive hazardous chemical is improper and unsafe, it can cause events like Boiling Liquid Expanding Vapor Explosion, Vapor Cloud Explosion, Pool Fire etc. resulting in casualties, property damage and environmental pollution. An appropriate and effective method of hazard identification, evaluation and prevention is required to avoid any catastrophic incident in the process industries. Numerous approaches i.e. qualitative methods, quantitative methods and combination of two or more methods had been being proposed to facilitate the risk management in petrochemical storage. For this research a quantitative methodology: Bayesian Network (BN) Analysis was chosen on priority basis over the qualitative ones for the case study of i-Butane storage tank. The objective of this research was to identify and analyze hazards and assess risks in i-Butane storage facilities using Bayesian Network Analysis. Prior to this, a systematic HAZOP was performed with the help of piping and instrumentation diagram and risk had been also assessed quantitatively by Bow-Tie method.

Bow-Tie diagram was constructed by combining fault tree and event tree. The top event was i-Butane release from the storage tank. Four protective barriers were introduced here: Release prevention barrier, Dispersion prevention barrier, Ignition prevention barrier and Escalation prevention barrier. Based on the failure or success of safety barriers, five types of consequences were considered: Safe, Near Miss, Mishap, Incident and accident. Frequency of i-Butane release from storage tank was found 9.985×10^{-7}/year. Bayesian network analysis was performed using Bayesian theorem with the help of a trial version of a software named: Agena Risk. In this model, the fault trees and event trees from previous Bow-Tie were put into the Bayesian inference based software to update the event frequencies. The fault trees and event trees had been updated by implementing additional causes for the occurrence of top event and barrier failure. As a result frequency of i-Butane release from storage tank was increased to 1.71001×10^{-5}/year.

Larger frequency of the top event contributed to more consequences such as: Catastrophe. It was compensated by two more barriers: 1) Emergency Management and Damage Control Barrier and 2) Human Factor Barrier. Therefore, this study proposed to develop a Bow-Tie model and fault trees and map them into a Bayesian Network which produces more reliable results and an easy approach to dynamic update of risks.

Nomenclature

Notations and their meaning

Notation	Meaning
μ	Frequency of barrier failure
BV	Ball valve
C_3	Three carbon hydrocarbons
C_4	Four carbon Hydrocarbons
EFCV	Effective flow check valve
FLLG	Fixed liquid level gauge
NRV	Non return valve
P	Probability of barrier failure
PG	Pressure Gauge
Pr(Aj)	Prior probability of event Aj
Pr(Aj|E)	Updated probability of event Aj
QI-LD	Leak detector
SRV	Safety relief valve
t	Failure time
TG	Temperature gauge
TP	Transfer pump
TRV	Pop action valve
U	Set of variables
UP	Unloading Pump

Abbreviations and their elaborations

Term	Elaboration
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ATV	All-Terrain Vehicle
BFSCD	Bangladesh Fire Service and Civil Defense
BLEVE	Boiling Liquid Expanding Vapor Explosion
BN	Bayesian Network
BPC	Bangladesh Petroleum Corporation
BS EN	British Standard European Norm
BT	Bow-Tie
CE	Current Event
CPT	Conditional Probability Table
CSB	Chemical Safety Board
DAG	Directed Acyclic Graph
DC	Direct Cause
DC&EMB	Emergency Management and Damage Control Barrier
DDC	Detailed Direct Cause
DE	Dangerous Event
DPB	Dispersion Prevention Barrier
DRA	Dynamic Risk Analysis
E&P	Exploration and Production
EPB	Escalation Prevention Barrier
ERL	Eastern Refinery Limited
FMEA	Failure Mode Effect Analysis
FO	Fuel Oil
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability
HFB	Human Factor Barrier
HOBC	High octane blending component
HSD	High speed diesel
IFSTA	International Fire Service Training Association
IPB	Ignition Prevention Barrier
IPCC	Intergovernmental Panel on Climate Change
IS	International Standard
JBO	Jute batching oil
LDO	Light diesel oil
LNG	Liquefied Natural Gas
LOPA	Layer of Protection Analysis
LPG	Liquefied Petroleum Gas
MS	Motor spirit
MTT	Mineral turpentine

Term	Elaboration
NFPA	National Fire Protection Association
NPS	Nominal Pipe Size
NPT	Node Probability Table
NSC	Necessary and Sufficient Conditions
P&ID	Piping and Instrumentation Diagram
PD	Pressure Equipment Directive
PFD	Process Flow Diagram
RPB	Release Prevention Barrier
SBPS	Special boiling point solvent
SE	Secondary Event
SKO	Superior kerosene oil
TE	Top Event
UE	Undesired Event
UVCE	Unconfined Vapor Cloud Explosion

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Chapter 1. Introduction

The offshore/onshore gas/oil exploration, chemicals, petrochemicals, food, paper, polymer and other process industries contain numerous equipment and units, control loops and thousands of operations. These plants have to deal with different hazards and risks. At the same time they have to maintain the product quality by following environmental and safety regulations. Failure in managing hazards can lead to devastating accidents. For example, storage tanks store flammable and hazardous chemicals and petrochemicals even at high temperature and pressure. The storage tanks should be designed and handled properly so that any kind of deviation cannot further lead to the damage to people, infrastructure and environment. Accidents in storage tank can occur due to mal-operation or mechanical failure or any external factor. Accidents in storage tanks are very common. So safety has been a primary concern in designing, constructing and operating storage tank facilities containing hydrocarbons specially. By minimizing equipment failure rate the frequency of risks reduces but still the consequence is severe. So we need to think of new and more safety barriers keeping the finance in head. So the scope of risk assessment in this sector is so wide. This research proposes techniques for the risk assessment of petrochemical storage tanks.

1.1 Petrochemicals: Petrochemicals are chemical products derived from crude oil, although many of the same derivatives are also obtained from other fossil fuels such as coal and natural gas. Crude oil is the basic component to produce all petrochemical and petroleum components after a long process of refinement in oil refineries. The major hydrocarbon products produced from petroleum by refining are: liquefied petroleum gas, gasoline, diesel fuel, kerosene, fuel oil, lubricating oil, and paraffin wax. They are an essential part of the chemical industry as the demand for synthetic materials grows continually and plays a major part in today's economy and society. Petrochemicals are used to manufacture thousands of different products that people use daily, including plastics, medicines, cosmetics, furniture, appliances, electronics, solar power panels, and wind turbines. Petrochemicals can be classified into three general groups: olefins, aromatics, and a third group that includes synthesis gas and inorganics[1].

1.1.1 Olefin: Olefins' molecules form straight chains and are unsaturated, include ethylene, propylene, and butadiene. Ethylene is the hydrocarbon feedstock used in greatest volume in the petrochemical industry. From ethylene, for example, are manufactured ethylene glycol, used in polyester fibers and resins and in antifreezes; ethyl alcohol, a solvent and chemical reagent; polyethylene, used in film and plastics; styrene, used in resins, synthetic rubber, plastics, and polyesters; and ethylene dichloride, for vinyl chloride, used in plastics and fibers. Propylene is used in making such products as acrylics, rubbing alcohol, epoxy glue, and carpets. Butadiene is used in making synthetic rubber, carpet fibers, paper coatings, and plastic pipes [2].

1.1.2 Aromatics: Aromatics are hydrocarbon molecules that form rings and are unsaturated. The major aromatic feedstock are benzene, toluene, xylene, and naphthalene. Benzene is used to make styrene, the basic ingredient of polystyrene plastic. It is also used to make paints, epoxy resins, glues, and other adhesives. Toluene is used primarily to make solvents, gasoline additives, and explosives. Xylene is used in the manufacture of plastics and synthetic fibers and in the refining of gasoline [38]. Naphthalene is notably used in insecticides.

1.1.3 Synthesis gas: Synthesis gas is used to make ammonia and methanol. Ammonia is used primarily to form ammonium nitrate, a source of fertilizer. Much of the methanol produced is used in making formaldehyde. The rest is used to make polyester fibers, plastics, and silicone rubber[2].

1.2 Present Scenario of Petrochemical Sector in Bangladesh: Bangladesh is not a petroleum producing country though it has a refinery plant- eastern refinery limited, where imported crude oils from Saudi Arabia and Abu Dhabi are processed with a small quantity of oil from Haripur Gas Field and the products are marketed by several marketing companies. Hence, Bangladesh have to depend on imported oil. To meet total demand of commercial energy, Bangladesh imports annually about 1.3 million metric tons of crude oil. In addition to this, another 2.7 million metric tons (approx.) of refined petroleum products per annum is imported. Condensate is mixed with crude oil. Major consumer of liquid fuel is transport sector followed by agriculture, industry and commercial sector which is mostly met by imported liquid fuel. Eastern Refinery Limited, a subsidiary company of Bangladesh Petroleum Corporation (BPC), is capable of processing 1.3 million metric Tons of crude oil per year.

The present annual demand of petroleum products in the country is 3.7 million metric tons. Total storage capacity of petroleum products in the country is 687,500 tons, of which the storage capacity at Eastern Refinery Limited is 365,000 tons. In the main installations of three oil-marketing companies of ERL in Chittagong (Padma Oil Company Ltd, Jamuna Oil Company Ltd, Meghna Petroleum Ltd), the total storage capacity is 205,600 tons [37].

Figure 1.2.1 shows the import scenario of refined petrochemicals from overseas state owned organizations by Bangladesh Petroleum Corporation from 2017 to 2022. Gas oil is imported in the largest quantity and marine fuel is in the lowest.

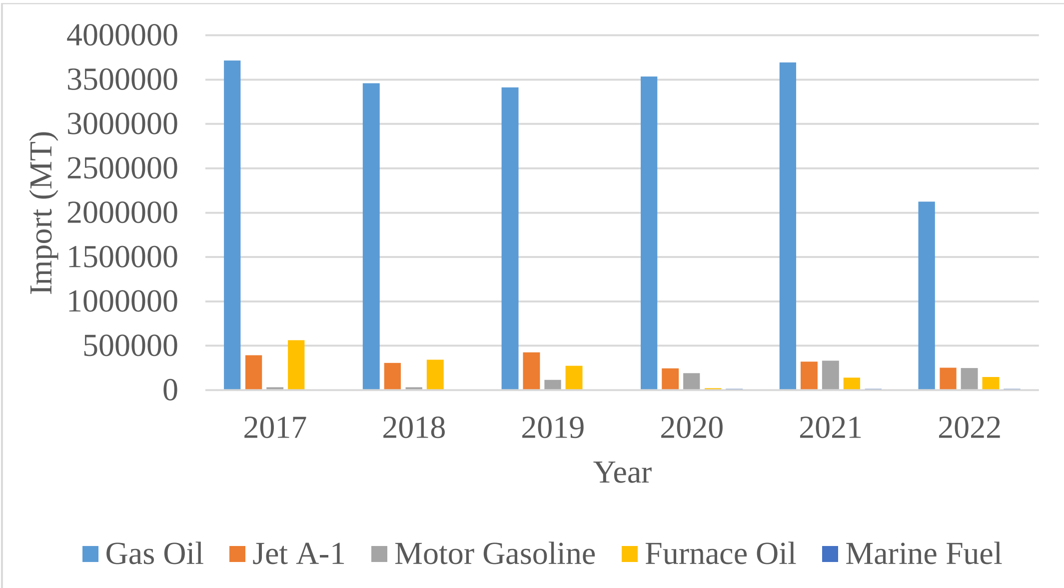


Figure 1.2.1: Import of refined petrochemicals by BPC [44].

BPC also import unrefined crude which are mainly of two grades only: Arabian light crude oil and Murban. Figure 1.2.2 illustrates the quantity of import in each year from 2017 to 2022. This year import of unrefined oils has decreased slightly.

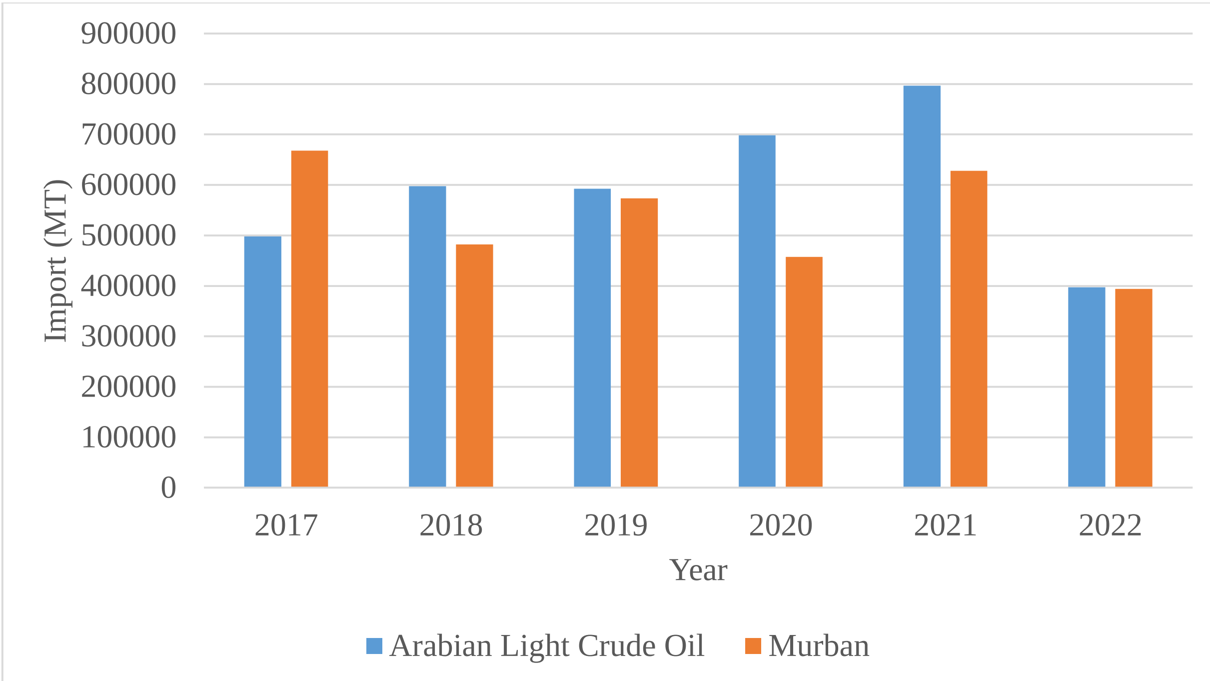


Figure 1.2.2: Import of unrefined petrochemicals by BPC [45].

After refining, ERL produces the following quantity and types of petrochemicals described in figure 1.2.3. The figure depicts the production of Liquefied petroleum gas (LPG), Naphtha, Special boiling point solvent (SBPS), Motor spirit (MS), High octane blending component (HOBC), Mineral turpentine (MTT), Superior kerosene oil (SKO), High speed diesel (HSD), Jute batching oil (JBO), Light diesel oil (LDO) refined and unrefined, Fuel oil (FO) refined and unrefined and Bitumen in each year from 2017 to 2022.

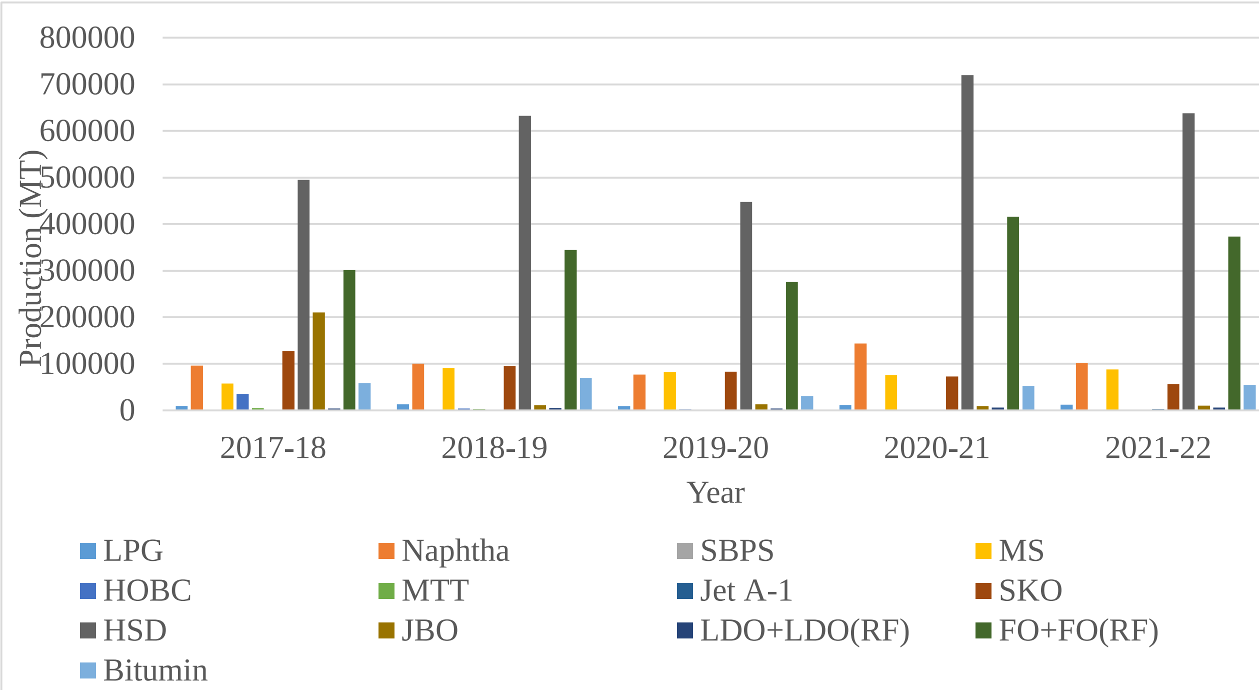


Figure 1.2.3: Crude oil process and production of ERL [46].

1.3 Liquefied Petroleum Gas: Liquefied petroleum gas (LPG) is very common fuel in domestic and industrial use, and is transported by road, rail and through pipeline. So potential hazards of this facility cannot be overlooked. If the storing procedure of LPG is not proper, it will initiate vicious disasters such as fire, explosion with deaths, property damage and environment pollution. In this research, the storage facility of LPG was taken as the case study for risk assessment.

LPG consists of propane, butane, propylene and butylene. It is a variable combination of C_3 and C_4 isomers with some traces of lighter and heavier hydrocarbons. The composition of LPG plays an important role in outflow, evaporation and dispersion of both liquid pool and dense gas cloud[3]. LPG is obtained as a byproduct while refining crude oil or natural gas. Since it is a mixture of all these flammable gases, it needs to be stored carefully. 1 m^3 of liquid LPG will vaporize into 245 to 275 m^3 of vapor. The heating value of LPG is 2.5 to 3 times higher than that of natural gas. There is a big amount of potential energy in a very small volume of LPG. When LPG is transported by 114 m^3 (30,000 gal) rail tank cars or stored in containers up to 680 m^3

(180,000 gal), the amount of energy available for catastrophe is huge if precautions are not taken to prevent LPG release[4]. It is a liquid below normal pressure but gaseous at ambient conditions. Gaseous LPG is two times heavier than air. The boiling point of LPG normally is between -42 degrees and 0 degree Fahrenheit. The boiling point depends on what proportions are Butane and Propane there in the mixture. It is colorless and needs to be stored as pressurized liquid. Its weight is about half of that of the same volume of water. Ethyl Mercaptan is mixed with it to detect LPG leaks. It is an odorant and helps to know if there is any LPG leak. LPG's Flash point is -76 degree Fahrenheit. It is normally a non-toxic substance but it can be dangerous if not handled cautiously. It forms a flammable mixture with air in concentration of between 2% and 10%. LPG is also known to cause suffocation. It is mildly anesthetic and can be harmful if it is found to be present in high proportions. In spite of its anesthetic properties, LPG has never been used or considered safe enough for medicinal purposes. The ignition temperature of LPG is found to be in the range of 41^0 to 58^0 degree Celsius. It is also known that liquid LPG has resulted in cold burns to human skin since it causes vaporization at a very fast rate[5].

Figure 1.3.1 summarizes the flammability nature of LPG (mostly propane and butane) in one diagram. LPG has flammability hazard of score 4 which labels it as deadly. The reactivity level is 0 and health hazard score is 2 that means LPG is hazardous for health.

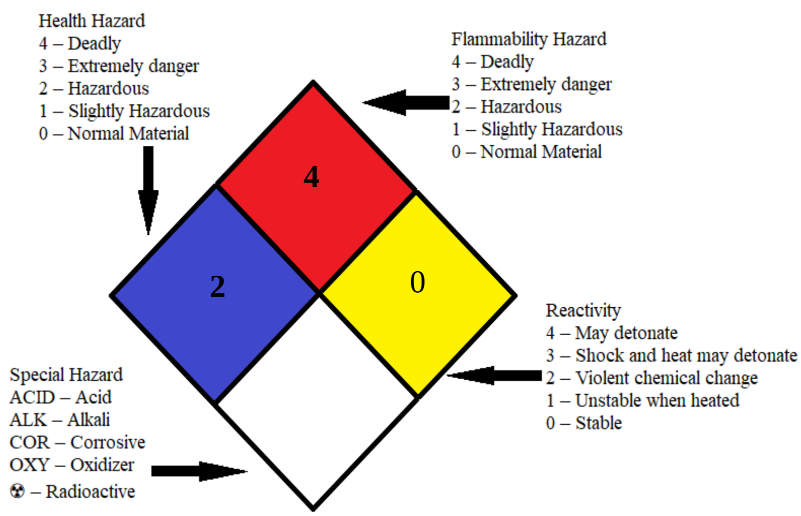


Figure 1.3.1: NFPA diagram of Propane [43].

Now a days LPG is being imported from abroad to meet the huge industrial and domestic needs as the reservoir of natural gas in Bangladesh is decreasing day by day. Use of gaseous fuels are being replaced by usage of LPG as the long distance transportation and supply of bulk amounts of LPG is feasible. Transformation to LPG is 50% more cost effective than that to CNG. LPG possess less volume, less weight and less pressure inside the cylinder than CNG. So shifting the national economy towards LPG is a very timely decision.

Figure 1.3.2 shows the increasing demand of LPG with time where import by private companies holds the maximum stake. It is estimated that LPG demand will reach as high as 1.4 million metric ton in the year 2022-23 of which only 1% will come from domestic source.

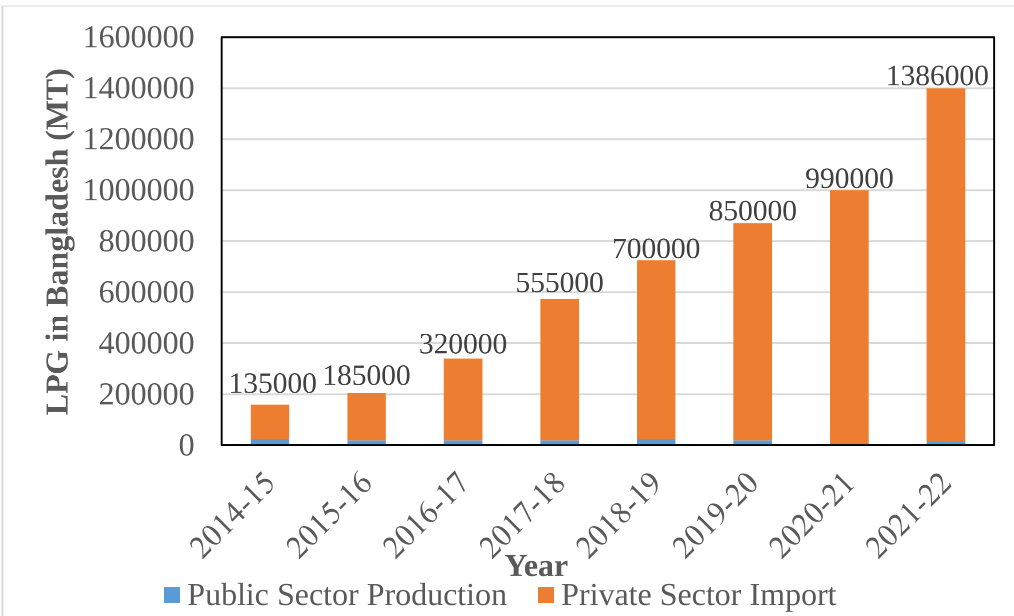


Figure 1.3.2: LPG production and import scenario in Bangladesh [37].

Petromax, Bashundhara, Omera, Jamuna, Laugfs, etc. are major brands which are importing LPG from abroad and distributing all over the country. Bashundhara occupies the biggest place in market which is 24%, then comes Omera. In year 2021, 1 million ton LPG has been imported and it will increase up to 2.8 million ton by 2025 [6].

Figure 1.3.3 shows the percentage share of LPG demand by market sector. Most of the LPG is used in residences to meet day to day purposes. The second largest use of LPG is in the petrochemical industries.

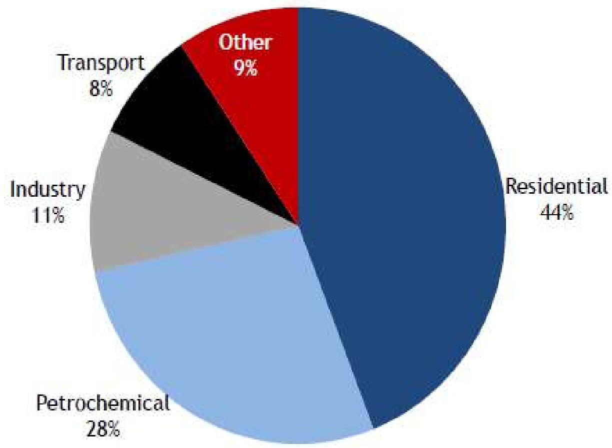


Figure: 1.3.3: Use of LPG in different sectors in Bangladesh [42].

1.4 Problem Statement: Petrochemical process industries as well as storing facilities run in dynamic ways. So, any static risk assessment cannot provide us with a practicable and acceptable result. Besides the failure frequency of different safety barriers are not always available. So one needs to incorporate expert's judgment and assume some value. Being a dynamic process, the process parameters and event frequencies keep changing from time to time. Therefore, it is important to assess risk considering the above mentioned properties of a process unit.

There are many research works for hazard identification and evaluation such as HAZOP, Checklist, What if, Indexed method etc. For example, Mariani et al. (2008) proposed an indexed method for risk and safety analysis in LPG storage. Sachan et al. (2015) analyzed risk in LPG bottling plant using HAZOP. Ajeysuriya et al. (2016) examined HAZOP study in LPG installation area to focus on the improvement of health and safety in the workplace. Riad et al. (2020) applied BT and HAZOP methods in an LPG plant for gas separation and simulated the scenarios using ALOHA software. Sharma et al. (2018) performed Bow-Tie approach qualitatively using Bow-Tie XP software. These methods were used only to identify hazards within a process unit. But in order to manage and mitigate risks, one must assess and evaluate risk. One way to do that is estimating incident frequencies by a reliable quantitative method.

Many researchers chose static but quantitative methodology for risk estimation though the results don't give us the dynamic and updated model. For example, Fuentes-Bargues et al. (2017) combined HAZOP with quantitative FTA and applied in the risk assessment of the unloading terminals of petroleum products and two fuel storage facilities. Cherubin et al. (2011) combined a quantitative risk assessment method with bow-tie using a software: baseline risk assessment tool. Rajakarunakaranet al. (2015) showed the application of fuzzy fault trees for evaluation of risk in LPG refueling station.

Some other studies show the methodology similar to that of the present study. As mentioned earlier, the actual scenario in a process plant is not static, some researchers performed quite an advanced study to meet the dynamic criteria such as: Khakzad et al. (2013) performed dynamic safety analysis by mapping BT into Bayesian model. Badreddine et al (2012) constructed bow-tie diagram using Bayesian approach. Unlike these available researches, the present research didn't approach straight with the dynamic risk analysis, rather, at first, static model of risk analysis was shown here. Sarvestani et al. (2021) constructed Bow-Tie model using data extracted from databases for LPG storage tank and developed a dynamic model by constructing likelihood function and updating prior probability with Bayesian theorem. They took hypothetical past accident data for posterior probability calculation because of the lack of data. Zarei et al. (2017) also mapped Bow-Tie into a Bayesian network to perform both probability reasoning and uncertainty handling for dynamic risk analysis around LPG storage tank. They also performed consequence modelling using BN analysis which made the model somewhat complex.

It can be stated that available studies are not enough to incorporate real data from plant to perform the risk analysis. Also these studies did not utilize any simple hazard identification process to facilitate the assessment. Hence it is important to develop a method that has the ability to identify hazards and utilize them in developing fault trees. This study developed a simplified quantitative and dynamic risk assessment model that incorporated real plant hazards and collected the relevant failure frequency. The same hazards or probable risks were shown in the fault trees. Also unlike other studies this research updated not only the dynamic BN model, but also the static bow-tie diagram which helped to visualize the changes.

1.5 Research Objective: The purpose of this study was to develop a quantitative operational risk assessment method that can update risk. Mapping of fault tree calculation of risk events into the Bayesian network backed by HAZOP analysis have been used to develop a tool of operational risk assessment method for safety management in storage tank facilities. The objectives of research were as follows:

- To develop the methodology of risk analysis for a petrochemical storage facility
- To use i-Butane storage tank as a case study to apply the methodology
- To assess risk probability quantitatively by fault tree and event tree of a Bow-Tie representation of the top event
- To map the Bow-Tie model into a Bayesian network analysis
- To identify safety barriers and to quantify the failure rates of the barriers

In this thesis paper, Chapter 1 presents an introduction which provides background information, research scope and research objectives. The detail review on conventional risk assessment methodologies, previous researches on developing dynamic risk assessment techniques and Bayesian network's application for reliability and risk analysis are discussed in Chapter 2. The research methodology is presented in the following chapter 3. In this chapter, overall research framework is explained. In chapter 4, a case study of i-Butane storage tank is demonstrated to illustrate the application of developed method and discuss the research findings. Chapter 5 provides overall summary, research contribution and recommendations for future research.

2. Literature Review

2.1 Background: Storage tanks are very important in storing flammable chemicals, besides, introduce fire and explosion hazards to the facilities. With the growth of process industries, the workers employed in the plant have also increased. Thus, workers and the general public living in the vicinity to the plant could face the risks. Petrochemical vapor-air mixture arising from leakage can ignite some distance from the point of leakage and the flame can travel back to the point of release. Even an empty vessel that contained petrochemicals earlier may have some little amount remained and be potentially dangerous[7]. When LPG mixes with water, an explosive vaporization happens and the explosion is called Rapid Phase Transition which builds up overpressure creating damage. The petrochemical accident process consists of three steps: initiation, propagation and termination. Some typical accidents are: Boiling Liquid Expanding Vapor Explosion, Unconfined Vapor Cloud Explosion, Confined Explosions, Flash Fire, Pool Fire, Jet Fire, Fire Ball etc. The typical consequence includes material and energy release, spreading of material and energy, ignition, propagation of fire and exposure to human, property and environment[8]. Accidents in the storage tank can be occurred by either mechanical failure, mal-operation or external impact, poor maintenance, inadequate safety instrumentation system or poor safety management.

From case histories it is evident that petrochemical accidents have a significant effect on people, environment, economy and society. For example, derailment and LPG release from 14 LPG tank cars near Viareggio, Italy resulted in 31 fatalities and damage of residential buildings nearby in 2009. U.S. Chemical Safety and Hazard Investigation Board reported a BLEVE occurred in 1998, at the Herrig Brothers Feather Creek farm, situated in Albert city, Iowa. The explosion caused about $240,000 loss to buildings and turkey barns located on the farm and took lives of two firefighters and injured seven other. A tanker transporting gasoline exploded after it had stopped due to mechanical issues and began leaking gas in the northern Haiti last year which caused 71 fatalities. Last year, also a fuel tanker exploded following a collision in the capital of Sierra Leone, causing numerous casualties and 91 fatalities.

Hence, it is important to develop a method that has the ability to quantify failure frequency and risk arising from the release from storage tanks. People will accept LPG in day-to-day life if proper safety standards are followed which will result in low risk for the people and the environment. Safety and security in petroleum sectors requires special attention due to the related concentrated hazards. The loading and unloading operations regarding the storage tank are more vulnerable to accidents. In a number of countries, e.g., in Europe, risk assessment became mandatory to perform for all petrochemical and LPG industries to carry out their operation. The Piper Alpha disaster in North Sea developed a safety case for offshore installation. For onshore plants European Seveso Directives demand a 'safety report' concerning the dangerous substances present in the installation or storage facilities, possible major accidents scenarios or risk analysis, prevention and intervention measures and management systems in order to reduce the risk and define the necessary steps to be taken [2]. An appropriate and effective method of hazard identification, risk assessment and process control system are required to avoid any disaster [3].

2.2 Fire and explosion risks for petrochemical storage facilities: Petrochemicals represent substantial hazards in the form of fire and explosion. The essential elements for combustion are fuel, an oxidizer and an ignition source. When fuel, oxidizer, and an ignition source are present at the necessary levels, burning will occur. This means a fire will not occur if any of the elements is not present or not present at the necessary level. The major distinction between fires and explosions is the rate of energy release. Fires release energy slowly, whereas explosions release energy rapidly, typically on the order of microseconds. Fires can also result from explosions, and explosions can result from fires. Fire, or burning, is the rapid exothermic oxidation of an ignited fuel. The fuel can be in solid, liquid, or vapor form, but vapor and liquid fuels are generally easier to ignite. The combustion always occurs in the vapor phase; liquids are volatilized and solids are decomposed into vapor before combustion. An explosion is a rapid expansion of gases resulting in a rapidly moving pressure or shock wave. The expansion can be mechanical (by means of a sudden rupture of a pressurized vessel), or it can be the result of a rapid chemical reaction. Explosion damage is caused by the pressure or shock wave[9]. The fire and explosion risk at petrochemical storage tank is extremely high where the fuel, oxidizer and ignition source are available at required levels. There are a number of possible hazardous scenarios that can occur in the petrochemical storage facilities.

2.3 Types of Incidents in Petrochemical Storage Tanks[10]

Boil Over: Boil over is a phenomenon which occurs in storage tank fire consist of heavy hydrocarbon or a blend of hydrocarbon liquids e.g. Crude oil. It is released in explosive form when burning oil comes in contact with water, which settled at bottom of the tank. The heat is dissipated downwards and converts water into steam which expands 1500 times and carries burning crude with it.

Slope-over: Slope-over is an incident which occurs when water is applied to full surface fire tank and the water gets accumulated downwards resulting in overfill of product from the tank.

Vent Fire: Vent fire takes place in the fixed roof tank when one or more of vents get ignited due to vapor flammable vapor released. The presence of flammable vapors has been always there either due to tank filling operation or tank’s daily breathing cycle. More of vent fire found due to lightning strikes or found some ignition source nearby.

Full Surface Fire: A full surface of the fixed roof can occur due to vent fire escalation. A vapor cloud explosion can occur if flammable vapor is found within flammable range during the flame flashback, mainly if flame arrestors/PV is not in working condition. Another case is when the tank roof has lost its buoyancy and some or the entire liquid surface has been exposed and involved in fire.

Rim Seal Fire: A rim seal fire takes place where the seal between the tank shell and roof has lost its integrity and released vapors exposed to an ignition source and involved in fire.

Bund Fire: A fire in the bund is a type that occurs outside the tank shell within the containment area. These types of fire involved small spillage fill up to fire covering whole bund area.

Table 2.4.1 briefs some accidents in petrochemical storage facilities.

2.4 Major accidents in petrochemical storage facilities all over the world

Table 2.4.1: Some of the most disastrous fuel tank accidents [11, 12].

	Date	Location	Life Loss	Description
1	24/02/86	Thessaloniki, Greece	330	Sparks from a flame cutting torch ignited fuel from a tank spilling in a dike of a fuel tank. The fire spread to other areas which destructed 10 out of 12 crude oil tanks.
2	03/04/77	UMM said Qatar	179	A 260,000-barrel tank containing 236,000 barrels of propane refrigerated at -45^{o}F failed massively. An adjoining refrigerated butane tank and most of the process area were also destructed by fire.
3	14/09/97	Vishakhapatnam, India	64	LPG ignited during tank loading from a ship. A thick blanket of smoke spreading panic among the residents resulted in 37 death and 100 injuries. 15 storage tanks were burning for two days.
4	21/12/85	Naples, Italy	60	24 of the 32 tanks at a marine petroleum terminal were destroyed by fire that began with overfilling of a tank. Explosion caused complete destruction of the terminal buildings and adjacent industrial and residential infrastructures.

	Date	Location	Life Loss	Description
5	07/01/83	Newark, New jersey, USA	52	An overfilling of a floating roof tank spilled 1300 barrels of gasoline into the tank dike. The vapor cloud carried by wind to a nearby incinerator and was ignited. The resulting explosion destroyed two adjacent tanks and the terminal.
6	09/04/98	Herrig Brothers Feather Creek farm, in Iowa	2	BLEVE occurred when a vehicle struck the two above ground propane pipes (liquid and vapor lines) that came from the propane tank. Propane from the broken pipes formed a cloud, and within few minutes the propane vapor ignited.
7	13/12/2021	Cap-Haitien, northern Haiti	71	A tanker transporting gasoline exploded after it had stopped due to mechanical issues and began leaking gas. People gathered to collect fuel directly from the truck when the explosion occurred.
8	03/06/2021	Tehran, Iran	-	An explosion and a fire in a refinery ten miles south of the capital Tehran became a spectacle to 9 million residents as it burned for 20 hours. No evacuations took place, and the government did not mention possible health hazards. Reports said that 20 storage tanks where waste fuel was kept completely burned.

	Date	Location	Life Loss	Description
9	06/06/2021	Tehran, Iran	-	A massive fire broke out at an oil refinery in Tehran. 18 tanks of the Tehran refinery have burned down in the fire.

2.5 Accidents in LPG storage facilities:

Flammable and combustible LPG storage tanks are found in refineries, petrochemical plants, marine terminals, local fuel companies, power plants and large manufacturing facilities such as automobiles, tea factory etc. LPG storage tank accidents are similar to those of the most petrochemical storage facilities. Main hazard in a LPG storage tank is: Fire and Explosion. There are different types of explosions and consequent fire incident which had taken place or have a potentiality to take place. Several types of explosions and fire may take place at the same time or one after another as a domino effect. Some types of explosions and accident histories of LPG storage facilities are described below.

Boiling Liquid Expanding Vapor Explosion: A BLEVE takes place if a tank that contains a liquid at a temperature above its atmospheric pressure and boiling point, ruptures. The subsequent BLEVE is the explosive vaporization of a large portion of the tank contents; possibly followed by combustion or explosion of the vaporized cloud if it is combustible. This type of explosion occurs when an external fire heats the contents of a tank of volatile chemical. As the figure 2.5.1 shows, when the tank content is heated, the vapor pressure of the liquid inside the tank increases and the tank's structural integrity falls down because of the heating. If the tank ruptures, the hot liquid volatilizes explosively[9]. Heat radiation is the main hazard associated with BLEVE.

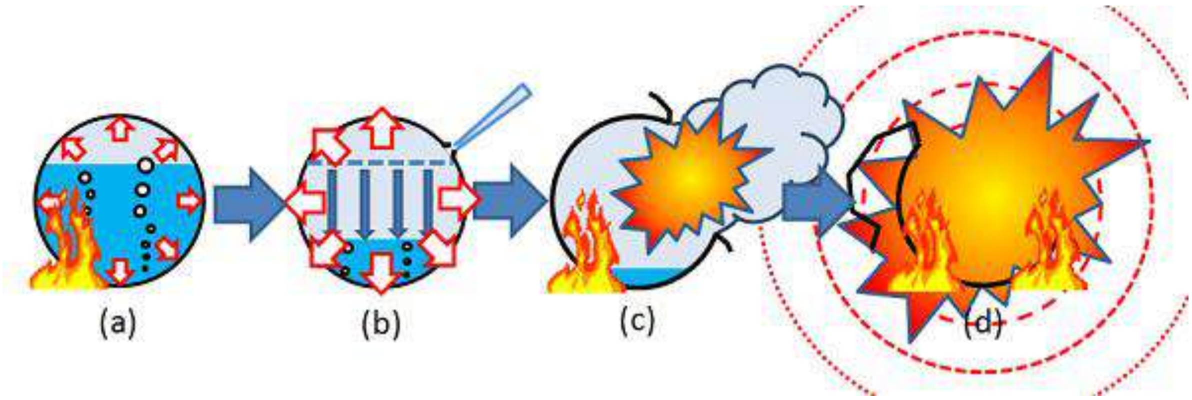


Figure 2.5.1: BLEVE mechanism [47].

A LPG storage facility at a refinery in Feyzin, France which held 12,850 m^3 of pressurized hydrocarbons in 10 spherical tanks exploded in 1966 causing 18 deaths and 31 injuries[13]. The LPG inventory in San Juarnico, Mexico, (1984) confronted 12 separate BLEVE explosions. Fatality was estimated as ranging from 500 to more than 600. Number of injuries ranged from 5000 to 7000[12].

Unconfined Vapor Cloud Explosion: Unconfined explosions occur in the open space. This type of explosion is generally the result of a combustible gas spill. The gas is spread out and mixed with air until it comes in contact with an ignition source. Unconfined explosions are rarer than confined explosions because the explosive chemical is frequently diluted below the LFL by wind flow. These explosions are destructive because large quantities of gas and large areas are normally involved[9]. This occurs when large quantities of flammable vapors are released from the tank and ignite at a later time at a considerable distance from the release point. The consequence of this incident is chemical burning and over pressure[14]. In 1992 an unconfined vapor cloud explosion (UVCE) occurred on the above-ground installations of an underground LPG storage of Brenham storage facility due to LPG overflowing. Three people died and 21 people were injured. The surface blast demolished all buildings at the Brenham station and caused varying degrees of damage to all homes within a 7.8 km^2 area. Total costs were estimated at 9M Dollar[39].

Confined Explosions: An explosion occurring within a vessel or a building or a closed system is known as confined explosion. These are most common and usually result in injury to the building residents and enormous damage. Confined explosions have been the reason of many further incidents[4]. In 1997 there was an explosion of LPG at the auto gas filling station in Warsaw, Poland. The accident was caused by a drunken driver who collided with one of 4 storage tanks containing LPG. A gas leak and fire occurred. The explosion and rupture of the tank was caused by a fire. Two people were killed, and dozens were injured[15].

Fire ball: When superheated LPG releases and immediately ignites, it may burn as a fireball. The fireball grows larger and moves upward continuously because of buoyancy. The duration of fireball is small but the radiation level is intense. Within the radius of the fireball, equipment and facilities will be severely damaged. This radius is known as the domino radius. Beyond this radius, the area is safe except for the radiation wave hazard[14].

After the 2011 Tohoku earthquakes, in Chiba, Japan, a refinery operated by Cosmo Oil lost 17 LPG storage vessels which were either heavily damaged or totally destroyed by fires and explosions in the refinery. Five BLEVEs of LPG occurred, resulting in huge fire balls measuring about 500 m in diameter[16].

Flash fire: A flash fire is a sudden, intense fire caused by ignition of a mixture of air and a dispersed flammable substance such as a solid, flammable or combustible liquid, or a flammable gas. Flash fires may occur in environments where fuel, typically flammable gas or dust, is mixed with air in flammable limit. In a flash fire, the flame propagates at subsonic velocity, so the overpressure damage is usually negligible and the bulk of the damage comes from the thermal radiation and secondary fires. It involves less gas and energy output than UVCE. The final scenario is thermal radiation and over pressure.

On June 29th, 2009 the derailment of a freight train carrying 14 LPG tank-cars near Viareggio, in Italy, caused a massive LPG release. A gas cloud formed and ignited triggering a flash fire that resulted in 31 fatalities and in extended damages to residential buildings around the railway line[17].

Jet Fire: Jet fire is the ignition of high pressure release of vapor or aerosol into open space. This may be caused by ignition of LPG escaping from minor leakage of pipeline, valves, hoses etc. Any equipment on which that flame jet impinges will be subjected to very high thermal loads often exceeding the capacity of fixed water spray. This occurs for limited length of time. If the jet fire is directed to any storage facility for a long time, it can initiate disaster. Good control and design can reduce this accident. Key parameters of the radiation intensity are the orifice diameter of the leak and phase of the flammable material. Outside the flame jet radiation hazard is very small.

In Wenling, Zhejiang Province, China, on June 13, 2020, an LPG tank truck overturned and collided with the concrete guardrail; the subsequent explosion of the tank released 25.36 ton LPG. Shortly afterward, the LPG tank was shot into the air with a continuous two-phase jet[18].

Pool fire: Pool fires take place when significant quantity of flammable liquid is released and immediately ignited. It can be confined in case of release in containment dikes or can be unconfined in case of release from storage tank. This is caused by leakage and ignition of liquid phase when it does not immediately drain away. This is not a big problem in a plant of good layout and drainage system and when LPG has low percentage of butane, the release velocity is low and the ambient temperature is not high. When a pool fire surface area is increased more heat is radiated in the environment to larger distance.

Many of the past accident reports state that dike fire of pool is the common disaster forms in petrochemical industry and result in more intense radiation, and higher flame, which can cause serious impact on the surrounding personnel and equipment and can also lead the boiling liquid to a vapor explosion or vapor cloud explosion. For example the pool fire that took place at a LPG filling station in Bucheon, Korea in 1998 has been studied. The direct cause of the incident was concluded to be faulty joining of the couplings of the hoses during the butane unloading process from a tank lorry into an underground storage tank. The faulty connection of a hose to the tank lorry resulted in a massive leak of gas followed by catastrophic explosions[19].

2.6 Case Study Scenario: For the present study the top event considered was loss of containment from the i-butane storage tank. Because, if the i-butane is leaked or spilled, then only it can trigger further fire accident. Overfilling was the initiating/primary reason for leak/spill. Besides, explosion was also another vital unavoidable scenario and overpressure was the usual reason behind it. The ‘fire and explosion’ term had been used as a generalized consequent scenario after i-butane release from the tank because it can turn into any form of BLEVE, VCE, Flash fire, Pool fire, Fire ball, Jet fire and so on. Risk assessment had been performed considering the worst case scenario and failure of almost all existing safety guards had been taken into account. For the release from tank to take place, the things may go wrong are:

Leakage from the pressure relief valve: Tank contents releases from pressure relief valve when the valves such as safety relief valve, flow check valve do not work properly. Besides the pressure indicator and transmitter, pressure control valve also needs to act in a proper way to stop this event to occur. The internal pressure of the storage tank can also increase due to vapor accumulation caused by temperature rise and the cooling system failure.

Mechanical damage: It can happen if sabotage or terrorist invasion occurs for the weak or obsolete security system and passive defense system. Apart from this, corrosion, fatigue and material defect also can lead to mechanical damage.

Overfilling: The storage tank overfills when the level indicator and alarm does not work or give wrong indication or wrong alarm. Also, operator’s no response, pump failure and failure of normal operation of valves are also responsible for it.

Leakage from drain valve: Operation error and design error of drain valve, operator’s negligence etc. are the main reasons of this event.

Natural event: Strong natural calamities like tsunami, earth quake, lightning and thunder storm etc. can cause mechanical harm to the structures.

2.7 Safety features of Storage Facilities: Petrochemical is stored in containers of capacity ranging in few grams to thousands of tons or in both fixed and portable system. For economically feasible transportation petroleum gas is liquefied. This LPG is stored in either pressure, semi-pressure or refrigerated vessels. The vessels are surrounded with a bund in case of any leakage due to vessel/tank failure. Small quantity, like 100 tons is usually stored in pressure vessel, large quantity is stored in semi-pressure or refrigerated vessels. These storage tanks should be designed and handled properly as even a small accident can lead to damage to the properties. Therefore, various organizations and engineering societies such as American Petroleum Institute (API), American Society of Mechanical Engineers (ASME) and National Fire Protection Association (NFPA) published strict guidelines and standards for construction, material, operation and maintenance procedures for storage tanks and the accessories[7].

It has now become an essential part in any industry to identify and minimize the associated hazards. To prevent accidents and to eliminate effects of accidents petrochemical storage system must have some features: Emergency shut off valve, Gas leak detection system, double walled tank, dikes, a standby tank and standby pump, water sprinkler system, excess flow check valve, pressure, temperature and level gauge, high and low pressure, temperature and level alarm, at least 600 m distance of storage facilities from publicly accessible area, grounding system etc.[7]. Pressure relief valves are used to prevent the pressure inside the storage tank from building up. A pressure build-up evaporator is often attached to the storage tank. This converts liquid from the tank into gas and returns it to the tank, as a result, the pressure does not go down. Sometimes a pressure reducing valve regulates the pressure in the tank. As an alternative, an automatic control valve may be used, which is controlled by a pressure switch. A facility containing gas must be carefully controlled to ensure the safety of the system. As the tank pressure gauge and pressure control valve control the pressure of the tank, if the pressure reaches the maximum level, it activates the relief valves.

There may also be a temperature controller to keep the temperature of the content at desired level. The level in the tank is usually measured using a differential pressure measurement. All liquid connections to the tank are fitted with shut-off valves to prevent the storage tank from emptying in case of accidents. One or two pumps are used to fill the tank. The pumps deliver the required booster pressure to the tank to be filled. The pressure of the storage tank needs to remain low. The temperature of the petrochemical then also becomes low. The temperature of the tank will therefore need to be increased, so that the pressure in the transportation pipe does not fall, and the supply to the process is not interrupted. A re heater can be installed to do this. Sometimes nitrogen is used to build up necessary pressure and provide inert environment to avoid any formation of flammable mixture.

Hazardous scenarios can be reduced by proper design, construction, maintenance and operation of storage tank, proper separation distance between two equipment, increasing the reliability of the relief valve, by avoiding valve, flanges, sampling points, or any other sampling location for potential leakage beneath the tank, trained/skilled labors, appropriate fire-fighting systems, implementation of safety management program and regular safety audit of the plant.

2.8 Counter measures to mitigate risks: Accidents can be minimized if following actions are taken and facilities are installed with the tanks.

2.8.1 Overfill and Overpressure Protection

Past accidents regarding overpressure and overfilling tells us the need for dependable, robust level and pressure indicating tools installed to give sound of alarms at high level and automatically close the fill and open the safety relief valve at high level and high-pressure situations. These control systems must be carefully designed, picked, installed and taken care of. However, perfectly trained personnel are more dependable than liquid level indicators. A proper second option would be a standby level measuring instrument installed to sound an alarm and terminate flow at a high-high level if operators do not notice or instrument malfunction allows the level to cross over the high-level alarm point of the primary device.

2.8.2 Pull away-Protection

A big number of accidental releases at petrochemical storage facilities have been occurred at loading and unloading points. The two main causes behind these incidents are

1) The driver of the tank truck forgets to unplug the hose before driving away or

2) The explosion of a hose or hose joint due to bad connection or defective hose.

For petrochemical installations of above 15 m^3 (4000 gal) capacity, NFPA 58, Standard for the Storage and Handling of Liquefied Petroleum Gases, needs an emergency shut-off valve in a liquid transport line and in a vapor line near the point of joint of the hoses to the plant piping system. The emergency shut-off valves are controlled by a heat-sensing device located not more than 1.5 m (5 ft) far from the hose connection point and by manual actuation stations situated at one or more remote sites. There is a concrete or other substantial bulkhead between the hose connections and the emergency valves so that any rupture resulting from a pull-away takes place on the hose side of the emergency shut-off valves leaving the valves and the plant piping between them and the tank safe.

2.8.3 Other Spill Limiting Feature

Excess-flow check valves are often installed in the outlets from the tanks. These are usually mounted inside the tank and thus are very difficult to service them and cannot be often relied on. A better safety feature is to install a fire-safe, fail-safe block valve on the first flange of all tank connections except pressure relief valves. These valves should be arranged to automatically close upon detection of fire or leaking gas anywhere in the area or manually from a number of remote points. Fire detection could be from heat-actuating devices or optical fire detectors. Leaks can be detected by diffusion-type combustible gas detectors. Water in the storage tanks has been used by some plants as a way of preventing petrochemical to spill from pipes attached to the bottom outlets of the tanks.

2.8.4 Sampling Points

Sampling points should not terminate under tanks, especially large storage spheres. Remote actuated valves on the sampling connection to the tank should be provided in case the sample valves do not close or cannot be reached. In areas subject to freezing weather, the sample lines should be traced to prevent freezing of water in these lines.

2.8.5 Fire Protection

There are a number of methods to protect petrochemical tanks from fire exposure. The four elementary methods are 1) Water-spray, 2) Water running down, 3) Insulation or fireproofing, and 4) Mounding or burial.

2.8.6 Water spray

Open-head water-sprinkle systems is installed to give a density of 14 L/min.m^2 (0.35 gpm/ft^2) of tank surface area over the entire tank area which keeps a tank cool in a fire where flames are approaching the tank. If, anyway, a torch type of flame hits on the surface of the tank, the water spray may not be enough to cool down the tank at that heated point. For being effective, water spray systems must be backed by clean water supplies.

2.8.7 Water Run Down

The idea of water run down is utilized to protect the exterior surface of spheres and "bullet" tanks from a fire exposure. This type of system can use a "water wire" on the top of the tank to hold water transported to the top of the tank through large diameter pipes. The water overflows the wire and cascades down the sides of the tank. Instead of the water wire, nozzles of large diameter and capacity can be used to spray down from the top of the tank. These systems thus keep most of the vulnerable portions of the tank such as the vapor space at the top safe.

2.8.8 Insulation and fireproofing

Protecting the tanks from the heat of a fire exposure by a passive form of measures such as fireproofing or thermal insulation will prevent a BLEVE from occurring. A "torch" exposure to the tank shell is normally from damaged piping or hoses.

2.8.9 Mounding or burial

Probably the best way of protecting tanks is to mound them below earth using an arrangement which includes sufficient safety measures but still allows easy removal of the top cover so that the tanks can be inspected and maintained. This kind of safety measure along with passive thermal protection provided by insulation, offers a dimension of protection from missile attack or from bursting of adjacent tanks. It is urgent to design a manhole type of top connection point for access to valves and relief devices. The tank should be protected from corrosion by a suitable coating or cathodic protection.

2.9 National Standards and Code of Practice

There are some national standards and codes of practice for LPG import, storage, transportation and marketing imposed by different government organizations of Bangladesh to prevent LPG related accidents which should be followed.

2.9.1 LPG Standards by Bangladesh Energy Regulatory Commission (BERC), 2016

Chapter 4 of Bangladesh Energy Regulatory Commission LPG Storage, Bottling, Transportation and Dispensing Codes and Standards, 2016 contains codes and standards for LPG storage tank. The codes and standards of **section 4.1** Tank and Tank Accessories are listed below.

4.1.1. Tanks shall be constructed in accordance with API 650 and meet the requirements of ASME code, section VIII, division 1 and 2 or equivalent recognized by good engineering standards container and vessel shall meet the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2 or other equivalent internationally accepted codes and standards. All material of construction shall meet the requirements of section II of this code for LPG having minimum design pressure 17 kg/ cm^2 at 38^0 C.

4.1.2. Low-melting-point materials of construction, such as aluminum and brass, shall not be used for LPG vessels or container.

4.1.3. Flange connections shall be a minimum of ASME Class 150.

4.1.4. All fittings shall be a minimum of NPS ¾.

4.1.5. Stationary Storage facilities shall have equipment to add odorant to LPG.

4.1.6. The LPG container shall be located outside of Buildings.

4.1.7. No container or tank shall be located within spill containment area.

4.1.8. The minimum horizontal distance between:

4.1.8.1. The shell of a pressurized LPG tank and the line of adjoining property, installation, building, public gathering place, heater or furnace shall be in accordance of the Table 2.9.1**.**

Table 2.9.1: Minimum Horizontal distance.

Water Capacity, Liter	**Minimum Distance, Meter**	
	Above ground tank	Underground/Mounded tank
Up to 2000	5	3
2001-10,000	10	5
10,001-20,000	15	7.5
20,001-40,000	20	10
40,001-250,000	25	15
250,001-350,000	30	15
350,001-450,000	40	15
450,001-750,000	60	15
750,001-3,800,00	90	15
Over 3,800,000	120	15

4.1.8.2. The shells of LPG tanks, spheres or pressurized vessels shall be 1.5 meters or half of the diameter of the larger vessel, whichever is the larger.

4.1.8.3. The shells of LPG Sphere or tanks and other non-pressurized tanks:

4.1.8.3.1. 1(one) diameter of the larger tank, if the flash point of the contain material is less than 38^{O} Celsius

4.1.8.3.2. ½ (half) the diameter of the larger tank, if the flash point of the contain material is greater than 38^{O} Celsius.

4.1.9. Pressurized LPG tanks or containers shall not be located within buildings, within the spill containment area of flammable or combustible liquid storage tanks.

4.1.10. The containers shall not be located and installed underneath any building. It shall be set upon firm foundation.

4.1.11. Horizontal LPG tanks with capacities of 45 M^3 or greater shall not be formed into groups of more than six tanks each.

4.1.12. Fire or radiation walls may permit separation distances to be reduced. They should be of such length that the distance from the tank to a boundary or fixed ignition source measured around the end of the wall is not less than the required safety distances.

4.1.13. Tanks shall not be located less than 4 m from the fire wall.

4.1.14. Fire wall must be solid, without openings, and constructed from brick, concrete or suitable non-combustible material and for tanks up to and including 500 liters water capacity, they shall not be less than the height of the tank. For larger tanks they shall be not less than 2 m high or the height of the tank, whichever is the greater.

4.1.15. Not more than two fire walls should be provided for any storage tank and the remaining two sides should be such that natural ventilation is not significantly impaired.

4.1.16. A fire wall may be built on a boundary but in such cases, it must be wholly under the control of the occupier of the LPG storage site.

2.9.2 LPG Standards by Department of Explosives

Chapter 6 of Liquefied Petroleum Gas Rules, 2004, published by Department of Explosives, Government of Bangladesh, provides codes and standards for storing LPG. According to section 79 of this chapter the safe distance among the storage tanks are given in table 2.9.2.1:

Table 2.9.2.1: Minimum distance for general storage of LPG.

Water Capacity, Liter	**Minimum Distance from public access, structures, buildings, other facilities and ignition source**		**Distance between two tanks, Meter**	
	Above ground tank	Underground /Mounded tank	Above ground tank	Underground/ Mounded tank
Up to 2000	5	3	1	1
2001-7,500	10	3	1	1
7,501-10,000	10	5	1.5	1
10,001-20,000	15	7.5	2	1
20,001-50,000	20	10	2	1
50,001-120,000	25	15	2 meters or whichever is larger between 1/4th of the summation of radii of two adjacent tanks and half of the radius of the larger tank	1
120,001-350,000	30	15	Same as above	1
350,001-450,000	40	15	Same as above	1
450,001-7,500,00	60	15	Same as above	1
7,500,01-3,800,000	90	15	Same as above	1
Over 3,800,000	120	15	Same as above	1

Table 2.9.2.2 and table 2.9.2.3 illustrate the minimum distance for bottling plant, storage terminal, gas process plant, petroleum refinery above 100 ton and up to 100 ton capacity tank from chapter 6 of this book.

Table 2.9.2.2: Minimum distance for bottling plant, storage terminal, gas process plant, petroleum refinery above 100 ton.

	Storage Tank	**Boundary of building or other establishment apart from storing and operation building**	**Shed of storing, filling and delivery of cylinders**	**Space for loading and unloading of tank-truck**	**Space for Tank-Wagon loading and movement**	**Pump/ compressor shed**	**Fire extinguisher pump room**
Storage Tank	Table 2.9.2.1	Table 2.9.2.1	30	30	50	15	60
Boundary of building or other establishment apart from storing and operation building	Table 2.9.2.1	-	30	30	50	30	-
Shed of storing, filling and delivery of cylinders	30	30	15	30	50	15	60

(Cont'd on next page)

	Storage Tank	Boundary of building or other establishment apart from storing and operation building	Shed of storing, filling and delivery of cylinders	Space for loading and unloading of tank-truck	Space for Tank-Wagon loading and movement	Pump/ compressor shed	Fire extinguisher pump room
Space for loading and unloading of tank-truck	30	30	30	30	50	30	60
Space for Tank-Wagon loading and movement	50	50	50	50	50	30	60
Pump/ compressor shed	15	30	15	30	30	-	60
Fire extinguisher pump room	60	-	60	60	60	60	-

Table 2.9.2.3: Minimum distance for bottling plant, storage terminal, gas process plant, petroleum refinery up to 100 ton.

	Storage Tank	**Boundary of building or other establishment apart from storing and operation building**	**Shed of storing, filling and delivery of cylinders**	**Space for loading and unloading of tank-truck**	**Fire extinguisher pump room**
Storage Tank	Table 2.9.2.1	Table 2.9.2.1	Table 2.9.2.1	15	30
Boundary of building or other establishment apart from storing and operation building	Table 2.9.2.1	15	15	15	30
Shed of storing, filling and delivery of cylinders	Table 2.9.2.1	15	15	15	30
Space for loading and unloading of tank-truck	15	15	15	15	30
Fire extinguisher pump room	30	-	30	30	-

Section 83 of this book provides rules and regulations for loading and unloading of storage tank.

1. Following standards should be followed for pumps for loading and unloading works of storage tank.

   a) Pump should be positive displacement or centrifugal type.

   b) The design, material of construction and manufacturing of pumps should be such that it suited for the nature of LPG and in the maximum allowable pressure of the tank, and it does not hamper the safety system.

   c) There should be a bypass valve with the positive displacement pump or any other arrangement to counter excess pressure.

2. The design, material of construction and manufacturing of compressors should be such that it suited for the nature of LPG and in the maximum allowable pressure of the tank, and it does not hamper the safety system.

3. In the probable emergency cases during gas loading and unloading there must be an effective arrangement outside the distances described in section 79 to prevent the gas flow.

4. To prevent LPG filling above the design level, there must be an automatic alarm or shutoff system.

5. The design of hose pipe used in loading and unloading works should be such that it can stand 4 times of the flow pressure inside the hose pipe.

6. All hose pipes should be mechanically and electrically isolated.

Section 134 describes code of construction of tanks and groups of cylinders founded in a reticulated design

This types of tanks and cylinders should be approved by the inspector and constructed according the following standards. Table 2.9.2.4 and Table 2.9.2.5 represents the standards of LPG tank and cylinder.

Table 2.9.2.4: Standards of LPG tank.

Code of construction	**ASME Section VIII Div-2 or other identical standard specification approved by Chief Inspector of Explosives in official gazette notification**
Design pressure	17.5 kg/cm (g)
Radiography	100%
Heat treatment	Yes (680^0 C-840^0 C)
Coating	450 Microns total
Mechanical test	Must be maintained at 34 bar for 30 minutes
Chemical composition of cylinder making raw materials	H.R coil must be tested at chemical lab. Test result should be submitted to Chief Inspector of Explosives for custom clearance
X-Ray test of welded cylinder	100%

Table 2.9.2.5: Standards of LPG cylinder.

Code of construction	**DOT 4 BA, BS 5045 part-2 IS 3196 Part-1. AS 2469, AS 2470, ISO4706, ASNZ3509, DOT 4BW, AS/NZ-3509**
Design pressure	17.5 kg/cm (g)
Radiography	100%
Heat treatment	Yes
Coating	40 Microns with Zinc galvanizing and 40 microns with powder coating

2.10 Hazard Identification and Risk assessment procedures: Hazard identification and risk assessment are sometimes merged into a general category called hazard evaluation. Risk assessment is sometimes called hazard analysis. A risk assessment procedure that determines probabilities is called probabilistic risk assessment, which has been chosen for the present study. Whereas a procedure that determines probability and consequences is called quantitative risk analysis. Risk is the likelihood of harm, that is, the probability for a certain effect to appear in a specific time under predefined conditions. Risk can be defined as

Risk = Event Frequency x Event's effect

American Institute of Chemical Engineers established some guidelines for Hazard Identification and Risk assessment. The steps are shown in a flow chart (Figure 2.10) below.

In this research HAZOP study was used for hazard identification and quantitative Bow-Tie method was used for determining probability at first by fault tree calculation. Then, the calculation was updated by running Agena Risk software. The scope of study does not include consequence modelling but the aftermath effects probability was calculated using event tree analysis.

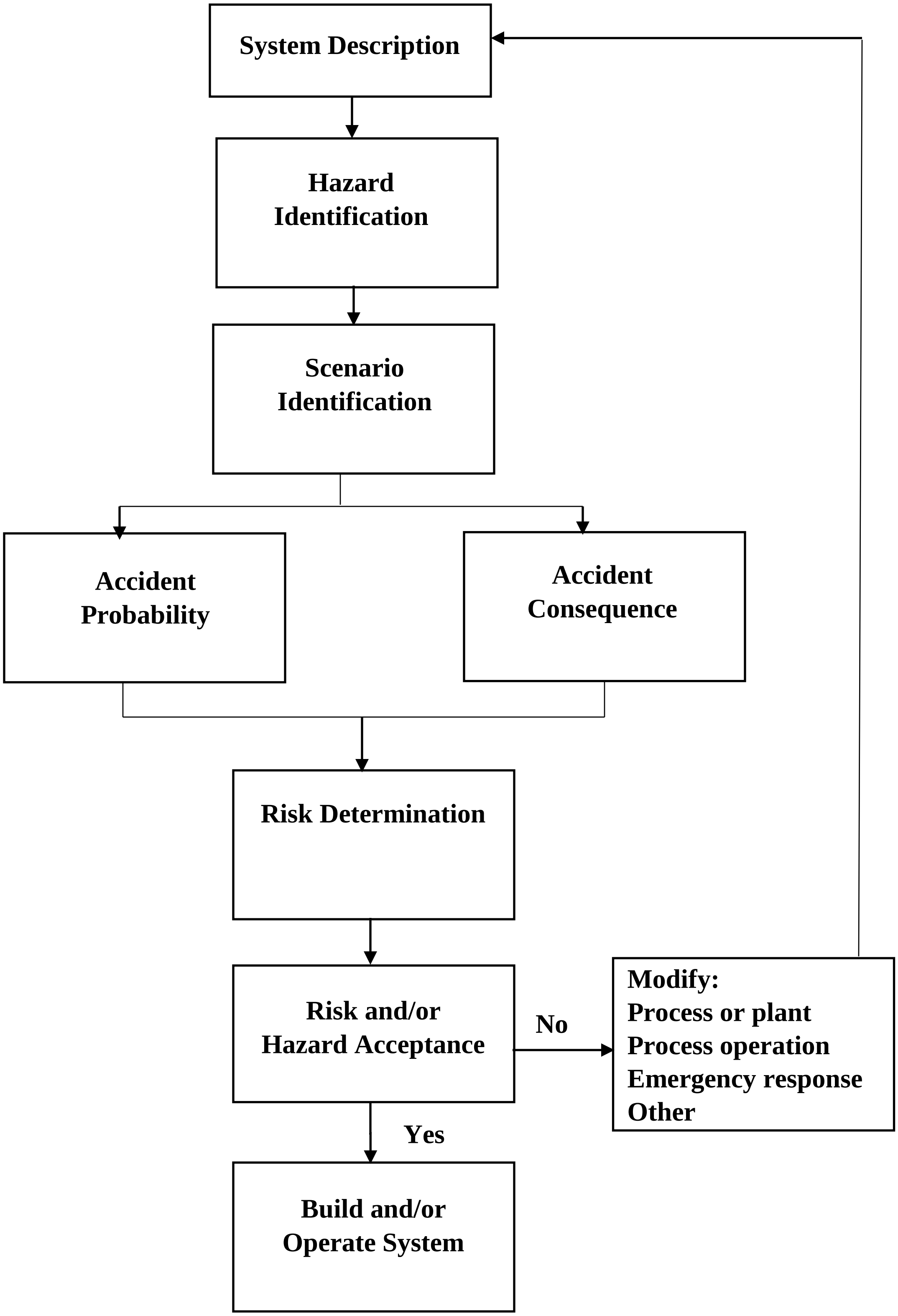


Figure 2.10: Flow diagram of Hazard Identification and Risk assessment procedures.

2.10.1 Hazard Identification:

Hazard identification can be performed independent of risk assessment. However, the best result is obtained if they are done together. In this thesis, system description was taken from a case study which is an i-butane (r600-a) storage tank of Walton group: a refrigerator manufacturing plant. Many methods are available for performing hazard identification. Only a few of the more popular approaches are described here.

a) Checklist: Checklist is the simplest methodology for hazard identification. It is a series of questions about plant layout, operation procedure, maintenance and other areas of importance to examine if all requirements have been fulfilled and nothing is ignored or skipped. Checklist is originally based on the researchers' past experience, but it can also be based on codes and standards. The checklist needs to be maintained during the lifetime of the plant and should be updated after each modification, and after every major overhauling when equipment is replaced or modified substantially[20].

b) What if: What if method involves asking a series of questions beginning with what if as a procedure of identifying hazards. Apart from checklists, What if analysis is possibly the oldest method of risk identification and is still under usage by the industrialists, engineers and operators. The method primarily involves a review of the entire design by a team using questions of this type, often using a checklist. No specialized technique or computational tool is required in this method. Once the questions have been made and answered they can be used throughout the life of the project or plant with slight change. The complete dependence on the required experience and assumption of the expert study team both to develop questions imaginatively and to get the answer proves that any limitations in this aspect of the study can make the study totally futile.

c) Indexing: This a method for hazard surveying. There are few types of indexing methods.

Dow Index: Dow's Index is a quantitative risk analysis method that has been used for hazard identification at plant level. This method was introduced by the Dow Chemical Company for fire and explosion hazard analysis. The potential occurrence of fire and explosion can be estimated by using the Dow Index combining it with a damage factor. Fire and explosion damages can be estimated economically and efficiently by using this index. It is a user-friendly and useful tool for evaluation of fire and explosion hazards in chemical process plants that uses available parameters such as temperature, pressure, and energy of chemical substances for inherent safety assessment and safer design

Mond Index: The Mond fire, explosion and toxicity index is an extension of the Dow Index. The Mond Index is a procedure of making a primary assessment of risks in a way similar to that of the Dow Index, but considering additional hazardous situations. The potential hazard is represented in terms of a set of indices for fire, explosion and toxicity. These includes fire load index, unit toxicity index, major toxicity incident index, explosion index, aerial explosion index overall index, and overall risk rating.

Instantaneous fractional annual loss (IFAL): IFAL Index considers a plant as a set of blocks and verifies each major item of process equipment in turn to examine its contribution to the index. The main hazards considered in the index are: pool fires, vapor fires, unconfined vapor cloud explosions, confined vapor cloud explosions, internal explosions etc. Unlike the Dow and Mond Indices, the IFAL Index is too complex for manual calculation and needs a computer.

d) Failure mode effect analysis (FMEA): FMEA is an examination of individual components such as vessels, pumps, valves, etc. to identify the failures which could affect process operation. FMEA is a qualitative inductive method and is easy to be used. It identifies each failure mode of the sequence of events associated with it, its causes and effects. It classifies each failure mode by relevant properties, including deducibility, diagnosing, testability, item replace ability, and compensating and operating provisions. It is said that FMEA may be a laborious and ineffective method unless considerably applied. FMEA is not able to deal with the relation among different components and needs a highly expert team with enough experience and time to carry out the study.

e) Hazard and Operability Studies (HAZOP)

Khan et al. (1998) described that HAZOP study is an elaborated hazard and operability problem identification method which is carried out by an experienced team. It is a simple but structured method for hazard identification and assessment. The hazards involved may include both those essentially relevant only to the immediate area of the system and those with a much wider sphere of influence. HAZOP is a structured and systematic technique which involves a multi-disciplinary group to examine a defined system. The HAZOP study is a formal method to identify risks in a chemical process unit. The method is effective in identifying risks and is well accepted by the chemical process industries. The primary theme is to let the thought go free in a controlled way in order to consider all the possible paths that process and operational failures can take. The basic principle of a HAZOP study is that normal and standard conditions are safe, and hazards occur only when there is a deviation from normal conditions. It is a procedure that allows its user to make intelligent guesses in the identification of hazard and operability problems. It identifies potential operability problems with the system and in particular identifying causes of operational disturbances and production deviations likely to lead to nonconforming products.

Hazard is an operation that could possibly cause a release of toxic, flammable or explosive chemicals, or any action that could result in injury to personnel. Operability means any operation inside the design envelope that would cause a shutdown that could possibly lead to a violation of environmental, health or safety regulations or negative impact profitability. It is used to identify possible modifications in process plants where accident or event frequency is abnormally high. It can be used with plant safety audits. HAZOP helps to decide where to build/install plant, check operating and safety methods, examine if safety instrumentation is working optimally, facilitate smooth, safe an robust start-up and shut-down, minimize extensive last moment changes, ensure trouble-free long-term operation.

According to Shinu et al. (2015) the elaborated process information must be available to perform HAZOP studies including updated PFD, P&ID, equipment specifications, material of construction, mass and energy balance. The special point to be analyzed is called “the node” in the process or operation. The full HAZOP study needs a committee consisting of a cross-section of experienced plant, laboratory, technical, and safety personnel. One individual must be a trained HAZOP leader and work as the committee chair. To cover all the possible deviations in the plant the brainstorming of the HAZOP team members is guided in a systematic way with a set of guide words based on determining of the effects of deviations from design intent for producing the process parameters deviations. The deviation term is used as ‘Less’/ ‘More’/ ‘No’ for process control variables available in the unit to be studied.

The guide words AS WELL AS, PART OF, and OTHER THAN can be sometimes conceptually difficult to be applied. As WELL AS means that something else happens in addition to the intended design parameters. This could be evaporation of a liquid, transfer of some other component, or the transfer of some liquid somewhere else than expected. PART OF means that one of the components is missing or the stream is being partially pumped to only one part of the process unit. OTHER THAN is applicable to conditions in which an expected material is substituted by another material, is transported to somewhere else, or the material solidifies and cannot be transported. The guide words SOONER THAN, LATER THAN, and WHERE ELSE are applied to batch processing[9].

Ajeysuriya et al. (2016) examined HAZOP study in LPG installation area to focus on the improvement of health and safety in the workplace. Fuentes-Bargues et al. (2017) combined HAZOP with quantitative FTA and applied in the risk assessment of the unloading terminals of petroleum products and two fuel storage facilities. This study shows that the most likely event is fuel spill in tank truck loading area. Riad et al. (2020) applied BT and HAZOP methods in an LPG plant for gas separation and simulated the scenarios using ALOHA software. Yadav (2015) identified relevant potential risks and necessary control measures in decanting process of LPG from dispatching unit to road tanker using HAZOP study.

1. Definition:

- Defining scope, objectives and responsibilities.
- Team selection.

2. Preparation:

- Planning the studies.
- Data collection.
- Agreeing style of study.
- Time estimation.
- Arranging a schedule.

3. Examination:

- Dividing process unit into parts.
- Choosing a part and defining design intent.
- Determining deviation, consequences and causes.
- Identifying protection system.
- Determining possible remedial/mitigation actions.
- Agreeing tasks.
- Repeating for each component, variable and each part of the system.

4. Documentation and follow up:

- Recording the examination.
- Signing off the documentation
- Producing the report of the study.
- Following up that the actions are implemented.
- Re-studying any part of system (if necessary).
- Producing final output report.

The HAZOP study utilizes the following steps to complete an analysis:

1. The flow sheet is broken into a number of process units.

2. A study node (vessel, line, operating instruction) is chosen.

3. The design intent of the study node is described.

4. A process parameter is picked: flow, level, temperature, pressure, concentration, pH, viscosity, state (solid, liquid, or gas), agitation, volume, reaction, sample, component, start, stop, stability, power etc.

5. A guide word to the process parameter is applied to suggest possible deviations.

6. If the deviation is applicable, possible causes are determined and any protective systems are noted.

7. The consequences of the deviation (if any) are evaluated.

8. Action (what? by whom? by when?) is recommended.

9. All information are recorded.

10. Steps 5 through 9 are redone till all applicable guide words are applied to the selected process parameter.

11. Steps 4 through 10 are repeated till all applicable process parameters have been studied for the selected study node.

12. Steps 2 through 11 are repeated till all study nodes have been analyzed for the selected section and move to the next section on the flow sheet[9].

HAZOP can be done at the beginning of a project, at the end of process definition, or when P&IDs are at the phase of approval for design. HAZOP should also be held for start-up, turn-around and shut-down operations. Khan et al. (1998) stated some positive and negative aspects of this method.

Advantage of HAZOP

- HAZOP provides an idea of prioritizing basis for elaborated risk analysis. It provides first information of the potential risks, their reasons, and results.
- It exhaustively examines the potential consequences of process upsets or failure to follow procedures.
- It systematically finds out technical and management safeguards and the consequences of safeguard failures.

- HAZOP gives all participants a thorough understanding of the system.
- It covers safety as well as operational aspects and considers human factors and operational procedures.
- It indicates some ways to mitigate the hazards. It can be performed at the design stage as well as the operational stage. It provides a basis for subsequent steps in the total risk management program. It is creative, structured and systematic.

Disadvantage of HAZOP

- The limitation of HAZOP stems from the idea underlying the method which is also a limitation of scope. The method assumes that the process unit design has been carried out according to the appropriate codes and standards. For example, it is pre assumed that the design is proper for the requirements of normal operating conditions.
- It is neither planned nor desired, but is inherent in the design. For example, HAZOP is not inherently applicable to spatial features associated with plant layout and the consequences.
- HAZOP is time consuming and needs labor from expert manpower.
- It needs exceptional care to fully define the scope and aims of the study.
- Despite detailed operation knowledge, much of the original design intent is often unknown.
- There is no quantitative part.
- There are chances of overlooking some events that are not related to the selected guide-words.
- People acting may lack of competence; lack of creative thought. There may arise group think; complexity; unfamiliarity and design intent ambiguity in terms; study fatigue, guide words limitation.
- Not all relevant deviations are considered. Initiating events (IEs) causes are not always found.
- Operability scenarios may be missed. Technical coverage may be incomplete, too much emphasis on major hazards; inability to address chemical reactivity hazards, incomplete documentation, bad description are some other drawbacks.

2.10.2 Scenario Identification:

Two events had been considered as prime causes of petrochemical storage facility disaster.

- ✓ Over pressure
- ✓ Over filling

Over pressure: It was considered that tank can rupture by overpressure that can release tank content. Pressure rise occurred due to blockage of safety valve, sudden drop in barometric pressure, rollover, failure of high-pressure alarm to actuate, failure of operator to take action at right time and recognize the high-pressure alarm, failure of relief valve or loss of instrument air, high temperature etc.[7]. The discharge time was supposed to decrease with the increase of storage pressure because of higher release rate which was proportional to the square root of pressure[3]. Proper instrumentation and process controls were not working, so the tank became completely full without any vapor space for expansion or contraction of the liquid. Relief devices failure to operate was the prime reason of over pressurization of the tank or rupture of associated piping[4]. Excess temperature in the storage tank lead to vapor accumulation and then to over pressure. Thus, fire and explosion might take place. Temperature could have risen due to external fire or heating, failure of temperature indicator or controller or alarm, failure of cooling system etc. In the event of a pump seal failure and ignition of escaping gas it would be possible to have the tank overheated.

Over filling: Over filling can release a large amount of petrochemical from tank. The causes of high level were considered as the level indicator failure to show the true level to operator or the operator fails to notice the indicator[7], level controller failure to actuate or the operator's failure to take necessary action after recognizing the level alarm, and the inlet or outlet valve's or pumps' failure to work.

2.10.3 Accident Probability Calculation

Accidents in chemical plants are usually the result of a complicated interaction of a number of process components. The overall process failure probability is computed from the individual component probabilities. Data are collected on the failure rate of a particular hardware component. With adequate data accident probability are calculated using the following methods which are some of the mostly practiced probability calculation methods.

a) Fault Tree Analysis: Fault tree analysis is an analytical tool that uses deductive reasoning to identify the occurrence of an undesired event. FTA, along with the data of component failure and human reliability, can determine the frequency of occurrence of an accident (Khan et al., 1998). This method indicates the aspects of the system which is relevant to an understanding of the mechanism of probable failure. It provides a graphical concept helping those people responsible for system management to visualize the hazard. Although it is the best tool available for a detailed analysis, it is not foolproof and, in particular, it does not assure us of detection of all failures, especially common cause failures. The correctness of assumption is uncertain and depends on the reliability and failure rate of components of the fault tree.

b) Event Tree Analysis: An event tree is an influential method that represents the failure sequences of various safety barriers and human action failure due to the critical event that trigger undesired consequences. An event tree graphically describes possible consequence scenarios if a top event occurs and various safety barriers either work or not. It is an inductive way to start with an initiating critical event and describe the sequences of different safety barriers and human action. Implementation of event tree is very useful to assimilate the logical relationship between the top event and the success or failure of the safety barriers. The event consequence of any main incident is analyzed after getting the main initial causes and determining the potential consequences and their impacts. However, all prevailing safety barriers are detected and their risk preventing and mitigating contributions are considered in the analysis. The series of events following an initiating cause to the loss of containment event may be impeded because of the presence of protective barriers. The possibility of the loss event to happen depends on the number of barriers in right place and their effectiveness in preventing the top event from occurring. Similarly, after the occurrence of the top event, protective barriers play role to identify and control the release source parameters or to minimize the effects of the released materials or energy on human, asset, and the environment. The extent of consequences of the top event depends on the number of protective barriers in right place and their impact on minimizing the top event consequences[21].

c) Bow-Tie Method: Bow-tie is one of the best graphical methods to present a complete incident scenario which starts from incident causes and ending with its consequences. Khakzad et al. (2013) performed dynamic safety analysis by mapping BT into Bayesian model as BT has limitations in updating data. This study preferred probability adapting to probability updating in order to get posterior probabilities dynamically. Bow-tie is an effective graphical approach normally used for process accident hazard analysis. The bow-tie diagram is a risk assessment method that is used to identify critical events, build accident scenarios, to revise causes of accidents, and to study the effectiveness and influence of safety barriers in the diagram. The application of bow-tie in risk analysis of large systems where common cause failures and dependent failures are present, is limited according to Khakzad et al. (2013). They performed quantitative risk analysis using Bow-Tie and Bayesian network on an offshore drilling operation. Bow-tie analysis has been used for analyzing occupational risk and it can also be used for mapping other types of risk in process industries including probability calculation, human error, dynamic risk analysis etc. The management of risks and their consequences, through the application of Hazard and Effect Management Process, producing bow-tie diagrams at its core, describes the various hazards that can take place and the existing process and equipment controls to impede these from occurring, or reducing the impact coming from these hazards to cause a loss event.

Bow-tie analysis can be applied in both qualitative and quantitative risk assessments for complicated situations according to Pereira et al. (2015). This study used BT coupled with Bayesian belief network in risk assessment of the operation system of a jet engine manufacturing unit considering the human failure factors, software and calibration failure factors. The bowtie methodology is an effective way of demonstrating that an organization’s risks are reduced to ALARP (As Low As Reasonably Practicable) without the over reliance on qualitative risk assessments that has been apparent in the past. The bowtie diagram graphically demonstrates that controls are in place to reduce the risk to ALARP. In that research BT has been used quantitatively. Cherubin et al. (2011) combined a quantitative risk assessment method with bow-tie using a software: baseline risk assessment tool (BART).

BT method is basically based on bow-tie diagram which is centered on a critical event and comprised of a fault tree on the left which provides all possible causes of the top event (TE) and an event tree on the right which identifies all possible consequences of the TE. The fault tree can be divided into several parts, like, initiating events which defines the principle causes of TE, undesired events, critical events etc. Badreddine et al. (2014) described that Undesirable Events (UE) and Current Events (CE) may combine to produce a Detailed Direct Cause (DDC) that may lead to a Direct Cause (DC) leading to Necessary and Sufficient Conditions (NSC) for a mishap event, and finally to the Critical Event. Consequences can be divided into three types namely. Secondary event which are the primary effects of TE, dangerous events which are the dangerous effects of SE and major event of each DE. That paper proposed a new approach to implement preventive and protective barriers based on three phases; a parameters learning phase, a simulation phase and a selection phase.

Bow tie helps to understand which possible combination of initiating events lead to the TE in the fault tree and which safety function failures will escalate the TE to a particular consequence in the event tree[22]. Badreddine et al. (2013) states in their paper that the construction of BT diagram is mainly based on experts' knowledge and follows the same basic rules as required in development of fault and event tree. They used Bayesian approach to construct bow tie diagram, to quantify the fault tree and event tree and to improve them by adding updated values. They also implemented preventive and protective barriers using Bayesian approach. It is possible to use bowtie method in conjunction with numerous techniques. Saud et al. (2013) applied BT method in downstream oil and gas facilities. Aqlan et al. (2014) combined lean manufacturing principles with fuzzy bow-tie analysis for risk assessment in chemical industries using FMEA as a lean tool. Fuzzy calculation is obtained for the risk factors and bow-tie analysis is used to estimate the combined risk probability and effects. The risks are prioritized using risk priority matrix and mitigation measures are chosen based on FMEA. Sharma et al. (2018) performed Bow-Tie approach qualitatively using Bow-Tie XP software.

According to Lu et al. (2015) fault tree analysis focuses on one particular potential incident and then constructs a logic diagram of all conceivable event sequences that could lead to the incident. After the building of fault tree, an event tree is built for each critical event. Event tree is to determine whether the initiating event will develop into a serious mishap or if the event is sufficiently controlled by the safety functions and procedures implemented in the system design. BT is an innovative approach and a good combination of quantitative risk analysis and accident consequence analysis. In that study a BT diagram was constructed for the fault tree and event tree of an underwater pipeline carrying natural gas, then a fuzzy method was used to calculate the failure probabilities and a risk matrix was proposed.

The critical event can be described as loss of containment or loss from physical unit. Preventive safety barriers are located in fault tree side and protective barriers are located in event tree side. The safety barriers can be physical and technical system or human actions based on particular procedures or management controls. So, a safety barrier can be the action of an operator, a protection system (layers of protection), emergency control system (pressure relief valve), physical unit (wall or dike) and safety maintenance system (fire extinguisher). There are four main categories of safety barriers. Figure 2.10.2 below depicts the symbolic diagram of Bow-Tie method.

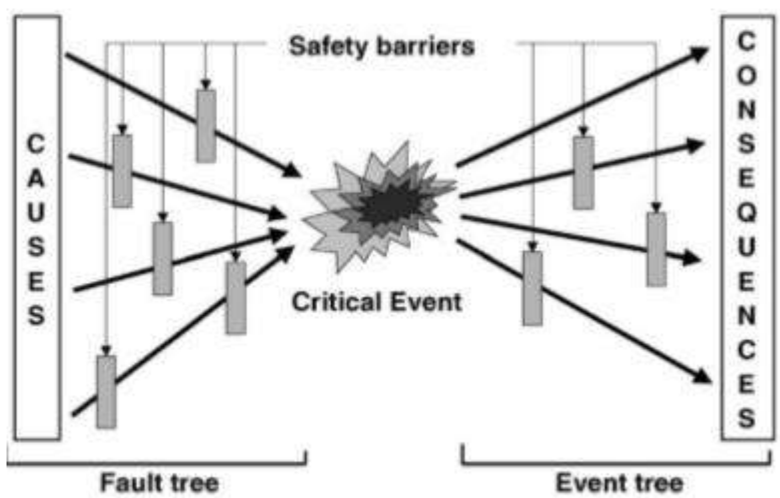


Figure 2.10.3: Bow-Tie diagram [25].

Dianous et al. (2005) described some types of safety barriers.

1. **Passive barriers:** Barriers which are always in function, does not need of human interaction, energy sources or information sources are called passive barriers. These can be physical, permanent and inherently safe.

2. **Active barriers:** These barriers set up preconditions that need to be met before the action can be taken. So, these barriers must be automatic or activated manually to function or these barriers might be mechanical barriers that need an activation so that they can function. Activated barriers always need a series of detection. This series can be performed using hardware, software or human action.

3. **Human actions:** The effectiveness of these barriers depends on the knowledge of the operator to meet the objective. Human actions are interpreted broadly including supervisions with all senses, communication, thinking, physical action and also rules, guidelines, safety regulations etc.

4. **Symbolic barriers:** These barriers need an interpretation by human in order to meet the purpose. Some conventional examples can be passive alarm, restricted areas, using labelled pipes, abstaining from smoking etc.

Each barrier has two states. Failure or success of the safety barrier. Major Hazard Scenarios are most often analyzed by the bow-tie method in which the consequence range is so bad that keeping control over these events is of major importance, whatever the actual probability of the consequences is[23]. Using the resulting BT, we can observe the behavior of some events and study their impact on TE in order to propose appropriate preventive and protective barriers at any time[24].

Advantage of Bow-tie method:

- The bow-tie concept is gaining popularity and it gives a better overview of the various considerable accident scenarios.
- All of the causes and consequences are clearly found in the bow tie.
- Moreover, it is an instrument specifically adopted to represent the influence of safety systems on the evaluation of incident scenarios.
- Safety systems, engineered or organizational can be positioned on the different classes of the bow-tie diagram[25].
- One of the major advantages of bow-tie concept is its elaborate pictorial nature which is easy to understand for administrative or technical group in omitting potential risk with the help of an effective barrier management system.
- The best part of the bow-tie is the understandable image of the risk that is easily understood by humans even less experienced ones.

Disadvantage of Bow-tie method:

- The greatest drawback is the uncertainty of quantification.
  It is not practical to make bowtie diagrams for all existing hazards. In order to quantify probability, ranking criteria and consequence severity criteria need to be developed[26].
- Process plants are complex and dynamic in nature. Dynamic properties include many time dependent parameters. Qualitative method as Bow-tie has limited ability to quantify dynamic changes in process[27].
- BT cannot capture the dependencies of safety barrier on TE. Because TE is just an initiating event for event tree and do not have effects on the failure or success of the safety barriers[22].
- The restriction to expert experience to define BT represents a real limitation of this method since it seems unrealistic to use static recommendation in real dynamic system[24].

d) Bayesian Network Analysis: Bayesian network (BN) is a probabilistic graphical model to quantify complex dependencies that can effectively deal with different uncertain problems and decisions on the basis of probabilistic data representation and inference[27]. More reliable risk data can be obtained by Bayesian estimation. BN uses the Bayes theorem to update the prior occurrence probability of events after getting new information called evidence to produce the posteriors[22]. Jiang et al. (2019) studied tanks vulnerability and domino effects using Netica software based on Bayesian theorem. Barua et al. (2015) addressed time dependent effects on risk calculation and mapped dynamic fault tree in Bayesian network. Zhang et al. (2018) applied BN model in atmospheric and vacuum distillation unit. Chen et al. (2018) estimated the handling time of transportation accidents of HAZMAT using Netica software.

Bayesian theory, named after Thomas Bayes, who established the theorem, can provide updated failure information using the prior generic data and particular conditions from process industries and from plants. Normally, the Bayesian network can be found via structure learning and variables learning based on enough data. Expert knowledge can also determine BN. According to Tong et al. (2018) some of the prior probabilities of parent nodes are obtained from accident database, safety report or previous studies, and the probabilities of child nodes are from expert opinions that are further calculated using some statistical methods. That study combined Bayesian Network analysis with Delphi method to assess mine gas explosion. Pereira et al. (2015) stated that because of the ability to adopt qualitative and quantitative data from different sources, Bayesian Network is also called Bayesian Belief Networks.

BN can give the analyst the ability to do forward and backward analyses. In the backward analysis, a series of proof is examined and posterior probability distribution can be obtained using different inference algorithm[28]. It has not been long time that the analysts have started using the advantage of BN for chemical process safety and risk assessment. BN has been incorporated in/ adopted to the layer of protection analysis[27]. BN has become an increasingly popular element of the risk and reliability analysis framework due to their capability to incorporate qualitative and quantitative data from various sources. BN is a perfect tool to understand interdependency, and to provide a causal structure which allows probability risk analysis practitioners to gain deeper insight into risk initiators and into particular interventions which reduces risks[23]. Ancione et al. (2020) developed a BN by using the data from the first application of the method accounting for aging of industrial equipment.

Bayesian calculation consists of variability and uncertainty data for resulting in Bayes' incredibility or probability intervals such as a 90% credible interval of updated information even though plant failure data are scarce. In other words, Bayesian method can compensate the weakness of failure data from LPG storage facility. Bayesian estimation is a fundamental tool to combine a prior judgment and analytical data based on Bayes' theorem. This theorem is based on the concept of conditional probability. According to Zhang et al. (2018), several basic statistical formulas and theories for quantitative BN's are presented on the basis of conditional dependence and the chain rule by estimating the product of conditional probability tables. The generalized form of Bayes' theorem for discrete variables is:

$$Pr(Aj|E) = \frac{\Pr(Aj).\Pr(E|Aj)}{\sum_{i=1}^{n} \Pr(Ai).\Pr(E|Ai)}$$

The joint probability of a set of variables U= {A1, A2,……..,An}

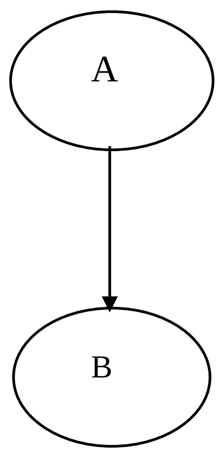
The right side of this equation contains Pr(Aj) is the prior probability. The relative likelihood depends on evidences from observations or plant specific information. Pr(Aj|E) which is updated probability of event Aj, is called the posterior probability of event Aj given that event E is occurring.

Yun et al. (2009) combined LOPA with BN analysis as BN can overcome the problem of data scarcity. They successfully applied Bayesian LOPA method to a case study. Here, probability data is renewed by compiling the prior probability and the relative likelihood. Equation represents the dynamic characteristic of the Bayesian network. The probability of each node can be renewed after having new evidence into the network with the use of the prior information of generic data and the likelihood data and then the posterior probability of the node will give an updated network[29]. The updated data can represent both statistical steadiness from the generic information and the particular conditions. Probability updating consists of the calculation of the Most Probable Explanation, which is the most probable condition of all the variables given the event occurrence. Villa et al. (2016) performed BN analysis to assess safety barriers using two techniques: probability updating and probability adapting. Probability adapting consists of the estimation of posterior probability for a generic event xi, given another event Q has taken place n times, which can be represented in statistical terms as P (xi | Q = n). Therefore, probability adapting means applying prior experience, in the form of cumulative information which is collected during a certain period of time to incorporate conditional probabilities distributions. They converted a conventional event tree to Bayesian network.

A Bayesian Network (BN) is a clear description of the direct dependencies among a set of variables in the form of a directed graph and a set of node probability table (NPT). A Bayesian network shows causal influence relations among variables by directed acyclic graph. It describes a set of random variables in nodes and their conditional dependencies via edges coming from one node going to another. It has the capability to show dependency among incidents explicitly, incorporate multi-mode and continuous discrete variables, and adopt generic or system specific information and expert opinion to support optimum decision making[30]. The NPT represents how one variable is related to another one or multivariable. Conditional probability tables (CPTs) is fundamental basis of Bayesian inference, which can be obtained by parameter learning based on enough data[29]. Ma et al. (2019) modelled an explosion at a petrol station using Bayesian network. There are three ways to fill the CPTs for the developed BN including historical information, numerical modelling and subjective opinions. Practical information includes historical record of fundamental risk factors. Subjective logical judgments are used when no data is available. The CPTs of primary nodes are filled with historical information, while numerical modelling is used to simulate various cases and produces a simulated database for filling CPTs. Subjective judgments are used for those nodes of which the CPTs can be filled on the basis of logical relationships[31]. Such judgments are helpful for deciding conditional interdependencies when logic between nodes is simple and straightforward.

Wang et al. developed BN for construction safety risk assessment using Netica software. In their paper the BN contains three layers including risk event, risk setting and risk factors. Risk setting or risk factor is considered as node and each node has two states: occurred and not occurred. Bayesian calculation includes variability and uncertainty data to result in Bayes' credibility or probability intervals such as a 90% credible interval of updated information[32].

The directed graph consists of a set of events denoted by nodes and arcs and describes casual influence relations among variable. The nodes represent the variables and the arcs link directly dependent variables. Each node state is related to probabilities. Every node is related with a probability function as input that chooses a specific set of values for the variables of the parent nodes and gives the probability or probability distribution of the variables which are shown as nodes[28]. Ifelebuegu et al. (2018), who demonstrated Bayesian-LOPA risk assessment method in critical subsea gas compression system, showed that the probability is measured through deductive reasoning for a parent node which is then computed to Bayesian logic by interference of other nodes. The nodes that influence other variables and have unconditional probability are called parent or root nodes. Nodes that are conditionally dependent on their direct parents are called intermediate nodes. The end node is defined as leaf node. Intermediate nodes are joined by arcs from primary nodes. The top event nodes are connected by arcs from intermediate nodes[27].



An arc from A to B denotes an assumption that there is a direct normal or significant dependence of B on A, the node A is then called the parent of B. There is an associated probability table with each node, called the node probability table (NPT) of A. This is the probability distribution of A which represents the set of parents of A. If the node A is without parents the NPT of A is just the probability distribution of A[33].

Parent nodes in BN are divided into two groups. These are: M type and N type. The M type nodes only occur in the probabilities between 0% and 100% given their parent nodes occur or do not occur which are obtained by logical elimination. On the other hand, the N type node occurs in the probability of any value between 0% and 100% when their parent nodes occur or do not occur which is obtained by machine learning with a set of information or by the experts' opinion. In this research M type nodes have been assessed after constructing a fault tree with those nodes. In the case of M type node, AND and OR gate can be applied to the parent node to illustrate their relationships. When OR gate is used, the probability of child node becomes extremely low[34]. In the study conducted by Yazdi et al. (2017), the fault tree is used for qualitative analysis to identify the root causes of hazardous events. The probability of the occurrence of hazardous events are calculated by translating the fault tree into Bayesian network. They have used the expert knowledge and fuzzy set theory to handle the data uncertainty and implemented BN model to demonstrate the dependence among the events. Once the frequencies of all accident scenarios are estimated, these will be compared to each other to prioritize the risks. This risk matrix may also be used to develop methods for maintenance or to implement safety measures[32].

In the following table 2.10.3 probability distribution has been classified in seven intervals as the quality probability narration of IPCC (Intergovernmental Panel on Climate Change).

Table 2.10.3: Qualitative Probability Description of IPCC[34].

Probability Interval	**Description**	**Probability interval**	**Description**
＜1%	Extremely unlikely	66–90%	Likely
1–10%	Very unlikely	90–99%	Very Likely
10–33%	Unlikely	＞99%	Virtually certain
33–66%	Medium likelihood		

However, the perfection of BN modelling is restricted by the problem of data shortage when quantification is done. Sarvestani et al. developed a bow-tie diagram and safety barriers for risk assessment of a propane storage tank. They calculated the prior probabilities of barrier failure and consequences. Then they used Bayesian equation to update the prior probabilities to posterior probabilities. Zarei et al. (2017) performed dynamic risk analysis of a flammable liquid storage system at a gas refinery. At first, they analyzed hazards using HAZOP study. Then they built a bow-tie diagram and mapped it into a Bayesian network. The BN model was simulated using the software: GeNIe. After that they carried out consequence modelling and established a risk profile and updated risk.

Advantage of Bayesian method

- Bayesian theory is robust and pliable because it gives us opportunity to rethink and change our assumptions and diagnoses in availability of new data and information.
- It is scientific and practical since it makes our model change its core.
- It has capability to modify prior information using Bayes' theorem by adopting new data.
- Besides, Bayesian network has a trait of managing different types of uncertainty.
- Bayesian network is a very helpful tool for the fields where data is not available and when one wants to exploit the sparse data available to the best[30].
- A Bayesian network will need less probability data and parameters than a complete joint probability model. This modularity and compactness mean that it is easy to elicit the probabilities and explaining model results is simple.
- BN has the capacity to estimate the probability of unknown variables and to update the probability of known parameters using conditional probability[27].

Disadvantage of Bayesian method

- Bayesian arguments can be complex.
- Doing Bayesian calculation by hand is tough.
- There may be large barriers to collect enough information in some research fields
- When there is no enough data such method not only fails to adopt expert judgment in scenarios, but also fails to show casual explanation.
- A BN is ignorant of the type of data in any variable and of the way the probability tables are arranged[33].

2.10.4 Accident Consequence Calculation:

Risk is the product of the probability of a release, the probability of exposure, and the consequences of the exposure. The actual risk of a process or plant is usually determined using quantitative risk analysis (QRA) or a layer of protection analysis (LOPA). Other methods are sometimes used; however, QRA and LOPA are the methods that are most commonly used. In both methods the frequency of the release is determined using a combination of event trees, fault trees, or Bayesian network analysis.

a) Quantitative Risk Analysis: QRA is a method that identifies where operations, engineering, or management systems need to be modified to mitigate risk. The complexity of a QRA depends on the objectives of the study and the available information. Maximum benefits result when QRAs are used at the beginning of a plant or facility and are maintained throughout the facility's life cycle. QRAs are used to evaluate potential risks when qualitative methods cannot provide an adequate management of the risks.

The major steps of a QRA study include:

1. Defining the potential event sequences and potential incidents.
2. Evaluating the incident consequences such as dispersion modeling and fire and explosion modeling.
3. Estimating the potential incident frequencies using event trees and fault trees.
4. Estimating the incident effects on people, environment, and property, and
5. Estimating the risk by combining the effects and frequencies, and recording the risk using a graph.

In general, QRA is a relatively complex procedure that requires expertise and a substantial investment of resources and time. In some instances this complexity may not be warranted; then the application of LOPA methods may be more appropriate.

b) Layer of protection analysis (LOPA): LOPA is a semi-quantitative method that assesses consequences qualitatively and quantifies failure frequency. It is a risk assessment technique commonly used in the chemical process industry that can provide a more detailed assessment of the risks and layers of protection associated with hazardous situation. It is derived from safety philosophy of the nuclear industry and was introduced to the process industries in the late nineties. The objective to perform layer of protection analysis is to determine sufficient independent safeguards available to prevent incidents from happening. It is noted all the barriers are not always independent layers of protection. LOPA is a way to identify the scenarios that present the most significant risk and determine if the consequences which could be decreased by the application of inherently safer design principles. LOPA can also be used to identify the necessity for safety instrumented systems (SIS) or other protection layers to improve process safety. LOPA allows the safety review team an opportunity to point out the weaknesses and strengths in the safety systems.

Chapter 3. Methodology

3.1 Risk Analysis Methodology

This chapter comprises of a step-by-step procedure which includes identification of potential risks, hazards, area of deviation and parameters to be analyzed within a process plant or facility. Figure 3.1.1 represents the process flow for probabilistic risk assessment of this study.

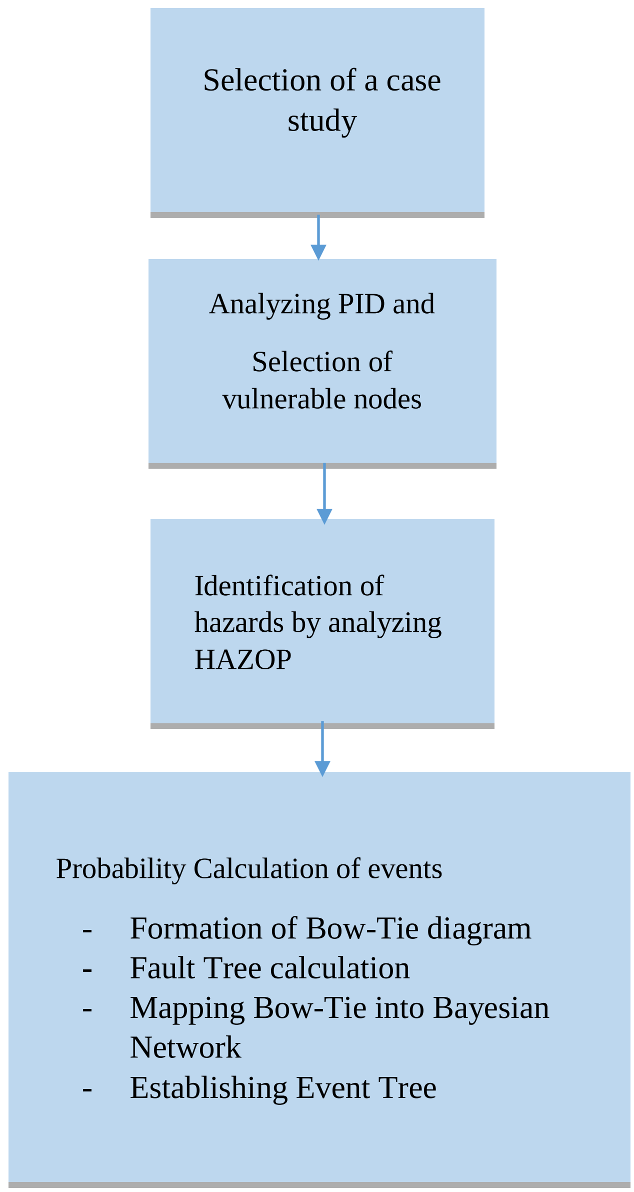


Figure 3.1.1: Development of a framework for probabilistic risk assessment.

3.1.1 Selection of a Case Study

For the present study, the storage tank of refrigerant r600a (i-butane) of the Walton Group's refrigerator manufacturing plant was taken as the case study as a petrochemical, LPG comprises of mainly butane.

3.2 Application of the methodologies

The storage tank was horizontal cylindrical and constructed of carbon steel. i-butane was kept at or below 45^0 C and 2.1 kPa (5 kPa maximum) in a fixed roof low pressure tank under a gas blanket. Suitable codes relating to the design and construction of tanks and their associated fittings were BS EN 14015 and API Standard 650. Pressure and vacuum relieving devices were designed in accordance with provisions of API Standard 620.

Figure 3.1.1 represents a simplified schematic of an i-butane storage tank. Figure 3.2.2 shows the PID of the i-butane storage facility of the case study. PG169V1 is the pressure indicator and transmitter of the storage tank whose maximum allowable pressure is 28 Kg/cm^2. If the pressure rises above 14.5 Kg/cm^2, safety relief valves SRV169V101 and SRV169V102 open and vent the excess vapor off which are pneumatically controlled by pressure controller PC169V1. If the pressure indicator or transmitter fails or the pneumatic air fails or SRV fails to open, then an excess pressure buildup occurs inside the tank. To build up necessary pressure inside the tank and to prevent condensation, vapor inserts through valves in series, 40BV16904, 40BV16903 and 40BV16902. To check excess flow there is an excess flow check valve 40EFCV16901. Liquid inlet to the tank is through 50BV16903 valve which is regulated by operator manually. Any kind of back flow is prevented by non-return valve 50NRV16901. Pressure build-up in liquid line is prevented by two pop action valve TRV16901 and TRV16902 of which the set pressure is 14.5 Kg/cm^2.

In the outlet, the liquid flow is checked by excess flow check valve 50EFCV16902 and a flow regulating valve 50BV16907 which can be regulated by operator on low level alarm or high-level alarm. FLLG169V1 is level indicator and alarm. When the liquid level alarm turns on high level, the flow controller FLLC169V1 activates and closes the liquid inlet by the emergency shutdown valve. There are two transfer pumps in the downstream, TP16901 and TP16902, between which, TP16902 is in bypass line. There are two pop action valves in the outlet, TRV16903 and TRV16904. QI-LD16901 and QI-LD16902 are leak detection systems. TG169V1 is the temperature indicator and alarm. In case of sudden overflow of the tank, there is a drain out system, checked and regulated by 25EFCV16901, 25BV16901 and 25BV16902. When level alarm turns on, the operator goes to the spot and regulates the inlet or outlet valves manually.

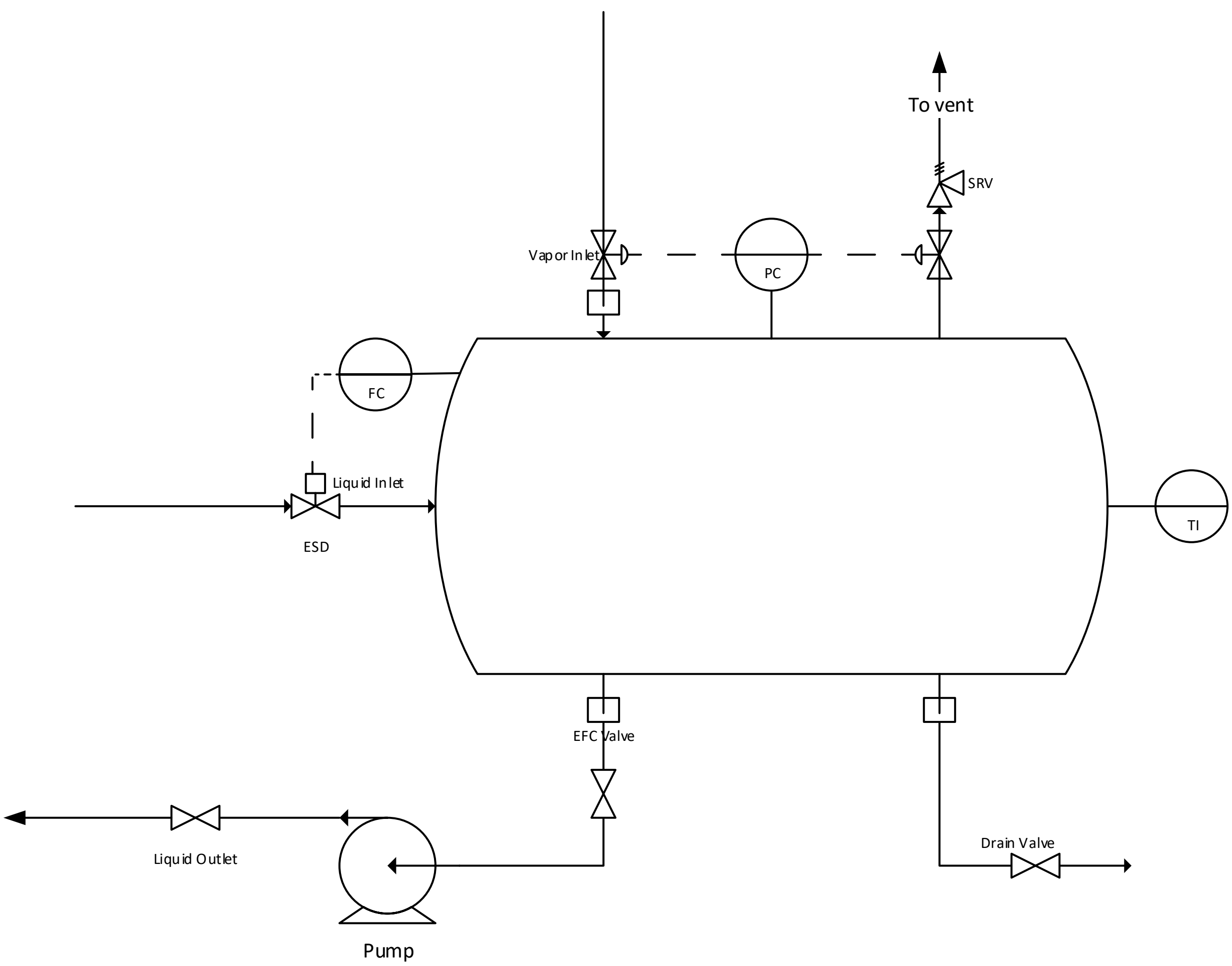


Figure 3.2.1: Simplified schematic diagram of i-butane Storage Facility.

	Excess flow check valve
	Leak detection
	Emergency Shutdown Valve
	Safety Relief Valve
	Pump
	Pop Action Valve
	Non-return Valve
	Unloading Hose
	Sight Glass
	Ball Valve
Fire Alarm	
Smoke Detector	

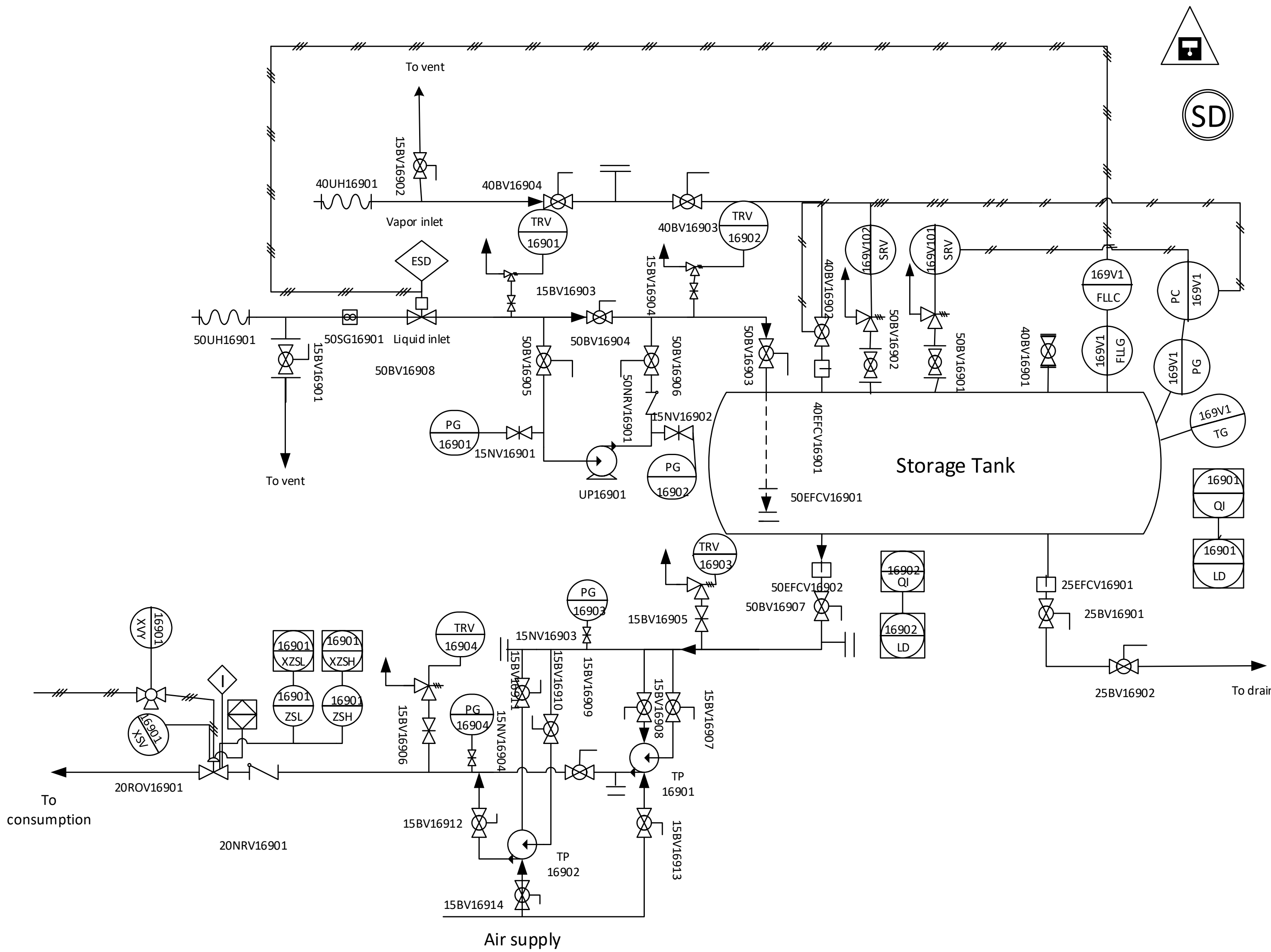


Figure 3.2.2: PID of i-butane Storage Facility.

3.3 Systematic approach of risk assessment:

The risk assessment of i-butane storage tank had been conducted by Bayesian Network following hazard and barrier identification by Bow-Tie analysis and HAZOP. Among these, HAZOP study was qualitative and the other two methods were quantitative. After identification of potential hazards using HAZOP study, fault tree calculation from Bow-Tie method had found out the frequencies of risks which was further updated using Bayesian approach. The calculation and analysis procedure of these three methods are discussed below.

3.3.1 HAZOP analysis

HAZOP study was carried out about i-butane storage tank. At first the PID of the i-butane storage tank was examined systematically. i-butane storage tank was considered as study node. The design intent of the node was to store flammable i-butane. The process parameters used in this study were pressure and level. The guide word applied to the process was ‘more’. Then the causes and consequences of the deviation were found out. Undesired reasons and bad results for all ‘more’ deviation from desired operation that could arise were found. Existing safeguards had been listed. Then recommendation had been discussed in the last column of the following HAZOP table 3.3.1. All the information was recorded.

The first column of table 3.3.1 indicating ‘Item’ was used to give a unique determiner for each scenario considered. And deviation or guide words were listed in the second column. The next three columns were the most important outcome of the analysis. The third column describes the possible reasons. These reasons were accountable for the specific deviation-guideword combination. The next column comprised of the probable results of the shifting. The last column described the action needed to prevent the hazard from resulting in an accident. The items contained in the last three columns were numbered serially. The last several columns were used to identify the work responsibility and ending of the study.

Table 3.3.1: HAZOP study applied to i-butane storage tank.

Project name: 169		Date: 05/07/2020	Page: 1 of 1		Completed:	
Process: i-butane storage tank shown in figure 3.2.2					No action:	
Section: i-butane storage tank shown in figure 3.2.2			Reference drawing: Figure 3.2.2		Reply date:	
Item / Line /Stage	Guide word	Causes	Consequences	Existing safeguards	Recommendation	Assigned to:
Pressure	More	1. Relief valve SRV169101 and SRV169102 fail closed 2. Pressure control valve 40BV16902 and excess flow check valve 40EFCV16901 fail open 3. Failure of pressure transmitter PG169V1and pressure-controller PC169V1 4. External heat or fire	1. Vapor accumulation 2. Tank or pipeline rapture, fire and explosion 3. Pressure remains unchecked and no regulation of pressure 4. Temperature increase	1. High pressure alarm 2. Safety relief valve 3. Pop action valve, excess flow check valve and operator's intervention 4. Temperature indicator and alarm (TG169V1)	1. Regular testing and calibration of safety relief valves SRV169101 and SRV169102, selection of safety relief valves: fail open 2. Regular inspection and maintenance of excess flow check valve 40EFCV1690 and pressure control valve 40BV16902 and select these valves: fail closed 3. Redundant pressure transmitter and Controller, calibration of PG169V1and PC169V1 4. Install cooling water service and open head water sprinkler over the entire tank area, installing temperature controller and tank insulation	
Level	More	1. Failure of level indicator (FLLG169V1) and level controller (FLLC169V1) 2. Emergency shutdown valve fails open 3. Pump surging 4. Failure of excess flow check valves 25EFCV16901, 50EFCV16901 and 50EFCV16902	1. Level remains unchecked and no regulation of level 2. Tank overflows and i-butane release, fire and explosion 3. i-butane accumulation and pressure increase inside the tank and associated pipelines 4. Tank or pipeline bursting	1. Excess flow check valve, drain out valve and operator's intervention 2. High level alarm and leak detection system 3. ESD valve, pop action valve and safety relief valve 4. Level controller and emergency shut-down valve	1. Redundant level indicator and controller and regular inspection and calibration of these 2. Select emergency shut-down valve: fail closed, installing dikes and standby tank 3. Regular inspection and maintenance of pumps and having redundant pumps 4. Regular inspection, and maintenance of EFC valves 25EFCV16901,50EFCV16901 and 50EFCV16902	

3.3.2 Bow-Tie Method

A bow tie diagram was built using Bow Tie XP software. The construction of bow tie diagrams was mainly based on experts' knowledge and follows the same basic rules as required in development of fault and event trees. The top or critical event was i-butane release from storage tank. The first step of the risk analysis was the identification of major accident hazards possibly to occur on a plant. The working steps with the software included:

- Creating new bow tie group
- Creating new hazard
- Naming the hazard and the top event
- Creating threats on the left side of the top event which represents a fault tree
- Creating consequences on the right side of the top event which represents the event tree
- The impacts of faults on the top event had been studied to define the possible barriers
- Creating preventive barriers after the threats and before the top event to limit the occurrence of top event
- Creating protective barriers after the top event and before the consequences to reduce the severity of the consequences

3.3.3 Bayesian Network Analysis

In this research, in order to facilitate the update of BT and reliable probability calculation with least error, the BT was updated and mapped in BN. Agenarisk^{TM} software was used for Bayesian node analysis. For each basic, intermediate and top event; root, intermediate and top event node were created respectively. Intermediate nodes were connected by arcs from those root nodes that caused the intermediate events from the basic events. Then top event node was connected by arcs from intermediate nodes and from one root node, as it directly affected the final top event. The steps included:

- Updating the fault trees of the Top Event and barrier failures by incorporating additional probable causes
- After increase in frequencies of the Top Event and barrier failures, probability of consequences increased
- To lessen the consequence severity, implementation of additional barriers
- Defining the nodes of new fault trees
- Connecting the nodes with arrows
- Changing the node names
- Defining the unique identifier
- Defining the node type, Boolean/Manual
- Preparing the node probability table
- NPT editing mode, manual/expression

Node analysis was done for barrier failure and occurrence of the top event based on the same fault trees as constructed for bow tie method. Using the event tree calculation and the probability failure of the barriers, frequency of consequences was updated.

3.4 Source of component failure data: The failure rate of safety/controlling equipment and safeguards were collected from 'Guidelines for Process Equipment Reliability Data with Data Tables, U. Centre for Chemical Process Safety of the American Institute of Chemical Engineers'. Chapter 5 of this book provides failure rate data table. Chapter 6 discusses how to collect and treat the data. Failure rate data generated from collecting information on equipment failure experience at a plant were referred to as plant-specific data. All used sources of available generic equipment reliability and failure rate data included reliability studies, published research works, reliability data banks, or government reports that contained information gathered from chemical process, nuclear, offshore oil, and fossil fuel industries around the world. The data presented in this book were characterized as equipment failures per 10^6 operating hours for time-related failure rates and failures per 10^3 demands for demand-related failure rates. For this research time related failure rates were utilized. The data came in form of failure frequency. These value were converted to probability before calculation.

$P = 1-e^{-\mu t}$ where, P=failure probability, μ= failure frequency, t=time range.

Some failure rate data were also collected from 'Failure Rate and Event Data for Use within Risk Assessments, Health and Safety Executive Unit'. In this handbook there were three types of data: Failure rate, Event data and Human factor. Many generic failure rates were derived from RISK Assessment Tool as detailed in the various parts of the Major Hazards Assessment Unit Handbook. The greatest difficulty in assigning failure rates was the lack of appropriate industry failure rate data but, in the absence of failure rate data specific to particular plant, processes and substances, the generic values given in this section were used as initial values. These generic values were modified to take account of site-specific factors. The specific failure rates were determined by expert judgment by the experts, taking significant factors along with any specific data available into account. Table 4.2.1, 4.2.2, 4.2.3, 4.2.4, 4.2.5, 4.3(a) and 4.3(b) of Chapter 4 contains those failure frequencies and were used in calculation. Not all the data of those tables were used in fault tree calculation, but in BN analysis.

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Chapter 4. Results and Discussion

Risk assessment was used to determine the threats or potential hazard that can initiate an accident and to acquire the frequencies of those events. For this work a study on i-butane storage tank was performed. Risk assessment was done considering the worst-case scenario. Necessary data for the risk assessment was taken from literature and i-butane storage plant. For the risk identification and estimation, following methods were considered:

1. HAZOP study
2. Bow-Tie Method
3. Bayesian Network Analysis

4.1 HAZOP Study

The HAZOP table 3.3.1 in chapter 3 shows the HAZOP study. To carry out the HAZOP analysis, the PID of i-butane storage tank had been studied first. Process information and data was collected from field visit of a refrigerator manufacturing industry. The node to be analyzed was the storage tank. Though there were many other drivers behind loss of containment from a storage tank, pressure and level had been chosen which influenced the process of storing flammable chemical to a great extent. The deviation term from intended pressure and level was 'More'. The causes of deviation from intended or design pressure and level had been identified. The design errors or potentially abnormal operating conditions had been discussed here. The consequences of the deviation had been anticipated. It also showed that failure of existing safeguards caused the deviation. Corrective measures for future or recommendations were another vital part of HAZOP analysis. The role or contribution of each part or section of the tank to maintain the process variables at desired level had been assessed.

4.2 Bow-Tie Method: A Bow-tie diagram was built and the barriers on the diagrams were determined. The safety barriers were classified as four principal barriers. For identifying safety barriers, the Bow-tie diagram was scrutinized keeping some facts in mind: Will the safety barrier control, limit, prevent, or avoid the accident? If yes, the safety barrier should be located in the required position. The failure rates of the basic events fault tree were taken from reliable sources and the prior failure probabilities of the barriers were calculated. Five levels of severity of consequences on the basis of the failure or success of safety barriers were considered. These are: safe, near miss, mishap, incident and accident.

With the prior probability of failure of the barriers, the probabilities of occurrence of each degree of consequences were calculated and shown in the event tree. Four protective barriers introduced here, are: Release Prevention Barrier (RPB), Dispersion Prevention Barrier (DPB), Ignition Prevention Barrier (IPB) and Escalation Prevention Barrier (EPB). After updating the event tree, two more new barriers were: Emergency Management and Damage Control Barrier (DC and EMB), and Human Factor Barrier (HFB).

The causes of the failure of these barriers were shown in different fault trees which triggered the consequences. The failures of preventive barriers were the reasons behind the top event which were also shown in a fault tree. The large fault trees were divided into some smaller fault trees for better understanding. The probabilities of the consequences were shown and calculated with the help of an event tree.

In this analysis there were two static gates, i.e., AND-gate, and OR-gate, that connected basic initial events with secondary events and top event. AND gate was used when the output event occurred only when all the input events existed simultaneously. OR gate was used when the output event occurred if any of the input events happened.

Figure 4.2.1 shows the bow-tie diagram with the top event i-butane release on the center of the diagram. The fault tree on the left side includes the causes: leakage from pressure relief valve, over filling and leakage from drain valve. The event tree on the right side includes fire and explosion. The preventive barriers on the fault tree before the top event are pressure transmitter and controller, pressure control valve, pressure relief valve, fluid level indicator and controller, maintenance of pumps and valves. The failures of these barriers were shown as the basic or root causes in the fault tree calculation. The protective barriers on the event tree after the top event are release prevention barrier, dispersion prevention barrier, ignition prevention barrier and escalation prevention barrier.

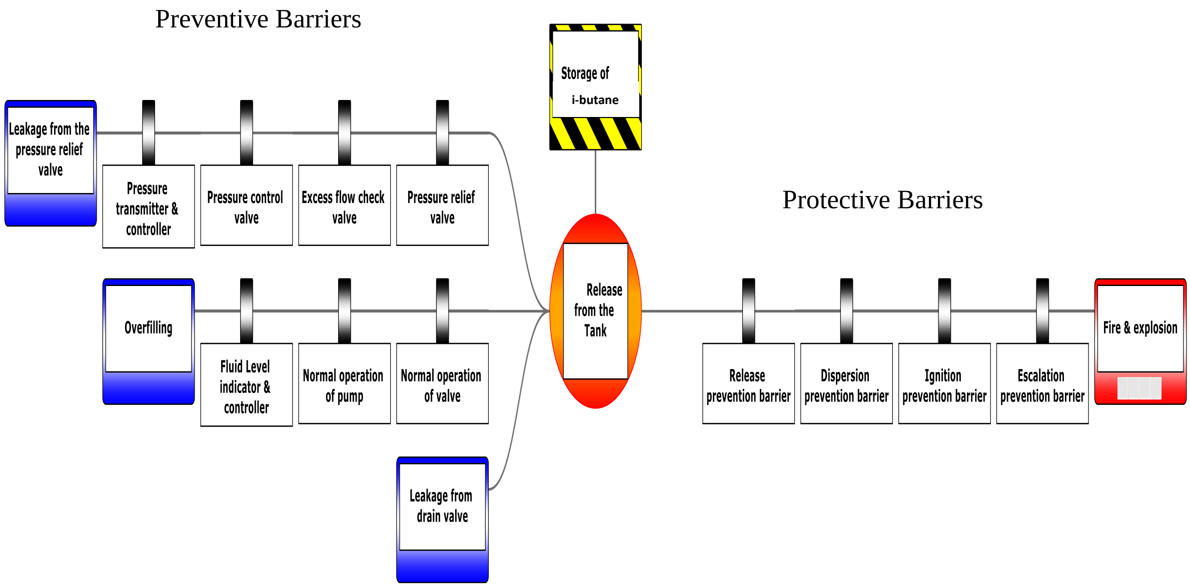


Figure 4.2.1: Bow-Tie diagram for i-butane release from storage tank.

The existing safety features of the PID being studied, were considered for the fault tree calculation of the bow-tie method. Later, more safety barriers had been recommended in the updated bow-tie diagram whose failure rates also had been updated Bayesian calculation. The frequency calculation was done based on the following fault trees using AND and OR gate of Boolean algebra for the top event occurrence and failure of barriers. The primary failure rates were taken from reliable data sources.

From figure 4.2.2(a), we can see that the causes: leakage from the pressure relief valve, overfilling and leakage from drain valve were connected with an AND gate, that means all of the reasons needed to be present for the occurrence of the top event: release from the tank. AND logic thus reduced the probability of occurrence of any incident. On the other hand increase of the internal pressure of the tank and failure of pressure relief valve were connected with an OR gate which means presence of any of these reason can make leakage from the pressure relief valve happen. OR logic increased the probability of any incident.

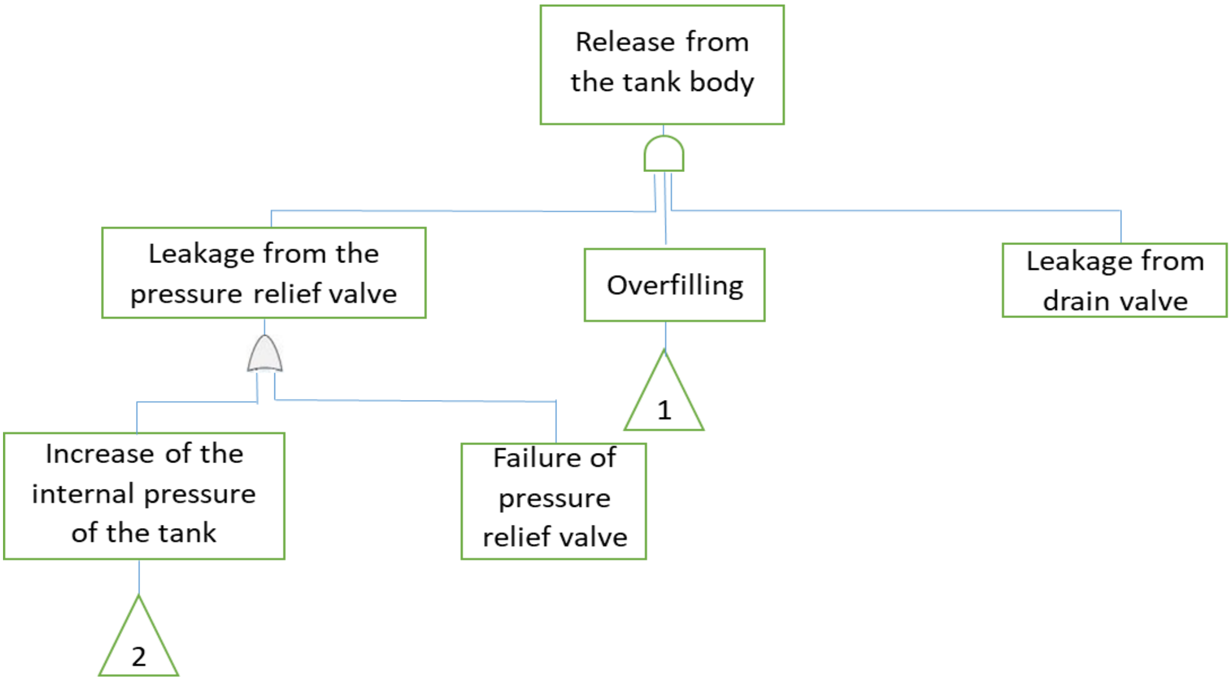


Figure 4.2.2(a): Fault tree diagram of release from tank body.

Figure 4.2.2(b) shows that the occurrence of overfilling depended on any of the causes: pump failure, fluid level indicator failure and failure of normal operation of valve.

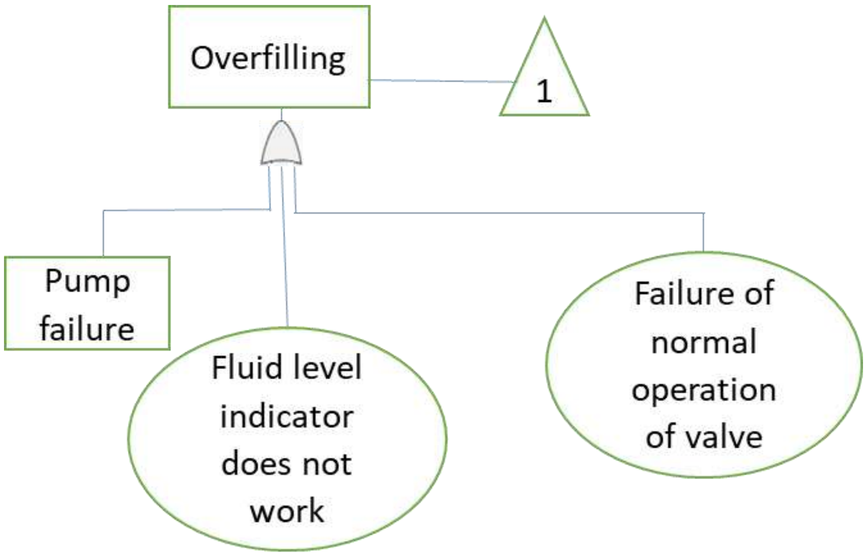


Figure 4.2.2(b): Fault tree diagram of overfilling.

Figure 4.2.2(c) explains how the probability of the occurrence of increase in the internal pressure of the tank depended on both of the lack of insulation and tank reaches relief valve set pressure. Tank would reach relief valve set pressure if any of these incidents happened: pressure transmitter failure, EFC valve failure and pressure control valve failure, as these causes were connected by an OR gate. Table 4.2.1 shows the failure frequency used in calculation.

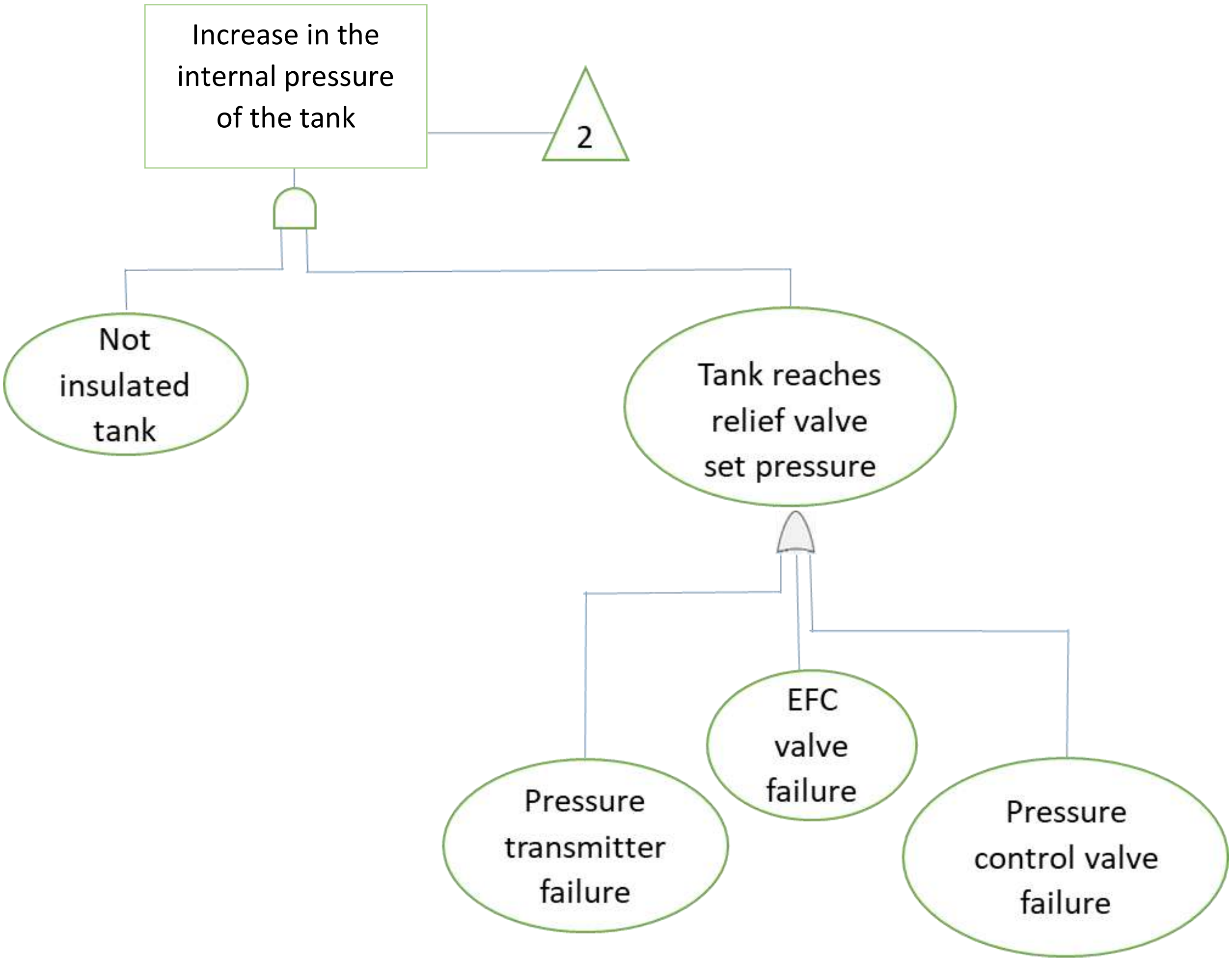


Figure 4.2.2(c): Fault tree diagram of increase in the internal pressure of the tank.

Table 4.2.1: Failure rate of basic events of the top event [40, 41].

Event Name	Event Description	Failure Rate μ (event per year)	Probability ($1-e^{-\mu t}$)
P1	Maintenance error of pump	4×10^{-2}	0.039210561
P2	Design error of pump	3.653×10^{-3}	0.003646336
P3	Operator's error	0.0348	0.034201443
P4	Fluid level indicator does not work	0.0203	0.020095342
P5	Close of valve to fire	2.409×10^{-3}	0.002406101
P6	Damage to valve	2.4×10^{-3}	0.002397122
P7	Damage to sprinkler system	1.4717×10^{-3}	0.001470618
P8	Partial or complete blockage of the pipe	3×10^{-4}	0.000299955
P9	Low cooling capacity	2×10^{-2}	0.019801327
P10	Freezing water inside pipe	5×10^{-4}	0.000499875
P11	Not insulated tank	3×10^{-2}	0.029554466
P12	External fire	1.472×10^{-3}	0.001470917
P13	Structural failure of the barriers around the site	10^{-2}	0.009950166
P14	Guardian negligence	2×10^{-2}	0.019801327
P15	Electronic system failure	8.76×10^{-6}	8.75996×10^{-6}
P16	Passive defense	2×10^{-3}	0.001998001
P17	Fatigue	10^{-3}	0.0009995
P18	External corrosion	0.1	0.095162582
P19	Internal corrosion	0.1	0.095162582
P20	Material or structural defects	10^{-2}	0.009950166
P21	Leaving the drain valve open	4×10^{-2}	0.039210561
P22	Failure to follow work instructions	5×10^{-2}	0.048770575
P23	Valve freeze	10^{-3}	0.0009995
P24	Insufficient control over the valve	2×10^{-2}	0.019801327
P25	Very large valve diameter	7×10^{-3}	0.006975557
P26	Improper discharge to environment	0.0592	0.057481753
P27	Tsunami and earthquake	5×10^{-2}	0.048770575
P28	Lightning	3×10^{-2}	0.029554466
P29	Design error of valves	0.042	0.041130219
P30	Maintenance error of valve	5×10^{-2}	0.048770575
P31	Failure of normal operation of valve	1.235×10^{-4}	0.000123492
P32	Failure of pressure control valve	10^{-4}	9.9995×10^{-5}
P33	Failure of pressure transmitter	8.8476×10^{-3}	0.008808575
P34	Failure of excess flow check valve	0.0278	0.027417136

Fault tree calculation of i-butane release:

Probability of pump failure, P36=P2= 0.003646336

Probability of overfilling, P37=P4UP36UP31

= 1- [(1-0.020095342)(1-0.003646336)(1-0.000123492)]

= 0.0237

Tank reaches relief valve set pressure, P40= P32 U P33 U P34

$=1-[(1- 9.9995x10^{-5})(1-0.008808575)(1-0.027417136)]$

= 0.036080602

Probability of increase in the internal pressure of the tank, P41= P40 ∩ P11

$=0.036080602x0.029554466 = 1.0663x10^{-3}$

Probability of leakage from drainage valve, P48= P23

=0.0009995

Probability of failure of pressure relief valve, P50= P29 = 0.041130219

Probability of leakage from pressure relief valve, P51= P41 U P50

$= 1-[(1-1.0663x10^{-3})x(1-0.041130219)]$

= 0.04215

Probability of release from the tank= P51∩P37∩P48

= 0.04215x 0.0237x 0.0009995

$= 9.985x10^{-7}$

Frequency of release of i-butane from tank= -ln(R)=-ln(1-P)

$= -ln(1-9.985x10^{-7})= 9.985x10^{-7}$/year

Figure 4.2.3(a) shows that any reason among faulty safety relief valve, faulty pressure gauge, failure of excess flow check valve and failure of the overfilling prevention system were responsible for the release prevention barrier failure. Also failure of excess flow check valve happened for any of improper diameter of the downstream pipe of the excess flow check valve and faulty excess flow check valve.

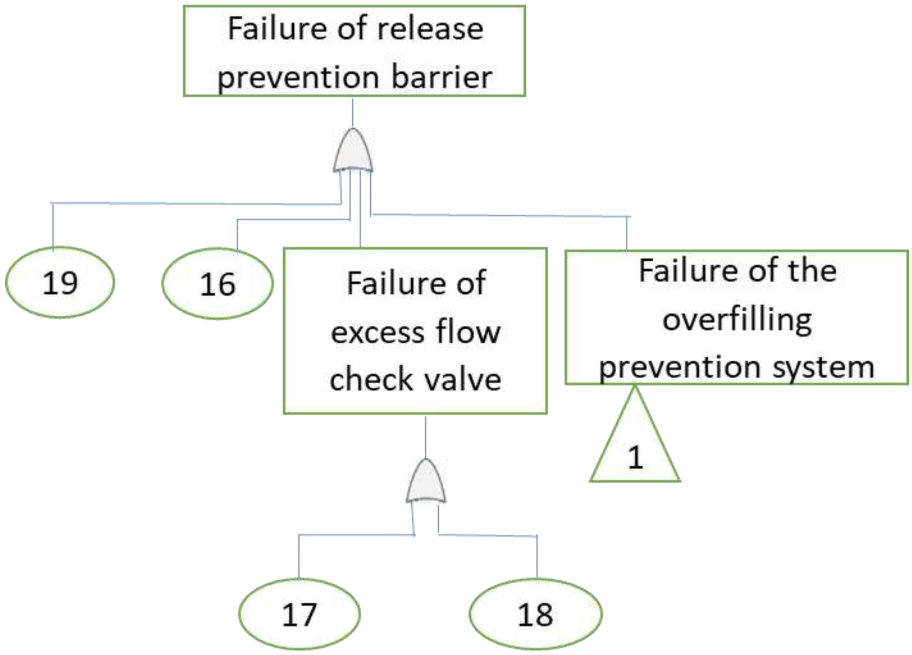


Figure 4.2.3(a): Fault tree diagram of release prevention barrier failure.

Figure 4.2.3(b) shows that failure of overfilling prevention system depended on all of failure in current stop, automatic shutdown valve failure and failure of liquid level control. Failure in current stop depended any of delay in stopping the pump after a release and operator's failure to stop the pump. Table 4.2.2 shows the failure rates of release prevention basic events.

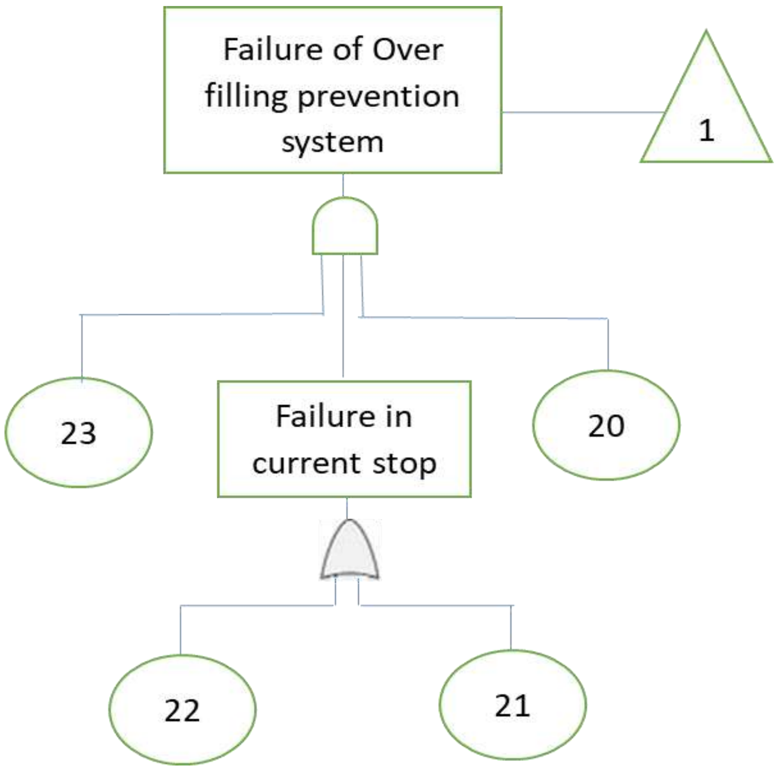


Figure 4.2.3(b): Fault tree diagram of the failure of overfilling prevention system.

19= Faulty pressure gauge, 16= Faulty safety relief valve, 17= Improper diameter of the downstream pipe of the excess flow check valve, 18= Faulty excess flow check valve

20= Automatic shutdown valve failure, 21= Operator failure to stop the pump, 22= Delay in stopping the pump after a release, 23= Failure of liquid level control

Table 4.2.2: Failure rate of release prevention basic events[40, 41].

Event Name	Event Description	Failure Rate μ (event per year)	Probability ($1-e^{-\mu t}$)
P1	Failure to perform the necessary inspections after maintenance	1.5×10^{-2}	0.01488806
P2	Improper connection of screws, flanges and fittings	3.8×10^{-2}	0.037287059
P3	Failure to follow the maintenance instructions	4×10^{-2}	0.039210561
P4	Use of inappropriate materials in repair or modification	1×10^{-2}	0.009950166
P5	Wrong position of the valve after repairs (valve left open)	4×10^{-2}	0.039210561
P6	Isolation failure	3×10^{-2}	0.029554466
P7	Failure of inspection of tank bases	1×10^{-2}	0.009950166
P8	Internal inspection failure in terms of corrosion	1×10^{-1}	0.095162582
P9	Exterior body inspection failure in terms of corrosion under insulation (CUI)	1×10^{-1}	0.095162582
P10	Small connection inspection failure in terms of corrosion	1×10^{-2}	0.009950166
P11	Not calibrated destructive test equipment	3×10^{-2}	0.029554466
P12	Failure of visual inspection	2×10^{-2}	0.019801327
P13	Fail of inspection of longitudinal and peripheral welds	6.6×10^{-2}	0.063869136
P14	Failure of subsurface cracking monitoring (hydrogen permeation cracking)	10^{-3}	0.0009995
P15	Failure of superficial crack monitoring (fatigue, caustic stress cracking and sulfide-induced cracking)	10^{-4}	$9.9995\text{x}10^{-5}$
P16	Faulty safety valve	1.7×10^{-2}	0.016856315
P17	Improper diameter of the downstream pipe of the excess flow valve	7×10^{-3}	0.006975557
P18	Faulty excess flow valve	2×10^{-3}	0.001998001
P19	Faulty pressure gauge	9.7×10^{-3}	0.009653107
P20	Automatic shutdown valve failure	10^{-2}	0.009950166
P21	Operator failure to stop the pump	10^{-1}	0.095162582
P22	Delay in stopping the pump after a release	10^{-2}	0.009950166
P23	Failure of liquid level control	1.5	0.77686984
P24	Lightening protection failure	3×10^{-2}	0.029554466
P25	Failure to strengthen tank foundations and bases	1×10^{-3}	0.0009995
P26	Sabotage/terrorism prevention barrier failure	2×10^{-3}	0.001998001
P27	Tank bases fireproofing barrier failure	3×10^{-2}	0.029554466
P28	Insulation of tanks barrier fall	3×10^{-2}	0.029554466
P29	Failure to comply with the standard distance between adjacent tanks and installations	8×10^{-2}	0.076883654

Event Name	Event Description	Failure Rate μ (event per year)	Probability ($1-e^{-\mu t}$)
P30	Failure to comply with the standard distance between the tanks	3×10^{-2}	0.029554466
P31	Lack of enough water	10^{-2}	0.009950166
P32	Failure to activate the cooling system	2×10^{-2}	0.019801327
P33	Freezing water inside the pipes	5×10^{-4}	0.000499875
P34	Partial blockage of pipes	3×10^{-4}	0.000299955
P35	Completely blockage of pipes	10^{-4}	$9.9995x10^{-5}$
P36	Blockage of sprinklers	8×10^{-4}	0.00079968
P37	Lack of protection of pipes and fittings	1×10^{-3}	0.0009995
P38	Lack of fences around the tanks	1×10^{-2}	0.009950166
P39	Failure to follow work instructions	5×10^{-2}	0.048770575
P40	Failure to activate the isolation valve	2×10^{-2}	0.019801327
P41	Drain/sampling valve left open	4×10^{-2}	0.039210561
P42	Lack of isolation valve	1×10^{-4}	$9.9995x10^{-5}$
P43	Isolation valve failure	1×10^{-3}	0.0009995
P44	Do not isolate the area	4×10^{-3}	0.003992011

Fault tree calculation of release prevention barriers:

Probability of failure in current flow stop, P52= P21 U P22

= 1-[(1-0.095162582)(1-0.009950166)]

= 0.104166

Failure probability of overfilling prevention system, P53= P20 ∩ P23 ∩ P52

= 0.009950166x0.77686984x0.104166

= 0.000805

Probability of failure of excess flow valve, P60= P17 U P18

= 1-[(1-0.006975557)(1-0.001998001)]

= 0.00896

Probability of failure of release prevention barrier, P(RPB)= P16 U P19 U P53 U P60

= 1- [(1-0.016856315)(1-0.009653107)(1-0.000805)(1-0.00896)]

= 0.035847

Figure 4.2.4 shows that both automatic and manual detector failure caused the detection system fail. Failure of any of gas detector system and flow stop valve made dispersion prevention barrier fail. Table 4.2.3 failure rate of dispersion prevention barrier basic events.

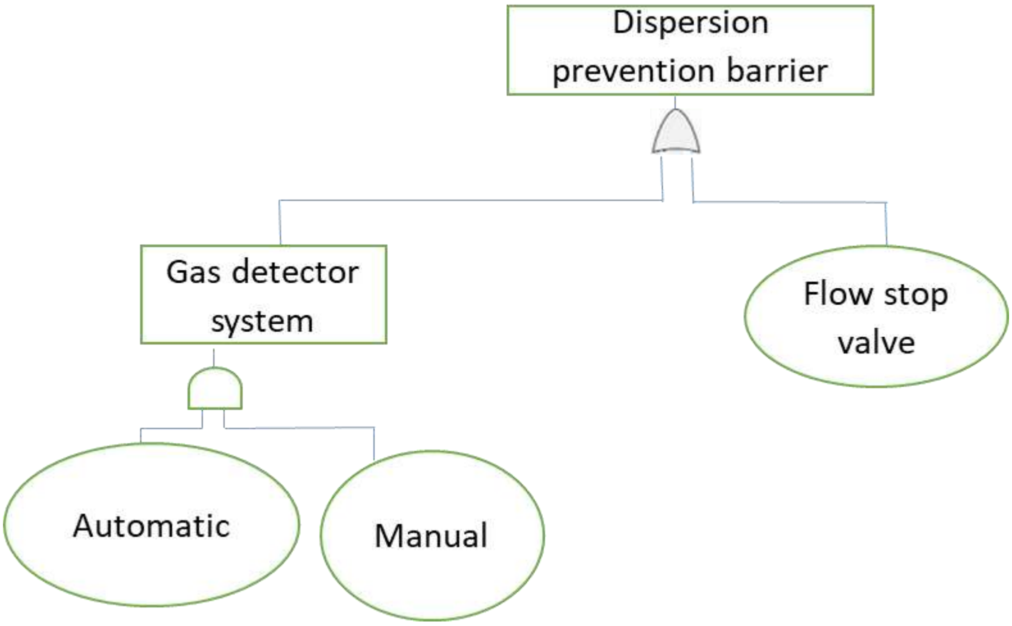


Figure: 4.2.4: Fault tree diagram of Dispersion prevention barrier.

Table 4.2.3: Failure rate of dispersion prevention barrier basic events[40, 41].

Event	**Event Description**	**Failure Rate, μ (event per year)**	**Probability ($1-e^{-\mu t}$)**
P1	Flow stop valve	10^{-3}	0.0009995
P2	Manual gas detector system	$1.73x10^{-4}$	0.000172985
P3	Automatic gas detector system	$4.64x10^{-4}$	0.000463892
P4	Passive barriers such as walls	10^{-2}	0.009950166
P5	Continuous site inspection	$2x10^{-2}$	0.019801327

Fault tree calculation of dispersion prevention barrier failure

Failure probability of gas detector system: P6= P2 ∩ P3

= 0.000172985x0.000463892

= $8.02464x10^{-8}$

Failure probability of dispersion prevention barrier, P(DPB) = P1 U P6

$$=1-[(1-0.0009995)(1-8.02464 \times 10^{-8})]$$

$$= 9.9958 \times 10^{-4}$$

Figure 4.2.5 depicts that ignition prevention barrier failure depended on any of the smoke detector failure and the lightning protection system failure. Table 4.2.4 shows the failure rate of ignition prevention barrier basic events.

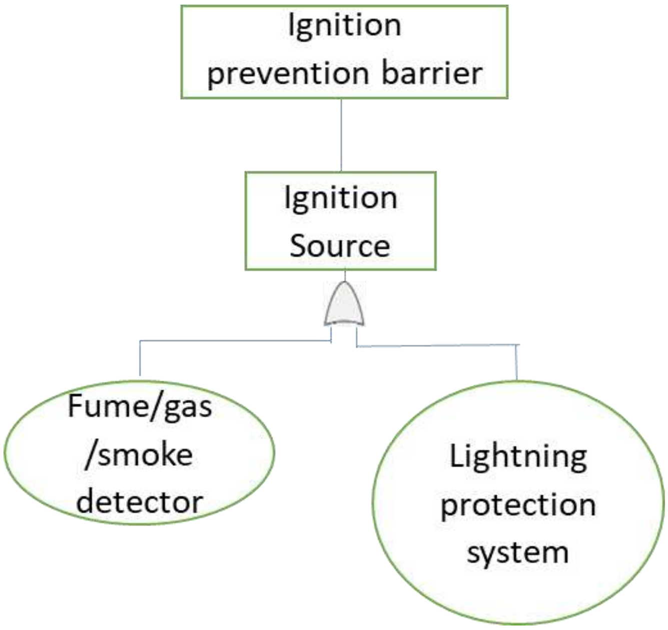


Figure 4.2.5: Fault tree diagram of Ignition prevention barrier.

Table 4.2.4: Failure rate of ignition prevention barrier basic events[40, 41].

Event	**Event Description**	**Failure Rate μ (event per year)**	**Probability ($1-e^{-\mu t}$)**
P1	Flame/smoke/gas detector	0.03066	0.030194749
P2	Hot work permit	9.9864×10^{-3}	0.009936701
P3	Lightning protection system	3×10^{-2}	0.029554466
P4	Dilution system	10^{-4}	9.9995×10^{-5}
P5	Tank insulation	3×10^{-2}	0.029554466
P6	Cooling system	2×10^{-2}	0.019801327
P7	Hot surface protection	2.3104×10^{-8}	2.3104×10^{-8}

Fault tree calculation of ignition prevention barrier failure

Failure probability of ignition source: P8= P1 U P3

=1-[(1-0.030194749)(1-0.029554466)]

= 0.0588

Failure probability of ignition prevention barrier, P(IPB)= P8 = 0.0588

Figure 4.2.6 illustrates that failure of both automatic and manual ESD valve caused ESD system to fail. On the other hand, failure of either fire extinguishing system or fire detector caused fire protection system failure. Any of the emergency shutdown valve failure and fire protection system failure might cause escalation prevention barrier to fail. Table 4.2.5 shows the failure rate of escalation prevention barrier basic events used in the calculation.

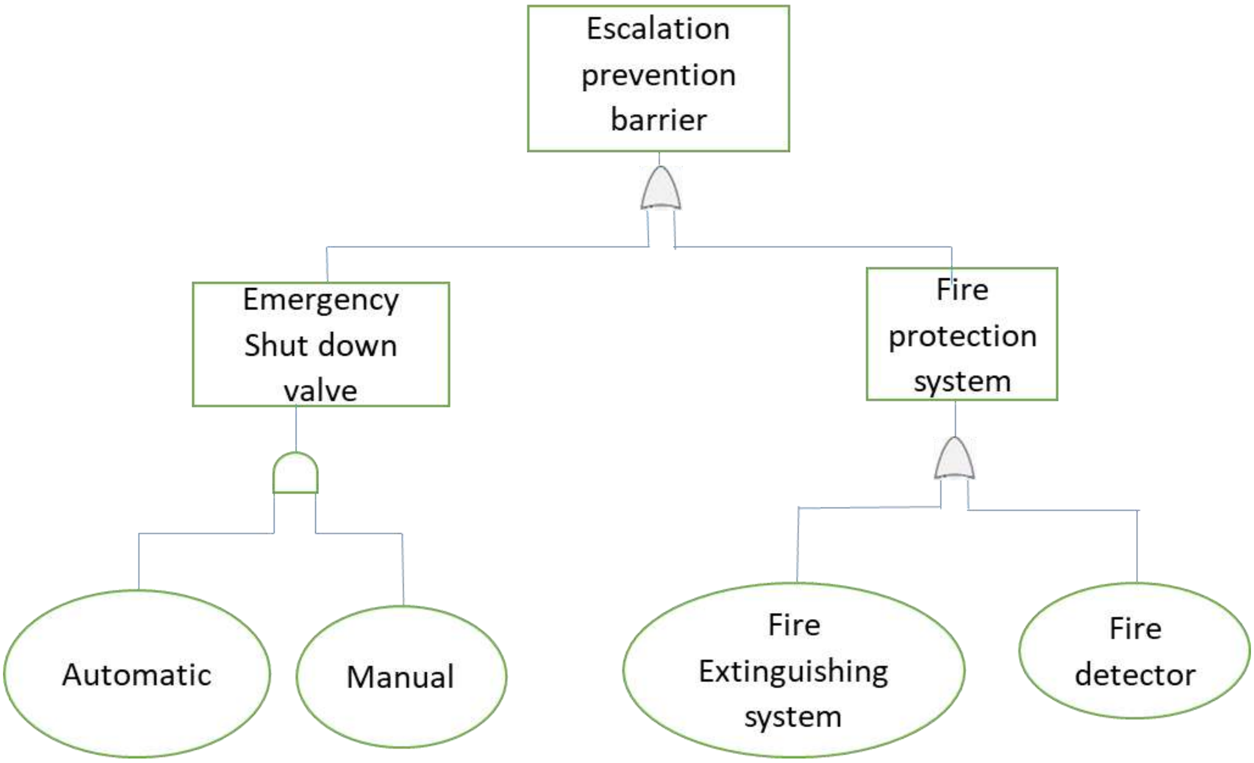


Figure 4.2.6: Fault tree diagram of Escalation prevention barrier.

Table 4.2.5: Failure rate of escalation prevention barrier basic events[40, 41].

Event	Event Description	Failure Rate, μ (event per year)	Probability ($1-e^{-\mu t}$)
P1	Neutral gas dilution system	10^{-4}	$9.9995x10^{-5}$
P2	Water spray dilution system	$1.47x10^{-3}$	0.00146892
P3	Standard distance between tanks	$3x10^{-2}$	0.029554466
P4	Automatic emergency shut-down valve	10^{-2}	0.009950166
P5	Manual emergency shut-down valve	$1.33x10^{-2}$	0.013211946
P6	Fire extinguishing system	0.0123	0.012224664
P7	Fire detector	$9.99x10^{-3}$	0.009940266
P8	Fire wall	$3x10^{-2}$	0.029554466

Fault tree calculation of escalation prevention barrier failure:

Failure probability of emergency shut-down valve P10= P4 ∩ P5

=0.009950166 x 0.013211946

= 0.000131461

Failure probability of fire protection system P11= P6 U P7

=1-[(1-0.012224664)(1-0.009940266)]

= 0.02204

Failure probability of escalation prevention barrier, P(EPB)=P10 U P11

=1-[(1-0.000131461)(1-0.02204)]

= 0.02216

Table 4.2.6 summarizes the failure probability of different barriers' failure which are further converted to failure frequency

Table 4.2.6: Failure frequencies of barriers.

Barrier Name	Barrier Failure Probability P	Barrier Failure Frequency μ= –ln(1-P)
Release Prevention barrier (RPB)	0.0358	0.0365
Dispersion Prevention Barrier (DPB)	$9.9958x10^{-4}$	0.0010
Ignition Prevention Barrier (IPB)	0.0588	0.0605
Escalation Prevention Barrier (EPB)	0.0221	0.0224

In the updated bow-tie diagram in figure 4.2.7 additional causes in the fault tree were natural event and mechanical damage. Additional preventive barriers were fixed water system, maintenance of valve, operator's intervention, normal operation of well-designed drain valve, corrosion prevention system, regular inspection of corrosion and fatigue, security and passive defense system. Additional protective barriers on the event tree were emergency management and damage control barrier and human factor barrier.

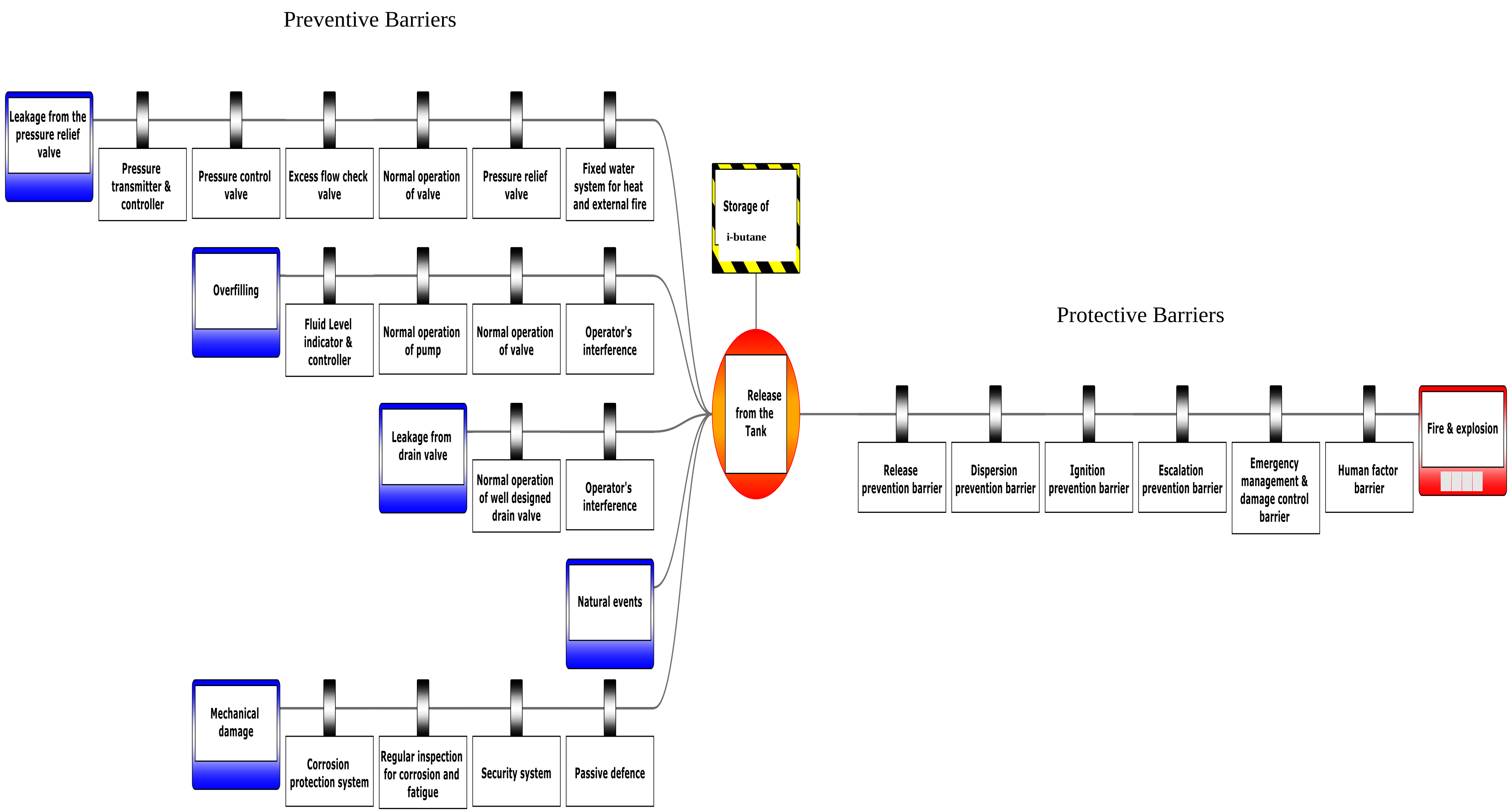


Figure 4.2.7: Updated Bow-Tie diagram for i-butane release.

Event Tree Analysis: The event tree shown in figure 4.2.8 quantified the resulting accident event sequences after the occurrence of initiating event and failure of safety barriers. When all the barriers succeeded, the situation was regarded as safe. When only the release prevention barriers failed but all other barriers worked, then near miss took place. Mishap occurred when releases prevention barrier and dispersion prevention barriers failed but ignition prevention barrier and escalation prevention barriers still prevented ignition and escalation. When only escalation prevention barrier succeeded, the condition was considered as incident. When all the barriers failed then accident happened.

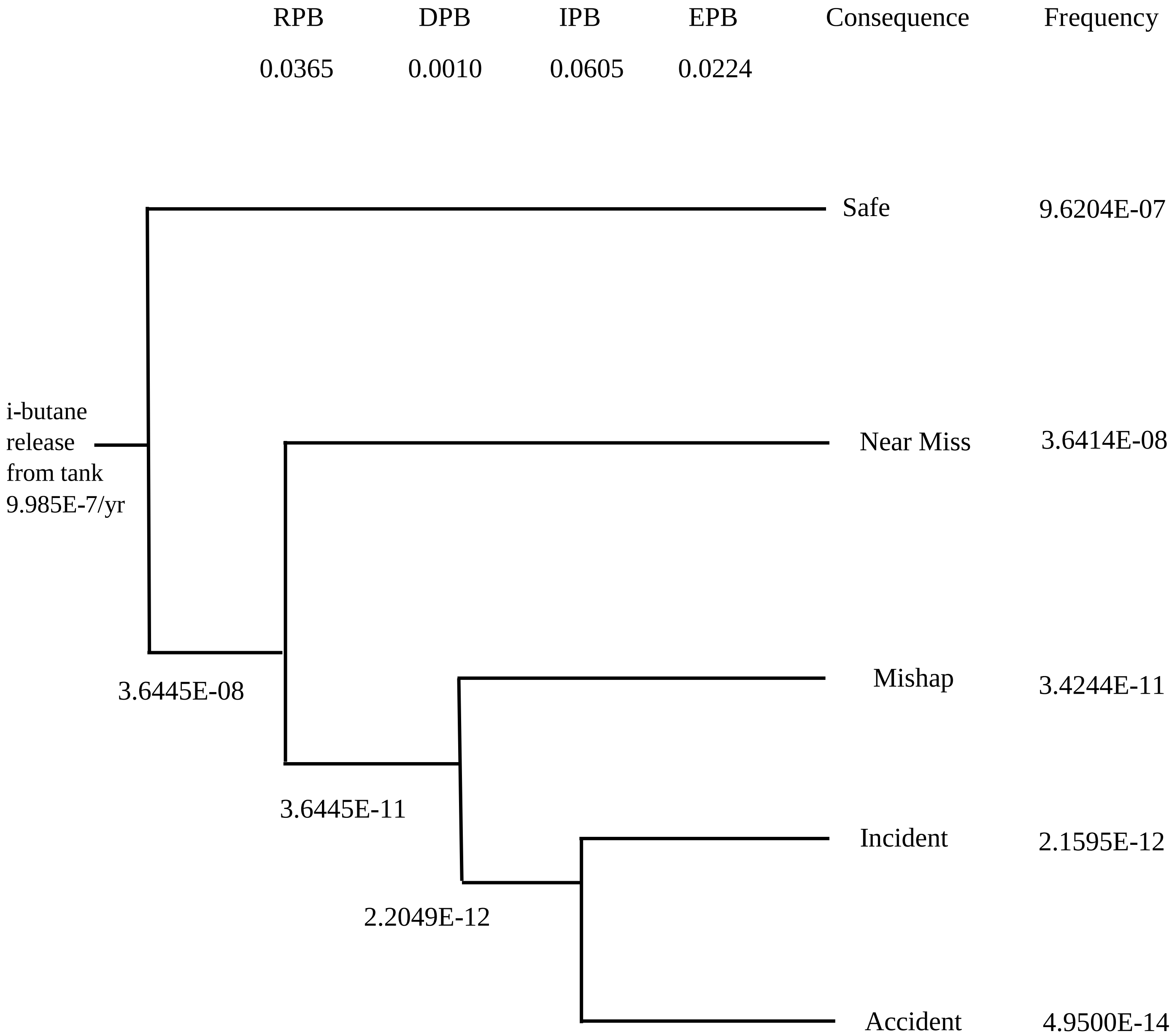


Figure 4.2.8: Event tree before update of fault trees (Barrier failure and different consequences).

4.3 Bayesian Network Analysis:

Node analysis: After initial fault tree calculation from Bow-Tie analysis, the fault trees of the top event and barrier failure had been updated using the Agena Risk software. Updated node analysis is shown below.

4.3.1 Node analysis of top event: i-butane release from the tank

Figure 4.3.1(a) shows that the frequency or probability value of release from the tank depended on the frequencies or probability values of leakage from pressure relief valve, overfilling, natural events, mechanical damage and leakage from the drain valve.

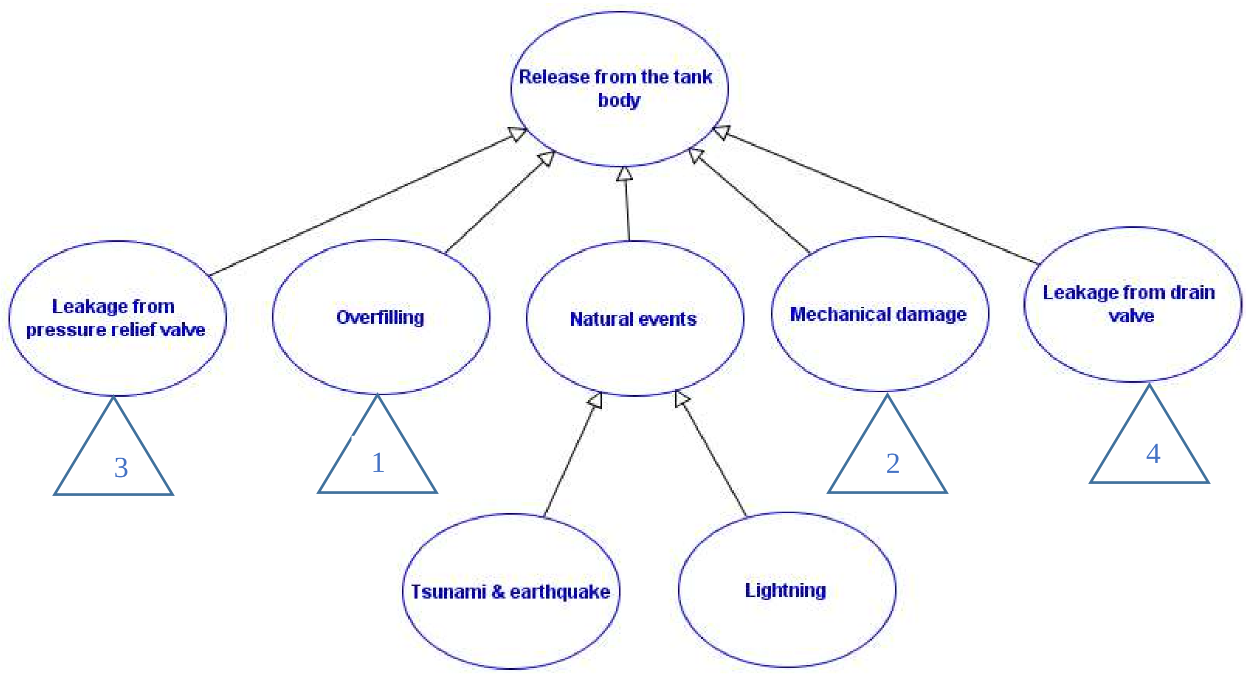


Figure 4.3.1(a): Node analysis of Release from the tank.

Figure 4.3.1(b) shows the conditional dependence of overfilling on operator's error, pump failure, fluid level indicator failure and failure of normal operation of valve. Again, two parent nodes of pump failure were maintenance error and design error of pump.

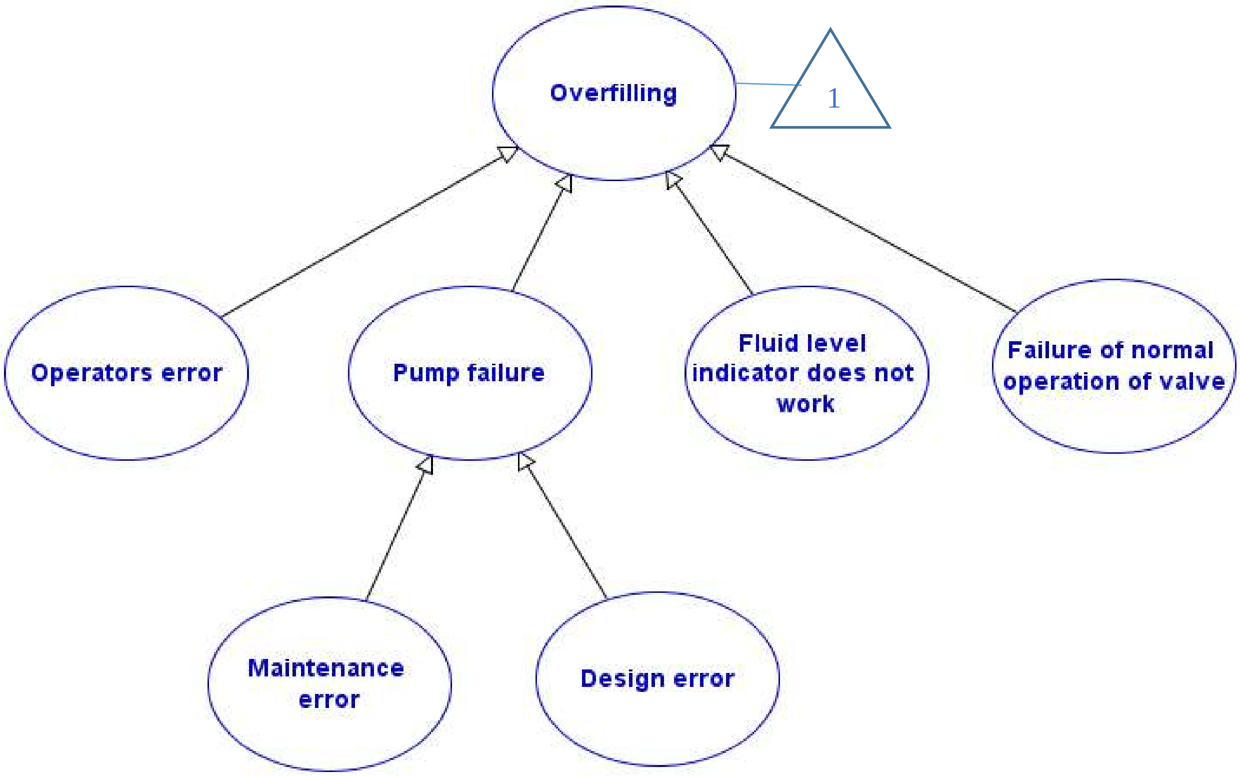


Figure 4.3.1(b): Node analysis of Overfilling.

Figure 4.3.1(c) illustrates the node analysis of mechanical damage. Its probability depended on the probabilities of material defects, corrosion, fatigue and sabotage. Internal corrosion and external corrosion were two parent nodes of corrosion node. Weak security system and passive defense affected the probability of sabotage or terrorism. Structural failure of the barrier, guardian negligence and electronic system were the root nodes of the weak security system.

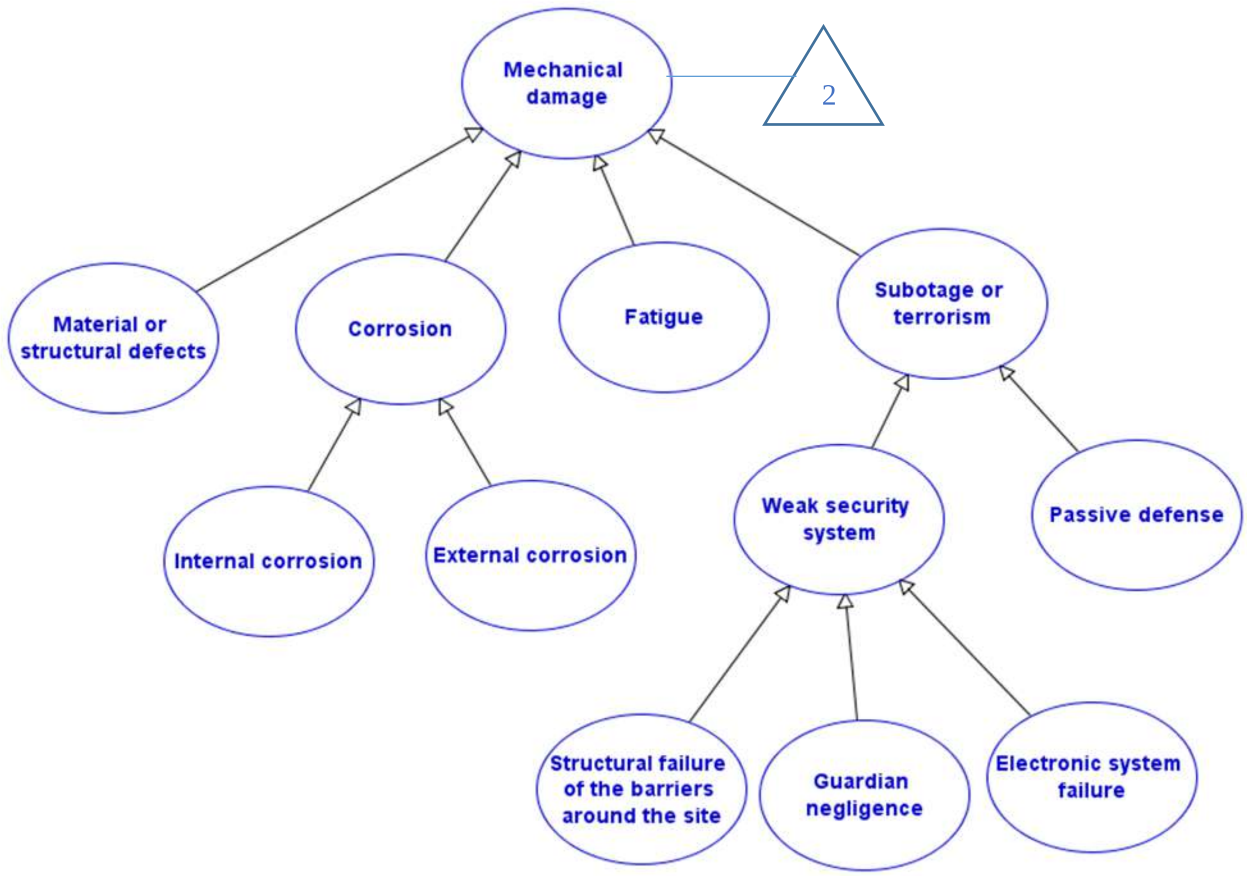


Figure 4.3.1(c): Node analysis of mechanical damage.

Figure 4.3.1(d) shows how the probability of leakage from pressure relief valve depended on the probabilities of increase of the internal pressure of the tank, failure of valves and failure of pressure relief valve. Pressure relief valve failed because of design error and maintenance error.

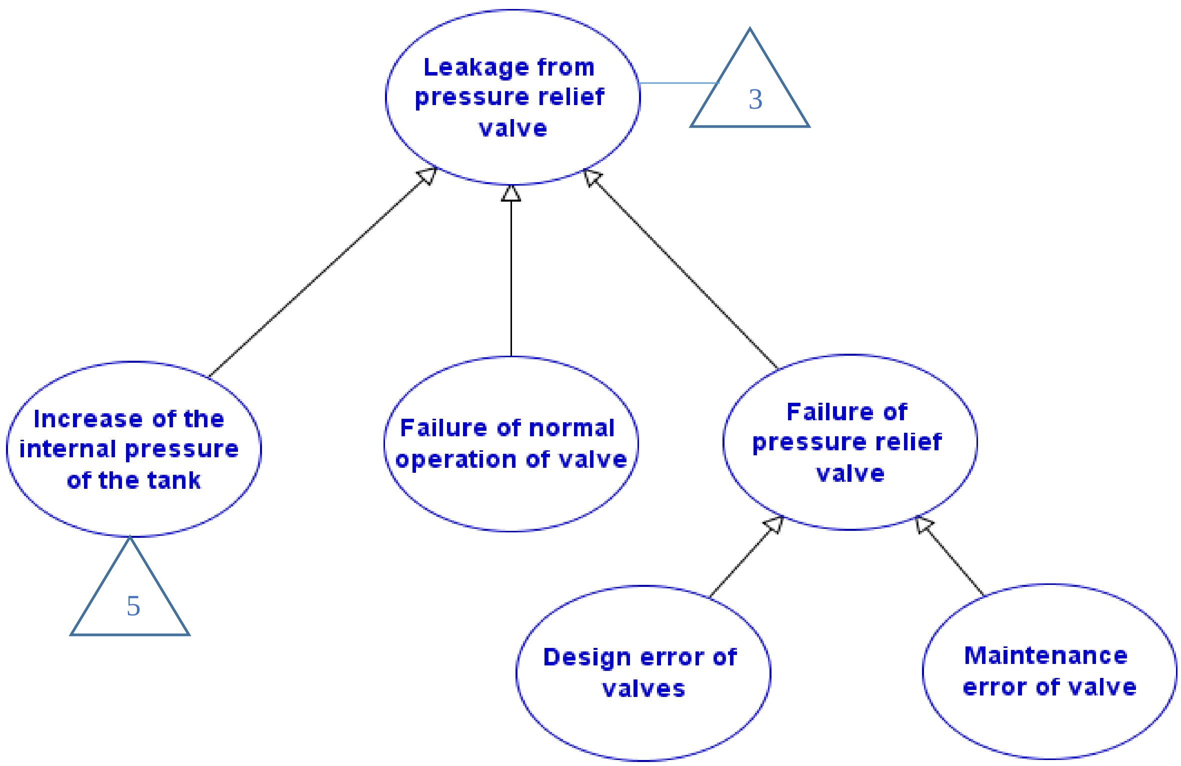


Figure 4.3.1(d): Node analysis of leakage from pressure relief valve.

The causes of the increase of tank internal pressure were analyzed in a fault tree shown by figure 4.3.1(e). The parent nodes of the top node of this fault tree were absence of insulation, external fire, fixed water system failure and tank pressure reaches relief pressure. Fixed water system failed because of damaged sprinkler system, low cooling capacity, valves fail to activate, partial or complete blockage of the pipe and freezing water inside the pipe. The root nodes of valves activation failure were close of valve because of fire and damage of valve. The reasons for tank reaching relief valve pressure were failure of pressure control valve, failure of pressure transmitter and failure of excess flow check valve.

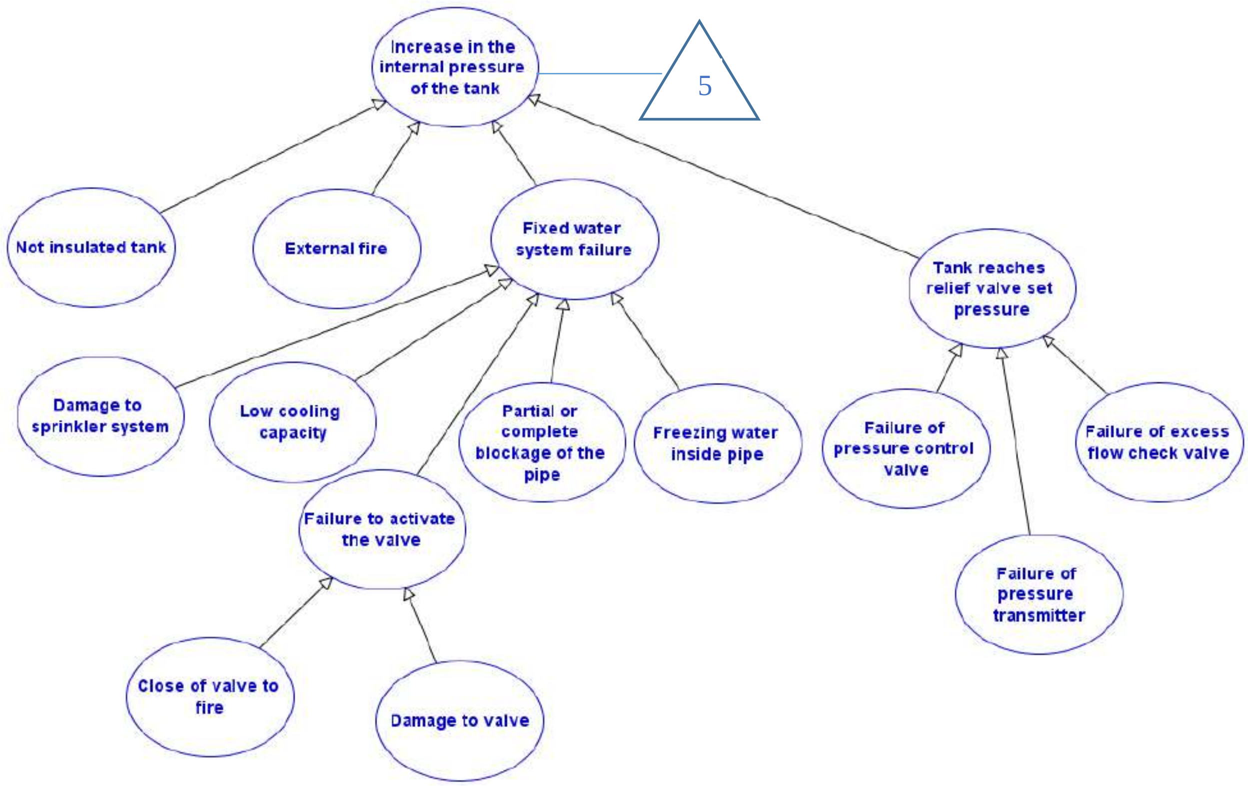


Figure 4.3.1(e): Node analysis of increase in the internal pressure of the tank.

Node analysis of leakage from drain valve is depicted by figure 4.3.1(f). The parent nodes of the top child node were design error of drain valve, frozen valve and operator error. The probability of design error of valve depended on the probabilities of root nodes: insufficient control over the valve, very large valve diameter and improper discharge to environment. Operator error happened because of failure to follow work instruction and leaving the drain valve open.

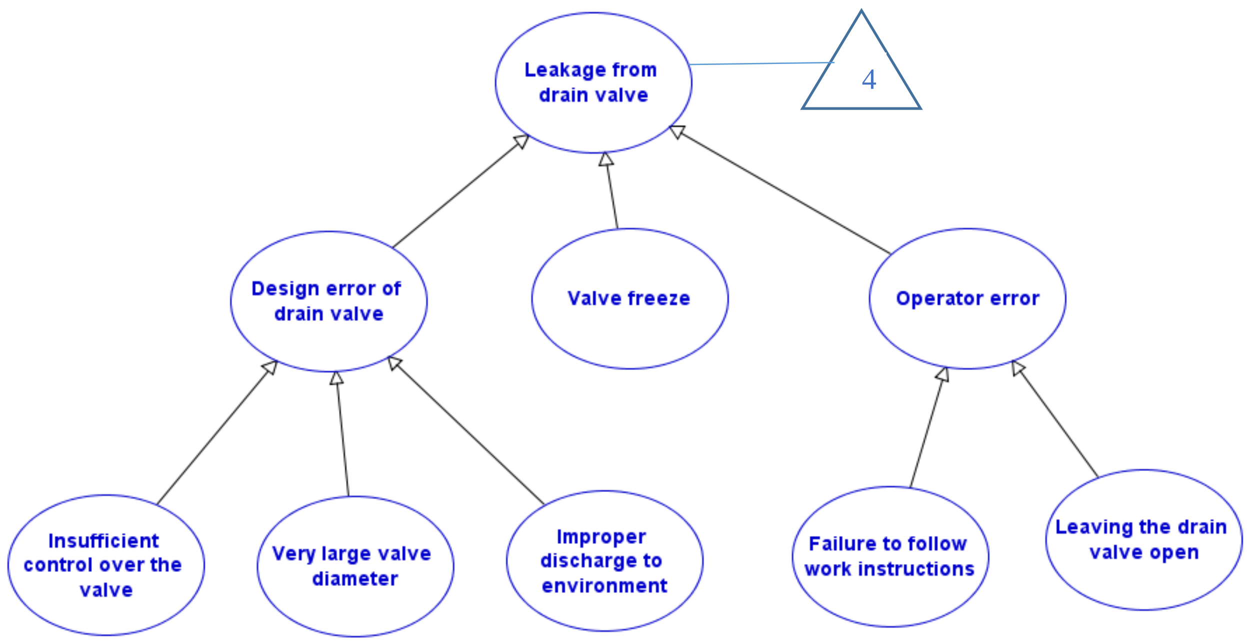


Figure 4.3.1(f): Node analysis of leakage from drain valve.

4.3.2 Node analysis of failure of Release Prevention Barrier

Figure 4.3.2(a) illustrates node analysis of the failure of the release prevention barrier. The parent nodes were failure of operational error prevention barrier, failure of mechanical damage prevention barrier, failure of preventive maintenance barrier and failure of safety systems. Preventive maintenance barrier failed for maintenance failure and failure of corrosion inspection. The root causes behind maintenance failure were failure of inspection after maintenance, improper connection of screws, flanges and fittings, not following maintenance instruction, use of inappropriate materials in repair and wrong position of valves after repair.

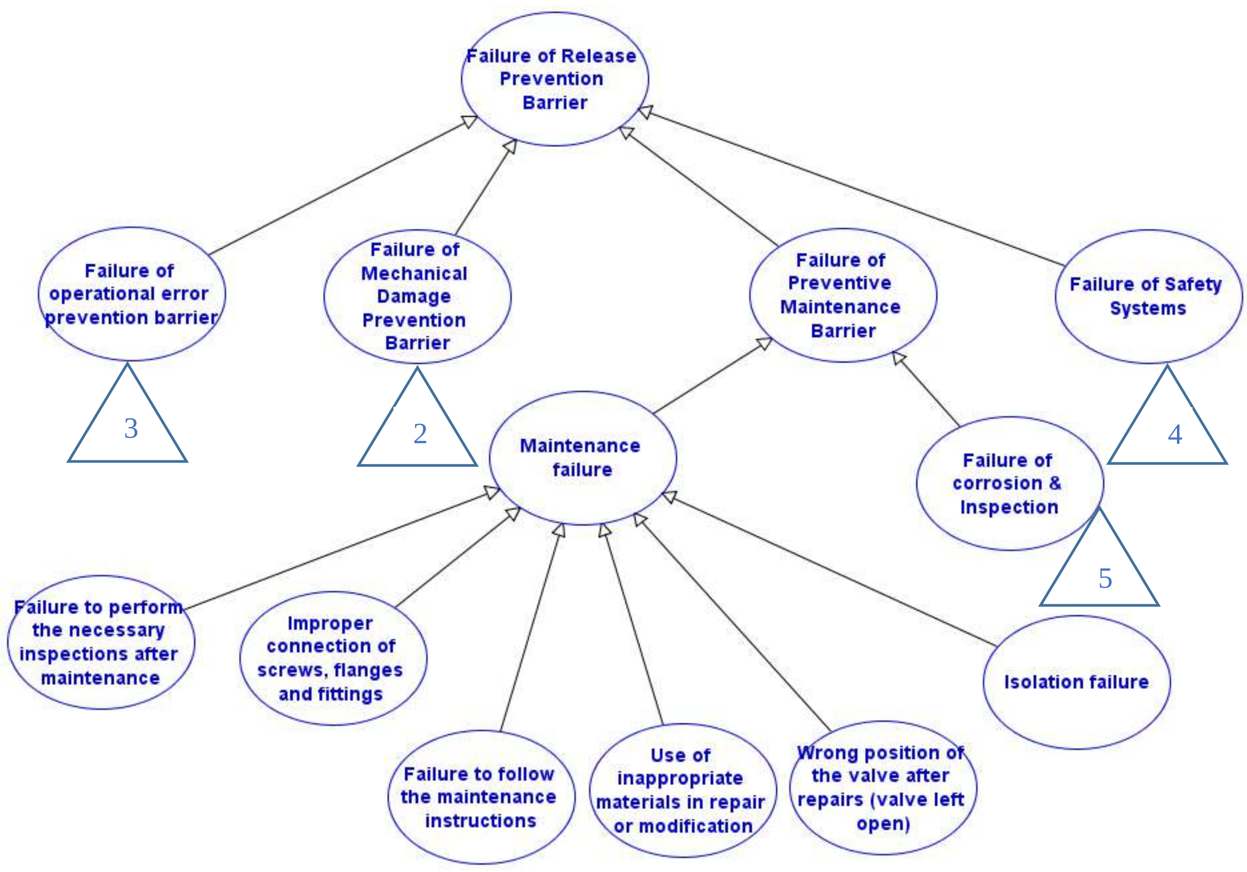


Figure 4.3.2(a): Node analysis of release prevention barrier failure.

From figure 4.3.2(b) we can see that the probability of occurrence of mechanical damage prevention barrier failure conditionally depended on the probabilities of vehicle collision prevention barrier failure, failure of external fire prevention barrier, sabotage prevention barrier failure and failure of natural hazard prevention barrier. Parent nodes of vehicle collision prevention barrier failure were lack of fences around the tank and lack of protection of pipes and fittings. Reasons of natural hazard prevention barrier failure were: tank foundation was not strong and failure of lightning protection system.

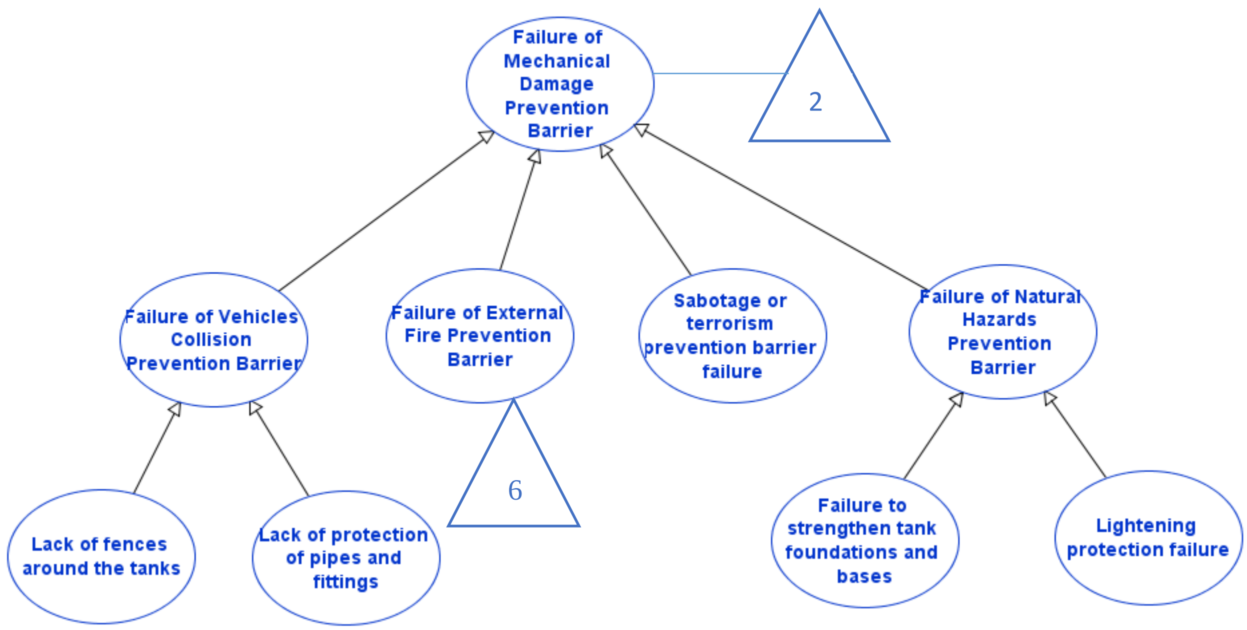


Figure 4.3.2(b): Node analysis of failure of mechanical damage prevention barrier.

From figure 4.3.2(c) it is clear that failure of tank cooling system, non-compliance with standards while placing equipment and fireproof failure were the reasons behind external fire prevention barrier. Non-compliance with standards happened when standard distance between two adjacent tanks and between tanks and installations were not maintained. Tank cooling systems failed because of blockage of sprinklers, complete or partial blockage of pipes, frozen water inside the pipes, failure of cooling system to activate and lack of sufficient water. The parent nodes of fireproofing failure were failure of tank base fireproofing and failure of insulation of tank.

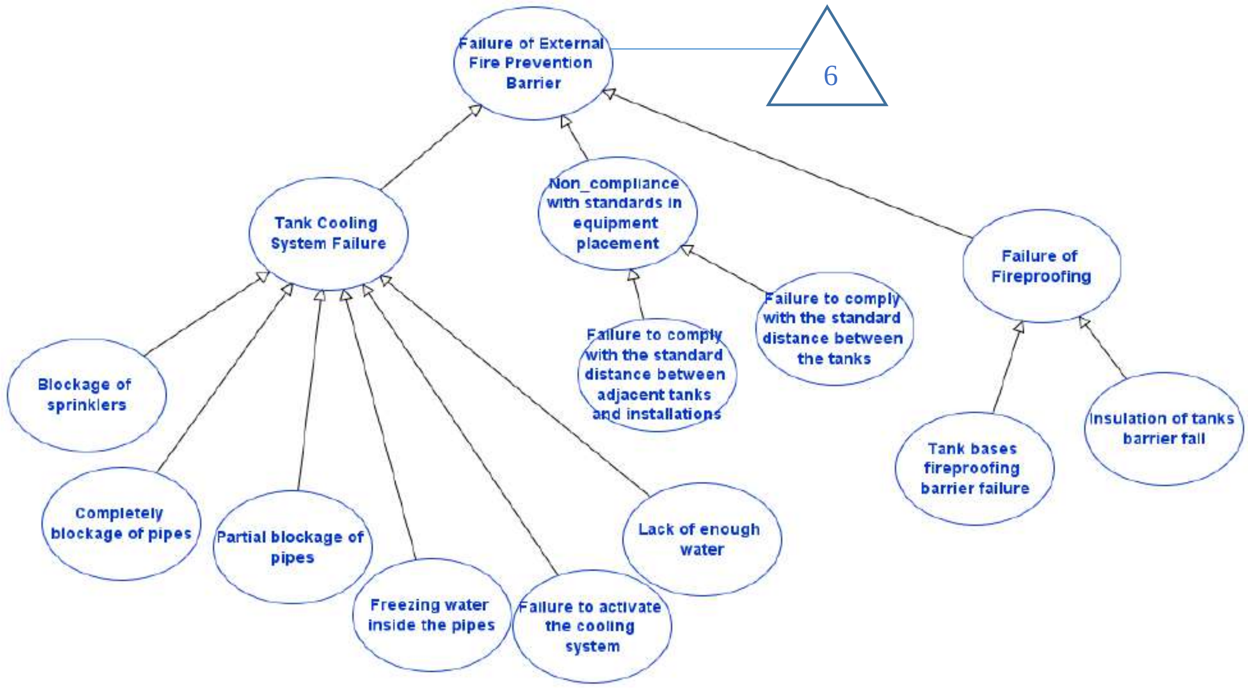


Figure 4.3.2(c): Node analysis of failure of external fire prevention barrier.

Figure 4.3.2(d) shows that isolation failure and operational error were the parent nodes of operational error prevention barrier failure. The root causes of isolation failure were: area was not isolated, isolation valve failure and absence of isolation valve. The parent nodes of operational error were: sampling valve was left open, isolation valve failed to activate and work instructions were not followed.

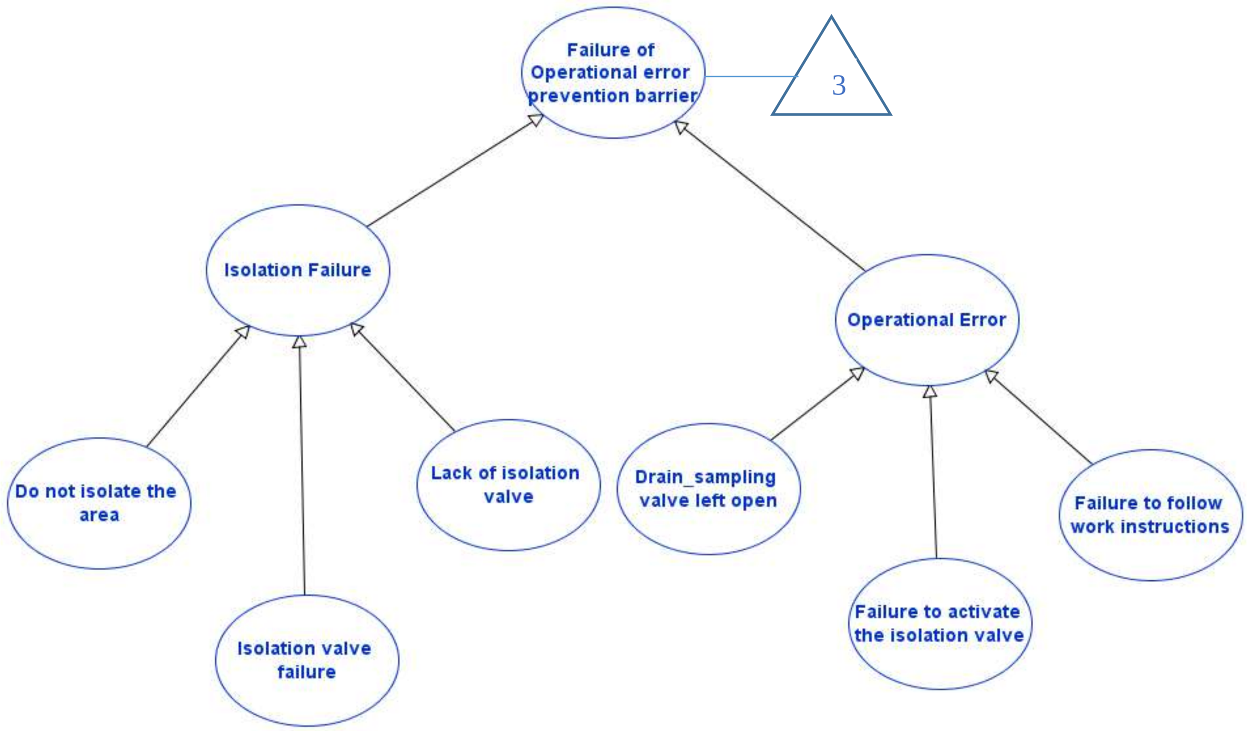


Figure 4.3.2(d): Node analysis of failure of operational error prevention barrier.

Figure 4.3.2(e) illustrates the node analysis of safety system failure where safety system failure was the child node of faulty pressure gauge, faulty safety valve, failure of excess flow check valve and failure of the overfilling prevention system. Excess flow valve failed because of faulty excess flow valve and improper diameter of downstream pipe of the excess flow valve.

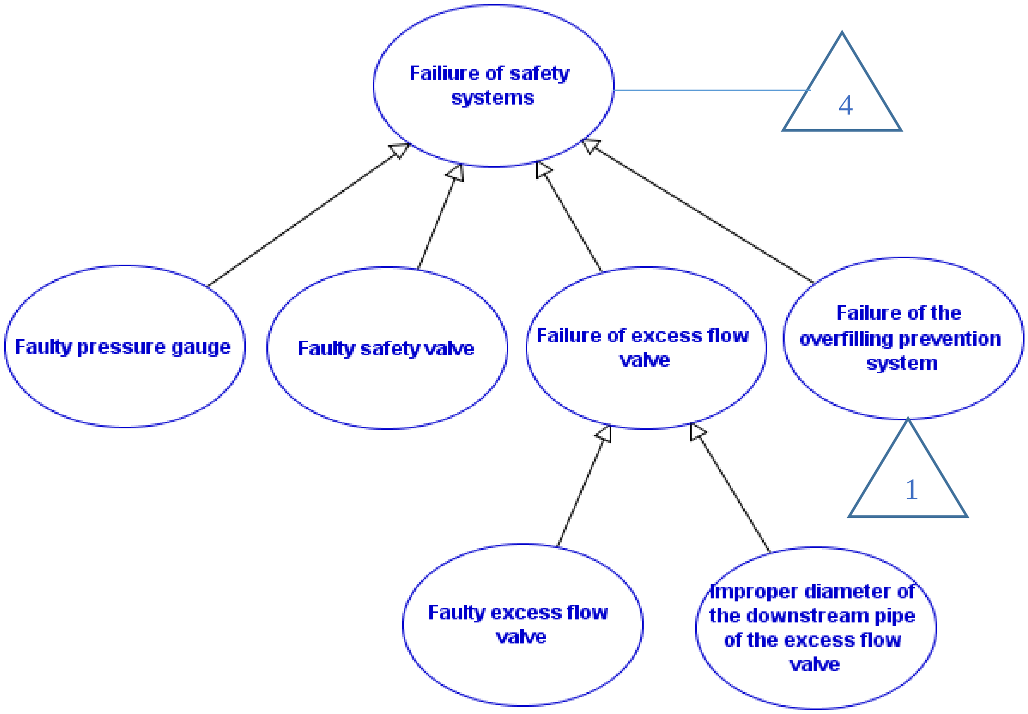


Figure 4.3.2(e): Node analysis of failure of safety systems.

From figure 4.3.2(f), the failure rate of overfilling prevention system depended on the failure rate of liquid level control, operator's failure in current stop and failure of shutdown valve. Operator's failure in current stop occurred due to delay in stopping pump after a release and operator's failure to stop the pump.

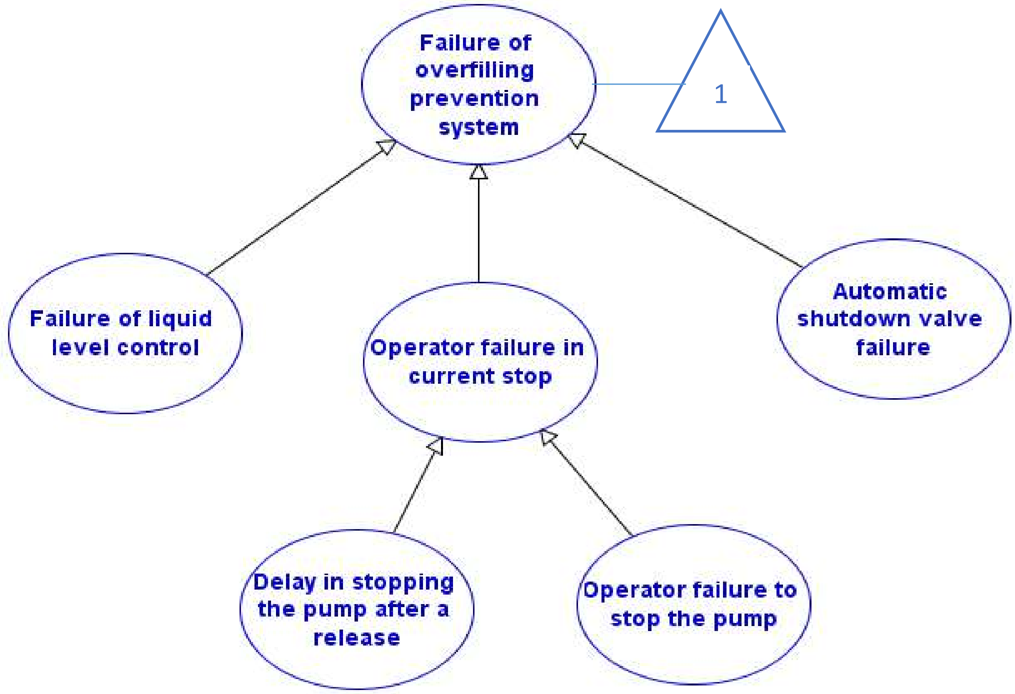


Figure 4.3.2(f): Node analysis of failure of overfilling prevention system.

Figure 4.3.2(g) shows how the probability of failure of corrosion prevention and inspection conditionally depended on the probabilities of corrosion inspection failure, failure of visual inspection, failure of inspection of welding and failure of metal cracking monitoring. The parent nodes of corrosion inspection failure were destructive test equipment are not calibrated, failure in inspection of small connection, exterior body inspection failure in terms of corrosion under insulation, internal corrosion inspection failure and failure of inspection of tank bases. Metal cracking monitoring failed because of failure of superficial crack monitoring and failure of sub surface cracking monitoring.

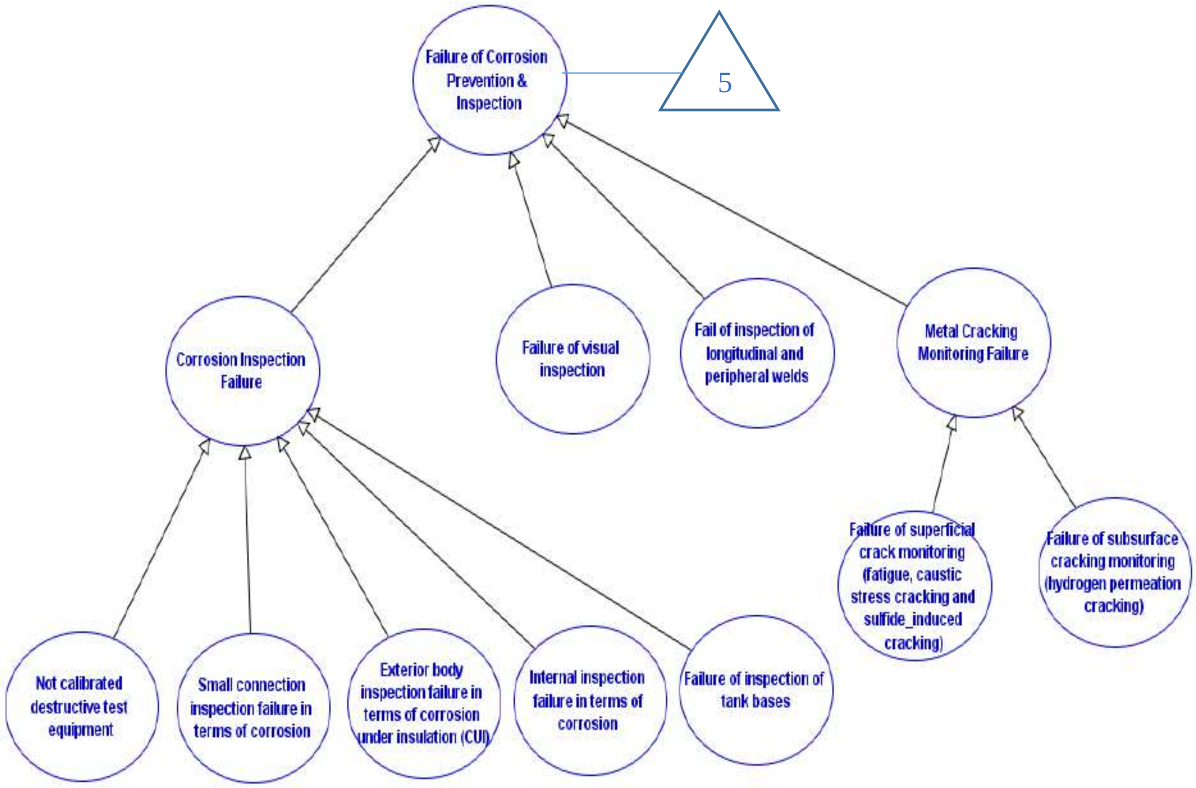


Figure 4.3.2(g): Node analysis of failure of corrosion prevention and inspection.

4.3.3 Node analysis of failure of Dispersion Prevention Barrier

Figure 4.3.3 depicts the node analysis of failure of the dispersion prevention barrier. The parent nodes of dispersion prevention barrier failure were gas detection system failure, flow stop valve failure, passive barrier failure and continuous site inspection failure. Failure of both of the automatic and manual gas detector had been considered.

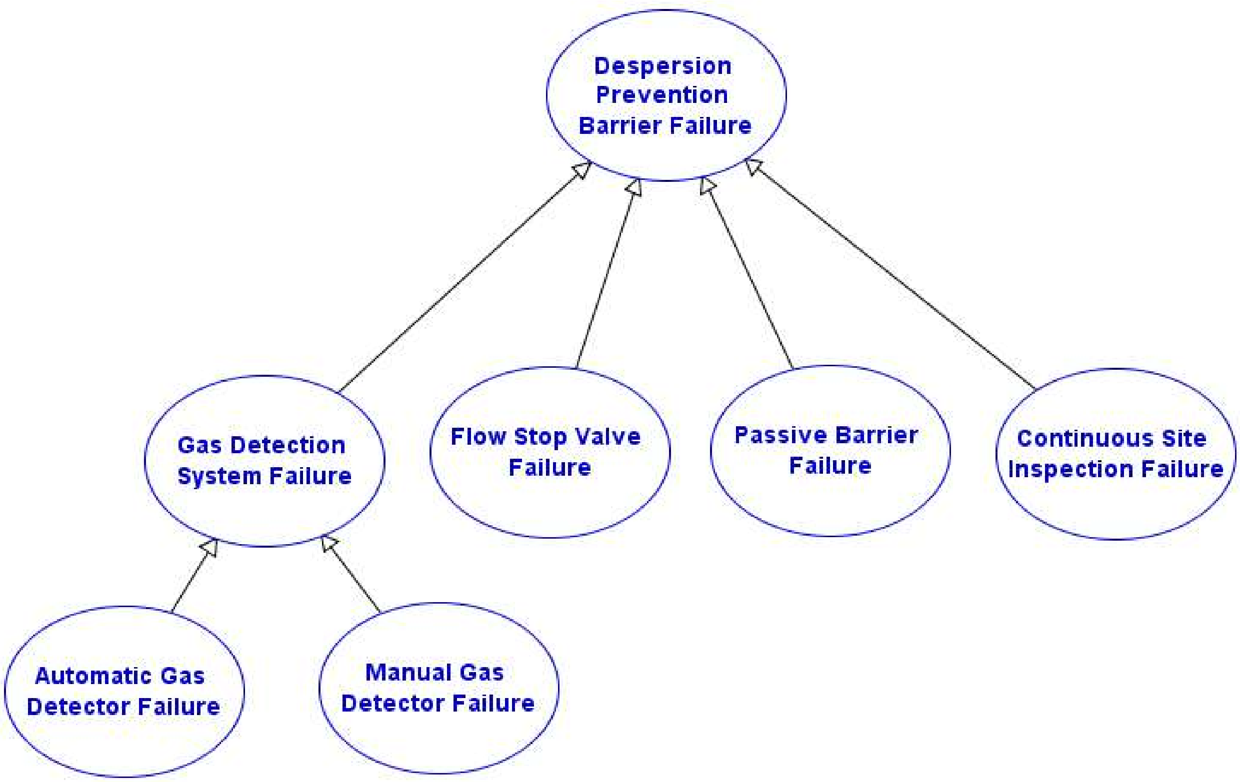


Figure 4.3.3: Node analysis of dispersion prevention barrier failure.

4.3.4 Node analysis of failure of Ignition Prevention Barrier

In figure 4.3.4 it is shown that the probability of ignition prevention barrier failure depended on the probabilities of ignition source, dilution system failure and temperature control failure. The ignitions sources can be available due to flame detector failure, hot work permit failure and lightning protection failure. The parent nodes of temperature control failure were: tank insulation failure, cooling system failure and hot surface protection failure.

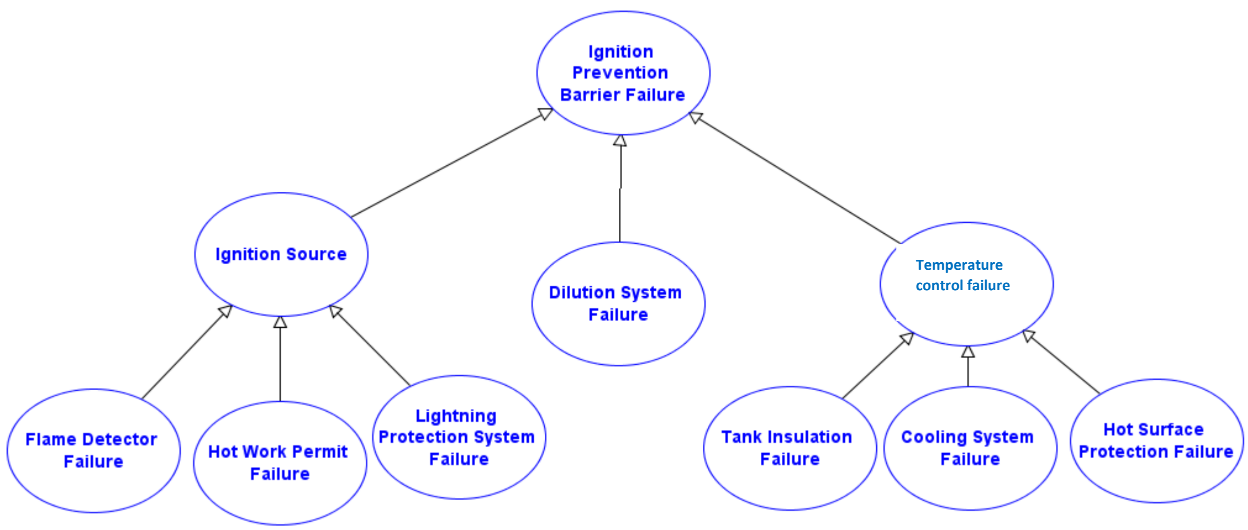


Figure 4.3.4: Node analysis of ignition prevention barrier failure.

4.3.5 Node analysis of failure of Escalation Prevention Barrier

From figure 4.3.5, escalation prevention barrier failure was the child node of dilution system failure, no standard distance between tanks, emergency shutdown valve failure and fire protection system failure. Dilution system can be of two types. Neutral gas dilution system and water spray dilution system. Emergency shutdown valve was also considered of two types. Automatic and manual. The reasons of fire protection system failure were fire extinguishing system failure, fire detector failure and fire wall failure.

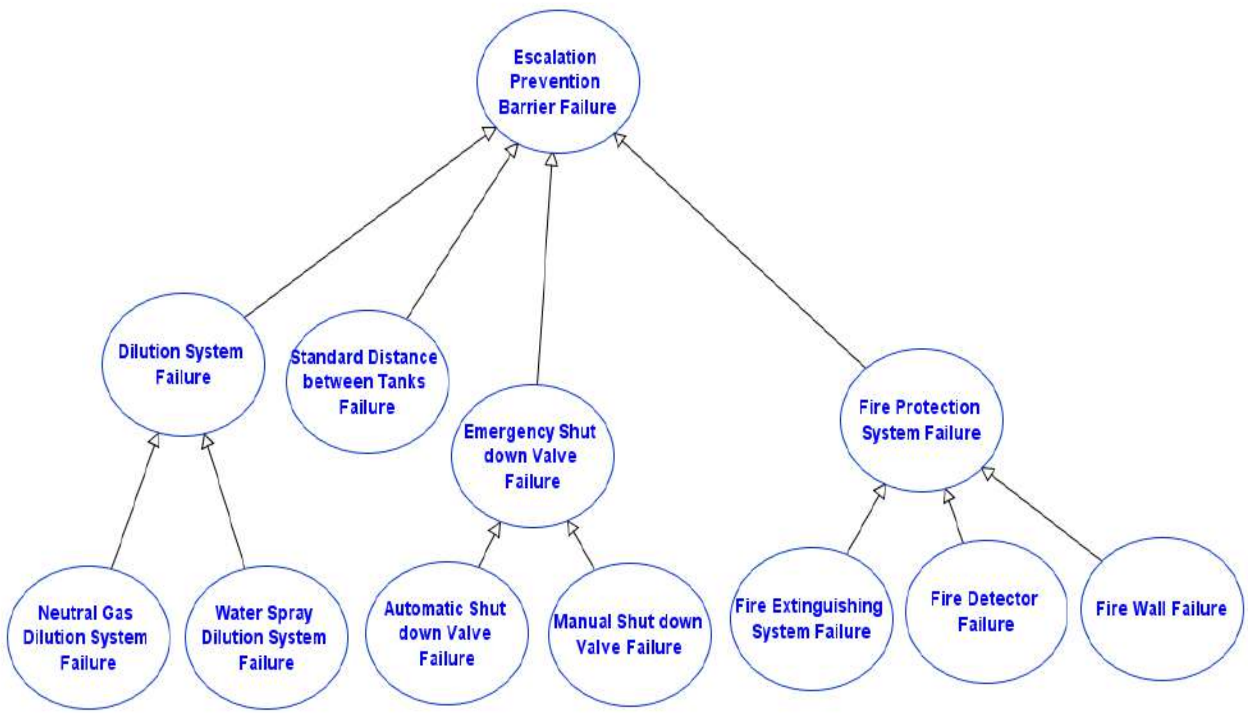


Figure 4.3.5: Node analysis of escalation prevention barrier.

4.3.6 Node analysis of failure of Emergency Management and Damage Control Barrier

Figure 4.3.6 illustrates the parent nodes of management failure which were communication failure, emergency medical service failure, emergency response plan failure, lack of appropriate training and evacuation instruction failure. The parent nodes of active control system failure were: alert system failure, lack of adequate equipment and emergency maneuver failure. Emergency management and damage control barrier failure was the child node of management failure and active control system failure.

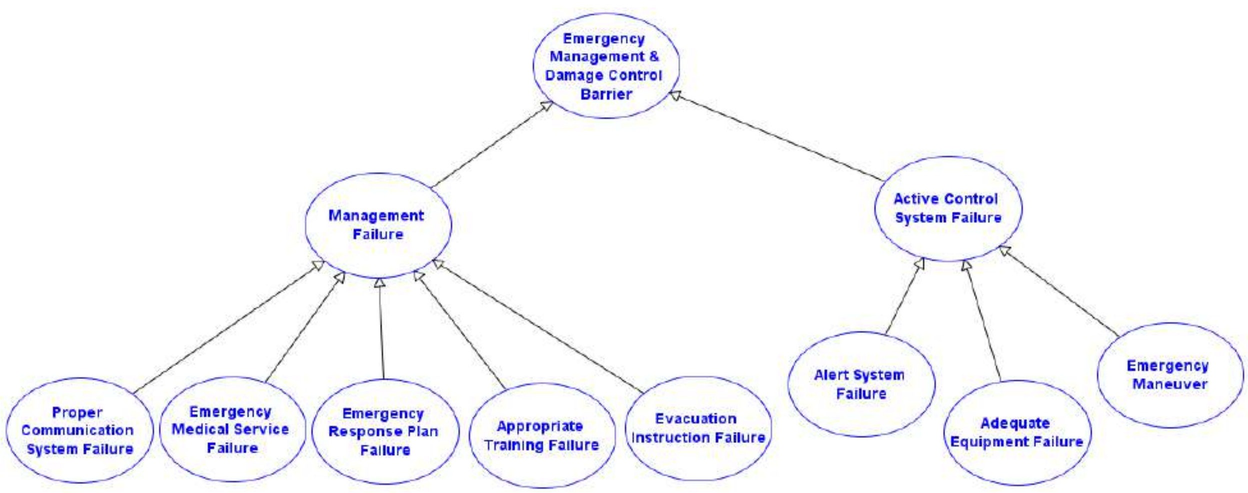


Figure 4.3.6: Node analysis of emergency management and damage control barrier failure.

4.3.7 Node analysis of failure of Human Factor Barrier

Figure 4.3.7(a) depicts the node analysis human factor barrier failure where the probability of this node depended on the probabilities of failure of individual's characteristics barrier, failure of workplace design barrier and failure of human system interaction barrier.

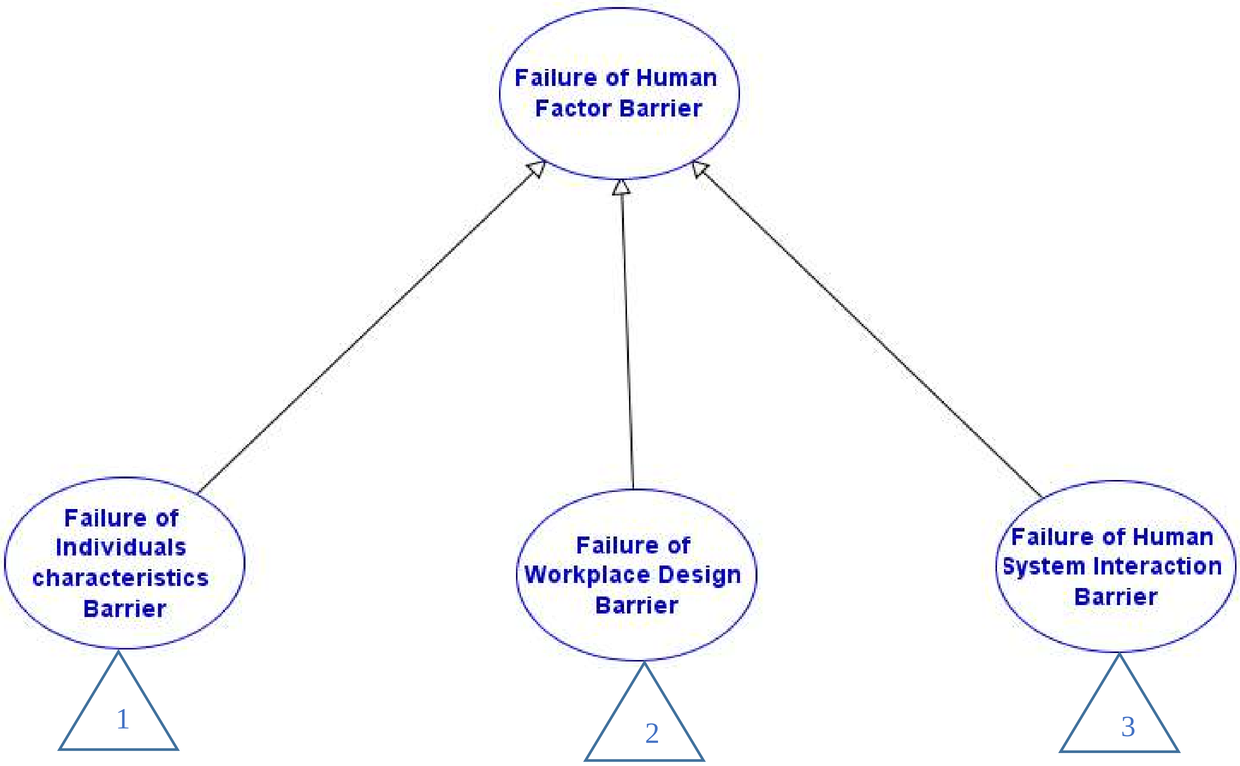


Figure 4.3.7(a): Node analysis of human factor barrier failure.

According to figure 4.3.7(b) the parent nodes of this top node were physical disability, failure of operators' incentive program and failure of supervision and monitoring.

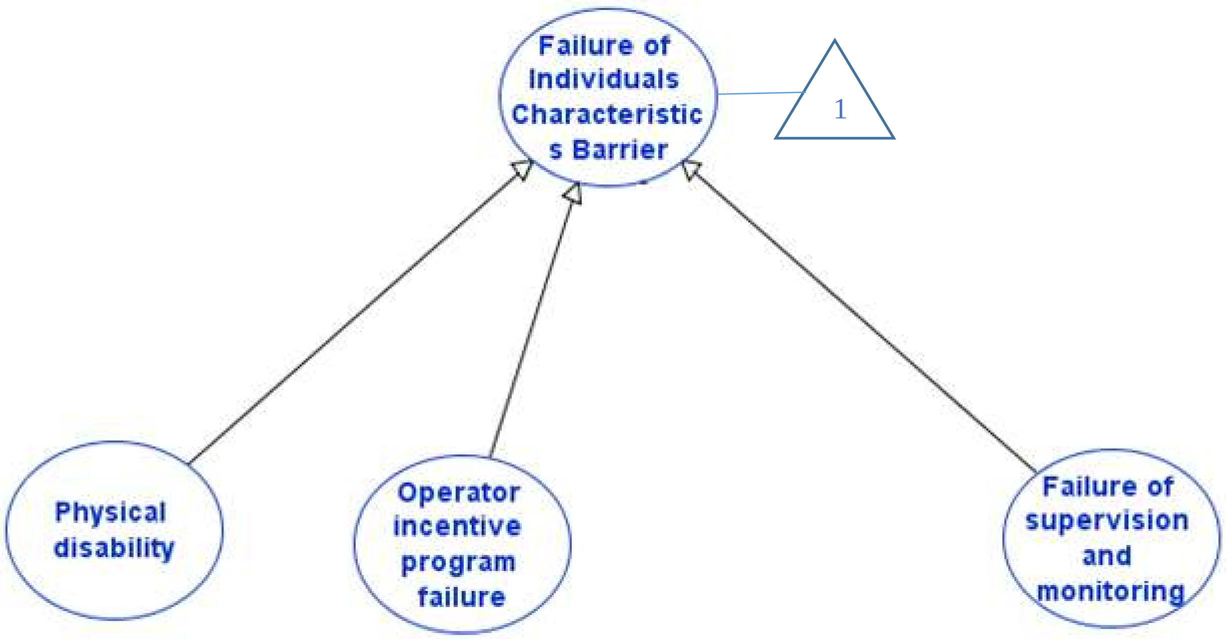


Figure 4.3.7(b): Node analysis of failure of individual's characteristics barrier.

Figure 4.3.7(c) shows that the only parent node of failure of workplace design was failure to control harmful factors in the workplace which means the child node and the parent node got the same probability value. The reasons behind failure to control harmful factors were: uncomfortable temperature conditions, insufficient lighting and high noise or mechanical vibration.

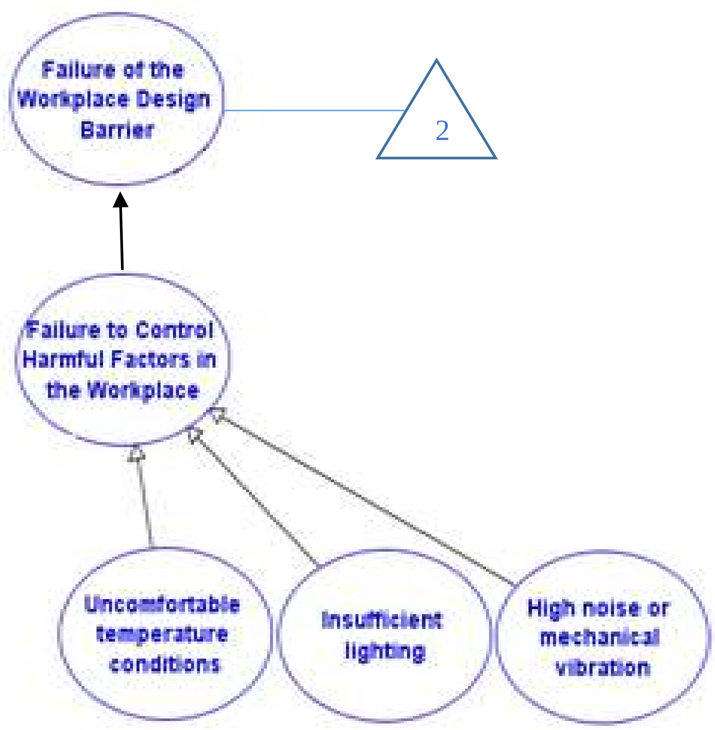


Figure 4.3.7(c): Node analysis of failure of workplace design.

Figure 4.3.7(d) illustrates the causes of human system interaction barrier failure. It was the child node of control panel failure, improper tools, alarm or display failure and labeling failure. The parent nodes of improper tools were unreliable measuring equipment and insufficient equipment.

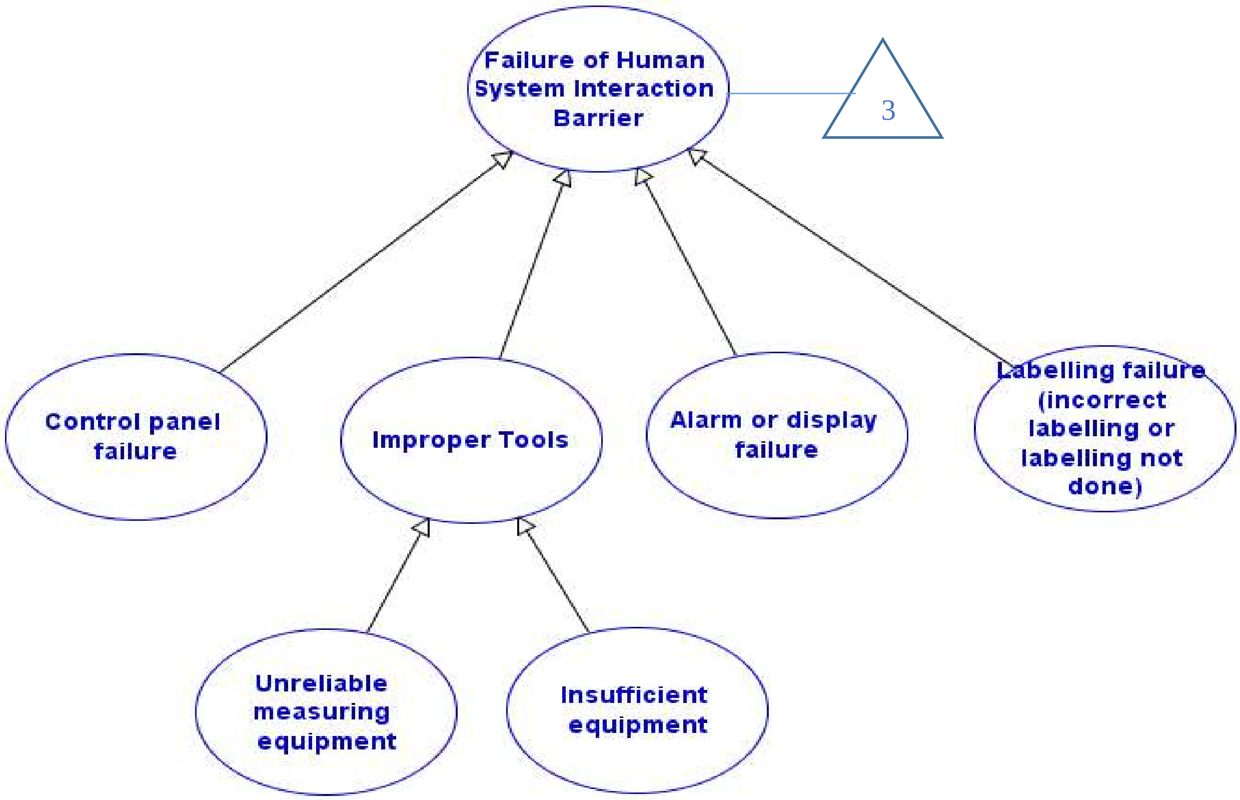
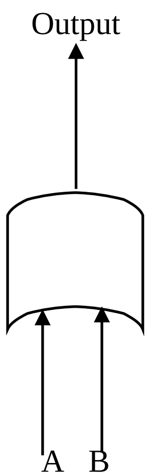


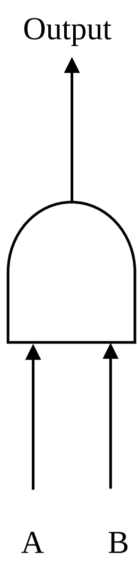
Figure 4.3.7(d): Node analysis of human system interaction barrier failure.

Figure 4.3.8 explains the role of logical gate in calculating probabilities in Bayesian approach which has been used in Agena Risk. This CPT is the input for the calculation. Output 0 indicates that the event is not occurring and 1 indicates that the event is occurring.



OR Gate

A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1



AND Gate

A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

Figure 4.3.8: Conditional probability table (CPT) for OR and AND gate.

4.4 Bayesian Network Analysis in Agena Risk

The failure probability of top event: release from the tank body was calculated using Agena Risk software on the basis of Bayesian theorem about conditional probability. The fault tree had been divided into several parts for better understanding. Two types of logic gate: AND and OR had been used to define the conditional relations among the causes of the top event. Two types of node states: yes means the event was happening and no means the event was not happening.

Node analysis of top event is shown below:

In figure 4.4.1 after update of the fault tree of overfilling two parent nodes were connected by an OR gate with the pump failure node. Also two other nodes: operator's error and failure of normal operation of valves were added to the top event by the existing OR gate.

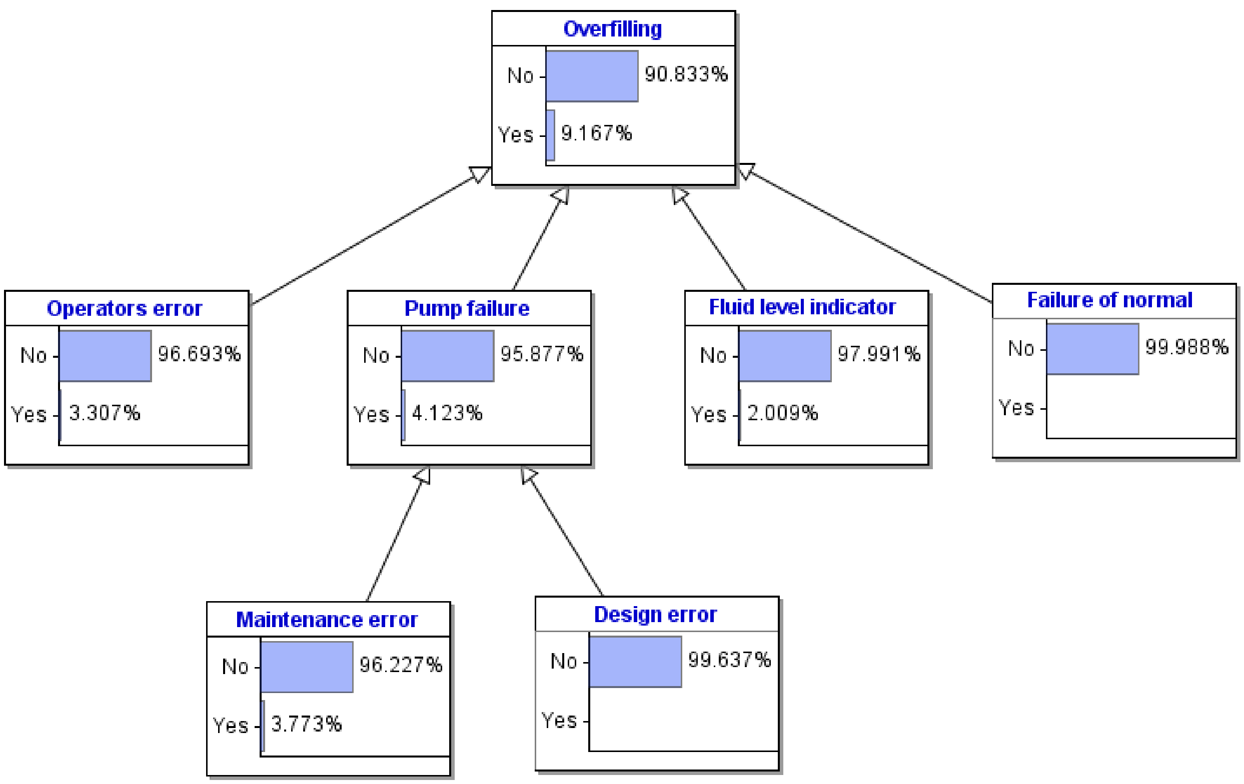


Figure 4.4.1: Risk Map on Agena Risk for overfilling.

In figure 4.4.2 the fault tree of increase in the internal pressure of the tank had been updated by adding external fire node and fixed water system failure node with AND gate. The parent nodes of the failure of the fixed water system were damage to the sprinkler, low cooling capacity, failure to activate the valve, partial or complete blockage of the pipe and frozen water inside the pipe which were connected with OR gate. The failure to activate the valve occurred if either of the close of valve to fire and damage to valve would occur.

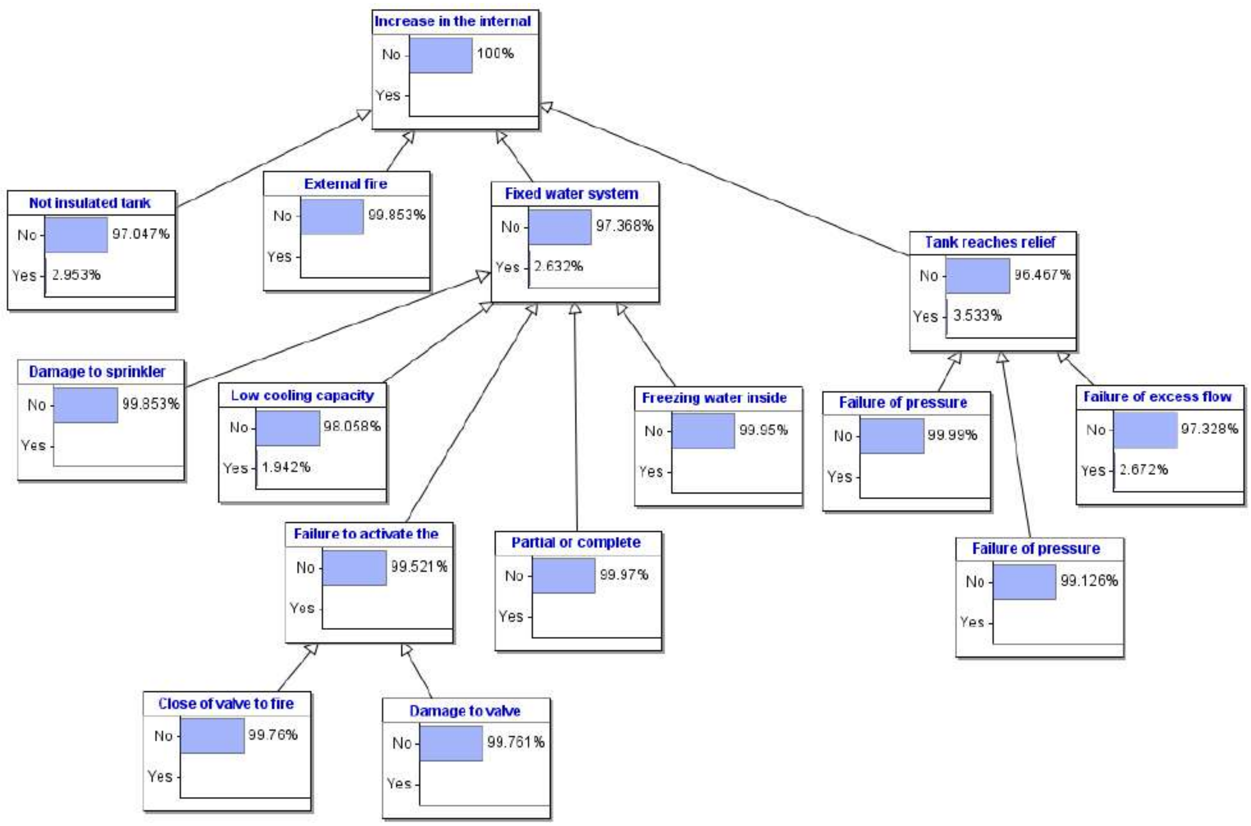


Figure 4.4.2: Risk Map on Agena Risk for increase in the internal pressure of the tank.

The parent nodes of mechanical damage in figure 4.4.3, material or structural defects, corrosion, fatigue, and sabotage were connected with an OR gate. Internal and external corrosion nodes were connected with an OR gate which were responsible for overall corrosion. The parent nodes of the weak security system: structural failure of the barriers around the site, guardian negligence and electric system failure were also connected with an OR gate.

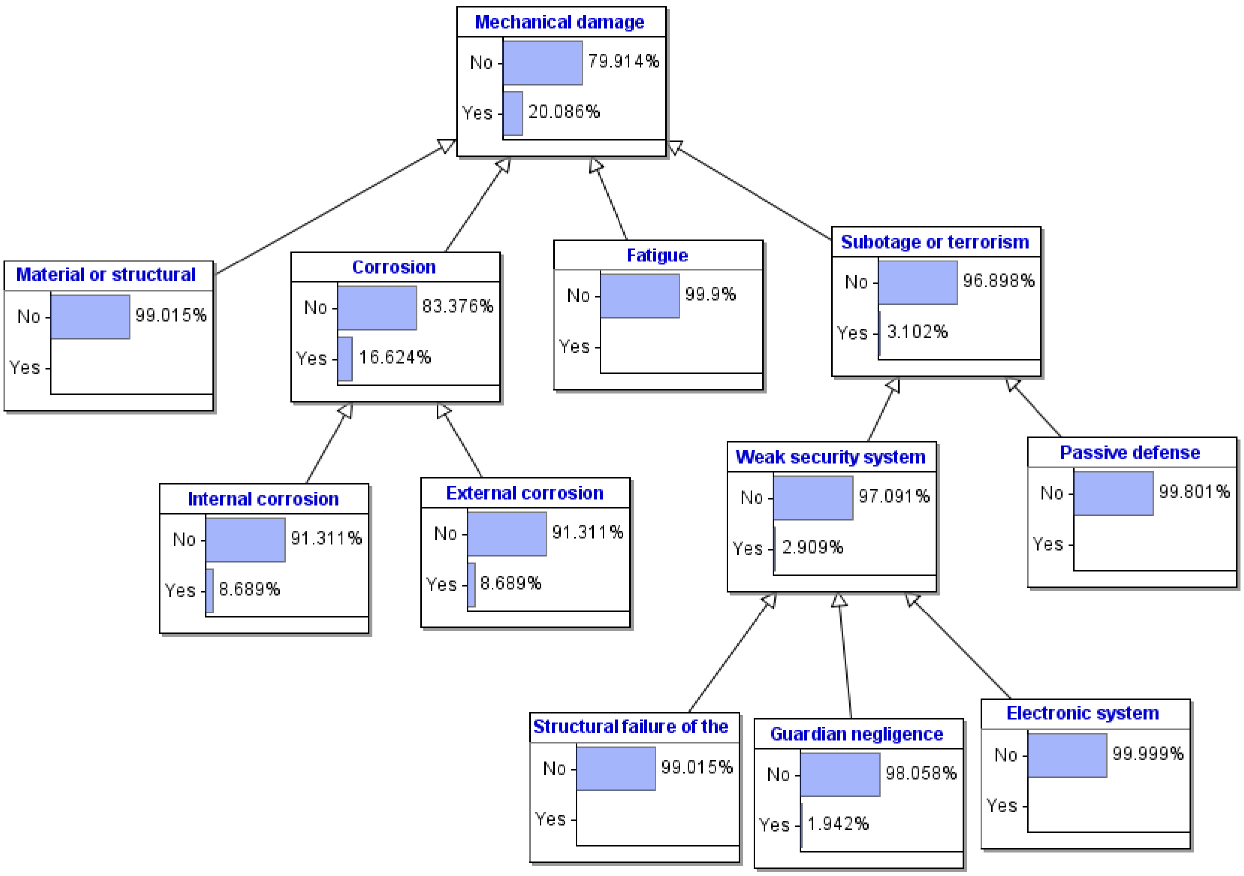


Figure 4.4.3: Risk Map on Agena Risk for mechanical damage.

In figure 4.4.4 two reasons were connected with an OR gate behind the failure of pressure relief valve node. These were: design error and maintenance error. Another node, failure of normal operation of valve had been added by the existing AND gate as another reason of leakage from pressure relief valve.

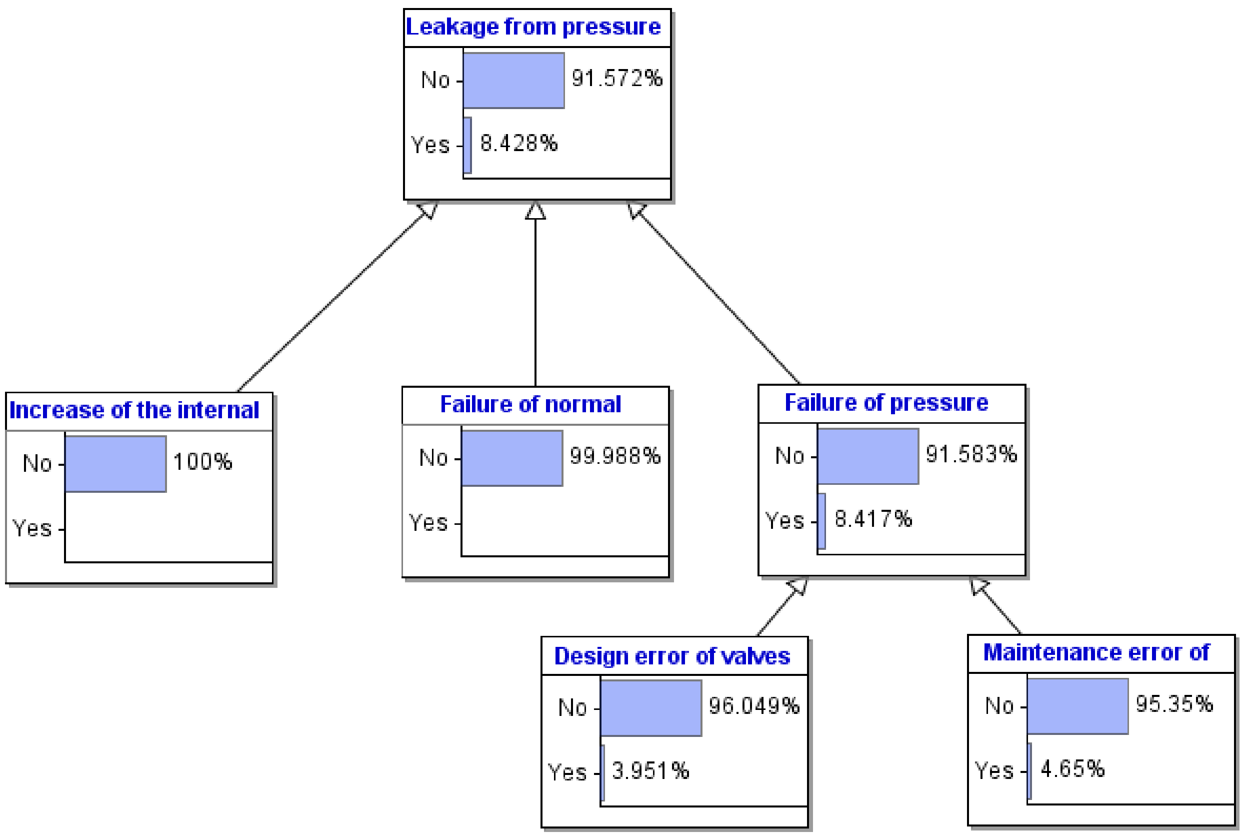


Figure 4.4.4: Risk Map on Agena Risk for leakage from pressure relief valve.

In figure 4.4.5 leakage from drain valve had been analyzed in a fault tree. The reasons for this top event were design error, operator's error and valve freezes which were connected by an OR gate. The root nodes of the design error of drain valve were: insufficient control over the valve, very large valve diameter, improper discharge to environment. These nodes were also connected with an OR gate. Operator's error was the child node of the nodes: failure to follow work instructions and leaving the drain valve open, connected by an OR gate.

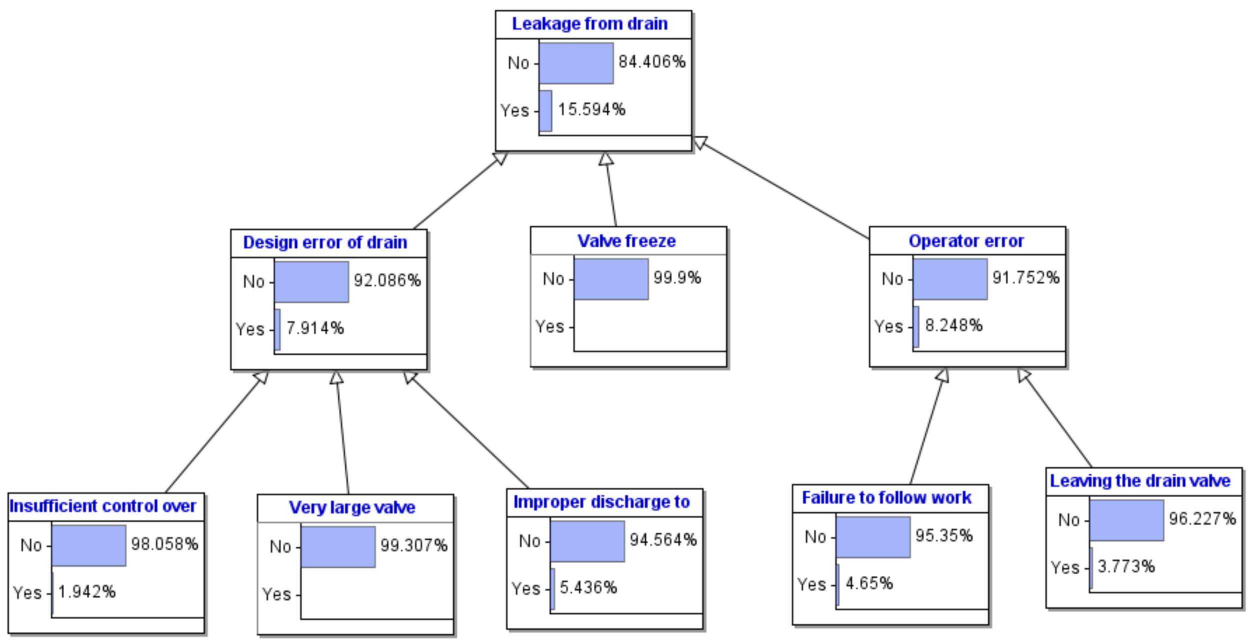


Figure 4.4.5: Risk Map on Agena Risk for leakage from drain valve.

In figure 4.4.6 the release from the tank body had been updated by adding two more parent node: natural events and mechanical damage by the existing AND gate. Two parent nodes of the natural event: tsunami and earthquake and lightning were connected by an OR gate.

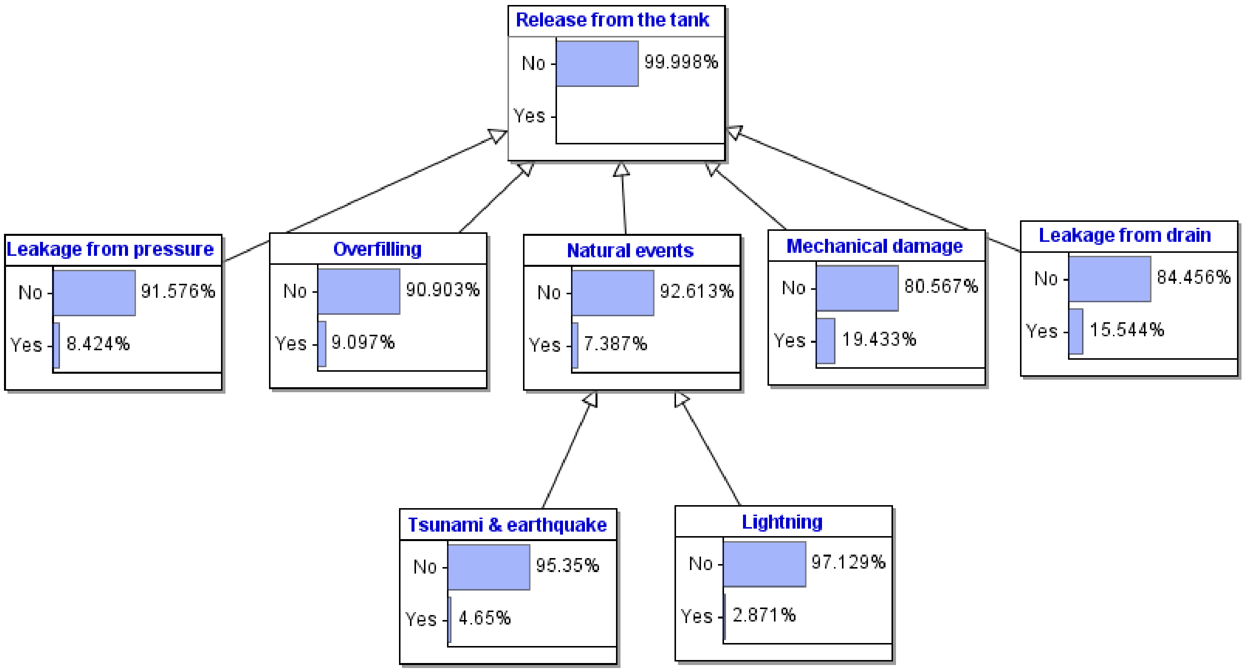


Figure 4.4.6: Risk Map on Agena Risk for release from tank body.

Bayesian Calculation of different barriers are shown below:

a) Release prevention barrier

From figure 4.4.7, failure of tank cooling system, non-compliance with standards while placing equipment and fireproof failure were the reasons connected with an AND gate behind external fire prevention barrier. Non-compliance with standards happened when either of the standard distance between two adjacent tanks and that between tanks and installations were not maintained. Tank cooling systems failed because of any of blockage of sprinklers, complete or partial blockage of pipes, frozen water inside the pipes, failure of cooling system to activate and lack of sufficient water. The parent nodes of fireproofing failure were failure of tank base fireproofing and failure of insulation of tank which were connected with an OR gate.

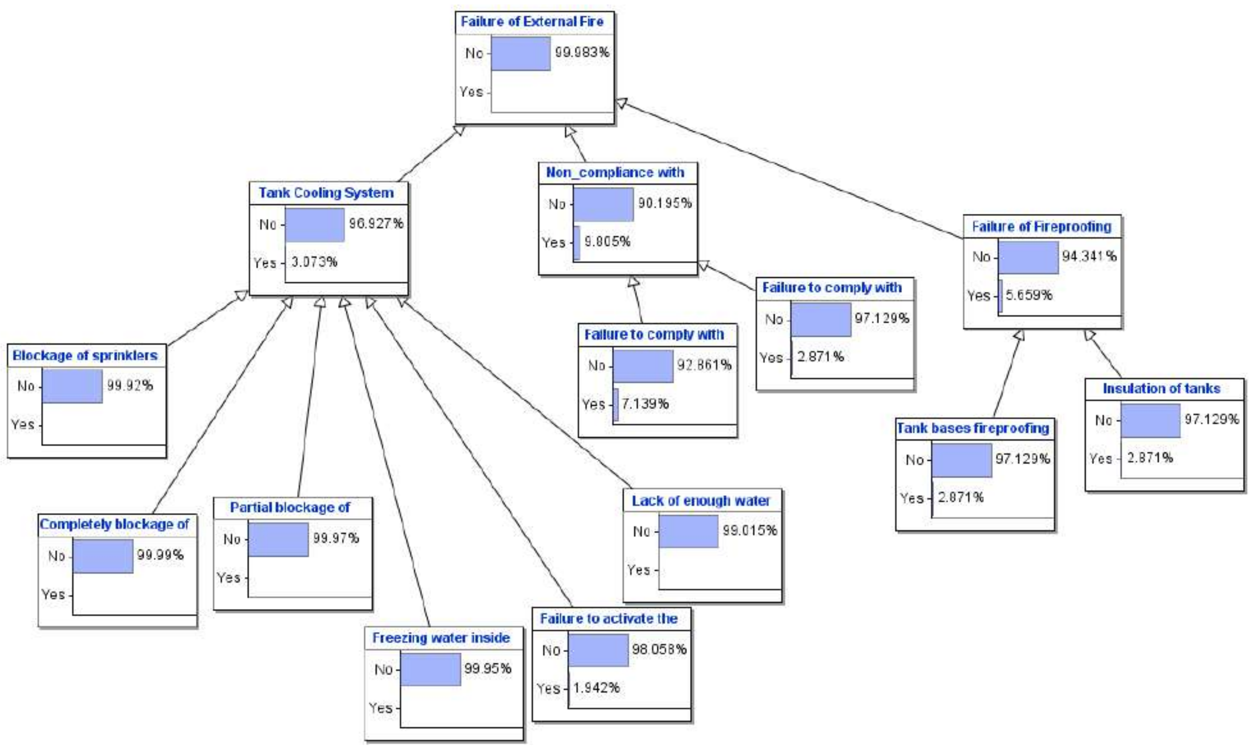


Figure 4.4.7: Risk Map on Agena Risk for failure of external fire prevention barrier.

From figure 4.4.8 we can see that the probability of occurrence of mechanical damage prevention barrier failure conditionally depended on the probabilities of vehicle collision prevention barrier failure, failure of external fire prevention barrier, sabotage prevention barrier failure and failure of natural hazard prevention barrier connected by an OR gate. Parent nodes of vehicle collision prevention barrier failure were lack of fences around the tank and lack of protection of pipes and fittings were connected by an OR gate also. Failure of natural hazard prevention was the child node of tank foundation was not strong and failure of lightning protection system which were connected by an OR gate.

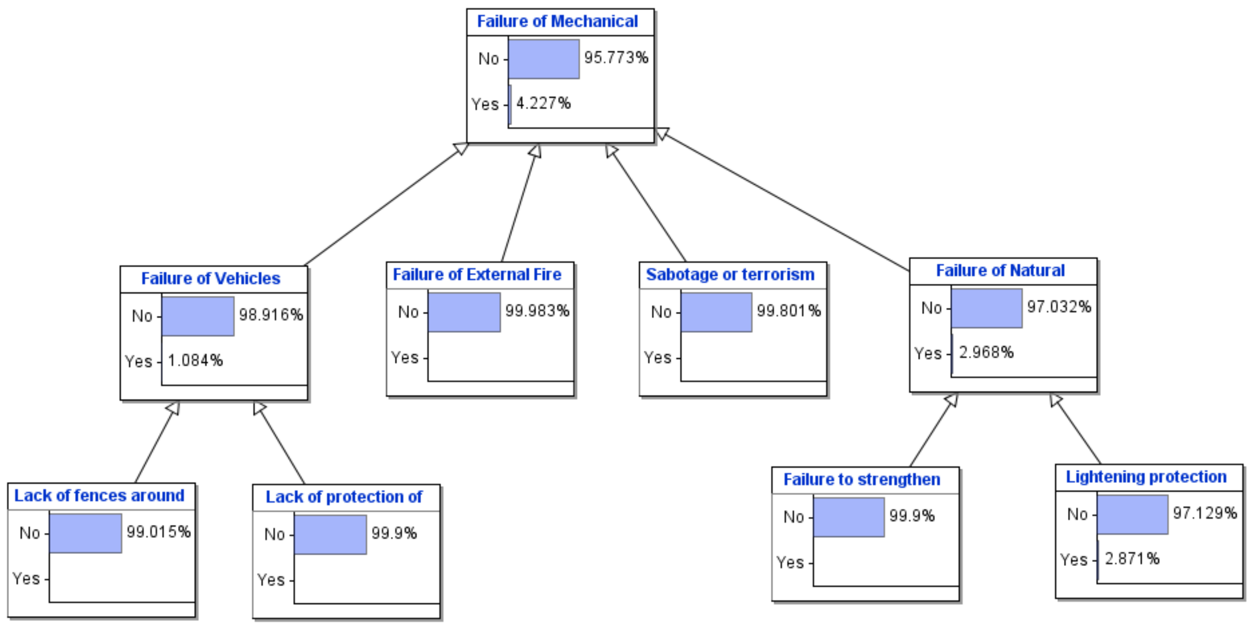


Figure 4.4.8: Risk Map on Agena Risk for failure of mechanical damage prevention barrier.

Figure 4.4.9 shows that isolation failure and operational error were the parent nodes of operational error prevention barrier failure connected by an AND gate. The root causes of isolation failure, area was not isolated, isolation valve failure and absence of isolation valve were connected by an OR gate. The parent nodes of operational error were: sampling valve is left open, isolation valve fails to activate and work instructions are not followed which were connected by an OR gate also.

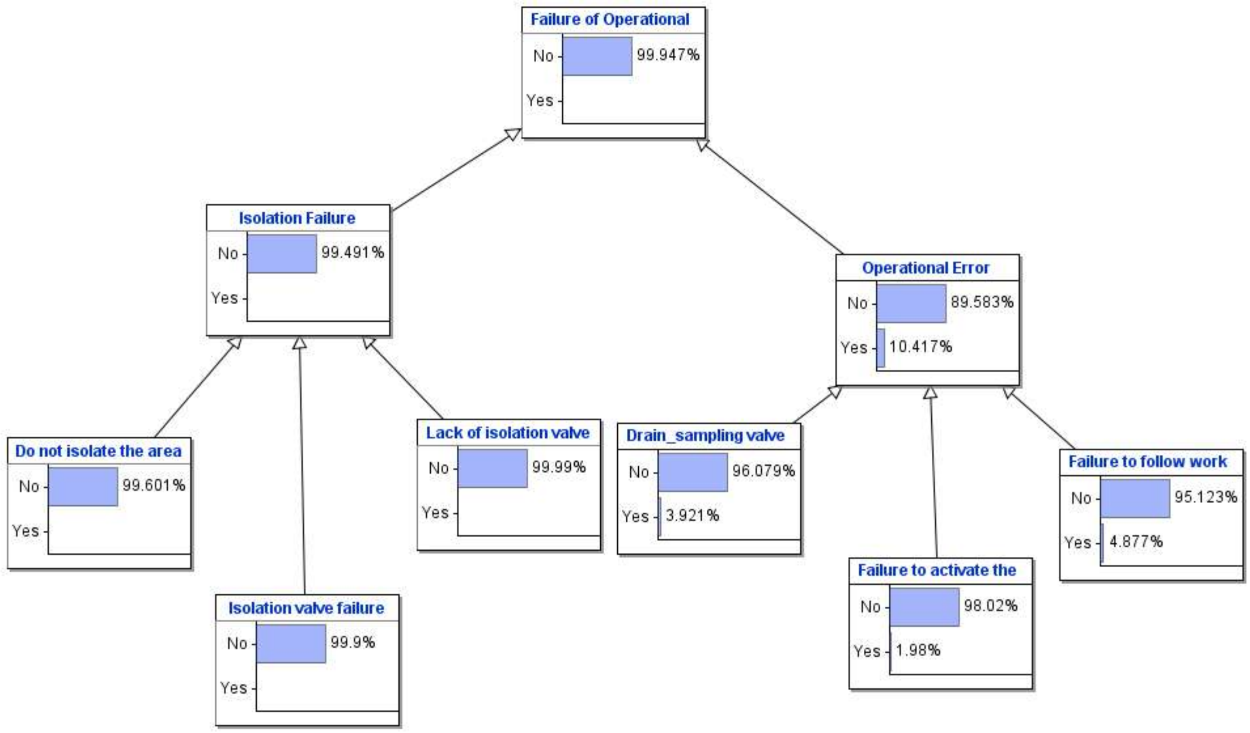


Figure 4.4.9 Risk Map on Agena Risk for failure of operational error prevention barrier.

From figure 4.4.10, the failure rate of overfilling prevention system depended on the failure rate of liquid level control, operator stopping the flow and shutdown valve via an AND gate. Operator's failure in current stop occurred due to any of delay in stopping pump after a release and operator's failure to stop the pump.

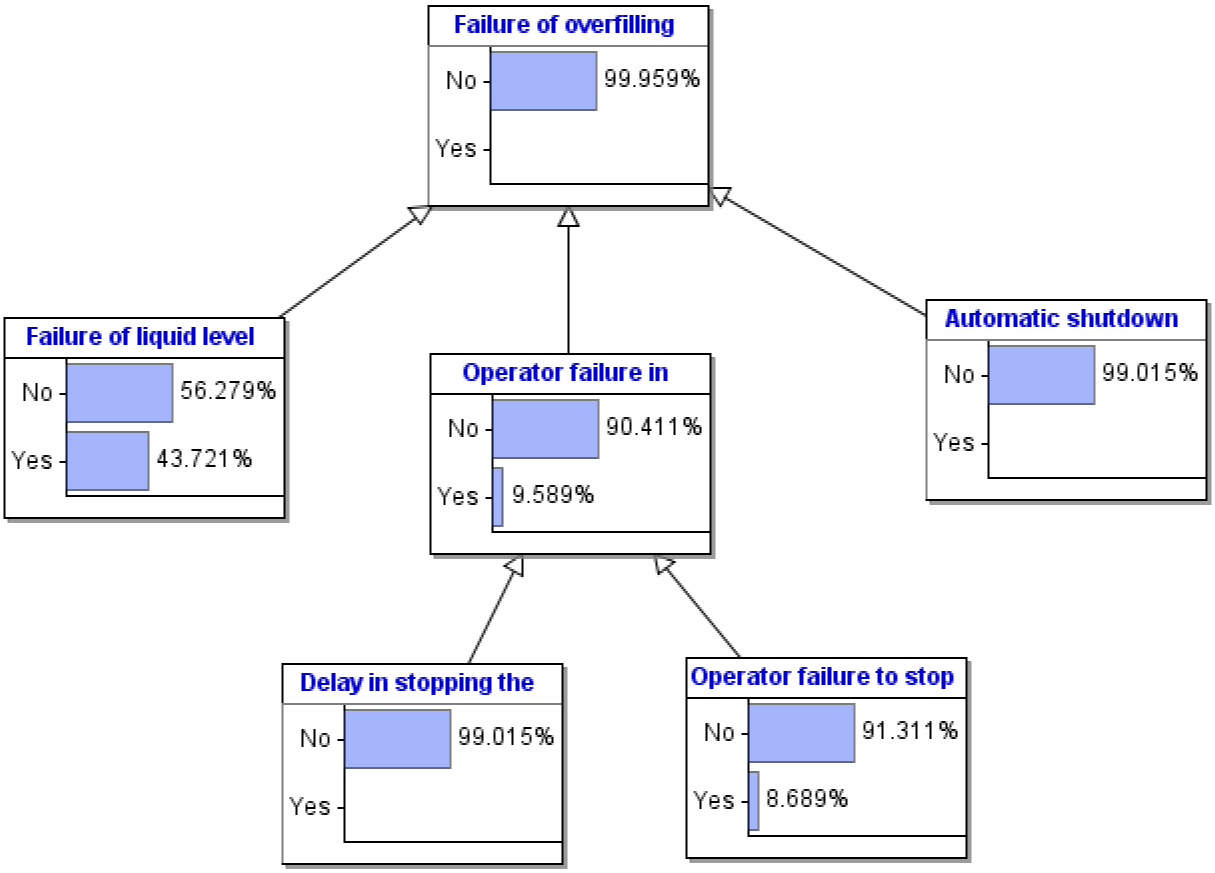


Figure 4.4.10: Risk Map on Agena Risk for failure of overfilling prevention system.

Figure 4.4.11 shows how the probability of failure of corrosion prevention and inspection conditionally depended on the probabilities of corrosion inspection failure, failure of visual inspection, failure of inspection of welding and failure of metal cracking monitoring via an OR gate. The parent nodes of corrosion inspection failure, destructive test equipment were not calibrated, failure in inspection of small connection, exterior body inspection failure in terms of corrosion under insulation, internal corrosion inspection failure and failure of inspection of tank bases were connected by an OR gate. Metal cracking monitoring failed because of any of the failure of superficial crack monitoring and the failure of sub surface cracking monitoring.

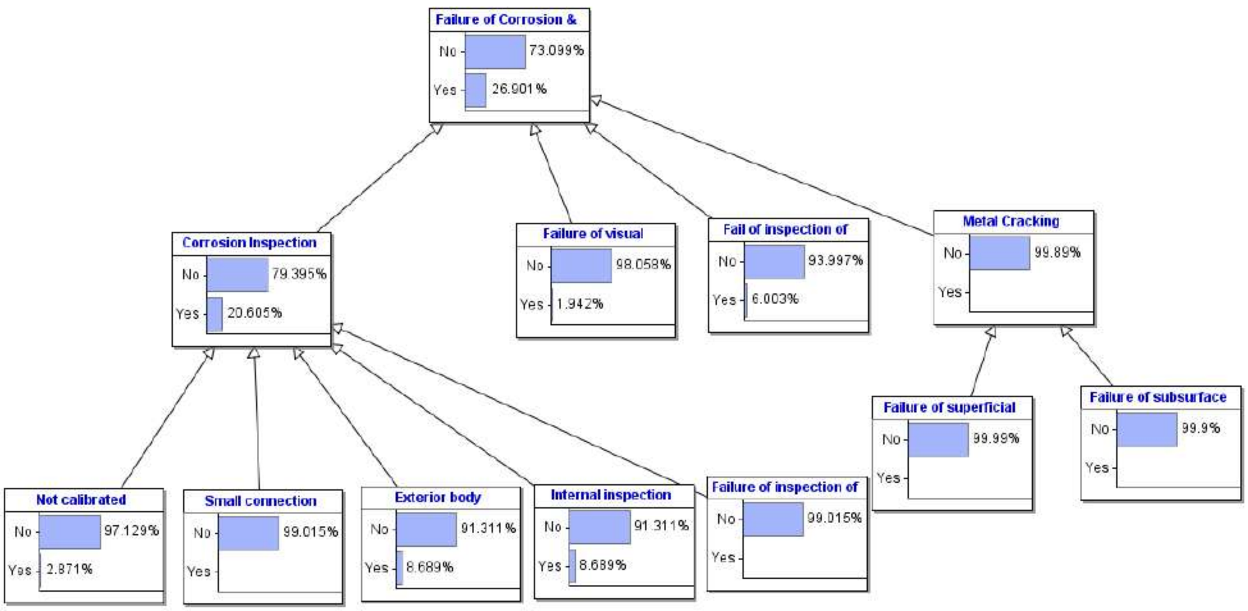


Figure 4.4.11: Risk Map on Agena Risk for failure of corrosion prevention and inspection.

Figure 4.4.12 illustrates the node analysis of safety system failure where safety system failure was the child node of faulty pressure gauge, faulty safety valve, failure of excess flow check valve and failure of the overfilling prevention system connected by an OR gate. Excess flow valve failed because of any of the faulty excess flow valve and the improper diameter of downstream pipe of the excess flow valve.

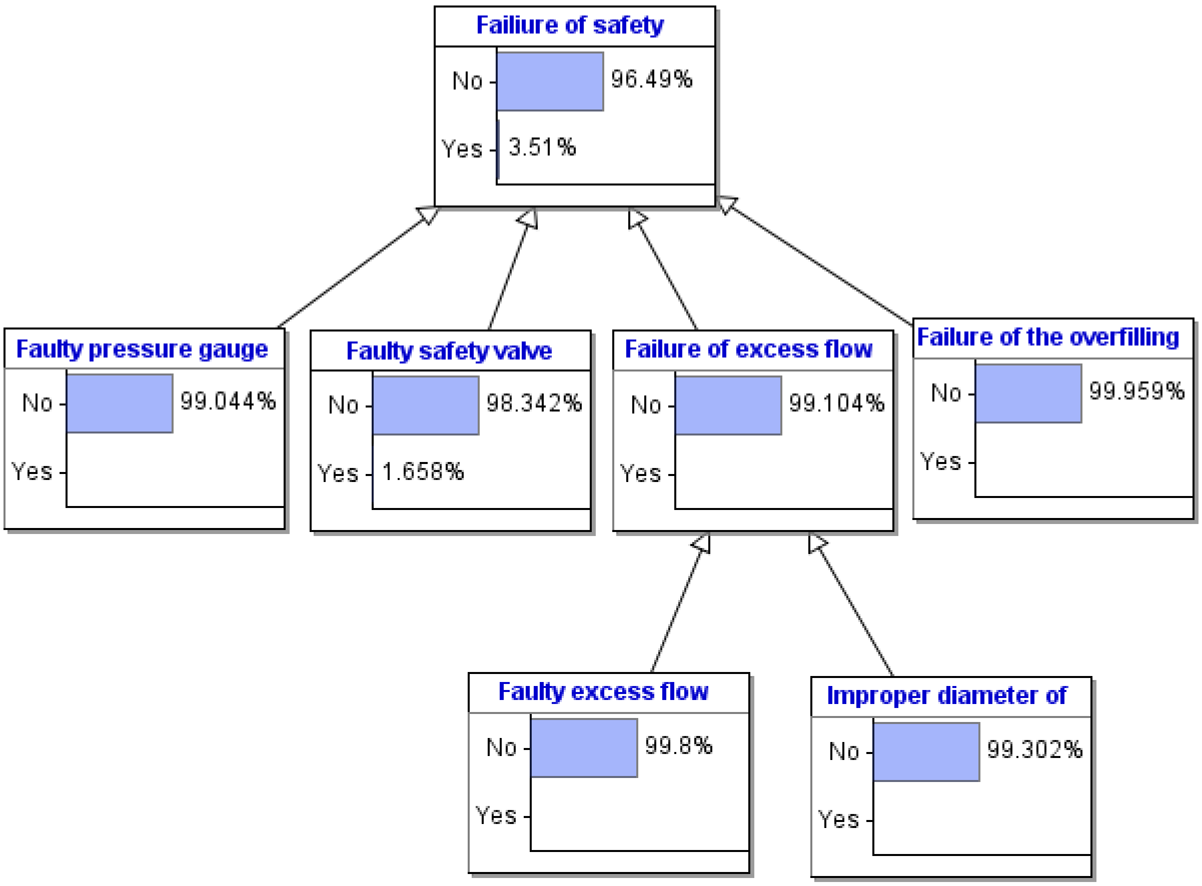


Figure 4.4.12: Risk Map on Agena Risk for failure of safety system.

Figure 4.4.13 illustrates the fault tree of the failure of the release prevention barrier. The parent nodes: failure of operational error prevention barrier, failure of mechanical damage prevention barrier, failure of preventive maintenance barrier and failure of safety systems were connected by an OR gate. Preventive maintenance barrier fail occurs for both of the maintenance failure and failure of corrosion inspection. The root causes behind maintenance failure were failure of inspection after maintenance, improper connection of screws, flanges and fittings, not following maintenance instruction, use of inappropriate materials in repair and wrong position of valves after repair which were connected by an OR gate.

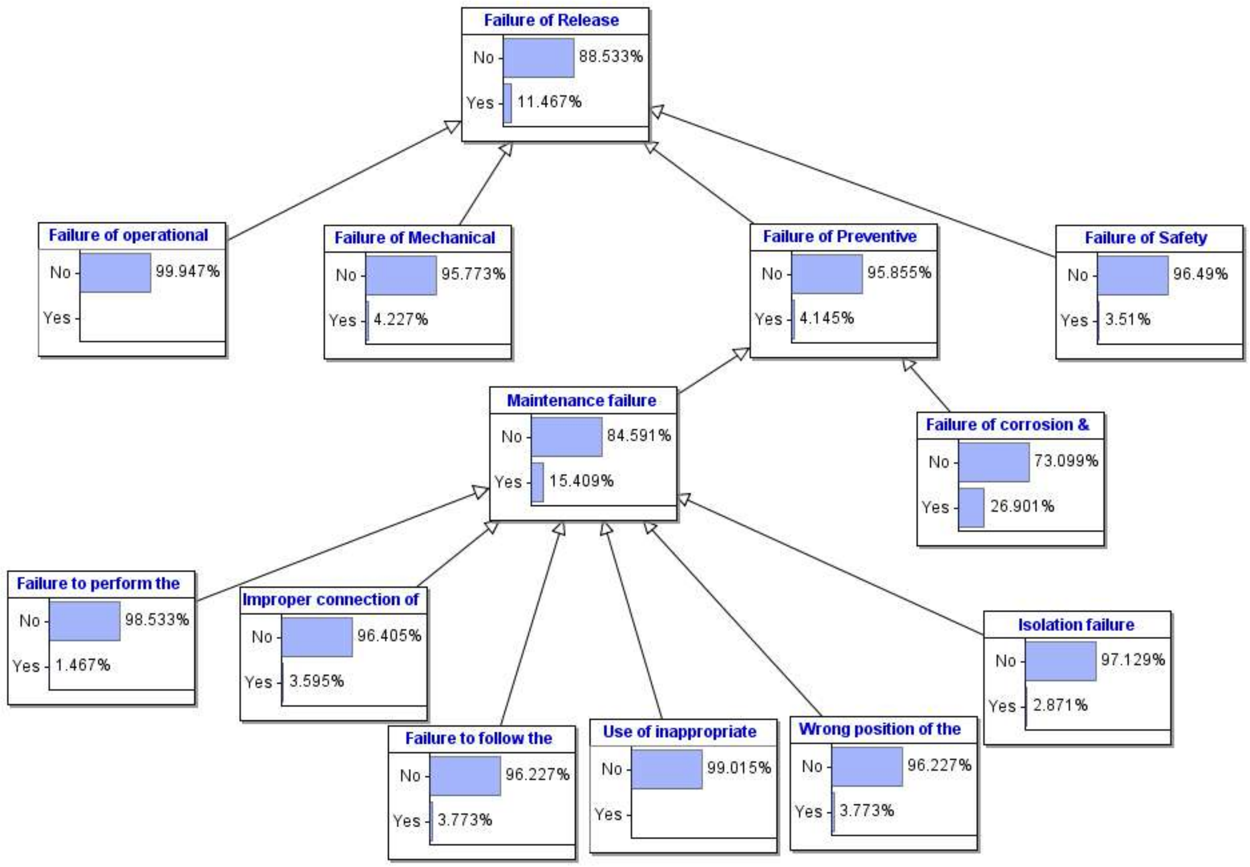


Figure 4.4.13: Risk Map on Agena Risk for failure of release prevention barrier.

b) Dispersion prevention barrier

In figure 4.4.14 the fault tree of DPB was updated by adding two more parent nodes: passive barrier failure and continuous site inspection failure by the existing OR gate.

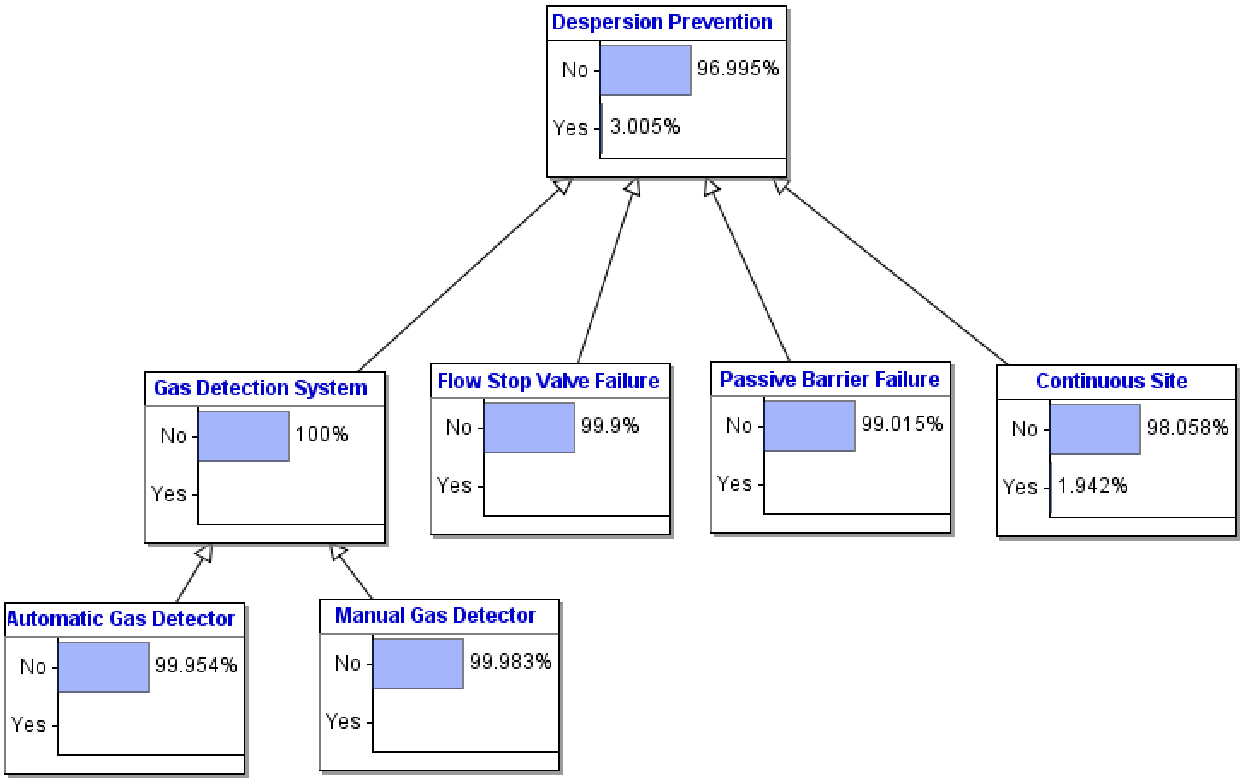


Figure 4.4.14: Risk Map on Agena Risk for failure of dispersion prevention barrier.

c) Ignition prevention barrier

In figure 4.4.15 the fault tree of ignition prevention, two more parent nodes: dilution system failure and temperature control failure had been added by an OR gate. The causes of temperature control failure were tank insulation failure, cooling system failure and hot surface protection failure connected by an AND gate. One more reason behind ignition source: hot work permit had been added by the existing OR gate.

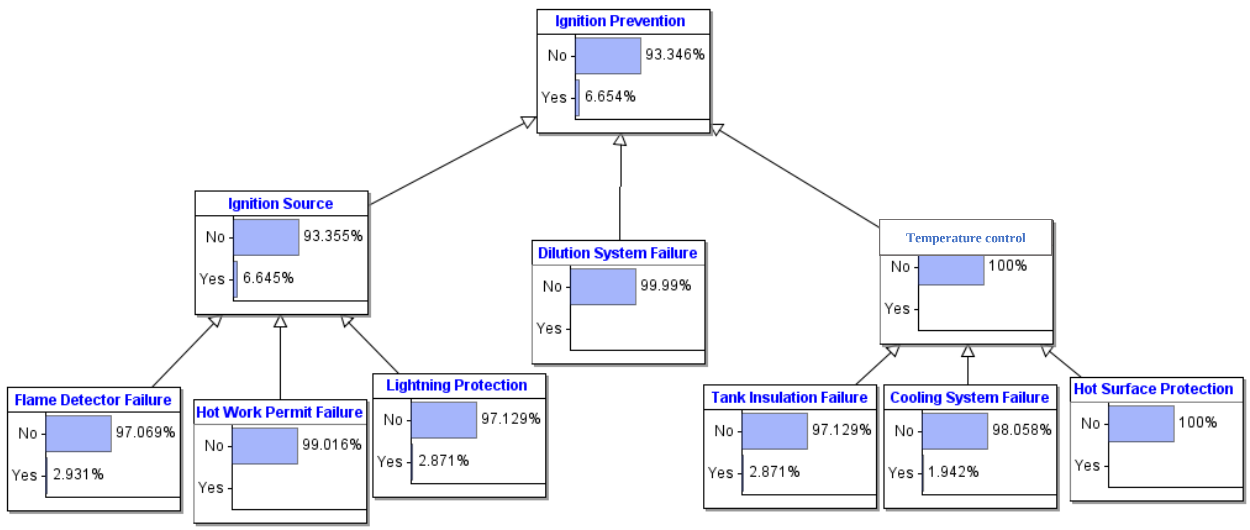


Figure 4.4.15: Risk Map on Agena Risk for failure of ignition prevention barrier.

d) Escalation prevention barrier

After update of the escalation prevention barrier fault tree, dilution system failure and lack of standard distance had been added in figure 4.4.16 by the existing OR gate. Fire wall node had been added as one parent node of fire protection system failure. The parent nodes of dilution system failure: neutral gas dilution failure and water spray dilution failure were connected by an AND gate.

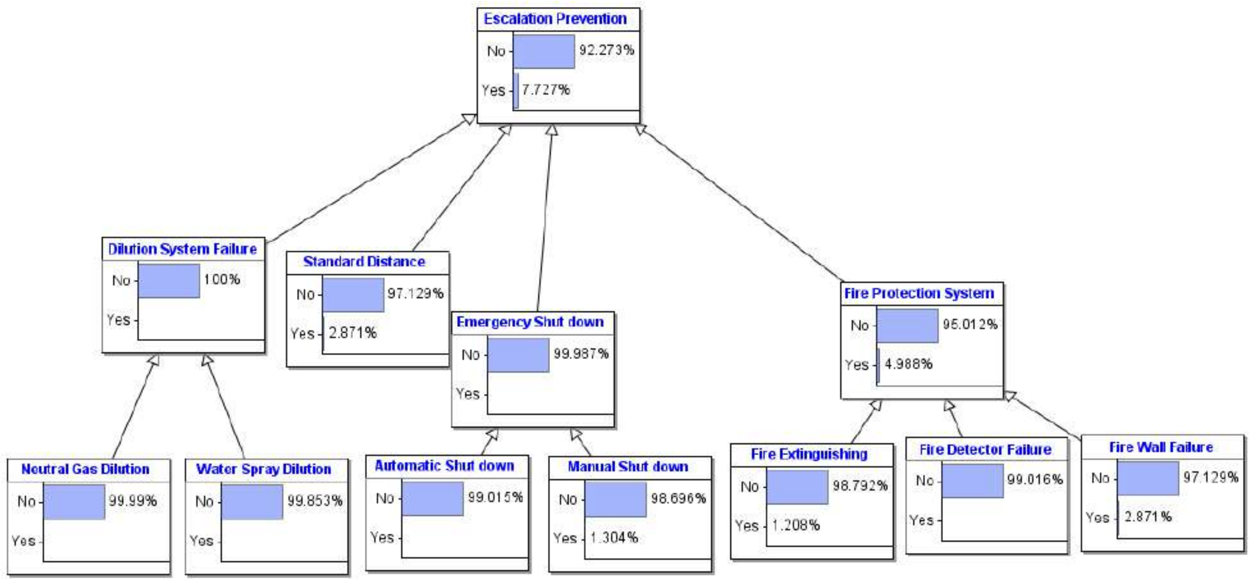


Figure 4.4.16: Risk Map on Agena Risk for failure of escalation prevention barrier.

e) Emergency management and Damage control barrier

Figure 4.4.17 shows that the causes of emergency management and damage control barrier failure were management failure and active control failure which were connected by an AND gate. The root causes of management failure: proper communication system failure, emergency medical services failure, emergency response plan failure, failure of appropriate training and failure of evacuation instruction were connected by an OR gate. The parent nodes of the active control failure node were: alert system failure, lack of adequate equipment and failure of emergency maneuver, which are also connected by an OR gate.

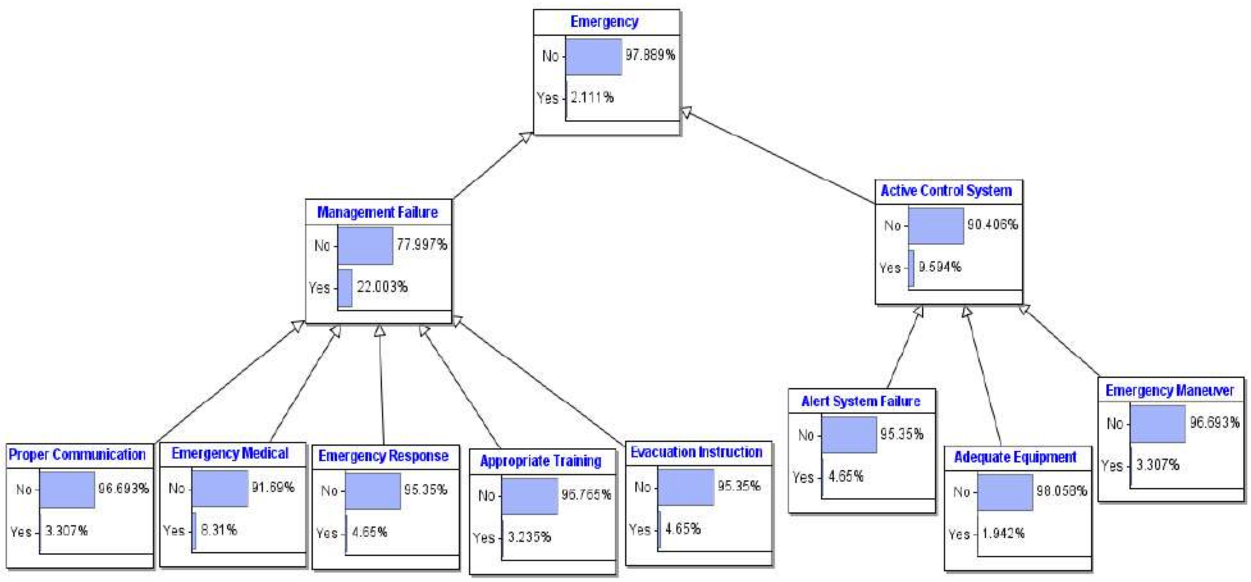


Figure 4.4.17: Risk Map on Agena Risk for failure of emergency management and damage control barrier.

Table 4.3(a) shows the failure rate of different primary events causing emergency management and damage control barrier failure which were used in Agena Risk calculation.

Table 4.3(a): Failure rate of emergency management and damage control barrier [40, 41].

Event	Event Description	Failure Rate μ (event per year)	Probability ($1-e^{-\mu t}$)
P1	Proper communication system	0.0348	0.034201
P2	Emergency medical services	0.095	0.090627
P3	Emergency response plan	$5x10^{-2}$	0.048771
P4	Appropriate training	$3.4x10^{-2}$	0.033428
P5	Evacuation instruction	$5x10^{-2}$	0.048771
P6	Alert system	$5x10^{-2}$	0.048771
P7	Adequate equipment	$2x10^{-2}$	0.019801
P8	Emergency maneuver	0.0348	0.034201

f) Human factor barrier

According to figure 4.4.18 the parent nodes of this top node were physical disability, failure of operators' incentive program and failure of supervision and monitoring which were connected by an AND gate.

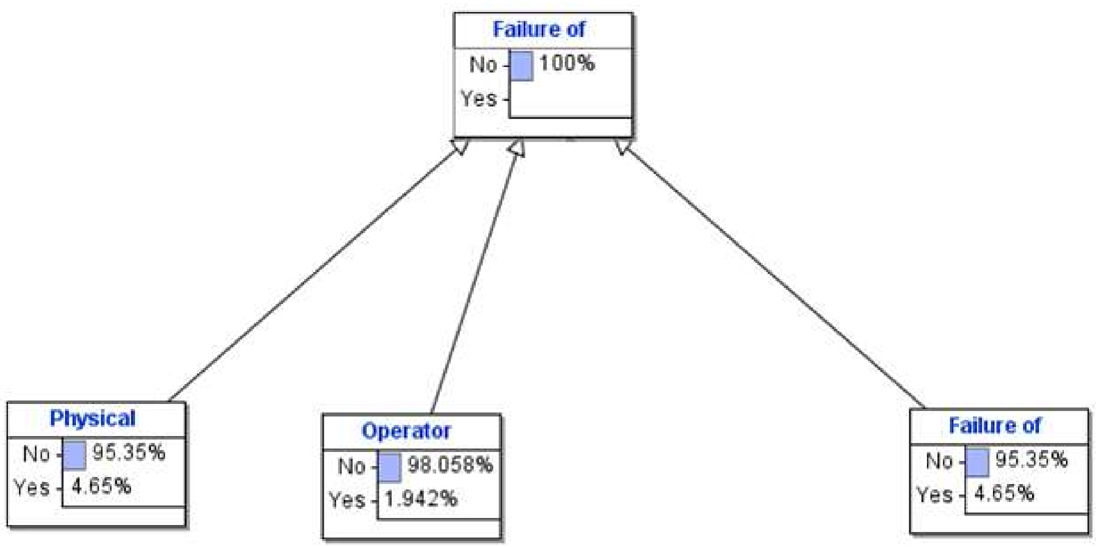


Figure 4.4.18: Risk Map on Agena Risk for failure of Individuals characteristics barrier.

Figure 4.4.19 shows that the only parent node of failure of workplace design was failure to control harmful factors in the workplace which means the child node and the parent node had the same probability value. The reasons behind failure to control harmful factors were: uncomfortable temperature conditions, insufficient lighting and high noise or mechanical vibration which were connected by an OR gate.

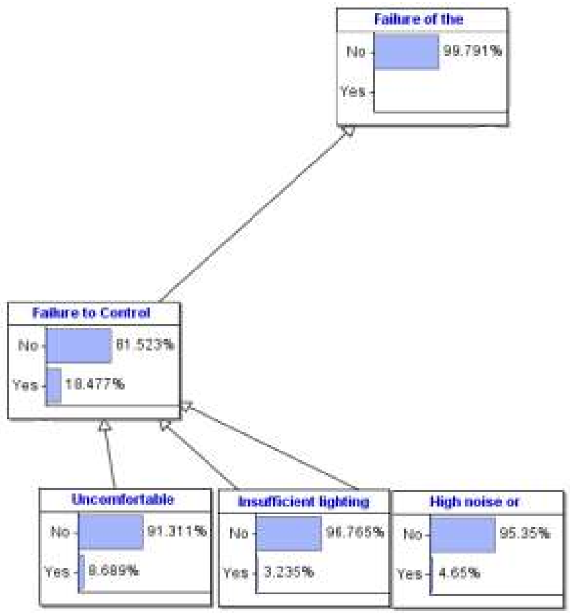


Figure 4.4.19: Risk Map on Agena Risk for failure of workplace design barrier.

Figure 4.4.20 illustrated the causes of human system interaction barrier failure. It was the child node of control panel failure, improper tools, alarm or display failure and labelling failure which were connected by an AND gate. The causes of improper tools: unreliable measuring equipment and insufficient equipment were connected by an OR gate.

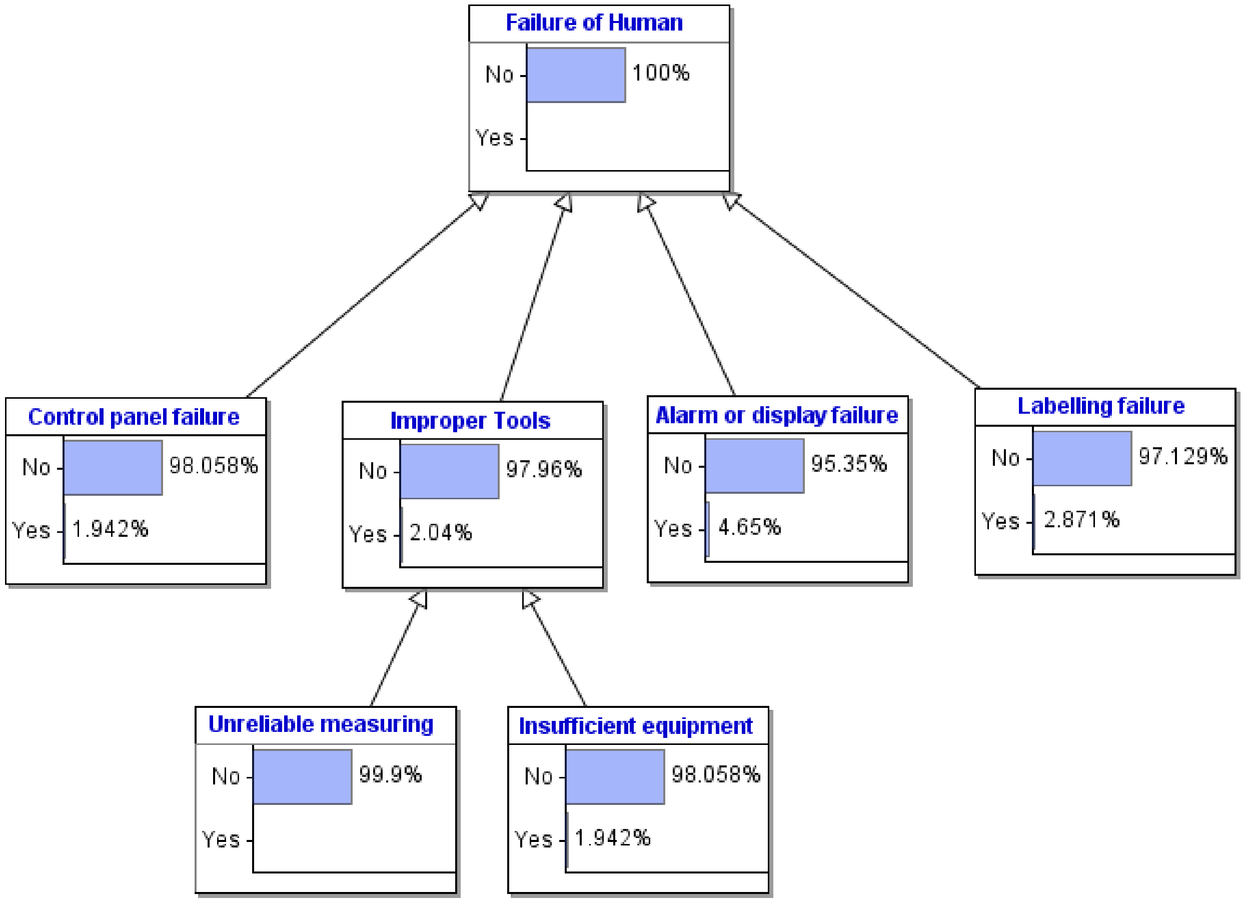


Figure 4.4.20: Risk Map on Agena Risk for failure of human system interaction barrier.

Figure 4.4.21 depicts the fault tree of human factor barrier failure where the probability of this node depended on the probabilities of failure of individual's characteristics barrier, failure of workplace design barrier and failure of human system interaction barrier via an OR gate.

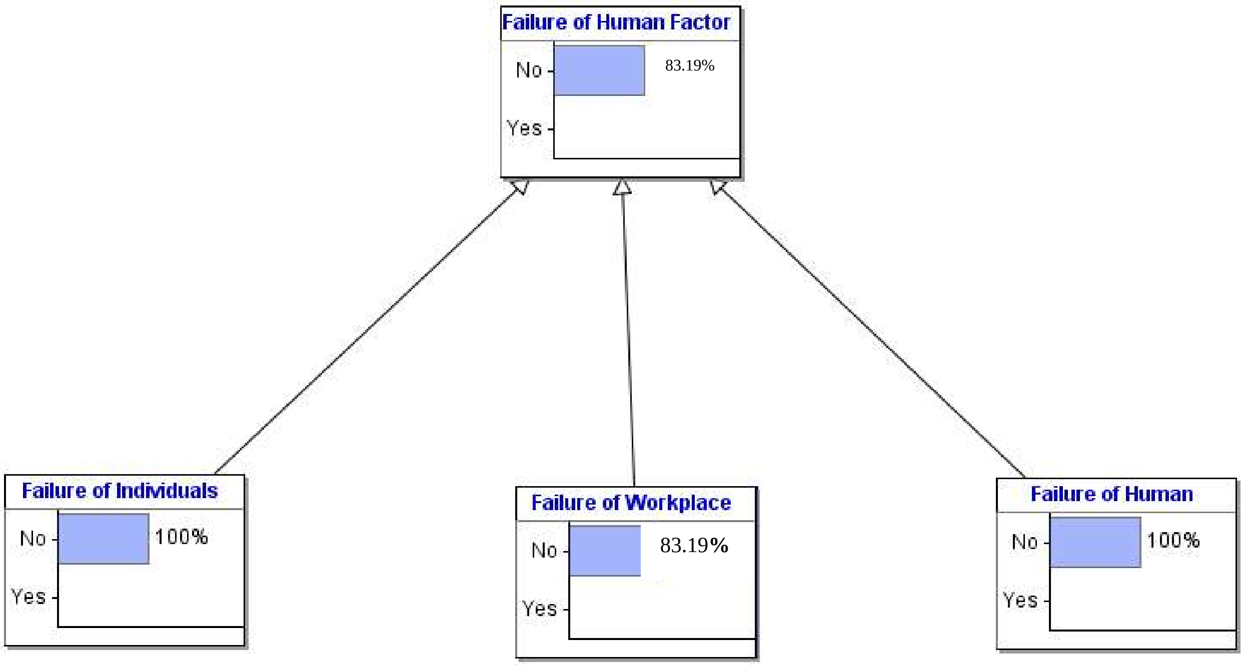


Figure 4.4.21: Risk Map on Agena Risk for failure of human factor barrier.

Table 4.3(b) shows the failure rate of basic events behind human factor barrier failure used in calculation.

Table 4.3(b): Failure rate of human factor barrier basic events [40, 41].

Event Name	Event Description	Failure Rate μ (event per year)	Probability ($1-e^{-\mu t}$)
P1	Unreliable measuring equipment	1×10^{-3}	0.0009995
P2	Insufficient equipment	2×10^{-2}	0.019801327
P3	Control panel failure	2×10^{-2}	0.019801327
P4	Poor house keeping	5×10^{-2}	0.048770575
P5	Insufficient access	2×10^{-2}	0.019801327
P6	Alarm/display failure	5×10^{-2}	0.048770575
P7	High work stress	6.7×10^{-2}	0.064804799
P8	Unspecified job description	3.4×10^{-2}	0.033428495
P9	Continuous night work	5×10^{-2}	0.048770575
P10	Existence of fumes and gases or low oxygen	3.4×10^{-2}	0.033428495
P11	Uncomfortable temperature conditions	1×10^{-1}	0.095162582
P12	Insufficient lighting	3.4×10^{-2}	0.033428495
P13	High noise or mechanical vibration	5×10^{-2}	0.048770575
P14	Physical disability	5×10^{-2}	0.048770575
P15	Operator skill improvement program failure	2×10^{-2}	0.019801327
P16	Operator training program failure	3.4×10^{-2}	0.033428495
P17	Insufficient skills	5×10^{-2}	0.048770575
P18	Insufficient knowledge	1×10^{-2}	0.009950166
P19	Operator incentive program failure	2×10^{-2}	0.019801327
P20	Failure of supervision and monitoring	5×10^{-2}	0.048770575
P21	Labelling failure (incorrect labelling or labelling not done)	3×10^{-2}	0.029554466
P22	Unplanned working hours	5×10^{-2}	0.048770575

Table 4.3.1 represents the failure probability of all barriers calculated with Agena Risk which were then converted to frequency.

Table 4.3.1: Frequencies of top event and barrier failure from BN calculation.

Barrier Name	Barrier Failure Probability P	Barrier Failure Frequency,μ= –ln(1-P) (per year)
i-butane release from storage tank	1.7100E-5	1.7100E-5
Release Prevention barrier (RPB)	0.11467	0.12179
Dispersion Prevention Barrier (DPB)	0.03004	0.03050
Ignition Prevention Barrier (IPB)	0.06654	0.06886
Escalation Prevention Barrier (EPB)	0.07727	0.08042
Emergency Management and Damage Control Barrier (DC&EMB)	0.02110	0.02133
Human Factor Barrier (HFB)	0.16809	0.18404

Event tree analysis: Figure 4.4.22 shows the frequencies of the consequences after release from the tank and the effects of the update in fault trees on the consequences. That phase when none of the barriers is failed is called safe phase. When only release prevention barrier fails, the situation is called near miss. Failure of DPB with RPB and failure of RPB, DPB and IPB in series arise mishap situation. Mishap= 5.9163E-08+4.0234E-09 = 6.3186E-08/year. When RPB, DPB, IPB and EPB fail, the phase is called incident. Accident occurs when emergency management and damage control barrier does not work after the release, dispersion and ignition of the tank containment and escalation of the fire. Then the accident turns into catastrophe when all of the barriers fail.

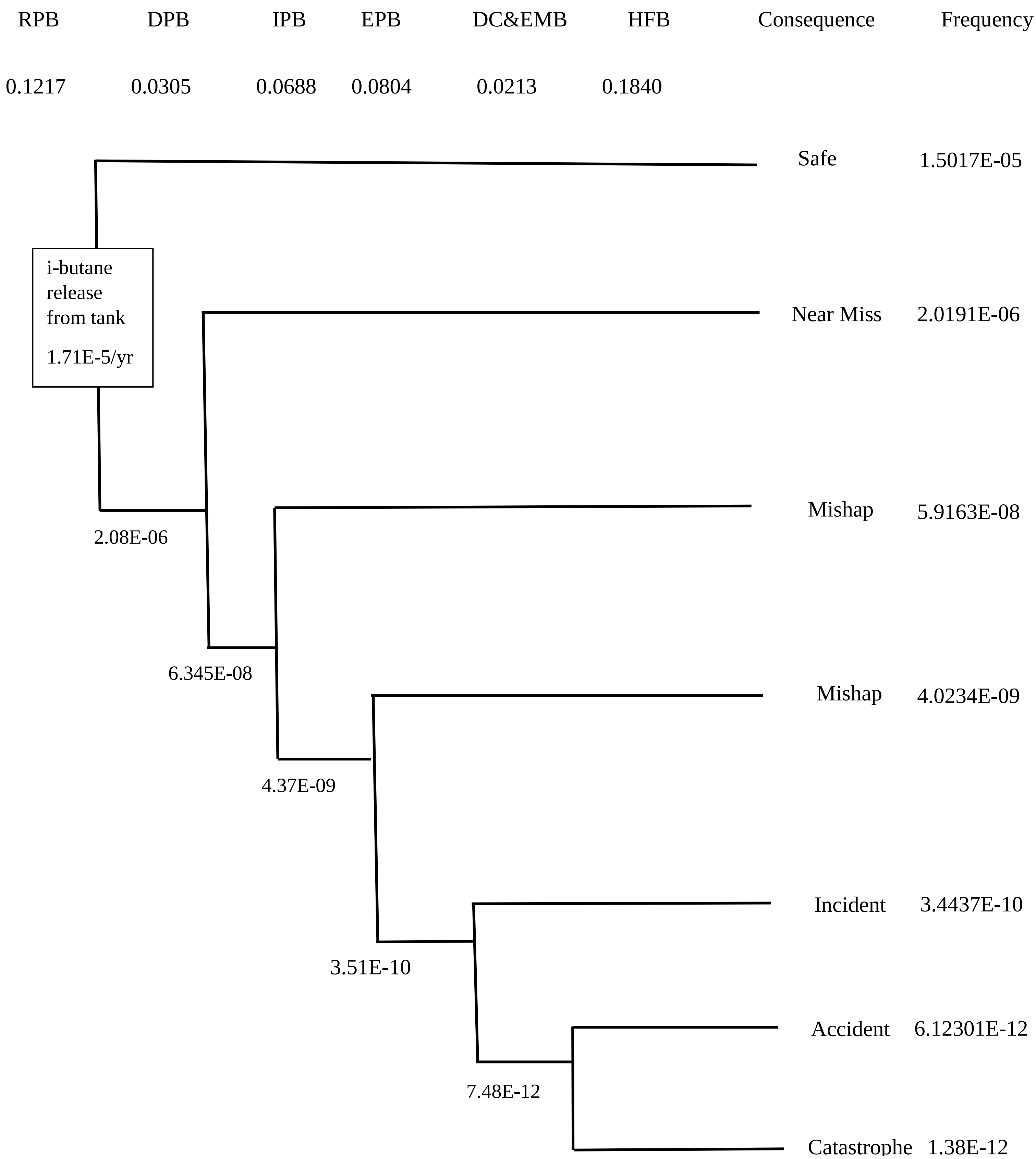


Figure 4.4.22: Event tree after update of the model by BN analysis (Barrier failure and different consequences).

Table 4.4 summarizes the frequency of the occurrence of the top event and failure of barriers and Table 4.5 represents the frequency of the consequences calculated from Bow-Tie fault tree and Agena Risk calculation.

Table 4.4: Frequencies of top event and barrier failure in BT and BN analysis.

Event	Bow-Tie	Bayesian Network
i-butane release from storage tank	9.9850E-7	1.7100E-5
RPB	0.0365	0.1217
DPB	0.0010	0.0305
IPB	0.0606	0.0688
EPB	0.0224	0.0804
DC and EMB	-	0.0213
HFB	-	0.1680

Table 4.5: Frequency of consequences from BT and BN analysis.

Consequences (/year)	Bow-Tie	Bayesian Network
Safe	9.6204E-07	1.5017E-05
Near Miss	3.6414E-08	2.0191E-06
Mishap	3.4244E-11	6.3186E-08
Incident	2.1595E-12	3.4437E-10
Accident	4.9500E-14	6.1230E-12
Catastrophe	-	1.3800E-12

5. Conclusion

This research successfully developed a risk analysis methodology for petrochemical storage tank taking an i-Butane storage tank as case study. After estimating risk probability using the fault tress and event trees of a Bow-Tie, it was mapped into Bayesian Network which generates a dynamic risk assessment method to facilitate the risk assessment and predict the potential risk. This study showed how some additional causes contributed to the probability of i-Butane release from tank. The frequency increased from 9.9850×10^{-7}/year to 1.7100×10^{-5}/year. This research had also found out how to mitigate or lessen these added threats by implementing additional barriers because this kind of analysis is open to all kinds of changes in hazards through which a plan or process unit keeps going all round the year. Some additional reasons of release prevention barrier: operational error, maintenance error, corrosion, fire protection system failure and mechanical damage increases its failure probability two times which means this barrier is the most vulnerable to failure. It also reveals that release prevention barrier is the most necessary barrier for mitigating consequences.

Research Contribution:

- Frequencies of critical event and failure of safety barriers have been calculated using quantitative Bow-Tie and also Bow-Tie mapped into Bayesian Network for i-butane storage facility
- Fault trees of every event have been updated considering additional risks and protective measures have been recommended
- The established model is able to adopt any change in process variables, design intent and failure probabilities of instruments
- This method can provide continuous update of risk and allows us to incorporate changes in the failure probability of safety barriers
- The studied model can be applied by data extraction from any PID of any plant
- This risk assessment can be done at any of the stages: design, construction, operation, modification and after overhauling.

Future scope of research

- In this study, the failure rate frequencies are considered constant with time, but in reality, due to deterioration, the failure rate increases likely with time. Quantification of time dependent parameters such as time interval of inspection and testing of plant and equipment, plant operator response time, instrument aging etc. can be an opportunity to take this research further.
- Quantifying updated/posterior probabilities using accident record/historical data and the probability distribution got from generic data bases which can be incorporated with plant specific data.
- Mapping HAZOP and LOPA and even event trees into Bayesian Network is another future goal.
- In this research nodes only occur in the probabilities between 0% and 100% given their parent nodes occur or do not occur which are obtained by logical elimination. The N type node occurs in the probability of any value between 0% and 100% when their parent nodes occur or do not occur which is obtained by machine learning with a set of information or by the experts' opinion. For future study, N type modelling can be taken to consideration.
- As further work, consequence modelling can be done and risk matrix can be established for prioritizing risks and taking action accordingly.

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Appendix

Definition of some terms:

Risk: Risk is generally defined as the product between the probability of an incident and its consequent damage, and is frequently expressed as an expectation of damage, taking into account all damage classes and their associated probabilities[36]. It is expressed as a function of probability of any event occurrence and its consequence severity.

Hazard: Hazard is a physical or chemical condition that has potential to damage the people, property and environment.

Accident: Accident is unplanned or uncontrolled event which had led to damage.

Consequence: Consequence is outcome of accident.

Severity: The nature and extent of the consequence is severity.

Likelihood: The chance or probability that a hazard may result in an accident is likelihood or frequency.

Risk: Risk is the likelihood that a hazard will give rise to a consequence with a particular severity in terms of damage.

Individual risk: The risk to a person in the vicinity of a hazard is called individual risk.

Societal risk: Societal risk is a measure of risk to a group of people.

Intentions: How the process is expected to operate or the activity is expected to be performed.

Causes: Ways deviations might occur.

Consequences: Results of the deviations.

Safeguards: Provisions for reducing the frequency or the consequences.

Actions: Suggestions for procedural changes, design changes, or further study.

Design intent: Defines how the plant is expected to operate at the nodes.

Node: Location on a process diagram at which process parameters are investigated for deviations.

Parameters: Aspects of a process that describe it and can be monitored.

Guidewords: Simple words or phrases used to qualify the intention and associated parameters in order to discover deviations.

Deviations: Departures from the design intent. Guideword + parameter = deviation.

Catastrophic accident- Events that though unlikely could cause widespread loss of life, or significant environmental harm, resulting also in major reputational or financial damage.

Accident - An undesired event that results in personal injury or property damage.
Incident - An incident is an unplanned, undesired event that adversely affects completion of a task.

Mishap- A minor problem or something that goes wrong.
Near miss - Near misses describe incidents where no property was damaged and no personal injury sustained, but where, given a slight shift in time or position, damage and/or injury easily could have occurred.

Safe- An event which does not introduce any risk or danger.