MARY KAY O'CONNOR PROCESS SAFETY CENTER
TEXAS A&M ENGINEERING EXPERIMENT STATION

18th Annual International Symposium
October 27-29, 2015 • College Station, Texas

Risk Assessment of LNG Storages using LOPA and FTA: An Integrated Approach

Renjith V. Ravindran
Safety and Fire Engineering Division
School of Engineering
Cochin University of Science and Technology (CUSAT)
Kochi- 682022, India
renjithvr75@gmail.com

Abstract

Liquefied Natural Gas (LNG), an economically attractive and environmental friendly fuel is the current energy alternative across the globe. Its market potential and high demand is felt currently in the Indian subcontinent as well. Government and private players are seriously getting into this energy option and establishing many LNG facilities on the west and east coast of India. While establishing in this new energy sector it is vital to identify and analyse the safety hazards likely to affect public and environment. LNG being a flammable chemical, loss of its containment manifests to consequences in terms of fire, explosion and other impacts. There are several methods currently available to carry out the risk analysis of such projects. LOPA is a quick and simple technique applied to determine the risk by estimate consequence frequencies. But application of LOPA becomes constrained when failures are compound and safety systems are integrated. Fault Tree Analysis (FTA) was integrated into LOPA to eliminate this draw back. FTA was used to find out the probability of failure on demand (PFD) of integrated protection layers. This FTA-LOPA integrated approach was used as an effective tool in this work to study hazard potentials and estimate the consequences due to such hazards. Based on the technical specifications provided and description of the work, the LOC scenarios are identified in the facility from the HAZOP study.

Introduction

Liquefied natural gas (LNG) is a convenient form of energy, which may play an important role in the global energy sector especially in the gas industry in the future. The predicted average consumption of natural gas is increasing 1.3 percent every year [1, 2]. Liquefied Natural Gas is a clear, colorless, non-toxic liquid that forms when natural gas is cooled to -162^{0}C. LNG is a clean and environmental friendly fuel when compared to other fuels [3].The liquefaction of natural gas raised the possibility of its transportation to distant destinations. LNG is made at a liquefaction

plant and transported in ships, safely and efficiently. When LNG reaches the destination, it is returned to gas by regasification facilities. It is then piped to homes, businesses and industries.
LNG is a mixture of gases such as methane, ethane, propane, nitrogen and various other minor components based on the sources of natural gas [4]. Methane is the predominant component of LNG and hence the properties of LNG are more or less same as that of methane. LNG can expand to 600 times its volume when converted into vapour. This property of LNG is used in the economical storage and transportation of compressed gas in the form of Liquefied natural gas [4,5]. LNG is a cryogenic liquid and its boiling point ranges from -157^{o}C to -166 ^{o}C [4,5]. Based on the composition of LNG, density of LNG varies from 430 to 470 kg /m^3 [5]. It is very economical to transport LNG through pipelines from the gas fields to the end users [5,6].

LNG is a hazardous substance. The hazardous nature of LNG is due to its cryogenic temperature, possible asphyxiation and other risk such as fire and explosion. Frostbite may occur, if persons contact with liquid LNG [4]. Prolonged exposure of LNG vapour may cause damage to the lungs. Embrittlement of materials like carbon steel and rubber are also considered as the secondary hazards of LNG. This secondary hazard may cause cracks in the storage tanks and leakage of LNG, which may result in primary hazards like fire and explosion [4]. The flammability limit of LNG is 5- 15% by volume in air [4].

Though LNG is convenient, economical and environment friendly, the societal acceptability of LNG regasification facilities depends on safe operations of such plant. Extensive researches are necessary to bring the risk associated with LNG operations as low as reasonably practicable. For this purpose, appropriate and in depth safety analyses should be performed in these types of industries [4, 5, 7]. Qualitative and quantitative hazard analyses are essential for identification and quantification hazards associated with LNG industries. No single technique can identify or quantify all of the safety concerns. However, the process of risk assessment can be achieved through a systematic approach using a combination of different techniques [8]. In this work both FTA and LOPA are used in the integrated form.

Layer of protection analysis (LOPA) is a powerful analytical tool for assessing the adequacy of protection layers used to mitigate the risk involved in the process. It is a semi quantitative analysis of hazards that evaluates the frequency of the cause/s and the probability of failure of the protective layers. It was developed to determine the Safety Integrity Level (SIL) of Safety Instrumented Functions (SIF) [9].

LOPA is based on the concept of protective layers. In order to prevent the occurrence of an undesired consequence, a protection barrier is implemented. If this barrier works well, no more protection layers are required. However, there is no perfect protection barrier and several are needed to reduce the risk to tolerable levels. LOPA is useful to reduce the risk of a process to a tolerable level through the analysis of independent protection layers (IPLs). IPLs satisfy the criteria of specificity, independence, dependability and auditability. CCPS [9] provides the required characteristics for IPLs as independence, Functionality, Integrity, Reliability, Auditability, Success surety and Management of change. Examples of IPLs are controls, alarms, Procedures, training and safety instrumented functions.

Fault tree analysis (FTA) is a powerful diagnostic technique used widely for demonstrating the root causes of undesired events in a system using logical, functional relationship among components, manufacturing process, and subsystems [10,11,12].

Layer of Protection Analysis (LOPA)

The Layer of Protection Analysis (LOPA) method is a Process Hazard Analysis tool. The method utilizes the hazardous events, event severity, initiating causes and initiating likelihood data developed during the Hazard and Operability analysis (HAZOP) [13, 14]. The LOPA method allows the user to determine the risk associated with the various hazardous events by utilizing their severity and the likelihood of the events being initiated. Using corporate risk standards, the user can determine the total amount of risk reduction required and analyse the risk reduction that can be achieved from various layers of protection. If additional risk reduction is required after the reduction provided by process design, the basic process control system (BPCS), alarms and associated operator actions, pressure relief valves, etc., a Safety Instrumented Function (SIF) may be required [9]. The safety integrity level (SIL) of the SIF can be determined directly from the additional risk reduction required.

LOPA is a semi quantitative technique which provides results with less time and effort than other QRAs. For LOPA application failure data are essential to compute the consequence frequencies. One limitation is that failure data required for a LOPA are generally available for component failures and human error failures [15], although many failure are so complex that there are multiple combinations of these basic failures. Secondly, in LOPA protection systems are taken as independent layer of protection (IPL) which satisfies conditions independent, dependable, auditable as per CCPS. [9,16,17].

Fault Tree Analysis (FTA)

Fault Tree Analysis is a deductive technique. The purpose of FTA is to identify the combination of equipment failure and human errors that can result in an incident. FTA is often employed in situations where another hazard evaluation technique has pinpointed an incident that requires more analysis [6,18]. FTA is also used widely in many fields, such as semiconductor industry [12], man-machine system [19], flexible manufacturing systems [11], nuclear power plants [20] transmission pipelines [6], chemical industries [10, 21] and LNG terminal emergency shut down systems [22]. Shu et al., [23] applied fuzzy set theory for fault tree analysis on the printed circuit board industry. Refaul et al., [24] developed computer aided fuzzy fault tree analysis. Doytcin and Gerd [25] combined task analysis with fault tree analysis for accident and incident analysis.

In many cases there are multiple causes for an accident or other loss making event. It can be used in accident investigation and in a detailed hazard assessment. The fault tree is a logic diagram based on the principle of multi causality, which traces all branches of events which could contribute to an accident or failure. It uses set of symbols, labels, and identifiers. The fault tree is a graphical model which uses different logic gates and event symbols.

FTA is a very effective risk assessment tool, but when it comes to a reasonably complex system, that includes a large number of equipment and process variables, the fault tree becomes enormous and takes quite of a time to be completed. The concept of partial failure in a fault tree does not exist. If the equipment is partially working it is considered as fully unavailable or in failure mode. This partial failure changes the reliability of a system, but the FTA has no effect of such condition in its results. If a fault tree is developed by different safety professionals, it will be of different nature depending on the developer. The probability calculation for a top event, failure data of all the events in the fault tree that are usually not known or not accurately known decreases the credibility of the analysis. On the other hand, the biggest advantage of using FTA is that it starts from a top event that is selected by the user for a specific interest and the tree developed will identify the root cause. The FTA has the ability to be used with a computer and generate results using computer application for improved analysis [18].

LOPA – FTA Integrated Approach

LOPA is a quick semi quantitative technique which provides results with less time and effort than other QRAs. For LOPA application failure data are essential to compute the consequence frequencies. One limitation is that failure data required for a LOPA are generally available for component failure and human error failure [13, 16], although many failure are so complex that there are multiple combinations of these basic failures. So it becomes extremely difficult to apply the conventional LOPA method. Secondly, in LOPA protection systems are taken as independent layer of protection (IPL) which satisfies conditions independent, dependable, auditable as per [17]. But in many cases the criteria of independence is not satisfied as protection layers are integrated or coincides with one another. It will be difficult to apply LOPA in the above scenarios [26]. Fault tree analysis (FTA) can be integrated into LOPA to eliminate the above mentioned drawback. Fault tree analysis (FTA) is a widely used tool for system safety analysis [23, 27]. It is a deductive (backward reasoning) logic technique that focuses on one particular hazardous event (e.g. Toxic gas release, explosion, fire, etc.) and provides a method for determining the causes of hazardous events. The basic process in the technique of FTA is to identify a particular effect or outcome from the system and trace backward into the system by the logical sequence to prime cause(s) of this effect [6, 27]. This helps in analysing complex failures. But using FTA for analysing an entire process is Herculean task. So FTA application is limited to PFD calculations. Again, if pre-solved fault trees could be used by the analyst those can be inserted into LOPA even faster computing of consequence frequency. FTA when integrated into LOPA can be used in complex systems and integrated layer of protections. This improves versatility of LOPA as a risk assessment tool without losing its swiftness and simplicity.

Case study Result and discussions

Geun Woong Yun [28] published the HAZOP work sheets for LNG terminal operations as Appendix B in his master thesis. He has also identified seven scenarios for LOPA study and presented in his thesis. He has used different database such as EIReDA, ORECDA and LNG plant failure rate database collected from LNG facilities. He has classified all these data into two groups in the form look up tables, one for PFDs of IPLs and other for initiating event frequency.
In this work LOPA –FTA integrated approach is used for the LOPA analysis of the scenario identified by Geun Woong Yun. In this paper all seven scenarios are presented for demonstrating the LOPA-FTA integrated approach for calculation of PFDs of IPL. Some scenarios demonstrate the applicability of LOPA-FTA integrated approach for not dependant and compound failures.

Scenario 1

Initiating event	Loading arm failure due to flange joint or swivel joint
Frequency of initiating event	$2.75x10^{-2}$ per year
IPL 1	Gas detector at jetty & human intervention
IPL2	Fire detector and emergency shut down

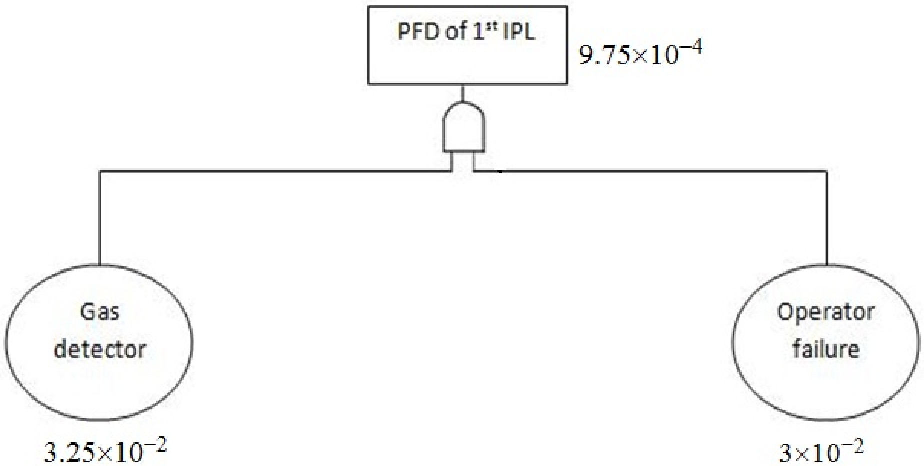

Figure1 Estimation of PFD of IPL1 using FTA for Scenario 1

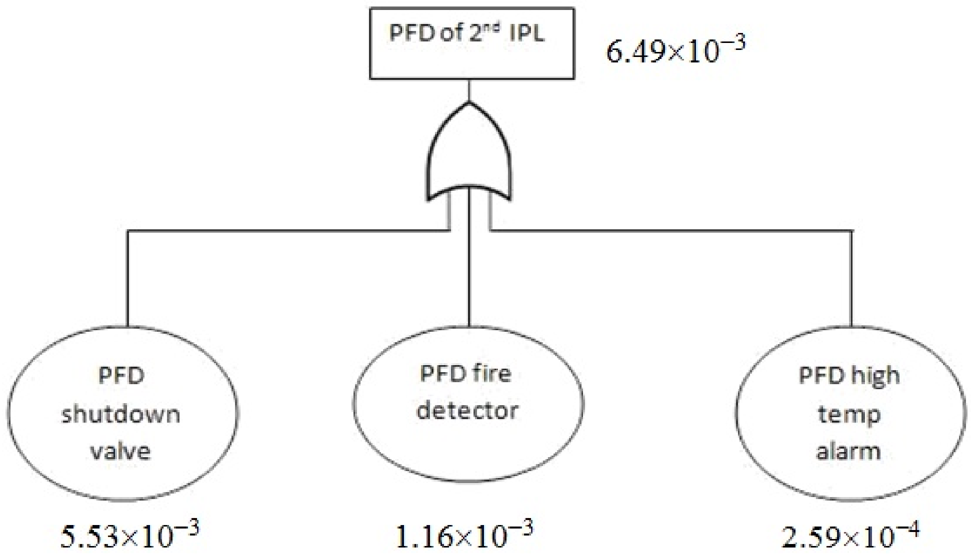

Figure 2 Estimation of PFD of IPL2 using FTA for scenario 1

Frequency of consequence = Initiating event frequency x Total PFD

$$= 2.75x10^{-2} \text{ x } 6.77x10^{-6}$$

$$= 1.86x10^{-7}$$

Scenario 2

Initiating event	Pressure increase of unloading arm due to BV-1 failed closure during unloading
Frequency of initiating event	$5.51x10^{-3}$ per year
IPL 1	Temperature safety motor operated valve (TMSO) system

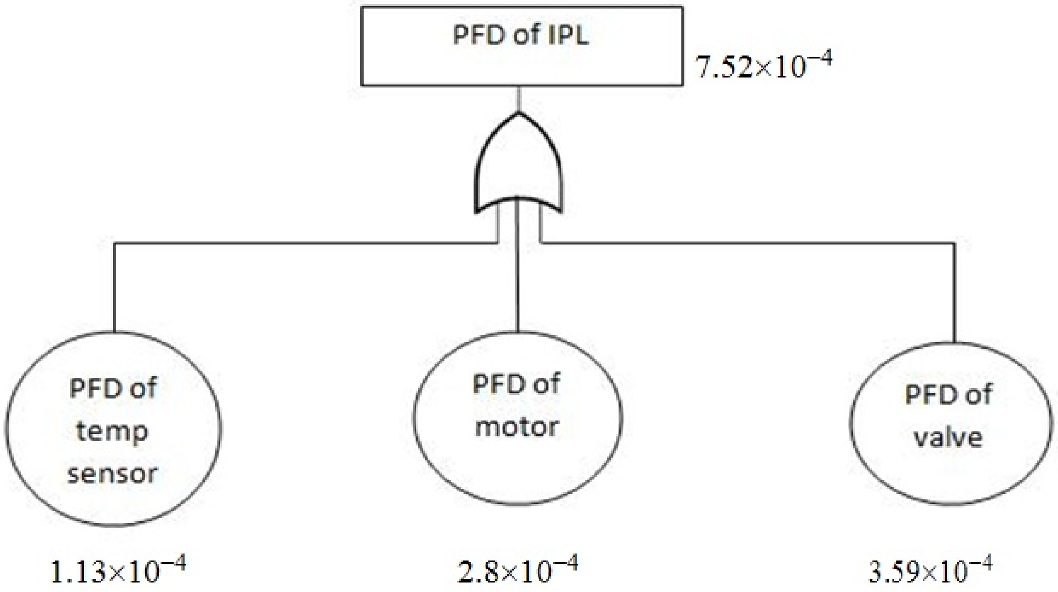

Figure 3 Estimation of PFD of IPL using FTA for scenario 2

Frequency of consequence = Initiating event frequency x Total PFD

$$= 5.51x10^{-3} \text{ x } 7.52x10^{-4}$$

$$= 4.14x10^{-6}$$

Scenario 3

Initiating event	HP pump cavitation and damage due to low pressure of the recondensor resulting from BV – 32 failed closure (Possible leakage and fire)
Frequency of initiating event	$5.51x10^{-3}$ per year
IPL 1	Low pressure alarm
IPL2	HP pump tripping
Note	Low pressure sensor which activates tripping circuit for Hp pump and same pump also send signal to control room for shut down (Compound)

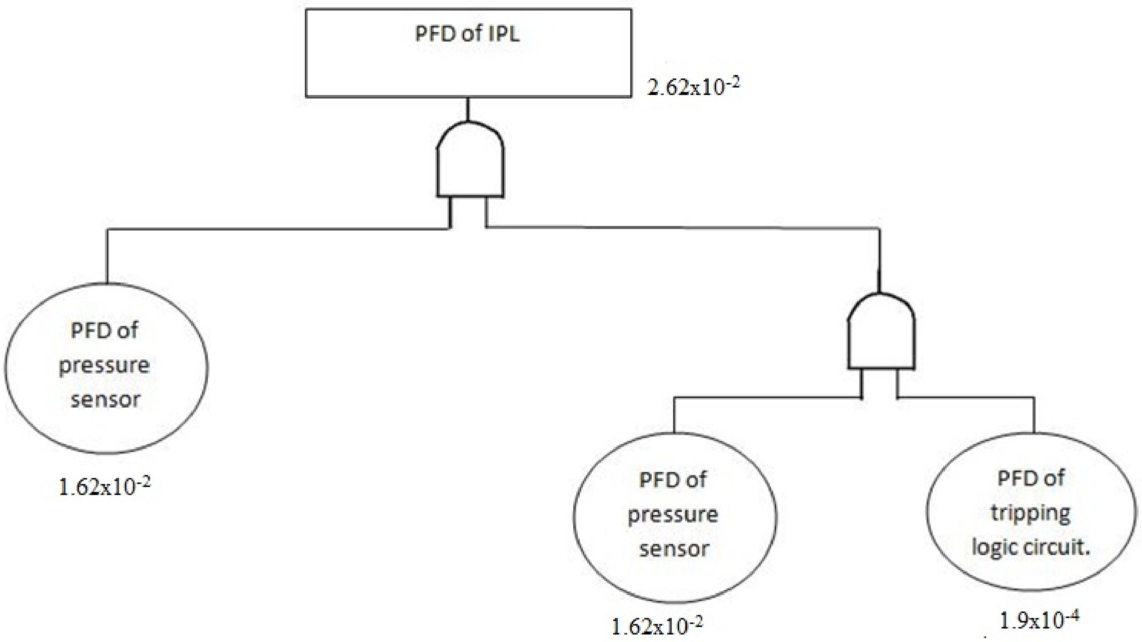

Figure 4 Estimation of PFD of IPL using FTA for scenario 3

Frequency of consequence = Initiating event frequency x Total PFD

$$= 5.51x10^{-3} \text{ x } 2.62x10^{-2}$$

$$= 1.44x10^{-4}$$

Scenario 4

Initiating event	High temperature in recondensor due to more BOG input resulting from FCV-33 spurious full open. (Possible cavitation and damage of HP pump leading to leakage)
Frequency of initiating event	$5.77x10^{-3}$ per year
IPL 1	High temperature alarm and human intervention
IPL2	Gas detectors and human intervention

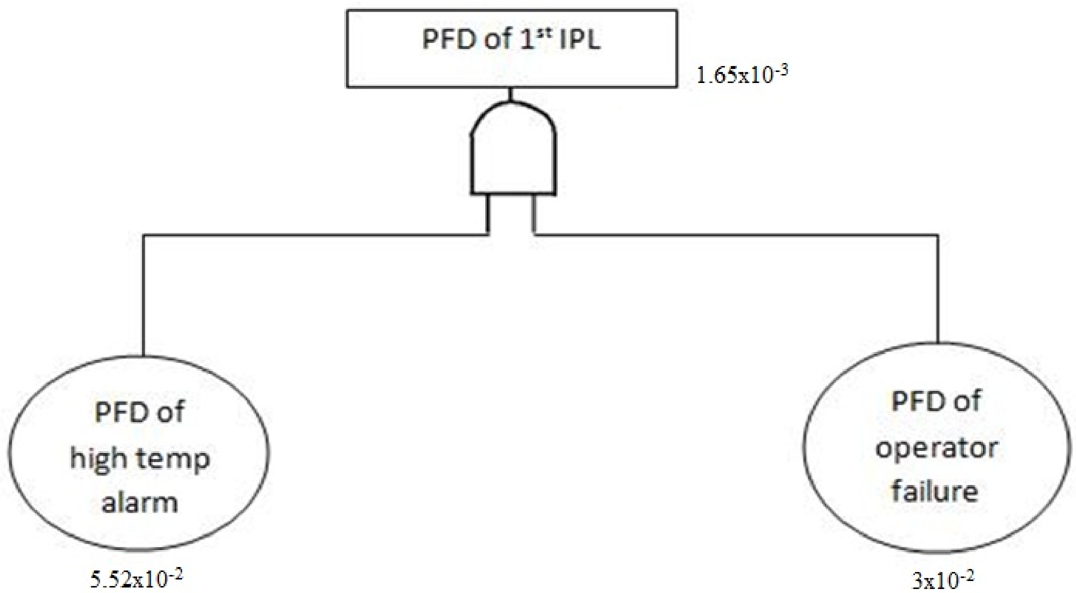

Figure 5 Estimation of PFD of IPL1 using FTA for scenario 4

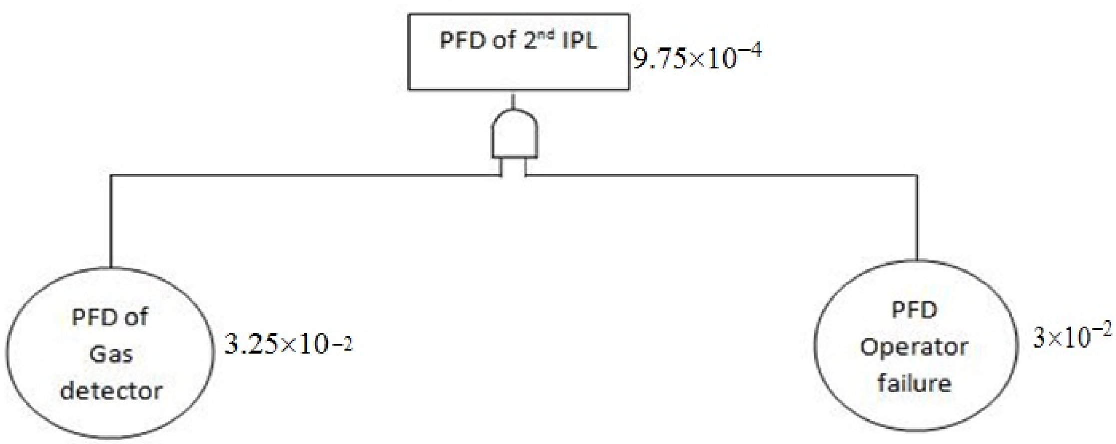

Figure 6 Estimation of PFD of IPL using FTA for scenario 4

Frequency of consequence = Initiating event frequency x Total PFD

$$= 5.77x10^{-3} x 1.61x10^{-4}$$

$$= 9.28x10^{-7}$$

Scenario 5

Initiating event	Over pressure in the tank due to roll over resulting from stratification and possible damage due to tank
Frequency of initiating event	$1.5x10^{-2}$ per year
IPL 1	Density monitoring and jet mixing using FCV
IPL2	High Pressure alarm and trip inlet line valve (EMOV)
IPL 3	Two pressure relief valve

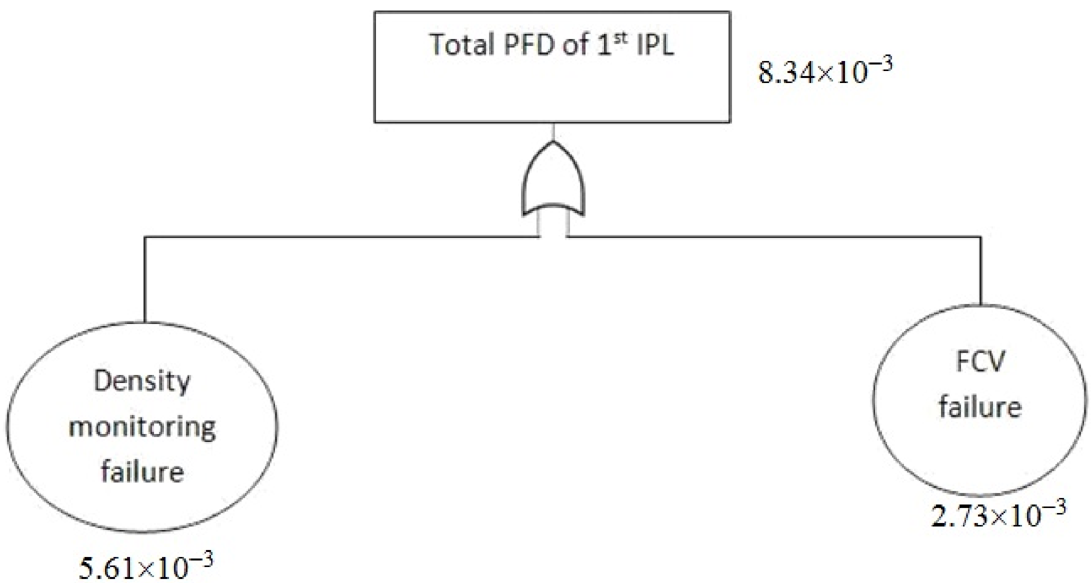

Figure 7 Estimation of PFD of IPL using FTA for scenario 5

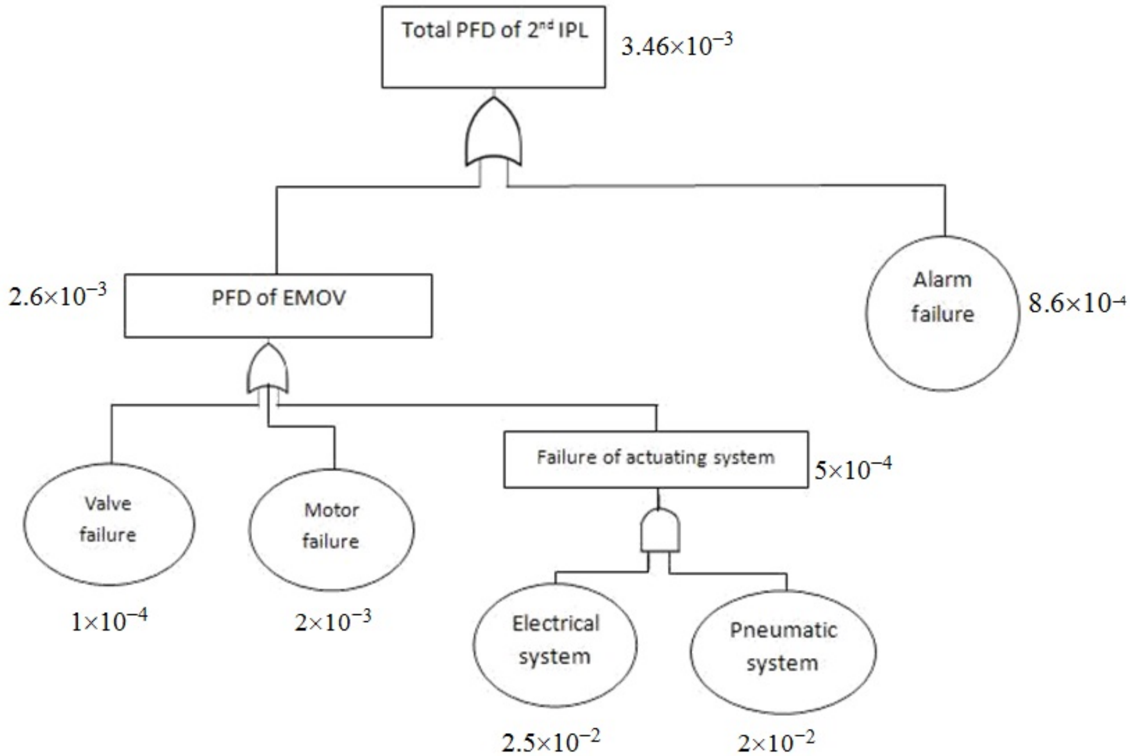

Figure 8 Estimation of PFD of IPL using FTA for scenario 5

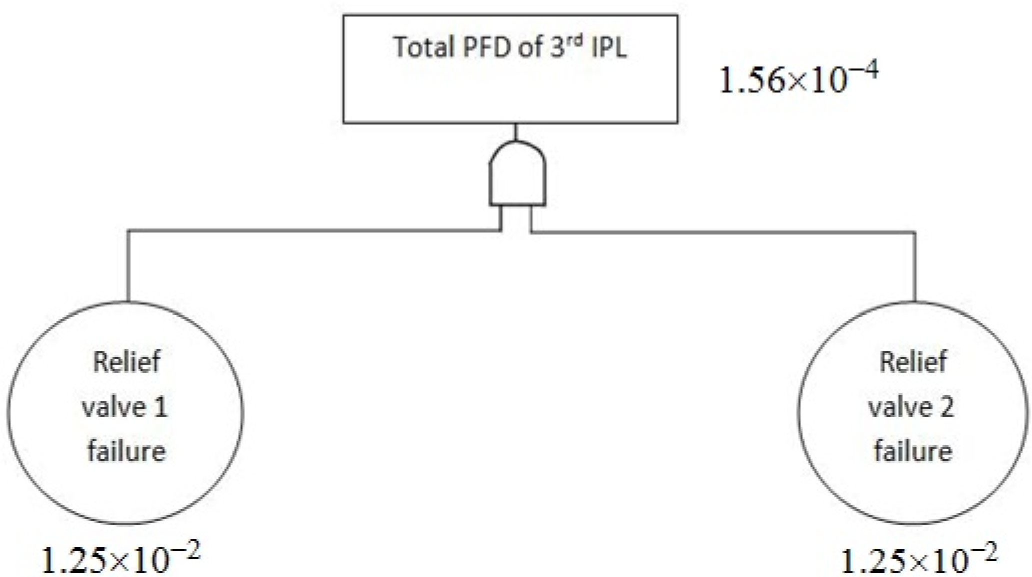

Figure 9 Estimation of PFD of IPL using FTA for scenario 5

Frequency of consequence = Initiating event frequency x Total PFD

$$= 1.5x10^{-2} \text{ x } 4.5x10^{-9}$$

$$= 6.75x10^{-11}$$

Scenario 6

Initiating event	LNG level increases and leads to carry over into annular space because operator line up the wrong tank. (possible overpressure in the tank)
Frequency of initiating event	$3.52x10^{-2}$ per year
IPL 1	Two level alarms and human intervention
IPL2	Two high level detectors and ESD

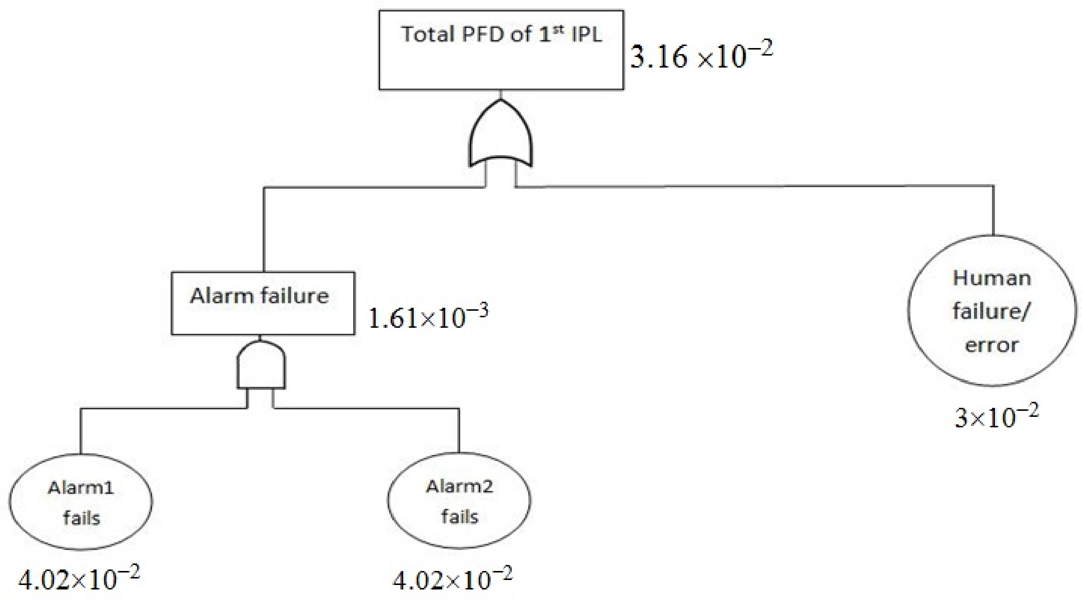

Figure 10 Estimation of PFD of IPL using FTA for scenario 6

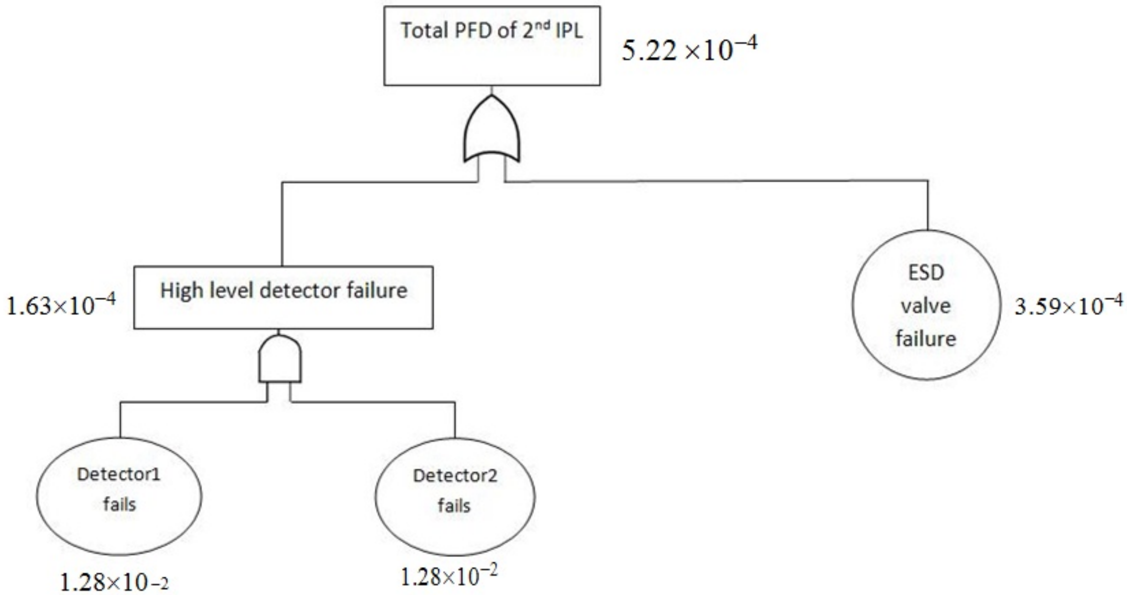

Figure 11 Estimation of PFD of IPL using FTA scenario for 6

Frequency of consequence = Initiating event frequency x Total PFD

$$= 3.53x10^{-2} x 1.64x10^{-4}$$

$$= 5.78x10^{-7}$$

Scenario 7

Initiating event	Under pressure in tank due to pump-out without BOG input resulting from BV-45 failed closure.
Frequency of initiating event	$5.52x10^{-3}$ per year
IPL 1	Low pressure alarm and BOG compressor trip
IPL 2	Low pressure detector and LP pump trip
IPL 3	Two vacuum relief valves

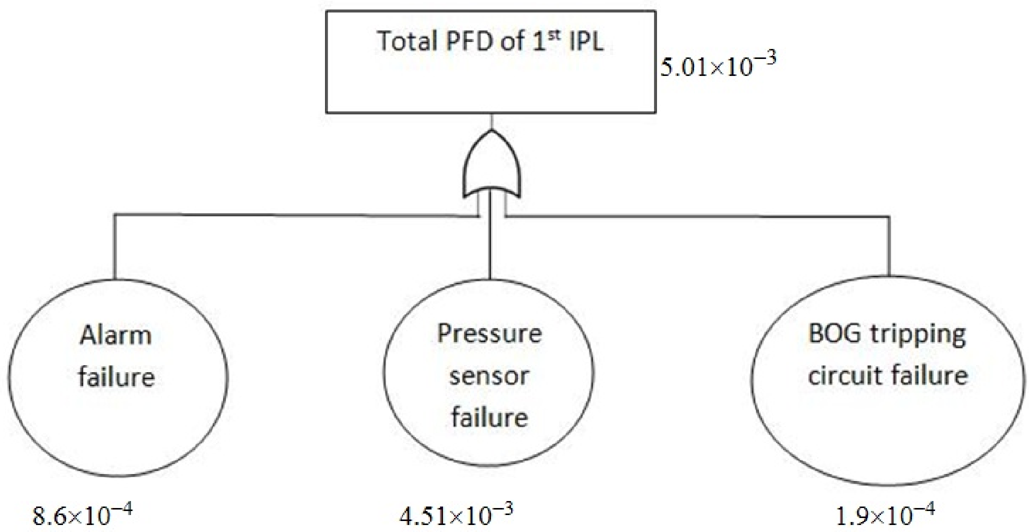

Figure 12 Estimation of PFD of IPL using FTA scenario for 7

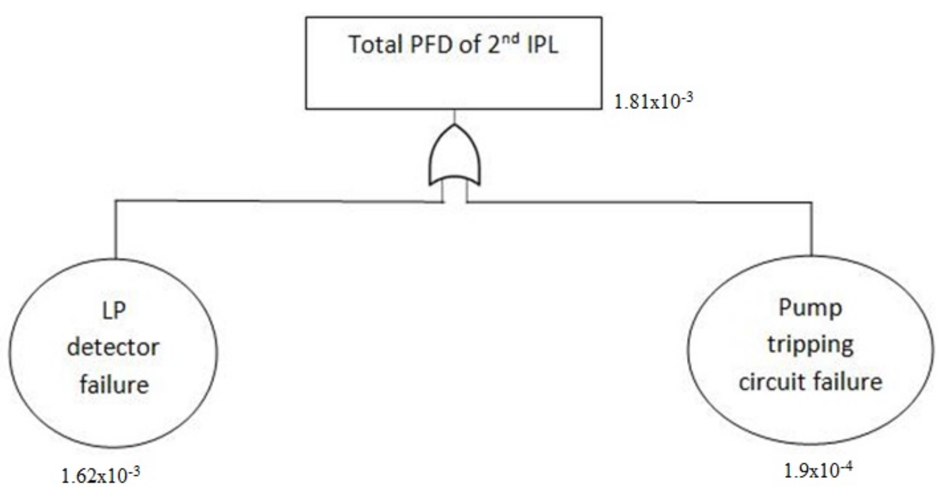

Figure 13 Estimation of PFD of IPL using FTA scenario for 7

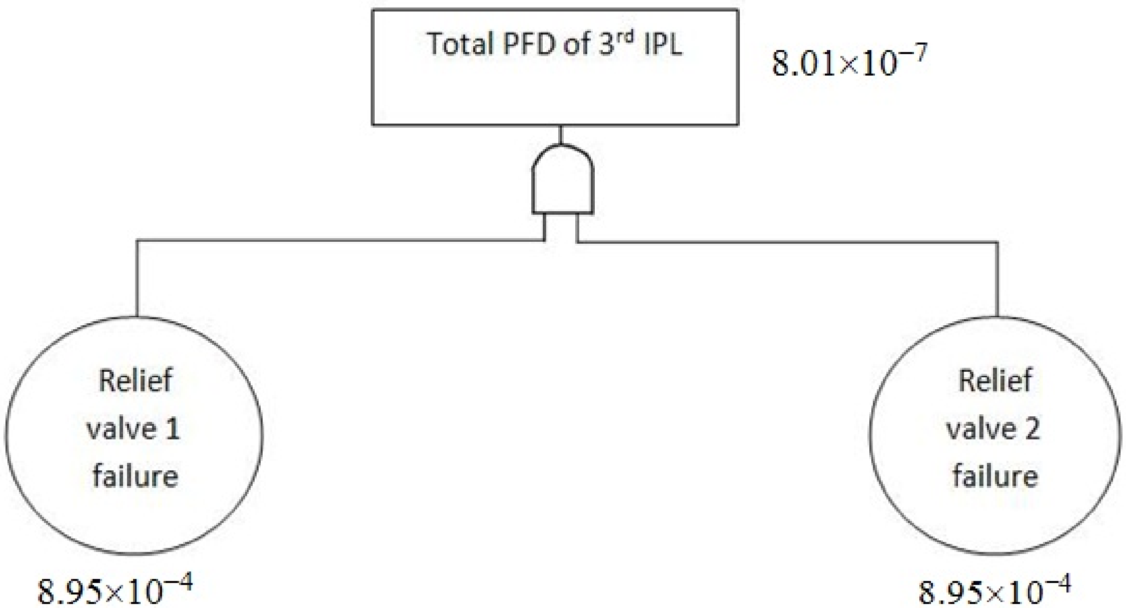

Figure 14 Estimation of PFD of IPL using FTA scenario for 7

Frequency of consequence = Initiating event frequency x Total PFD

$$= 5.5x10^{-3} \text{ x } 7.26x10^{-12}$$

$$= 3.99x10^{-14}$$

Conclusions

LOPA is a simplified form of risk assessment tool for prioritising hazardous scenarios and making risk based decisions. FTA is one of the many quantitative hazard quantification tools used extensively to assess the safety and reliability of the complex systems. LOPA is inadequate in dealing with compound failures. LOPA cannot give proper results when the failures are not independent. FTA can evaluate interdependant and coumpound failures. LOPA is very quick and simple, whereas FTA is complex and time consuming. Both LOPA and FTA have their own weakness. But if we integrate these two, we could avoid the limitations of LOPA in dealing with compound failures and dependent failures. In this paper an attempt has been made to implement FTA- LOPA integrated approach to LNG terminals. The above method may be applied to common cause failures in all the LOPA analysis.

References

1. Energy Information Administration – Office of Integrated Analysis and Fore- casting. International Energy Outlook. Washington, DC: U.S. Department of Energy; 2013.

2. Nicola Paltrinieri, Alessandro Tugnoli, Valerio Cozzani, Hazard identification for innovative LNG regasification technologies, Reliab. Eng. Syst. Saf.137(2015)18-26.

3. Saeid Mokhatab et. al., Handbook of liquefied natural gas First ed.,Elsevier,2014 Oxford.

4. A. Bernatik, P. Senovsky , M. Pitt. LNG as a potential alternative fuel- Safety and security of storage facilities. J.Loss Prev. Process Ind. 24 (2010) 19-24.

5. John L. Woodward and Robin M. Pitblado, LNG Risk based safety - Modeling and Consequence Analysis, John Wiley & Sons, 2010, New Jercy.

6. Dong Yuhua, Yu Datao, Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis. J. Loss Prev. Process Ind. 18 (2005) 83 –88.

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

8. Casamirra, M., Castiglia, F., Giardina, M., Tomarchio, E.,. A fuzzy modelling of HEART methodology: application in safety analyses of accidental exposures in irradiation plants. Radiat. Eff. Defects Solids 164 (2009) 291-296.

9. Center for Chemical Process Safety, American Institute of Chemical Engineers, Layers of Protection Analysis : Simplified Risk Assessment, New York (2001).

10. F.I. Khan, S.A. Abbasi, Analytical simulation and PROFAT II: a new methodology

and a computer automated tool for fault tree analysis in chemical process industries, J. Hazard. Mater. 75 (2000) 1 – 27.

11. W. Hu, A.G. Starr, A.Y.T. Leung, Operational fault diagnosis of manufacturing systems, J. Mater. Process Technol. 133 (2003) 108 – 117.

12. H.X. Li, M.J. Zuo, A hybrid approach for identification of root causes and reliability improvement of a die bonding process - a case study, Reliab. Eng. Syst. Saf. 6 (1999) 43 – 48.

13. Robert W. Johnson Beyond-compliance uses of HAZOP/LOPA studies. J.Loss Prev. Process Ind. 23, (2010) 727-733.

14. ILO-NSC, Major hazard control- a practical manual, International Labor office, Geneva, 1996.

15. Philip M. Myers, Layer of Protection Analysis Quantifying human performance in initiating events and independent protection layers. J.Loss Prev. Process Ind. 26 (2012) 534–546.

16. Dowell, A. M., Layer of Protection Analysis and Inherently Safer Process, Process safety progress 18 (1999) 214-220.

17. Sam Mannan, Lees Loss prevention in the process industries, Vol. 1,third ed.,Elsevier,2005.

18. L.M. Bartlett, E.E. Hurdle, E.m. Kelly, Integrated system fault diagnostics utilising digraph and fault tree-based approaches. Reliab. Eng. Syst. Saf . 94(2009)1107-1115.

19. C.T. Lin, M.J.J. Wang, Hybrid fault tree analysis using fuzzy sets, Reliab. Eng. Syst. Saf. 58 (1997) 205 – 213.

20. S.D. Sohn, P.H. Seong, Quantitative evaluation of safety critical software testability based on fault tree analysis and entropy, J. Syst. Softw. 73 (2004) 351 – 360.

21. P.K. Roy, B. Arti, R. Chitra, Quantitative risk assessment for accidental release of titanium tetrachloride in a titanium sponge production plant, J. Hazard Mater. A102 (2003) 167 –186.

22. R.C. Shuen, L. Binshan, M.H. Bi, H.S. Ming, Fault tree analysis for liquefied natural gas terminal emergency shutdown system, Expert Syst. Appl. 36 (2009) 11918 – 11924.

23. M.H. Shu, C.H. Cheng, J.R. Chang, Using intuitionistic fuzzy sets for fault-tree analysis on printed circuit board assembly, Micro electron Reliab. 46 (2006) 2139 – 2148.

24. F. Refaul, K. Faisal, V. Brian, R. Paul, Methodology for computer aided fuzzy fault tree

analysis. Process Saf. Environ. Prot. 87 (2009) 217 – 226.

25. E.D. Doytcin, S. Gerd, Combining Task analysis and fault tree analysis for accident and incident analysis; a case study from Bulgaria, Accid. Anal. Prev. 41 (2009) 1172 – 1179.

26. Geun Woong, Young, William J. Rogers, M. Sam Mannan.) Risk assessment of LNG importation terminals using the Bayesian–LOPA methodology. *J. of Loss Prevention in the Process Ind.* 22, (2009)91–96.

27. V.R. Renjith et. Al. Two-dimensional fuzzy fault tree analysis for chlorine release from a chlor-alkali industry using expert elicitation, J. Hazard Mater. 83 (2010)103–110.

28. Geun Woong Yun, Bayesian-LOPA methodology for risk assessment of an LNG importation terminal. M.S. Thesis, Texas A&M University, Texas 2007.