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Fuzzy Fault Tree Analysis of LPG Cross Country Pipelines -A Case Study

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Abstract **-** Chances of accidents during the transportation of flammable products like LPG through road and rail tankers, ships and pipelines are higher. Most safe and eco-friendly transportation method for flammable substances for long distance is cross country pipelines. Major hazard associated with LPG gas pipeline is flammable gas release which leads to fire and explosion causing fatalities and property damages. In this research the possible hazards are identified by preliminary hazard analysis and Hazard and operability study (HAZOP). Fault Tree Analysis is used to estimate the failure frequency of LPG pipelines. Failure probability values for the basic events that lead to failure of LPG pipeline are required for estimating the failure frequency of LPG pipelines. Unfortunately such data are unavailable or limited. Fuzzy logic and expert elicitation can be used to generate such failure frequency values. In this research two dimensional fuzzy fault tree analysis (TDFFTA) was performed for the 238km proposed LPG pipeline located in the southern part of India. Fault tree is constructed and 36 basic events were identified. Failure frequencies of these basic events are generated using fuzzy logic and expert elicitation. TDFFTA is performed in this case to include the hesitancy factor in expert elicitation.

Keywords **-** *Cross country pipe line, Fault Tree Analysis (FTA), Fuzzy Fault tree analysis, Two-dimensional fuzzy fault tree analysis (TDFFTA).*

I. INTRODUCTION

Cross country pipeline transportation is the widely accepted and economic method of transportation of hazardous substances like crude oil, petroleum products, LPG and LNG. In India, a number newer cross country pipeline projects are in progress. As it is economic and reliable, Government of India has also taken initiative to lay down city gas pipe lines even to the house hold consumers of LPG. In major cities which consist refineries, major industries, seaports and airports the density of these types of pipelines are increasing. Moreover these pipelines are buried underground along the side of National and State highways. LPG being a flammable chemical, loss of its containment manifests to consequences in terms of fire, explosion and other impacts. A number of pipeline failures with release of hazardous materials to the environment and associated risk to the public have reported worldwide [1, 2, and 3]. So risk assessments of cross country pipelines are essential for quantifying the risk associated with the cross country pipeline transportations of hazardous substance. This information will be vital in infrastructural and land use planning of cities to avoid disasters and associated fatalities.

Risk assessment requires database pertaining to failure frequency rate of the different components in the pipe line system. There are different qualitative and quantitative tools used in risk analysis for identification and quantification of risk associated with cross county pipelines. This research uses qualitative and quantitative techniques such as Process Hazard Analysis (PHA), Hazard and Operability studies (HAZOP) and fault tree analysis (FTA) at different stages of the analysis. It has been reported in the literature that the failure probability data of pipeline components are uncertain [4] and imprecise [5]. In this research an attempt has been made to use fuzzy logic and expert elicitations to generate the failure frequency values of the basic events that are responsible for pipeline failures.

Fuzzy fault tree analysis

Fault tree analysis (FTA) is a deductive technique that focuses on a particular accident or main system failure, and provides a method for determining causes of that event [6]. A fault tree is logical and graphical description of various combinations of failure events [7]. 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 sub systems [8, 9 and 10]. FTA is extensively used in a wide range of applications in different fields such as LNG terminals [11], nuclear power plants [12] and printed circuit boards industry [13].

Failure frequency values of the basic events that are logically responsible for the top event is necessary for the estimation of the top event frequency. In order to estimate the top event probability, the probability of failure of basic events must be known in advance. But failure frequency of the basic events that are responsible for the top events are not available or not reliable due to a number of reasons. It has been reported in the literature, especially in India, such failure frequency values are limited [5]. Theory of fuzzy sets along with expert elicitation could be useful in such case to generate the failure probability values when little quantitative information is available [14, 7 and 15].

II. CASE STUDY

In this study, a fault tree analysis of a proposed 238 km long cross country pipe line for the transport of LPG from a major refinery located in Kerala state (southern part of India) to a major city in Tamil Nadu state is considered. The purpose of this pipeline is to connect all the LPG bottling plant along the length of pipeline to the refinery and hence by reducing the transportation of the LPG by road. The diameter of the pipeline is 12 inch with a transportation capacity of 0.5 MMTPA to 1.53 MMTPA. Twenty two sectionalising valves are provided for reducing the quantity released during an accident.

III. MATERIALS AND METHODS

A Process Hazard Analysis (PHA) is performed as the first step. HAZOP is carried out after the PHA. The HAZOP technique systematically analyses system nodes and defines qualitatively how operational deviations could occur, and whether further protective measures, operating procedures upgrade or design changes are required to reduce or eliminate hazardous situations. Both PHA and HAZOP study interpret the causes which lead to pipeline leak. Using these references fault tree can be prepared to identify the likelihood of the failure events for the pipeline release in a systematic manner. LPG transmission pipelines are mainly installed underground, and hence there are many deteriorating factors affecting them and the main causes include corrosion, interference from the third party, material defects, malfunction, and natural hazard. FTA is constructed for the proposed LPG pipe line as shown in Figure 1a and 1b after careful evaluations of the guidelines provided by Oil Industry Safety Directorate of India (OISD) 141, 214,188,110,139 which deals with the design and construction aspects of LPG cross country pipeline. Fault tree is constructed taking 'LPG release' as the top event. The top event is the undesired event that is the subject of fault tree analysis. Intermediate events are identified and connected with logic gates. Ultimately basic events are identified. In conventional FTA based on a probabilistic approach the basic events are represented by the probabilities (crisp numbers). It assumes that exact probabilities of events are given and sufficient failure data is available. However, it is often very difficult to obtain sufficient statistical data to estimate precise failure rates or failure probabilities. Moreover, the inaccuracy associated with system models due to human errors is difficult to deal with solely by means of the conventional probabilistic reliability theory. Fuzzy set theory can be used to deal with this issue. Therefore, Fuzzy fault tree analysis is developed to deal with such issues. In industrial practice for a variety of basic events, failure data are not available.

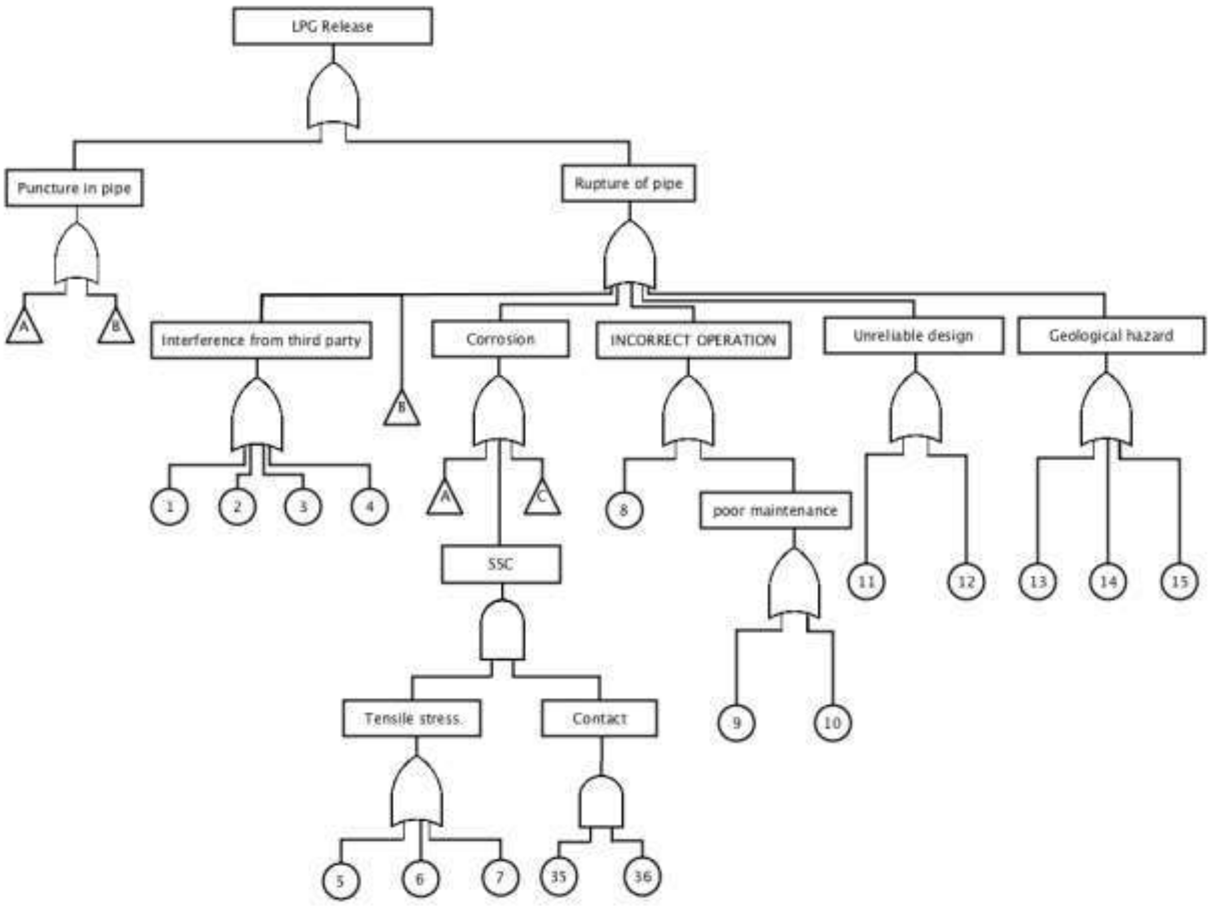

Figure 1a. Fault tree for LPG cross country pipeline failure

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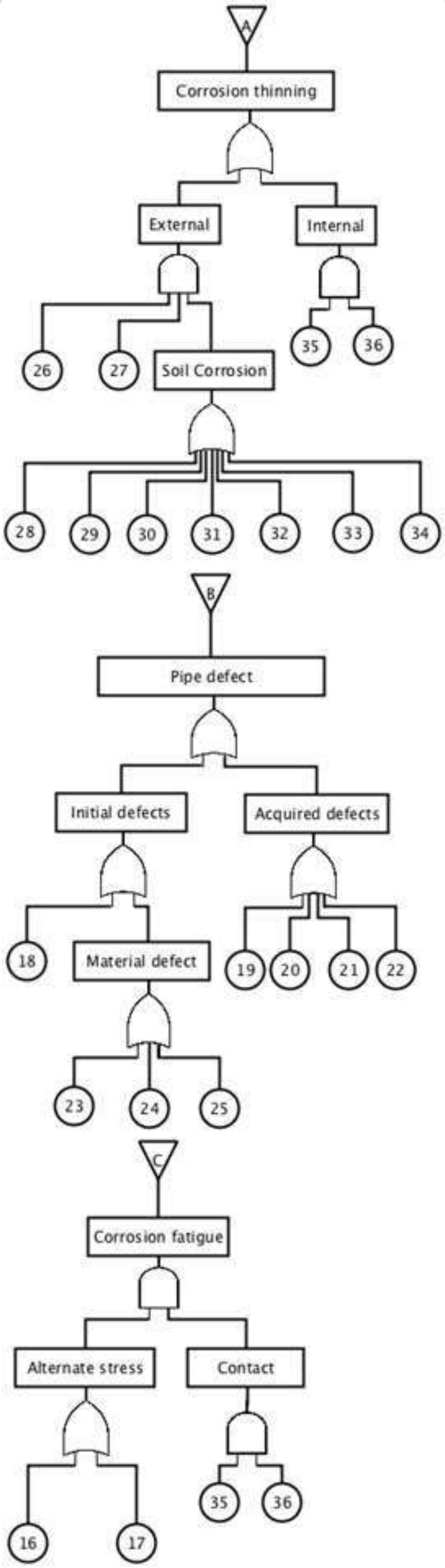

Figure 1b. Fault tree for LPG cross country pipeline failure

Expert opinion and engineering judgement needs to be used to estimate such basic event data. Structured expert-elicitation approaches can be used to increase the fidelity of the estimates of basic event failure data. Expert elicitation and fuzzy logic are used to generate the probabilities of the basic events. A framework is developed by Renjith *et al.* [14] based on the fuzzy set theory with the FTA method, capable of quantifying the judgement from experts who express opinions qualitatively. This method provides some useful information for assessing risks and making decisions accommodating the uncertainties in the probabilities of basic events involved.

Evaluation of expert elicitation generates a set of qualitative data representing basic event failure possibilities. A set of basic events from the system fault tree under evaluation, form the input for expert elicitation. A set of experts subjectively evaluate these basic event failures. A questionnaire is prepared for this purpose. Though number of methods is available for expert elicitation, interview method is adopted in the present study. This method provides some useful information for assessing risks and making decisions. Feedback has been obtained from 35 experts working in pipe line design, maintenance, operation and inspection fields through interview. A weighting factor is used to represent the relative quality of the response of a better expert. Experts cannot exactly evaluate the probability of events, so it is collected in natural linguistic expressions. In the proposed method, conversion scale with 5 verbal terms is selected for performing the subjective assessment of hazards with unknown failure rate. The failure possibility distribution is a set of five qualitative linguistic expressions (very low, low, medium, high and very high) represented as [VL,L,M,H,VH] used to scale basic event failure possibilities from the lowest rate to the highest rate. Conventional mathematical methods cannot handle natural linguistic expressions efficiently because of their fuzziness. Fuzzy set theory is used to overcome this shortcoming. The objective of this fuzzification step is to quantify basic failure possibilities into their corresponding quantitative data in the form of membership function of fuzzy numbers. A failure possibility distribution is implemented in the linguistic value based on the failure occurrences and the respective membership functions of fuzzy sets are generated in the membership function using the inductive reasoning approach. The membership functions to represent these qualitative linguistic values are in the form of triangular fuzzy numbers or trapezoidal fuzzy numbers [7]. Experts make uses of linguistic terms to judge the failure probability of the pipeline installations. For converting the linguistic terms to their corresponding fuzzy number, a numerical approximation system is proposed there are eight conversion scales to be used in the literature [16]. In this work, one of the conversion scales is used as in Figure 2 to represent assessment of the experts and the corresponding membership functions of different linguistic terms are as follows.

$$f_{VH}(x) = \begin{cases} 0 & x \le 0.8 \\ \dfrac{x-0.8}{0.1} & 0.8 < x \le 0.9 \\ 1 & 0.9 < x \le 1 \end{cases}$$

$$f_{H}(x) = \begin{cases} \dfrac{x-0.6}{0.15} & 0.6 < x \le 0.75 \\ \dfrac{0.9-x}{0.15} & 0.75 < x \le 0.9 \\ 0 & otherwise \end{cases}$$

$$f_{M}(x) = \begin{cases} \dfrac{x-0.3}{0.2} & 0.3 < x \le 0.5 \\ \dfrac{0.7-x}{0.2} & 0.5 < x \le 0.7 \\ 0 & otherwise \end{cases}$$

$$f_{L}(x) = \begin{cases} \dfrac{x-0.1}{0.15} & 0.1 < x \le 0.25 \\ \dfrac{0.4-x}{0.15} & 0.25 < x \le 0.4 \\ 0 & otherwise \end{cases}$$

$$f_{VL}(x) = \begin{cases} 0 & x > 2 \\ \dfrac{0.2-x}{0.1} & 0.1 < x \le 0.2 \\ 1 & 0 < x \le 0.1 \end{cases}$$

Where subscript VH, H, M, L, VL means very high, high, middle and low, very low respectively.

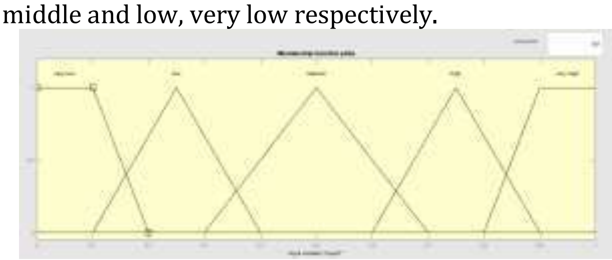

Figure 2. Fuzzy membership functions for various linguistic expressions

Due to different opinion of probability of the basic events, it is necessary to aggregate the opinion into a single one. Linear opinion pool of the experts' method is used here for aggregating the onions of these experts.

$$M_i = \sum_{j=1}^{n} w_j A_{ij}, i = 1,2,3,\ldots\ldots\ldots m$$

Where w_j is a weighting factor of the expert j, A_{ij} opinion of j^{th} expert on the basic event i and Mi represents combined fuzzy number of the basic event i. Based on the extension principle of fuzzy set theory, Mi is also triangular or trapezoidal fuzzy number [15]. Using α-cut of different membership functions of equations and equitation for aggregate opinion, the total fuzzy number for the opinion of 35 experts could be obtained as another fuzzy number represented in Figure 3. In defuzzification step, when fuzzy ratings are incorporated into a FTA problem, the final ratings are also fuzzy numbers. In order to determine the relationship among them, fuzzy number must be converted to a crisp score, named fuzzy possibility score (FPS) represents the most possibility that an expert belief of occurring of a basic event. Left and right fuzzy ranking method was used here. The corresponding expression is shown in the following equations.

$$\mu_L(N) = \frac{(1-a)}{\left[1+(b1-a)\right]}$$

$$\mu_R(N) = \frac{c}{\left[1+(c-b2)\right]}$$

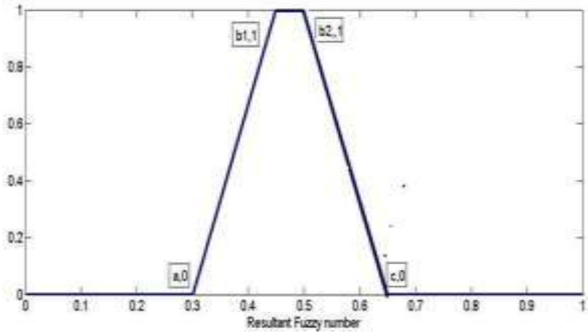

Figure 3. Aggregate fuzzy number for the opinion of experts

If the left and right scores are available, then the total fuzzy possibility score could be calculated as

$$FPS = \frac{\left[\mu_R(N) + (1-\mu_L(N))\right]}{2}$$

In order to ensure compatibility between real numbers and fuzzy possibility score, the fuzzy possibility score must be transferred to fuzzy failure probability. Fuzzy failure probability was defined in the following equation.

$$FFP = \begin{cases} \dfrac{1}{10^k} & FPS \neq 0 \\ 0 & FPS = 0 \end{cases}$$

Where

$$k = \left[(1 - FPS / FPS)\right]^{\frac{1}{3}} * 2.301(7)$$

A new model that is based on hesitant fuzzy fault tree analysis (two dimensional fuzzy fault tree analyses) was developed by Renjith *et al.* [14] to manage situations in which expert's hesitation during expert's elicitation [17]. During expert elicitation, the expert expresses his opinion about the failure probability of the basic components along with degree of hesitancy or confidence. In real life problems, one can model an expert's opinion more precisely by incorporating the hesitancy. Two dimensional linguistic terms, accounts for one's confidence and hesitation in modelling such situation. In this study two dimensional fuzzy fault tree analyses is conducted to incorporate the hesitancy factor of the expert elicitation.

Table 1. Failure probability values for the basic events

S. N.	Basic events	FFTA	2DFFTA
1	Parties ignore signage	6 x 10^{-3}	5.9 x 10^{-3}
2	Implicit signage	8.3 x 10^{-3}	5.6 x 10^{-3}
3	Sabotage	5.7 x 10^{-3}	4.2 x 10^{-3}
4	Overload	2.5 x 10^{-3}	2.3 x 10^{-3}
5	Stress concentration	3.5 x 10^{-3}	3.4 x 10^{-3}
6	Residual stress	3.0 x 10^{-3}	2.8 x 10^{-3}
7	Large internal stress	2.3 x 10^{-3}	2.1 x 10^{-3}
8	Quality of worker	1.5 x 10^{-3}	1.4 x 10^{-3}
9	Equipment	5.4 x 10^{-3}	5.4 x 10^{-3}
10	Apparatus	3.3 x 10^{-3}	3.2 x 10^{-3}
11	Unreasonable strength	9 x 10^{-4}	9 x 10^{-4}
12	Unreasonable material	1.8 x 10^{-3}	1.5 x 10^{-3}
13	Earth quake	3.2 x 10^{-3}	3.1 x 10^{-3}
14	Flood	2.7 x 10^{-3}	2.6 x 10^{-3}
15	Subsidence	2.6 x 10^{-3}	2.4 x 10^{-3}
16	Pressure surge	3.6 x 10^{-3}	3.4 x 10^{-3}
17	External load	1.7 x 10^{-3}	1.6 x 10^{-3}
18	Construction defects	3.4 x 10^{-3}	3.3 x 10^{-3}
19	Bad installation	4.9 x 10^{-3}	4.8 x 10^{-3}
20	Bad weld	4.8 x 10^{-3}	4.7 x 10^{-3}
21	Bad groove	3.6 x 10^{-3}	3.5 x 10^{-3}
22	Mechanical damage	6.4 x 10^{-3}	6.3 x 10^{-3}
23	Bad microstructure of material	2.5 x 10^{-3}	2.4 x 10^{-3}
24	Coarse grain of material	1.8 x 10^{-3}	1.7 x 10^{-3}
25	Metal contamination	1.4 x 10^{-3}	1.3 x 10^{-3}
26	Failure of external CP	1.13 x 10^{-2}	1.1 x 10^{-2}
27	Failure of external coating	8.7 x 10^{-3}	8.6 x 10^{-3}
28	High temperature of soil	1.4 x 10^{-3}	1.2 x 10^{-3}
29	High water ratio in soil	2.1 x 10^{-3}	2.0 x 10^{-3}
30	High salt in soil	4.1 x 10^{-3}	3.9 x 10^{-3}
31	Bacteria in soil	1 x 10^{-3}	9 x 10^{-4}
32	PH in soil	3.1 x 10^{-3}	2.9 x 10^{-3}
33	Low resistance in soil	2.4 x 10^{-3}	2.6 x 10^{-3}
34	Electrical interference in soil	4.9 x 10^{-3}	2.3 x 10^{-3}
35	Corroding with water medium	2.3 x 10^{-3}	2.6 x 10^{-3}
36	Corrosion due to acid medium	3.8 x 10^{-3}	3.6 x 10^{-3}

IV. RESULTS AND DISCUSSION

Risk assessment of proposed LPG pipe line is carried out with various methods like PHA, HAZOP and Fault tree analysis. PHA identified the major accident associated with LPG pipe line is due to puncture and rupture. Puncture and rupture caused due to corrosion, vibration, external loading, over pressure, operational error etc. HAZOP study conducted to identifies the cause and consequences arise due to the deviation from normal operating process in pipeline. Fault tree analysis is carried out for pipeline failure and 36 basic events are obtained from the fault tree analyses which are responsible for release of LPG from the cross country pipe lines. Two dimensional fuzzy fault tree analyses are carried out to incorporate the hesitancy in expert elicitation. Table 1 gives a list of basic events that lead to LPG release along with the FFTA and TDFFTA. Table 2 shows the failure probability values obtained from TDFFTA for different hesitation grades. It is observed from the Table 2 that the values obtained for 'no hesitation' grade is same as those obtained from FFTA. The difference between FFTA values and TDFFTA values narrows down when the hesitation grade changes from 'very high' to 'little'.

Table 2. Comparison of failure probability values based on different hesitation grade

Basic Event No.	No Hesitation	Little	High	Very High
1.	6 x 10^{-3}	5.6 x 10^{-3}	5.58 x 10^{-3}	5.31 x 10^{-3}
2.	8.3 x 10^{-3}	7.78 x 10^{-3}	7.691 x 10^{-3}	7.33 x 10^{-3}
3.	5.7 x 10^{-3}	4.069 x 10^{-3}	4.016 x 10^{-3}	3.807 x 10^{-3}
4.	2.5 x 10^{-3}	2.27 x 10^{-3}	2.245 x 10^{-3}	2.11 x 10^{-3}
5.	3.5 x 10^{-3}	3.28 x 10^{-3}	3.24 x 10^{-3}	3.06 x 10^{-3}
6.	3.0 x 10^{-3}	2.76 x 10^{-3}	2.721 x 10^{-3}	2.56 x 10^{-3}
7.	2.3 x 10^{-3}	2.09 x 10^{-3}	2.061 x 10^{-3}	1.93 x 10^{-3}
8.	1.5 x 10^{-3}	1.405 x 10^{-3}	1.38 x 10^{-3}	1.28 x 10^{-3}
9.	5.4 x 10^{-3}	5.08 x 10^{-3}	5.017 x 10^{-3}	4.76 x 10^{-3}
10.	3.3 x 10^{-3}	3.09 x 10^{-3}	3.048 x 10^{-3}	2.88 x 10^{-3}
11.	9 x 10^{-4}	8.57 x 10^{-4}	8.39 x 10^{-4}	7.73 x 10^{-4}
12.	1.8 x 10^{-3}	1.76 x 10^{-3}	1.739 x 10^{-3}	1.628 x 10^{-3}
13.	3.2 x 10^{-3}	2.96 x 10^{-3}	2.9202 x 10^{-3}	2.757 x 10^{-3}
14.	2.7 x 10^{-3}	2.52 x 10^{-3}	2.484 x 10^{-3}	2.339 x 10^{-3}

15.	2.6 x 10^{-3}	2.32 x 10^{-3}	2.291 x 10^{-3}	2.155 x 10^{-3}
16.	3.6 x 10^{-3}	3.32 x 10^{-3}	3.279 x 10^{-3}	3.101 x 10^{-3}
17.	1.7 x 10^{-3}	1.602 x 10^{-3}	1.5757 x 10^{-3}	1.47 x 10^{-3}
18.	3.4 x 10^{-3}	3.19 x 10^{-3}	2.98 x 10^{-3}	2.29 x 10^{-3}
19.	4.9 x 10^{-3}	4.56 x 10^{-3}	3.279 x 10^{-3}	2.36 x 10^{-3}
20.	4.8 x 10^{-3}	4.49 x 10^{-3}	1.575 x 10^{-3}	4.210 x 10^{-3}
21.	3.6 x 10^{-3}	3.36 x 10^{-3}	3.322 x 10^{-3}	3.142 x 10^{-3}
22.	6.4 x 10^{-3}	6.01 x 10^{-3}	5.943 x 10^{-3}	5.657 x 10^{-3}
23.	2.5 x 10^{-3}	2.32 x 10^{-3}	2.29 x 10^{-3}	2.15 x 10^{-3}
24.	1.8 x 10^{-3}	1.65 x 10^{-3}	1.62 x 10^{-3}	1.517 x 10^{-3}
25.	1.4 x 10^{-3}	1.27 x 10^{-3}	1.25 x 10^{-3}	1.19 x 10^{-3}
26.	1.13 x 10^{-2}	1.0 x 10^{-2}	1.05 x 10^{-2}	1.0 x 10^{-2}
27.	8.7 x 10^{-3}	8.24 x 10^{-3}	8.149 x 10^{-3}	7.774 x 10^{-3}
28.	1.4 x 10^{-3}	1.24 x 10^{-3}	1.226 x 10^{-3}	1.140 x 10^{-3}
29.	2.1 x 10^{-3}	1.93 x 10^{-3}	1.903 x 10^{-3}	1.784 x 10^{-3}
30.	4.1 x 10^{-3}	3.86 x 10^{-3}	3.81 x 10^{-3}	3.61 x 10^{-3}
31.	1 x 10^{-3}	9.22 x 10^{-4}	9.0411 x 10^{-4}	8.34 x 10^{-3}
32.	3.1 x 10^{-3}	2.85 x 10^{-3}	2.812 x 10^{-3}	2.654 x 10^{-3}
33.	2.4 x 10^{-3}	2.18 x 10^{-3}	22.146 x 10^{-3}	2.017 x 10^{-3}
34.	4.9 x 10^{-3}	4.56 x 10^{-3}	4.502 x 10^{-3}	4.273 x 10^{-3}
35.	2.3 x 10^{-3}	2.17 x 10^{-3}	2.142 x 10^{-3}	2.012 x 10^{-3}
36.	3.8 x 10^{-3}	3.52 x 10^{-3}	3.48 x 10^{-3}	3.29 10^{-3}

V. CONCLUSIONS

Cross country pipelines carry products that are very vital to the sustainability of national economies and remain a reliable means for transporting water, oil and gas. Like any other engineering facility, cross country LPG pipelines are subject to different degrees of failure and degradation. Pipeline failures are often fatal and disastrous when it transporting hazardous substance. Moreover majority of these pipelines are buried underground along the side of National and State highways which increases the vulnerability to the public. It is therefore important that these pipelines must be always under effective supervision. It is also necessary to carry out the risk assessment of such cross country pipelines for the early detection of accidental scenarios. In this work risk of proposed LPG cross country pipeline is carried out qualitatively using the PHA and HAZOP technique. For the quantitative analysis fault tree technique along fuzzy logic and expert elicitation are used. Fuzzy logic along with expert elicitations were used to generates the failure probability values of basic events which are responsible for LPG release. Expert elicitation and fuzzy logic converts the linguistic expression given by an expert, who having experience in LPG cross country pipelines into numerical values. The following specific conclusions are drawn from the present study.

- Puncture and rupture contribute the accidents associated with cross country pipeline.
- There are a number of reasons with different probabilities for these puncture and rupture.
- 2DFFTA shows variation from FFTA values due to the consideration of hesitation degree.
- This data is useful in the case of unavailability of published data.

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