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Two-dimensional fuzzy fault tree analysis for chlorine release from a chlor-alkali industry using expert elicitation

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ABSTRACT

The hazards associated with major accident hazard (MAH) industries are fire, explosion and toxic gas releases. Of these, toxic gas release is the worst as it has the potential to cause extensive fatalities. Qualitative and quantitative hazard analyses are essential for the identification and quantification of these hazards related to chemical industries. Fault tree analysis (FTA) is an established technique in hazard identification. This technique has the advantage of being both qualitative and quantitative, if the probabilities and frequencies of the basic events are known. This paper outlines the estimation of the probability of release of chlorine from storage and filling facility of chlor-alkali industry using FTA. An attempt has also been made to arrive at the probability of chlorine release using expert elicitation and proven fuzzy logic technique for Indian conditions. Sensitivity analysis has been done to evaluate the percentage contribution of each basic event that could lead to chlorine release. Two-dimensional fuzzy fault tree analysis (TDFFTA) has been proposed for balancing the hesitation factor involved in expert elicitation.

1. Introduction

Chemical industries are complex systems with innumerable chemicals being used in various phases in the operations. The raw materials, process, intermediate products, final products, and waste products in the operations can lead to a host of accident situations. Three significant hazards are fire, explosion, and toxic gas release. Of these, toxic gas release is the most damaging as it has the potential to annihilate a large number of people on exposure. Bhopal (India) gas disaster proved that a toxic gas release can be a catastrophe of massive proportion in an area with large populations causing many fatalities and long term health impact on the exposed population. Chlorine, a highly toxic chemical, a major byproduct of chlor-alkali industry is liquefied and stored at (−) 5 °C and has an expansion ratio of 460 which is a matter of great public concern. So this exercise has been taken up against this background to develop failure probability values for FTA using fuzzy logic and expert elicitation.

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 sub systems [1–3]. FTA is also used widely in many fields, such as semi conductor industry [3], man–machine system [4], flexible manufacturing systems [2], nuclear power plants [5] transmission pipelines [6], chemical industries [1,7] and LNG terminal emergency shut down systems [8]. Shu et al. [9] applied fuzzy set theory for fault tree analysis on printed circuit boards industry. Refaul et al., [10] developed computer aided fuzzy fault tree analysis. Doytcin and Gerd [11] combined task analysis with fault tree analysis for accident and incident analysis.

In conventional FTA, the process should be fully understood and the probability of failure of basic events must be known. However it is often difficult to estimate precisely the failure probability of the components due to insufficient data or vague characteristic of the basic event. It has been pointed out that in India, unavailability of the failure probability data pertaining to local condition is surprisingly limited [12].

Fuzzy methods could be the only way to generate failure probability values when little quantitative information is available regarding fluctuations of the parameters [13–15] and the probabilities of basic events are treated as fuzzy numbers. Lin and Wang [4] combined fuzzy set theories with expert elicitation to evaluate failure probability of basic events of a robot drilling system, based on triangular and trapezoidal fuzzy numbers. In a transmission expansion planning, Chanda and Bhattacharjee [16] considered

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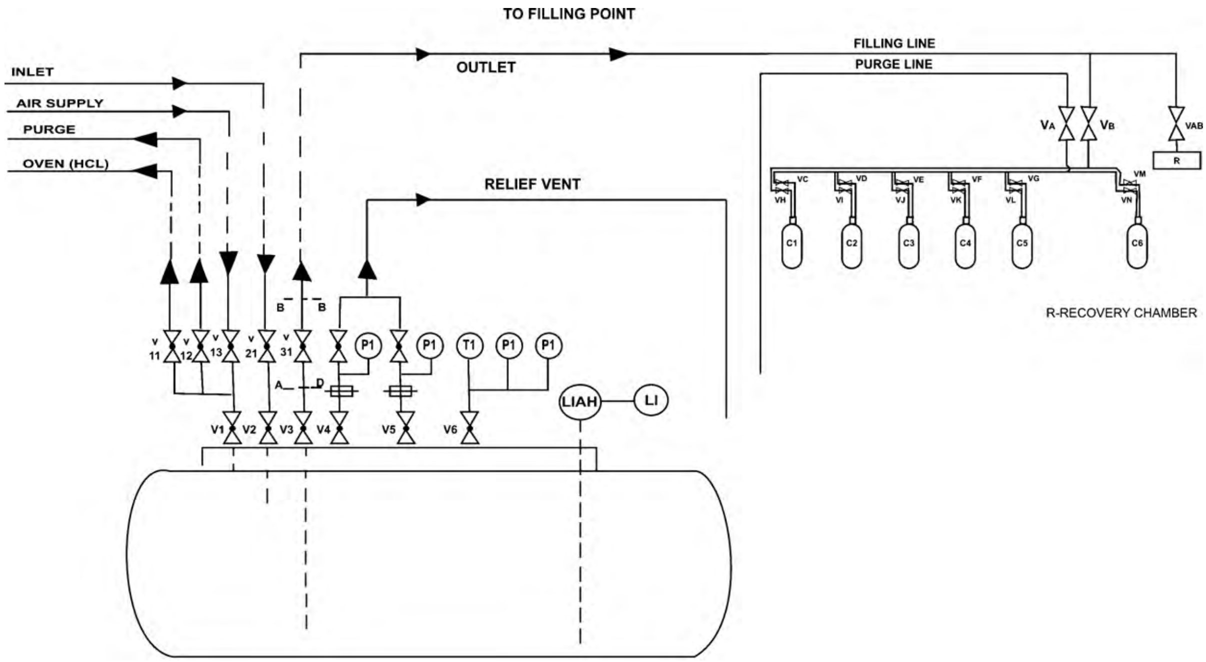

Fig. 1. Schematic diagram of chlorine storage and filling facility.

uncertain nature of failure rate of the components, and introduced fuzzy failure probability of the components. Antonio and Nelson [17] developed a new computational system for reliability analysis using fault tree and fuzzy logic. Khan and Abbasi [1] developed computer automated tool software for evaluating the reliability of chemical process industries. Roy et al. [7] used fuzzy logic in fault tree analysis of titanium tetra chloride plant using rough estimation or modified version of the available data for Indian conditions.

In the present study, an attempt is made to evaluate the probability of chlorine release from a storage tank of 50 tons capacity and filling facility (Fig. 1) using fault tree analysis (Fig. 2).

Failure probability values of basic events of chlorine release from the storage tank and chlorine filling facility were estimated using expert elicitation and fuzzy logic. Linguistic expressions about the failure probability of the basic events are obtained from the experts and are treated as fuzzy number. Two-dimensional fuzzy fault tree analysis is introduced to incorporate hesitation factor during expert elicitation.

2. Materials and methods

Fault tree analysis (FTA) is a widely used tool for system safety analysis. 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 event. 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.

2.1. Fault tree construction

The first step in the fault tree construction is defining the top event accurately. The top event is the undesired event that is the subject of fault tree analysis. After the identification of the top event, the immediate essential causes that result in the top event should be identified. The immediate causes should be connected to the top event with appropriate logic gates to show their relationship. Each of the immediate causes is then treated in the same manner as the top event and its immediate essential causes are identified and shown on fault tree with appropriate logic gates. This top-down approach continues starting from the top event and coming down through *intermediate* event until all *intermediate* events/faults have been developed into their basic events.

2.2. Fault tree evaluation

There are a number of methods for fault tree evaluation such as (1) minimal cut sets, (2) gate-by-gate method, (3) Monte Carlo simulation [18]. In the first method probabilities of the event may be calculated from the probabilities of the minimal cut sets C_i and is given by

$$P(T) = P\sum_{i=1}^{n} C_i \tag{1}$$

The second method consists of working up the tree gate-by-gate from the bottom, calculating the frequency or probability of the output event of each gate from those of the input events. The application of Monte Carlo simulation to fault tree evaluation involves a series of trials. In a given trial each primary event either occurs or does not occur, the occurrence being determined by the sampling.

In order to evaluate the failure frequency of the top event, it is necessary to assign numerical values to all inputs and the logic gates. The values are mathematically estimated through the tree from bottom to top and there arriving at predicted frequency for top events. The sensitivity of prediction to the data, which is uncertain, should always be checked to determine whether or not variation in such data would have serious effects on the results.

2.3. Failure rates of basic events

Failure rate of the basic events must be known in advance, in order to evaluate failure probability of the top event. This work uses expert elicitation and fuzzy logic to get the probabilities

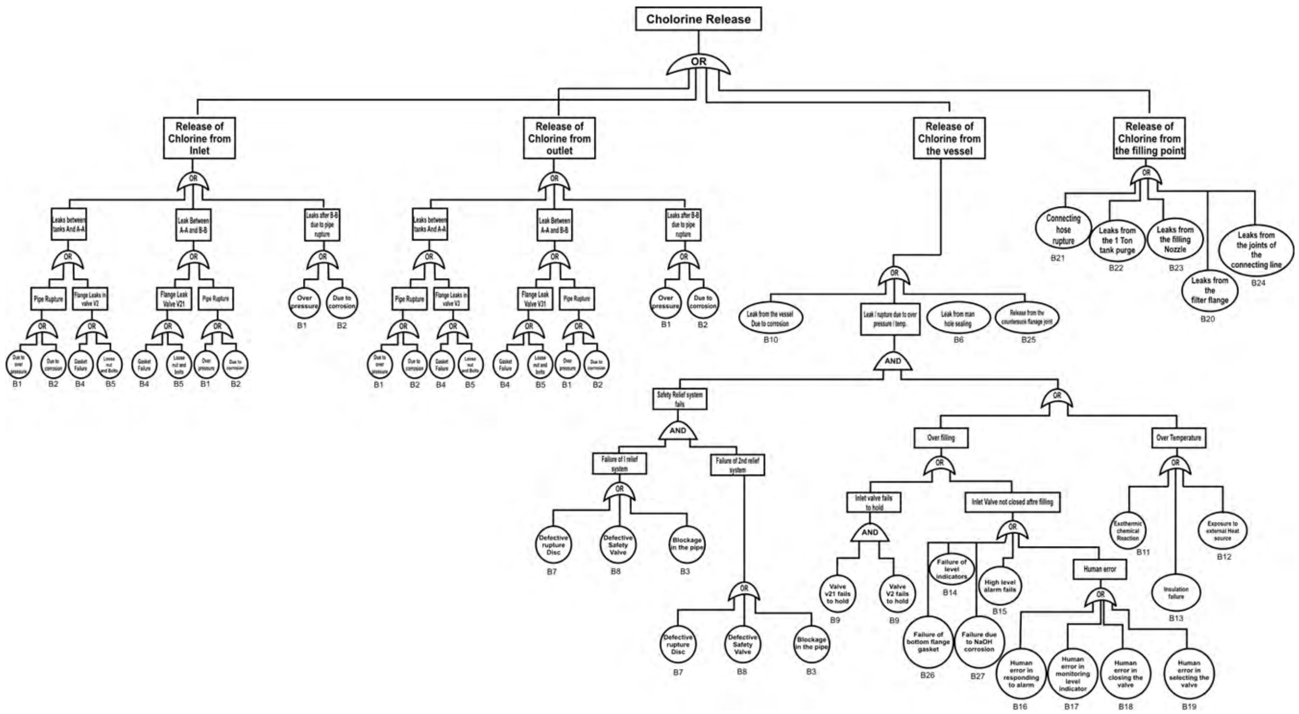

Fig. 2. Fault tree for chlorine release.

of the basic events. Expert elicitation or expert judgment is one of the methods of evaluating probability of events. This method provides some useful information for assessing risks and making decisions. It includes interview [19], Delphi method, ranking and scaling, method of paired comparison [20], and Saaty's [21] method.

Direct interaction/interview with the experts is adopted in the present study. Experts from different fields will make judgments about probability of events based on working experience and exposure to various situations. Because the experts cannot exactly evaluate the probability of events, and sometimes some of the events are vague, they tend to apply natural linguistic expressions, such as 'very low', 'low', 'medium', 'high' and 'very high', to describe the probability of events. Conventional mathematical methods cannot handle natural linguistic expressions efficiently because of their fuzziness [22]. Fuzzy set theory is used to overcome this shortcoming. There are many forms of fuzzy numbers such as triangular and trapezoidal to represent the linguistic expression [22].

Experts identified from major accident hazard (MAH) industries were requested to express their opinion. Experts were selected from different fields, such as design, installation, maintenance, operation and management of chlor-alkali and similar process industries. Experts from regulatory organizations such as petroleum and explosives safety organization (PESO), Government of India and department of factories and boilers, Kerala state and academicians with background in process safety were also approached for their opinion. Table 1 attached to the questionnaire was discussed with all the 100 experts, who were interviewed. A weighting factor is used to represent the relative quality of the response of different experts. The weighting factors obtained on the basis of interviews with 100 experts were determined as shown in Table 2.

Table 1
Scores assigned for different experts based on their merit.

Constitution	Classification	Score
Title	Professor, GM/DGM, Chief Engineer, Director	4
	Asst. Prof., Manager, Factory Inspector, Controller of Explosives	3
	Supervisors, Foreman, Graduate Apprentice	2
	Operator	1
Experience	Greater than 30	4
	20–30	3
	10–20	2
	5–10	1
Educational qualification	Ph.D./M.Tech.	5
	M.Sc./B.Tech.	4
	Diploma/B.Sc.	3
	ITI	2
	Secondary school	1
Age	Greater than 50	4
	40–50	3
	30–40	2
	Less than 30	1

2.4. Conversion of linguistic terms into fuzzy numbers

Since the experts applied natural linguistic terms to judge failure probability of the basic events that lead to a chlorine release, a numerical approximation system was proposed to systematically convert linguistic expressions to their corresponding fuzzy numbers by Chen and Hwang [23]. Eight different types of conversion scales have been suggested for the purpose. In this paper, one of the conversion scales (Fig. 3) is used to represent the expert's opinion corresponding to the membership functions of different linguistic terms. The linguistic terms 'very high', 'high', 'medium', 'low', and 'very low' are represented as *VH*, *H*, *M*, *L*, and *VL*, respectively, and the corresponding membership functions are given Eq. (2). They

Table 2
Determination of weighting factors for 100 experts.

Sl. no.	Title	Educational level	Service time	Age	Weighting score	Weighting factor
1	3	4	3	4	14	0.010
2	2	4	2	3	11	0.008
3	2	5	2	2	11	0.008
4	1	4	2	2	9	0.007
5	5	5	4	4	18	0.013
6	5	4	3	3	15	0.011
7	5	5	4	4	18	0.014
8	5	5	4	4	18	0.013
9	5	5	4	4	18	0.013
10	4	4	3	4	15	0.011
11	4	4	2	3	13	0.009
12	5	4	4	4	17	0.012
13	4	4	3	3	14	0.010
14	4	5	2	3	14	0.010
15	1	4	1	1	7	0.005
–	–	–	–	–	–	–
–	–	–	–	–	–	–
–	–	–	–	–	–	–
–	–	–	–	–	–	–
85	4	3	4	4	15	0.011
86	5	4	3	4	16	0.012
87	5	4	3	4	16	0.012
88	5	4	3	4	16	0.016
89	5	4	3	4	16	0.012
90	3	4	1	2	10	0.007
91	5	4	3	4	16	0.012
92	5	4	3	3	15	0.011
93	3	2	3	3	11	0.008
94	3	4	2	3	12	0.009
95	4	4	3	3	14	0.010
96	4	4	1	2	11	0.008
97	4	4	1	2	11	0.008
98	3	2	3	4	12	0.009
99	3	2	3	4	12	0.009
100	5	5	3	3	16	0.012
					1375	

are also represented in Fig. 3.

$$f_{VH}(x) = \begin{cases} 0 & x \le 0.8 \\ \dfrac{x-0.8}{0.1} & 0.8 < x \le 0.9 \\ 1 & 0.9 < x \le 1 \end{cases}$$
$$f_{H}(x) = \begin{cases} \dfrac{x-0.6}{0.15} & 0.6 < x \le 0.75 \\ \dfrac{0.9-x}{0.15} & 0.75 < x \le 0.9 \\ 0 & \text{otherwise} \end{cases}$$
$$f_{M}(x) = \begin{cases} \dfrac{x-0.3}{0.2} & 0.3 < x \le 0.5 \\ \dfrac{0.7-x}{0.2} & 0.5 < x \le 0.7 \\ 0 & \text{otherwise} \end{cases} \qquad (2)$$
$$f_{L}(x) = \begin{cases} \dfrac{x-0.1}{0.15} & 0.1 < x \le 0.25 \\ \dfrac{0.4-x}{0.15} & 0.25 < x \le 0.4 \\ 0 & \text{otherwise} \end{cases}$$
$$f_{VL}(x) = \begin{cases} 0 & x > 2 \\ \dfrac{0.2-x}{0.1} & 0.1 < x \le 0.2 \\ 1 & 0 < x \le 0.1 \end{cases}$$

Although there can be different opinions on probability of the basic events, it is necessary to aggregate the opinion into a single one. There are various methods to aggregate fuzzy numbers. One of the methods is linear opinion pool [Eq. (3)] proposed by Clemen and Winkler [24].

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

where A_{ij} is the linguistic expression of a basic event i given by expert j. m is the number of basic events and n is the number of experts. w_j is a weighting factor of the expert j and M_i represents combined fuzzy number of the basic event i. Based on the extension principle of fuzzy set theory [22], M_i is also a triangular or trapezoidal fuzzy number. Using α-cut of different membership functions of Eqs. (2) and (3), the total fuzzy number for the opinion of 100 experts could be obtained as another fuzzy number represented in Fig. 4 and the corresponding expression is[$(0.1339\alpha + 0.3097), (0.6140 + 0.1427\alpha)$].

2.5. Converting fuzzy number into fuzzy possibility score

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). FPS represents the most possibility that an expert believes in the occurrence of a basic event. Many investigators have proposed fuzzy ranking methods that can be used to compare fuzzy numbers. Of these, left and right fuzzy ranking method proposed by Chen and Hwang [23] is used here. The left and right utility score of fuzzy number N may be achieved with the help of Fig. 5 and the corresponding expressions are given

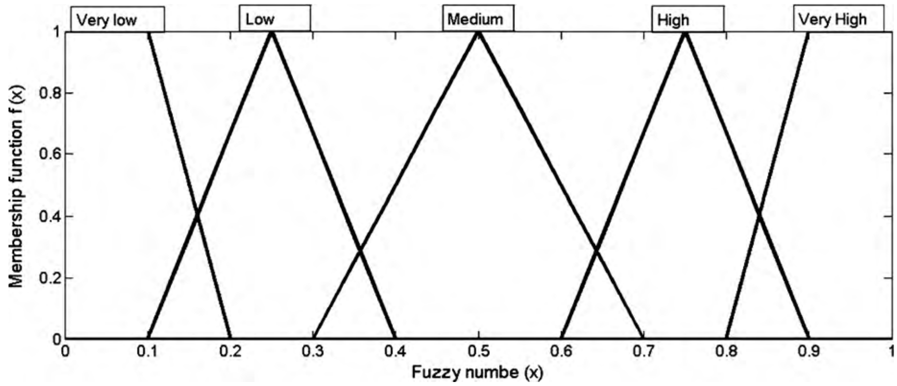

Fig. 3. Fuzzy membership functions for various linguistic expressions.

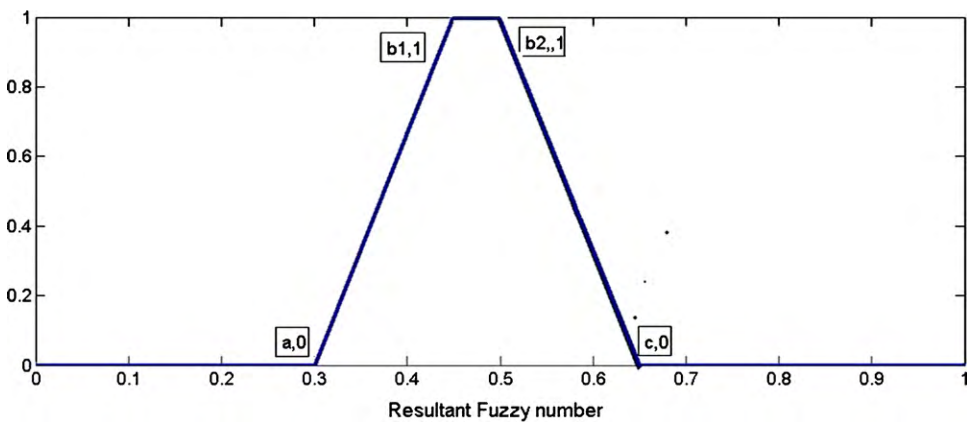

Fig. 4. Aggregate fuzzy number for the opinion of 100 experts.

by Eqs. (4) and (5).

$$\mu_L(N) = \frac{1 - a}{[1 + (b1 - a)]} \tag{4}$$

$$\mu_R(N) = \frac{c}{[1 + (c - b2)]} \tag{5}$$

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

$$FPS = \frac{\mu_R(N) + (1 - \mu_L(N))}{2} \tag{6}$$

2.6. *Transforming fuzzy possibility score into fuzzy failure probability (FFP)*

In the fault tree of chlorine release, the probabilities of the basic events are obtained by the expert judgment and fuzzy logic discussed earlier. 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 by Onisawa [25] as

$$FFP = \begin{cases} \dfrac{1}{10^k} & FPS \neq 0 \\ 0 & FPS = 0 \end{cases} \tag{7}$$

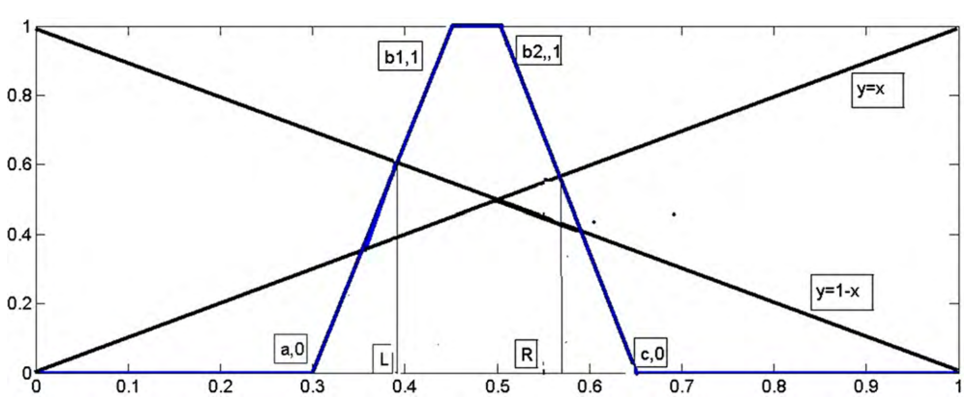

Fig. 5. Left and right utility score of aggregate fuzzy number for FFTA.

Table 3
List of basic events that lead to chlorine release.

Sl. no.	Basic event number	Description of basic event
1	B1	Pipe rupture due to overpressure
2	B2	Pipe rupture due to corrosion
3	B3	Pipe rupture due to blockage in the pipeline
4	B4	Flange leak due to gasket failure
5	B5	Flange leak due to loose nut and bolts
6	B6	Leak through man hole sealing
7	B7	Defective rupture disc
8	B8	Defective safety valve
9	B9	Leak due to valve fail to hold
10	B10	Leak from storage tank due to corrosion
11	B11	Leak from storage tank due to exothermic chemical reaction
12	B12	Leak from storage tank due to Exposure to external heat
13	B13	Leak from storage tank due to insulation failure and hence temp rise
14	B14	Failure of level indicators in the storage tank
15	B15	Failure of high level alarm
16	B16	Human error in responding to alarms
17	B17	Human error in monitoring level indicator
18	B18	Human error in closing the important valves during emergency
19	B19	Human error in selecting the valve during emergency
20	B20	Leaks at the filter flange
21	B21	Connecting hose rupture
22	B22	Leaks from the 1 ton tank-purge
23	B23	Leaks from the filling Nozzle
24	B24	Leaks from the joints of the connecting line
25	B25	Leaks from the countersunk flange joint (vessel)
26	B26	Failure of bottom flange (gasket failure) – level indicator
27	B27	NaOH corrosion – level indicator bottom

where

$$k = \left[\frac{1 - FPS}{FPS}\right]^{1/3} \times 2.301 \tag{8}$$

Similarly failure probability of all the basic events could be generated using the above-mentioned step. If probabilities of all the basic events are known, the failure probability of the top event can be calculated.

3. Two-dimensional fuzzy linguistic terms

Whenever we collect data, the expert expresses his opinion as well as hesitation. In real life problems, one can model an expert's opinion more precisely by two-dimensional linguistic terms which accounts for one's confidence and hesitation. In this paper two-dimensional linguistic terms (l_1, l_2) are used to represent the expert's opinion and hesitation. Hence l_1 denotes the opinion and l_2 denotes the hesitation. When an expert says 'very high' with 'little' hesitation or 'very low' with 'high' hesitation, then one can represent these as two-dimensional linguistic terms (very high, little), (very low, high). The linguistic terms used here for the degrees of hesitation are 'very high', 'high', 'little' and 'no hesitation'.

3.1. Conversion of two-dimensional linguistic terms

A two-dimensional linguistic term can be converted into two-dimensional fuzzy number using triangular fuzzy number. It is also possible to convert the degree of hesitation into triangular fuzzy number.

3.2. Scores of two-dimensional fuzzy numbers

Let (M, H) be a two-dimensional fuzzy number. Then the scores of two-dimensional fuzzy number T is given by Eq. (9).

$$T = \left(\frac{1 + R(M) - L(M)}{2}\right), \quad \left(\frac{1 + R(H) - L(H)}{2}\right) \tag{9}$$

where $[L(M), R(M)]$ and $[L(H), R(H)]$ are left and right scores of opinion and hesitancy fuzzy number, respectively.

3.3. Two-dimensional fuzzy scores of basic events

Two-dimensional fuzzy score of each basic event is the sum of the products of the weighing factors of the expert and their corresponding two-dimensional fuzzy numbers.

Table 4
Failure probability values of basic events that lead to chlorine release.

Sl. no.	Basic event number	From published data	Using fuzzy FFTA	Using TDFFTA	Relative percentage difference
1	B1	8.76×10^{-6}	8.57×10^{-4}	6.75×10^{-4}	21.23
2	B2	8.76×10^{-6}	3.90×10^{-3}	3.30×10^{-3}	15.38
3	B3	8.76×10^{-6}	9.23×10^{-4}	7.32×10^{-4}	20.69
4	B4	4.38×10^{-3}	8.00×10^{-3}	7.00×10^{-3}	12.50
5	B5	1.75×10^{-4}	1.80×10^{-3}	1.50×10^{-3}	16.66
6	B6	8.76×10^{-6}	1.30×10^{-3}	1.00×10^{-3}	23.08
7	B7	1.00×10^{-5}	6.60×10^{-4}	5.12×10^{-4}	22.42
8	B8	1.00×10^{-5}	1.10×10^{-3}	9.32×10^{-4}	15.27
9	B9	3.00×10^{-2}	3.40×10^{-3}	3.00×10^{-3}	11.76
10	B10	1.00×10^{-6}	1.40×10^{-3}	1.10×10^{-3}	21.43
11	B11	1.00×10^{-9}	2.89×10^{-4}	1.95×10^{-4}	32.53
12	B12	1.00×10^{-8}	2.59×10^{-4}	2.00×10^{-4}	22.78
13	B13	1.00×10^{-8}	3.78×10^{-4}	2.66×10^{-4}	29.63
14	B14	8.76×10^{-3}	2.60×10^{-3}	2.20×10^{-3}	15.38
15	B15	8.76×10^{-3}	2.10×10^{-3}	1.80×10^{-3}	14.29
16	B16	3.00×10^{-3}	2.30×10^{-3}	2.00×10^{-3}	13.04
17	B17	4.00×10^{-2}	2.10×10^{-3}	1.70×10^{-3}	19.05
18	B18	5.00×10^{-3}	2.20×10^{-3}	1.80×10^{-3}	18.18
19	B19	3.00×10^{-3}	1.60×10^{-3}	1.30×10^{-3}	18.75
20	B20	Not available	1.10×10^{-3}	8.55×10^{-4}	22.27
21	B21	8.76×10^{-6}	1.80×10^{-3}	1.50×10^{-3}	16.67
22	B22	2.63×10^{-3}	1.10×10^{-3}	8.84×10^{-4}	19.64
23	B23	2.63×10^{-3}	2.20×10^{-3}	1.80×10^{-3}	18.18
24	B24	4.40×10^{-3}	2.50×10^{-3}	2.10×10^{-3}	16.00
25	B25	Not available	5.33×10^{-4}	4.03×10^{-4}	24.39
26	B26	Not available	8.99×10^{-4}	7.10×10^{-4}	20.58
27	B27	Not available	6.71×10^{-4}	5.19×10^{-4}	22.65

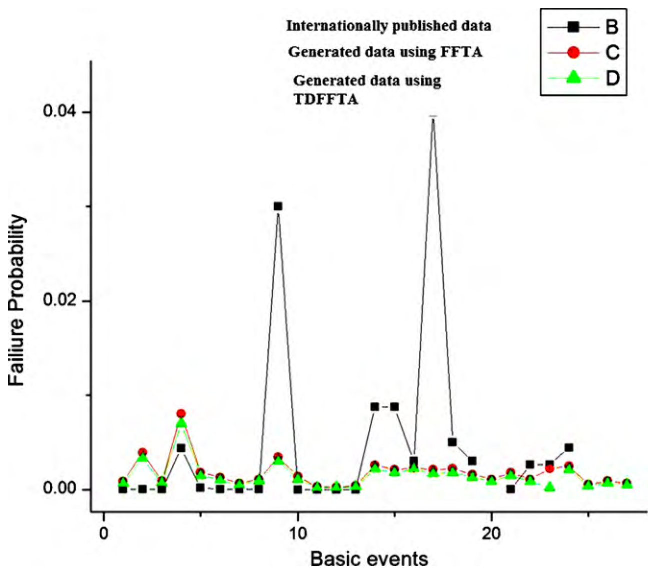

Fig. 6. Comparison of failure probability values generated using different methods. B: Internationally published data; C: generated data using FFTA; D: generated data using TDFFTA.

3.4. Crisp scores of basic events using TDFFTA

Let two-dimensional crisp scores be $M(A_i)$, $H(A_i)$ for each basic event. The score of opinion and hesitancy variables can be obtained by using Eqs. (4)–(6).

The crisp score $T(A_i)$ of each basic event = membership score $M(A_i) - k$ [hesitancy score $H(A_i)$], where

$$k = \frac{\text{minimum difference of scores in opinion variable}}{\text{number of hesistancy variable}}.$$

Table 5
Comparison of failure probability values based on different hesitation grade.

BE	Very high	High	Little	No
B1	6.75×10^{-4}	7.07×10^{-4}	8.02×10^{-4}	8.57×10^{-4}
B2	3.30×10^{-3}	3.40×10^{-3}	3.70×10^{-3}	3.90×10^{-3}
B3	7.32×10^{-4}	7.66×10^{-4}	8.65×10^{-4}	9.23×10^{-4}
B4	7.00×10^{-3}	7.20×10^{-3}	7.70×10^{-3}	8.00×10^{-3}
B5	1.50×10^{-3}	1.50×10^{-3}	1.70×10^{-3}	1.80×10^{-3}
B6	1.00×10^{-3}	1.10×10^{-3}	1.20×10^{-3}	1.30×10^{-3}
B7	5.12×10^{-4}	5.36×10^{-4}	6.14×10^{-4}	6.60×10^{-4}
B8	9.32×10^{-4}	9.66×10^{-4}	1.10×10^{-3}	1.10×10^{-3}
B9	3.00×10^{-3}	3.00×10^{-3}	3.30×10^{-3}	3.40×10^{-3}
B10	1.10×10^{-3}	1.20×10^{-3}	1.30×10^{-3}	1.40×10^{-3}
B11	1.95×10^{-4}	2.09×10^{-4}	2.50×10^{-4}	2.89×10^{-4}
B12	2.00×10^{-4}	2.20×10^{-4}	2.50×10^{-4}	2.59×10^{-4}
B13	2.66×10^{-4}	2.94×10^{-4}	3.47×10^{-4}	3.78×10^{-4}
B14	2.20×10^{-3}	2.20×10^{-3}	2.40×10^{-3}	2.60×10^{-3}
B15	1.80×10^{-3}	1.80×10^{-3}	2.00×10^{-3}	2.10×10^{-3}
B16	2.00×10^{-3}	2.00×10^{-3}	2.30×10^{-3}	2.30×10^{-3}
B17	1.70×10^{-3}	1.80×10^{-3}	2.00×10^{-3}	2.10×10^{-3}
B18	1.80×10^{-3}	1.90×10^{-3}	2.00×10^{-3}	2.20×10^{-3}
B19	1.30×10^{-3}	1.30×10^{-3}	1.50×10^{-3}	1.60×10^{-3}
B20	8.55×10^{-4}	9.12×10^{-4}	1.00×10^{-3}	1.10×10^{-3}
B21	1.50×10^{-3}	1.60×10^{-3}	1.70×10^{-3}	1.80×10^{-3}
B22	8.84×10^{-4}	9.43×10^{-4}	1.00×10^{-3}	1.10×10^{-3}
B23	1.80×10^{-3}	1.90×10^{-3}	2.10×10^{-3}	2.20×10^{-3}
B24	2.10×10^{-3}	2.20×10^{-3}	2.40×10^{-3}	2.50×10^{-3}
B25	4.03×10^{-4}	4.38×10^{-4}	4.93×10^{-4}	5.33×10^{-4}
B26	7.10×10^{-4}	7.61×10^{-4}	8.41×10^{-4}	8.99×10^{-4}
B27	5.19×10^{-4}	5.59×10^{-4}	6.30×10^{-4}	6.71×10^{-4}

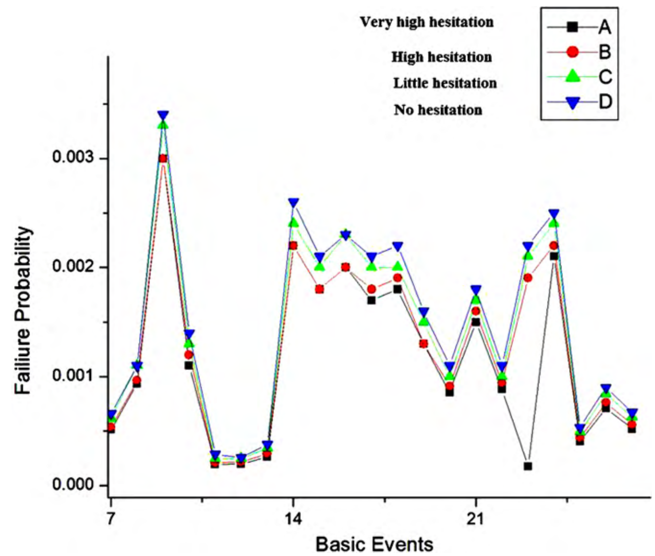

Fig. 7. Comparison of failure probability values for different hesitation grades. A: Very high hesitation; B: high hesitation; C: little hesitation; D: no hesitation.

4. Sensitivity analysis of failure probability values

The probability value of chlorine release provides an idea about the chances of release of chlorine. Sensitivity analysis is used to evaluate the impact of each basic event on the top event probability. Sensitivity analysis is carried out by eliminating each basic event from the fault tree and estimating the top event probability.

5. Results and discussion

Table 3 gives a list of basic events that lead to chlorine release. In Table 4 and Fig. 6, failure probability values of basic events obtained from the internationally published data are compared with those generated using fuzzy logic and TDFFTA. It is observed that the failure probability values obtained from published data are generally lower than the values generated using Fuzzy fault tree analysis (FFTA) under Indian conditions. This may be attributed to the tropical climatic conditions, inconsistent service conditions and unsystematic operating and maintenance practices. The probability of chlorine release estimated using published data and generated data using FFTA are 0.02793 and 0.07969 per year, respectively. Sensitivity analysis of the basic events reveals that flange leak due to gasket failure and pipe rupture due to corrosion play a very important role in chlorine release. Table 5 and Fig. 7 show the failure probability values obtained from TDFFTA for different hesitation grades. It is observed from Tables 4 and 5 that the values obtained for 'no hesitation' grade is the 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'. We have also estimated the relative percentage difference and shown in Table 4 [relative percentage difference (or error) = 100 × ((|FFTA − TDFFTA|)/FFTA)].

6. Conclusions

FTA is one of the many quantitative hazard identification tools used extensively to assess the safety and reliability of the complex systems in refineries, chemical process plants and many other industries. In conventional FTA probability of failure of basic events must be known in advance. These are, in general, obtained from the international database which may not be exactly applicable to Indian conditions. Therefore the failure probability values obtained here are different from the available values. The differences in the operating procedures as well as climatic factors contribute to the variations. The sensitivity analysis of probability of failure of basic events pin-point the areas where more attention is required for preventing chlorine release. Two-dimensional fuzzy fault tree analysis is an effective tool for expert elicitation where hesitation is to be included for accuracy. This study reveals that, flange leak due to gasket failure and pipe rupture due to corrosion play a very important role in the probability of release of chlorine. This has been substantiated by the extensive analysis carried out by correlating the data and expert opinions from the concerned industry. This method could be extended to all complex chlor-alkali industry as the basic events identified here are more or less common to all chlor-alkali units. The above method may be applied for refineries, petrochemical, fertilizer and pesticide industries.

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