Journal of Optimization in Industrial Engineering
Vol.13, Issue 2, Summer & Autumn 2020, 249- 266
DOI: 10.22094/JOIE.2020.575925.1590

Research Article

Overcoming the Uncertainty in a Research Reactor LOCA in Level-1 PSA; Fuzzy Based Fault-tree/event-tree Analysis

Masoud Mohsendokht[a], Mehdi Hashemi-Tilehnoee[b,*]

[a] *Department of Nuclear Engineering, Faculty of New Sciences and Technologies, University of Isfahan, Isfahan, Iran*

[c] *Department of Mechanical Engineering, Aliabad Katoul Branch, Islamic Azad University, Aliabad Katoul, Iran*

Received 18 October 2018; Revised 24 June 2020; Accepted 25 June 2020

Abstract

Probabilistic safety assessment (PSA) which plays a crucial role in risk evaluation is a quantitative approach intended to demonstrate how a nuclear reactor meets the safety margins as part of the licensing process. Despite PSA merits, some shortcomings associated with the final results exist. Conventional PSA uses crisp values to represent the failure probabilities of basic events. This causes a high level of uncertainty due to the inherent imprecision and vagueness of failure input data. In this paper, to tackle this imperfection, a fuzzy approach is employed with fault tree analysis and event tree analysis. Thus, instead of using the crisp values, a set of fuzzy numbers is applied as failure probabilities of basic events. Hence, in the fault tree and event tree analysis, the top events and the end-states frequencies are treated as fuzzy numbers. By introducing some fuzzy importance measures the critical components which contribute maximum to the system failure and total uncertainty are identified. As a practical example, under redesign Iranian heavy water research reactor loss of coolant accident is studied. The results show that the reactor protection system has the largest index in sequences lead to a core meltdown. In addition, the emergency core cooling system has a main role in preventing abnormal conditions.

Keywords: PSA; Fault tree analysis; Event tree analysis; Fuzzy set theory; HWRR; LOCA

1. Introduction

Since the late 1970s, probabilistic safety assessment (PSA) has been commonly used to evaluate the risk in the nuclear industry. PSA is a systematic technique for investigating the transformation of an undesired initiating event into a set of possible outcomes and their consequences (Keller, & Modarres, 2005). Today's reducing the unavailability of safety systems in nuclear power plants (NPPs) by utilizing the merits of the PSA methodology is a prime goal (Kančev, Čepin, & Gjorgiev, 2014). Many methods have been developed for modeling the availability such as a reliability block diagram (RBD), fault tree analysis (FTA), event tree analysis (ETA), Markov models, failure modes and effects analysis and stochastic simulation (IAEA, 1992) (Hasannejad, Seyyedi, & Hashemi-Tilehnoee, 2019). The selection of the appropriate method depends upon the complexity of systems and measures used to quantify the reliability index. However, uncertainties are inevitable in risk analysis due to the randomness of the failure/repair phenomena (Rao, Kushwaha, Verma, & Srividya, 2007). Among these models, FTA and ETA are two most popular system modeling procedures that form the main structure of the level-1 PSA (Keller, & Modarres, 2005) (IAEA, 1992) (Rao, Kushwaha, Verma, & Srividya, 2007) (Aldemir, 2013). FTA is a logical method to evaluate the failure probability of a system. The failure probabilities result from the sequences and the combinations of the faults and failure events. ETA is a type of branched graphs that starts from an initiating event and ends with various possible sequences with corresponding estimated probability (Keller, & Modarres 2005). Despite the significant merits and advancements in PSA, the conventional methods of PSA inherently contain shortcomings that originated from a large amount of uncertainty of the results. This is mainly because of using imprecise failure input data. The component's failure probabilities are considered as crisp values that are generally obtained from past occurrences which are uncertain. This is usually addressed to aleatory uncertainty (Lee, & McCormick, 2012). Moreover, if a system whose reliability assessment is new or its components have never failed before is known as epistemic uncertainty (Purba, 2014a). Onisawa (1989) introduced the fuzzy set theory (FST) as a useful tool to complement conventional reliability theories. Researchers studied the feasibility of FST to handle the imprecision of data and the uncertainties of models that are existent in PSA (Misra, & Weber, 1990). The studied cases are digital feedwater control system (Guimarães et al. 2011a), AP1000 Westinghouse NPP loss of coolant accident (LOCA) (Guimarães et al. 2011b), reactor protection systems of combustion engineering PWR (Purba, & Zhang, 2014) shutdown system of Gen-IV spherical isotropic power reactor (Woo, Noh, Kim, Kang, , & Kim, 2014) redesign of the Babcock and Wilcox reactor protection system (Purba, 2014b), Group-1 of the U.S combustion engineering reactor protection system (Purba,

*Corresponding author Email address: mehdi.hashemi.t@aliabadiau.ac.ir

Tjahyani, Ekariansyah, & Tjahjono, 2015), anticipated transient without scram (ATWS) event in Taiwan's nuclear power plant II, a case for fuzzy event tree analysis (Huang, , Chen, & Wang, 2001).

In this study, in order to tackle the shortcomings of conventional PSA, we applied the fuzzy set theory for safety analysis of LOCA in a heavy water research reactor (HWRR). For the calculation of the weak points of a system in any safety analysis, so fuzzy importance measures and fuzzy uncertainty measures are implemented in FTA and ETA. These fuzzy-based measures helped us to identify the components and safety systems that are critical and have the maximum contribution of uncertainty for the top event in fault tree and core meltdown frequency in event tree, respectively. The rest of the paper is organized as follows. Section 2 briefly describes FTA and ETA, fuzzy set theory, expert elicitation, fuzzy importance, and uncertainty indexes. In Section 3, the current implementation of fuzzy-based FTA/ETA in an understudy HWRR accident is reviewed and discussed. Finally, the paper is summarized in Section 4.

2. Theory and Methodology

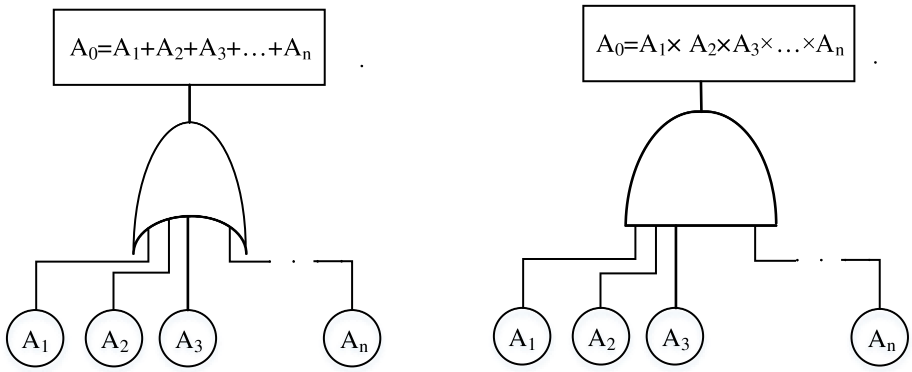
This section briefly describes the theory that is implemented in HWRR fuzzy-based PSA. The framework of the present study is shown in Fig. 1.

Fig. 1. Chart of fuzzy based PSA for HWRR

The process starts with the identification of basic events (BEs) in the system. Due to the aleatory and epistemic uncertainty, the BEs are classified into two groups of known and unknown failure rates. For the first group, the failure rates of BEs are collected from generic reliability data logs or the available historical data of similar systems. For the second group of BEs that their failure rates are unknown, the expert elicitation that conjugated with the fuzzy approach is recommended. Fault trees and event trees of related events and consequences are constructed and analyzed for the two classified BEs. Finally, some fuzzy importance measures are introduced to determine how much each BE would influence the failure probability of the top event in FTA and end-state sequences in ETA.

2.1. The theory of fault tree analysis

FTA, first conceived in 1961, is a widely used method for analyzing a system's failure logic and calculating overall reliability (Lee, Grosh, Tillman, & Lie, 1985). In other words, FTA is the translation of a physical system into a structured logic diagram using Boolean AND/OR gates. The main part of this diagram is the top events. Top events are the end states of basic events or causes (Gupta, & Bhattacharya, 2007). The output of two or more independent input events which combined with an OR gate and by an AND gate is shown in Fig. 2.



(a) Boolean OR gate (b) Boolean AND gate

Fig. 2. Fault tree representation

In Fig. 2(a), the top event A_0 will fail if one of the input events A_i fails. In Fig. 2(b), the undesired top event A_0 will fail if all input events A_i fail together at the same time. The failure probabilities of the top event A_0 that produced by OR/AND gates can be calculated using Eqs. (1-2), respectively.

$$P(A_0) = 1 - \prod_{i=1}^{n}\{1 - P(A_i)\} \tag{1}$$

$$P(A_0) = \prod_{i=1}^{n} P(A_i) \tag{2}$$

If the failure rate and other necessary data are available for the basic events, the FTA will provide estimates of the frequency of occurrence of the undesired events. However, the application of conventional FTA has some shortcomings. In conventional FTA, the failure probabilities are considered as an exact value, i.e. single estimated value or crisp value. However, it is difficult to estimate a precise failure rate or probability of the components due to the lack of insufficient data. This is crucial specifically in the preliminary design stages, when the details of the components may have to be established, thus an exact failure rate could not be known (Mahmood et al., 2013).

2.2. The theory of event tree analysis

ETA is an inductive logic and diagrammatic method for identifying the various possible outcomes of a given initiating event. For an initiating event, if two-state modeling is employed (one failed state and one success state), then an event tree can be constructed as a binary tree with nodes representing a set of possible failure and success states. In conventional ETA, system failures that cause these events are analyzed by using FTA to identify the interrelationships between systems and components. The failure rate of a component is treated as a random variable and often lognormal probability density function is used to describe the failure rate variability and uncertainty (Huang, Chen, & Wang, 2001).

2.3. Fuzzy set theory

Fuzzy probability represents a fuzzy number between zero and one, assigned to the probability of a basic event. According to the fuzzy set theory (Zadeh, 1965), let *X* be a collection of numbers or objects called the universe, whose elements are denoted by *x*; a fuzzy subset *A* in *X* is characterized by its membership function $\mu_A(x)$. This function associates with every single element, *x* in *X* in the interval [0,1]. The function $\mu_A(x)$ represents the degree of membership of *x* in the fuzzy set *A*. The closer the value of $\mu_A(x)$ to 1 is, the stronger the degree of membership of *x* in *A* is. On the other hand, the closer the value to 0 is, the weaker the degree of membership of *x* in *A* is. Meanwhile, a fuzzy number is a special type of fuzzy sets whose membership functions are convex and normalized. The membership function of fuzzy numbers $\mu_{\tilde{A}}(x)$ can be expressed as follows (Purba, 2014a).

$$\mu_{\tilde{A}}(x) = \begin{cases} \mu_{\tilde{A}}^{L}(x), & a \le x \le b \\ 1, & b \le x \le c \\ \mu_{\tilde{A}}^{R}(x), & c \le x \le d \\ 0, & otherwise \end{cases} \tag{3}$$

If both $\mu_{\tilde{A}}^{L}(x)$ and $\mu_{\tilde{A}}^{R}(x)$, left membership function and right membership function, be linear then the fuzzy number $\tilde{A}$ is a trapezoidal fuzzy number and can be denoted by $\tilde{A} = (a, b, c, d)$. In a special case when $b = c$, the trapezoidal fuzzy numbers are transformed into triangular fuzzy numbers. Some properties usually used to describe fuzzy numbers are; support, core, height, left and right membership functions as graphically shown in Fig. 3.

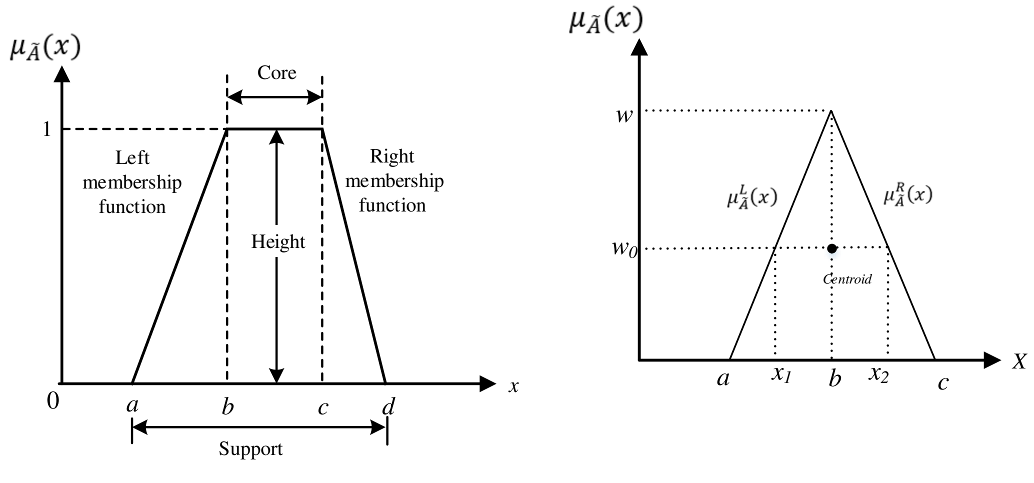


Fig. 3 Fuzzy number properties a) general Trapezoid fuzzy numbers b) Triangular fuzzy probability of Bes

2.4. Fuzzy fault tree analysis (FFTA) method

The FFTA is developed to deal with uncertainties, which are involved in the basic event reliability evaluation due to the use of limited data or generic data. In this approach, fuzzy probabilities are expressed by triangular fuzzy numbers whose values are statistically generated using limited available historical failure data. The lower bound value (p_1), the middle value (p_2) and the upper bound value (p_3) of the triangular fuzzy numbers are derived from the point median value (pmv) and the error factor (ef) of the available data as defined in Eqs. (4-6).

$$p_1 = \frac{pmv}{ef} \tag{4}$$

$$p_2 = pmv \tag{5}$$

$$p_3 = pmv \times ef \tag{6}$$

2.5. Fuzzy event tree analysis (FETA) method

In FETA, the evaluation of an event tree is generalized to the operations of some fuzzy sets. The FETA is summarized as following steps. For an initiating event identified, the set of possible failure and success states must be defined to construct the event-tree logic diagram. The construction of an event tree is mostly based on engineering experiences. For fuzzification, the occurrence frequency of the initiating event transforms into proper triangular fuzzy numbers. The upper and lower bounds can be estimated by using the concept of error factor. To illustrate how the fuzzy set theory is applied to event tree analysis and how the sequences are quantified, a sample event tree is represented in Fig. 4 (Huang, Chen, & Wang, 2001).

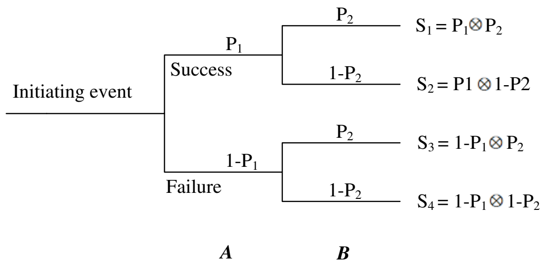


Fig. 4. A schematic of the fuzzy event tree

A and B are the two top events of the event tree. In each branch of the event tree, only two possible states are assumed; success or failure with the probabilities of 1-P and P, respectively. As it is shown in Fig. 4, P_1 represents the fuzzy failure probability of top event A, and P_2 represents the fuzzy failure probability of top event B. to calculate the end-state probabilities, the fuzzy subtraction, and multiplication rules are applied. After calculating all event tree paths, the sequences with the melt-down state are integrated and their fuzzy frequencies are summed up. Then, the defuzzification process of total core damage frequency is performed and the result is interpreted.

2.6. Identification of basic events with known failure rates

According to the study framework shown in Fig. 1, in the case where quantitative reliability data is readily available, the reliability functions are defined. Since the components and the systems in this research are safety systems and they are normally in standby mode, the definition of reliability is replaced by the definition of unavailability. Unavailability is the probability that a system or component is not able to perform its required function at a given point in time (Modarres, Kaminskiy, & Krivtsov, 2009). Unavailability contributions can be normally divided into two main categories as Unavailability due to hidden failures and unavailability due to surveillance tests, maintenance, and repairs (Martorell, Carlos, Sanchez, & Serradell, 2000).

According to this definition, the equation of unavailability of the components can be written as follows:

$$U(x) = \rho_0 + \frac{1}{2}\lambda T + \frac{s}{T} + \frac{d}{T}(\rho_0 + \lambda T) \quad (7)$$

Where λ is the failure rate, ρ_0 is per-demand failure probability, T is the Interval of the inspection or surveillance tests, s is the downtime due to the inspection tests, and *d* is the downtime due to maintenance and repair. In this study, the above reliability parameters for each component, BEs with known failure probabilities, are obtained through the reliability data logs (IAEA, 1997) (IAEA, 1998). After obtaining the fuzzy sets of basic events, as the input for fault tree analysis, by utilization of fuzzy combination rules (instead of Boolean algebra technique in conventional FTA), the top event fuzzy failure probability is calculated. In this approach, the "AND" and "OR" gates are replaced by a fuzzy multiplication rule and a fuzzy complementation rule, respectively (Zimmermann, 1991). Using the fuzzy set approach, the top event failure probability is represented by a possibility distribution of values (rather than a single value, i.e. crisp value). These distributions somehow represent the uncertainties raised in the basic events failure probabilities evaluations.

2.7. Identification of basic events with unknown failure rates (fuzzy-based expert elicitation)

A lack of complete knowledge about the failure probabilities of systems, processes and phenomena is known as the state of knowledge uncertainty or epistemic uncertainty. Epistemic uncertainty is usually due to the rare events or insufficient reliability data and may be reduced by additional measurement, testing or analysis. Therefore, in the absence of accurate historical data, we will have to work with rough estimates of failure probabilities which can be provided by expert elicitations or known as an educated guess (Rao, Kushwaha, Verma, & Srividya, 2007). The combination of expert elicitation and fuzzy set theory might be the only feasible and verified strategy for compensating the incompleteness of reliability data. According to the framework shown in Fig. 1, the below steps are applied to generate the BEs failure probabilities as follows:

Step 1. Gathering expert linguistic expressions and converting them into fuzzy numbers

The objective of step 1 is to collect the qualitative justifications of experts about the BEs failure probabilities. For this purpose, some questionnaires will be given to a selected group of experts. The advantage of using linguistic expressions is the intuition and ease of use for experts to put their opinion where the numerical estimations are hard to obtain. Based on Miller's (1956) research, the typical estimate of human working memory capacity is seven plus-minus two chunks, which can be concluded that the suitable number of comparisons for experts to judge at a time is between 5 and 9. In this research, seven linguistic values, including Very Low, Low, Fairly Low, Medium, Fairly High, High and Very High are applied to evaluate the failure probabilities. In order to represent these linguistic expressions in the form of numerical values, some mathematical membership functions of fuzzy numbers can be formulated (Hryniewicz, 2007). There have been represented numerous fuzzy membership functions in different fields of applications (Klir, & Folger 1988). But it must be noted that for different engineering systems, some special membership functions need to be defined (Markowski, & Mannan, 2008). Ferdous et al. (2001) and Wolkenhauer (2001) suggested that triangular and trapezoidal fuzzy numbers are the best practical alternatives to reflect the fuzziness of expert judgments. In order to assign numerical fuzzy values of linguistic expressions, there are some approaches proposed by Ross (2004), including inference, rank-ordering, intuition, neural network, genetic algorithm, and inductive reasoning. In the field of nuclear engineering, Purba et al. (2014) applied the inductive reasoning to assign numerical values to fuzzy probabilities of the seven mentioned linguistic expressions. Table 1 gives the numerical equivalent values pertaining to membership functions.

Table 1
The linguistic terms and their corresponding fuzzy values

Linguistic terms	Symbol	Fuzzy sets
Very Low	VL	(0.00, 0.04, 0.08)
Low	L	(0.07, 0.13, 0.19)
Fairly Low	FL	(0.17, 0.27, 0.37)
Medium	M	(0.35, 0.50, 0.65)
Fairly High	FH	(0.63, 0.73, 0.83)
High	H	(0.81, 0.87, 0.93)
Very High	VH	(0.92, 0.96, 1.00)

Step 2. Aggregation of experts' opinions into fuzzy numbers

Due to the diverse judgments of experts on failure probabilities of BEs, an aggregation and reaching a consensus on a single value is necessary. There are various forms of aggregation methods such as the arithmetic method, the maximum Delphi method (Ross, 2004), the linear opinion pool technique (Purba, Lu, Zhang, & Pedrycz, 2014) and so on. In the present study, the linear opinion pool is recommended and is defined as below:

$$CFN = \sum_{j=1}^{n} W_{ej} A_{ij} \quad (8)$$
$$i = 1,2,3, \dots, m \;\; , j = 1,2,3, \dots, n$$

where CFN is combined fuzzy number of basic event *i*, W_{ej} is weighting factor of expert *j*, A_{ij} is fuzzy number for basic event *i* by expert *j*, *m* is the total number of basic events, and n is the total number of experts. The evaluation of failure probabilities by experts is based on their experiences and knowledge about the systems and their failure status. Therefore, it is necessary to introduce a weighting factor to represent the relative quality of different experts. Four parameters of educational level, experience, age, and occupational position were applied for weight scoring. Table 2 gives the related scores for each parameter.

Table 2
Weighting scores of different experts

Constitution	Classification	Score
Professional position	Academician	5
	Operations manager	4
	Chief engineer	3
	Engineer	2
	Technician	1
Education	PHD	4
	Master	3
	Bachelor	2
	Junior college	1
Experience	>20	4
	15-20	3
	10-15	2
	<10	1
Age	>50	4
	40-50	3
	30-40	2
	<30	1

Step 3. Conversion of fuzzy numbers into fuzzy failure probabilities

The objective of this step is to provide a useful outcome of integrated fuzzy numbers. In order to ensure compatibility between the failure probabilities obtained through the historical data and expert elicitation, the generated fuzzy numbers in step 3 must be converted into a fuzzy failure probability. To this end, at first, the integrated fuzzy numbers are transferred to fuzzy possibility scores (FPS). FPS represents the most possibilities that an expert believes occurring of a basic event. In order to decode the triangular fuzzy numbers obtained in step 2 into the corresponding FPS, Purba et al. (2012) developed a suitable technique. Based on this technique, the centroid point of the membership function on the vertical axis and its intersection with left and right membership functions determines two separate areas as shown in Fig. 3(b) which the sum of the mentioned areas gives a single value known as FPS.
where the FPS denoted as:

$$FPS = x_1 w_0 + \int_{x_2}^{c} \mu_{\tilde{A}}^{R}(x)dx \tag{9}$$

where w_0 is the centroid point on the vertical axis, x_1 is the intersection point between line w_0 and the left membership function, x_2 is the intersection point between line w_0 and the right membership function. By considering $\tilde{A}$ = (a, b, c) as a normal triangular fuzzy number, the above parameters can be calculated using Eqs. (10-12).

$$W_0 = \frac{\int_0^w w_0 \mu_{\tilde{A}}^{R}(w)dw - \int_0^w w_0 \mu_{\tilde{A}}^{L}(w)dw}{\int_0^w \mu_{\tilde{A}}^{R}(w)dw - \int_0^w \mu_{\tilde{A}}^{L}(w)dw} \tag{10}$$

$$X_1 = \mu_{\tilde{A}}^{L}(w_0) = a + (b-a)w \tag{11}$$

$$X_2 = \mu_{\tilde{A}}^{R}(w_0) = c + (b-c)w \tag{12}$$

By substituting the Eqs. (10-12) into Eq. (9) and some mathematical simplifications, the FPS is calculated as below:

$$FPS = \frac{1}{18}(4a + b + c) \tag{13}$$

In order to convert FPS into fuzzy failure probability (FFP), Onisawa (1988) (1990) proposed a logarithmic conversion function as follows:

$$FPS = \begin{cases} \frac{1}{10^k} & FPS \neq 0 \\ 0 & FPS = 0 \end{cases}, \quad k = 2.301\left(\frac{1-FPS}{FPS}\right)^{\frac{1}{3}} \tag{14}$$

The above function is derived from satisfying the proportionality of human sensation to the logarithmic value of a physical quantity. Based on the above three-step process, the value of FFP gives the best estimate. For calculating the lower bound and upper bound values, the below process is applied. In order to generate the lower bound of fuzzy probability, among the expert opinions, the minimum equivalent fuzzy number is selected. Then the above-mentioned steps are repeated to calculate the lower bound of FFP. For obtaining the upper FFP, a similar process is applied, but the maximum equivalent fuzzy number is selected.

2.8. Fuzzy importance index

In safety analysis of a complex system, measuring the importance of components is often of significant value for determining the critical components, improving the system's reliability and finding the most efficient way for operation and maintenance. In conventional PSA, which the failure probabilities of components are considered as crisp value, importance measures are applied such as risk reduction worth, risk achievement worth, Birnbaum's and Fussell-Vesely's and so on. But in a fuzzy approach, the failure probabilities are fuzzy numbers. Hence, there is a need to develop some new and applicable formulas. Liang and Wang proposed a useful equation called the fuzzy importance index (FII) (Liang, & Wang, 1993). FII is used in FTA to indicate the importance of a basic event by observing the effects of eliminating or making it fully unavailable and available on top event failure probability. Thus, the total contribution of a basic event to the system failure probability is the difference between these two statuses. In conventional PSA, this process is known as Birnbaum's importance. However, in fuzzy FTA, due to the nature of fuzzy numbers, some changes are required to be applied. According to arithmetic operations between two fuzzy sets (Guimarães, Lapa, & Moreira, 2011) (Zadeh, 1965), the fuzzy fault tree importance index (FFII) is defined as:

$$FFII = ED[U_{P_i=1}, U_{P_i=0}] \quad (15)$$

Where $U_{P_i=1}$ is the top event unavailability by making the component i fully unavailable and $U_{P_i=0}$ is the top event unavailability by eliminating the failure of component i. $ED[X, Y]$is the Euclidean distance between two fuzzy sets X and Y and is defined as (Guimarães, Lapa, Simões Filho, & Cabral, 2011b):

$$ED[X, Y] = \sum [(x_L - y_L)^2 + (x_U - y_U)^2]^{0.5} \ \alpha_i \ ; \ \alpha_i = 1,2,3, \dots, N \quad (16)$$

where x_L,y_L and x_U,y_U are the lower and upper bounds of fuzzy set X and Y, respectively on each α level and N is the number of α-cuts. The same concept of FFII is also applicable to event tree analysis (ETA) to find out the relative importance among the events leading to different sequences (Huang, Chen, & Wang, 2001). Fuzzy event tree importance index (FEII) is defined as:

$$FEII = C_T - C_{T_i} = \sum \left[\left(C_T^L - C_{T_i}^L \right)^2 + \left(C_T^U - C_{T_i}^U \right)^2 \right]^{0.5} \alpha_i \ ; \ \alpha_i = 1,2,3, \dots, N \quad (17)$$

where C_T is α-cut of total core damage fuzzy failure rate and C_{T_i} is α-cut of total core damage fuzzy failure rate with top event i eliminated or completely failed. FEII is helpful to identify the critical events which have the most effect on core damage status and severe accidents.

2.9. Fuzzy Uncertainty Index

The uncertainty associated with PSA results is always a matter of concern for the safety analysts. Due to the uncertain nature of generic data, the uncertainty analysis of the top event probability of a fault tree or end-state frequencies of an event tree is highly recommended (Liang, & Wang, 1993). In this paper, for identifying the components whose uncertainty failure probabilities have a significant contribution to the uncertainty of system failure, the fuzzy fault tree uncertainty index (FFUI) is applied. FFUI is defined as:

$$FFUI = ED[U, U_i] \quad (18)$$

Where U_i is the top event unavailability when the error factor for component i is unity (i.e. EF=1) or in other words the parameter of basic event have a crisp value. The same concept is used for identifying the events which contribute maximum to the uncertainty of end-state frequencies. Fuzzy event tree uncertainty index (FEUI) is defined as:

$$FEUI = P_T - P_{T_i} = \sum \left[\left(P_T^L - P_{T_i}^L \right)^2 + \left(P_T^U - P_{T_i}^U \right)^2 \right]^{0.5} \alpha_i \ ; \ \alpha_i = 1,2,3, \dots, N \quad (19)$$

where P_T is α-cut of total core damage fuzzy probability rate and P_{T_i} is α-cut of total core damage fuzzy probability rate when the occurrence rate of i th event is a crisp value.

3. Case Study

A fuzzy safety analysis of LOCA is applied to an Iranian heavy water research reactor known as IR-40. IR-40 has been designed to fulfill several purposes, ranging from gaining experience and technical know-how for design and construction for non-power reactors to utilizing the reactor for activation, irradiation, and radioisotope production (Hashemi-Tilehnoee, Pazirandeh, & Tashakor, 2010). IR-40 is a 40 MW thermal tank-type reactor, with heavy water for moderation and cooling and natural uranium dioxide fuel. However, after IAEA agreement this reactor is going to be replaced by low-enriched uranium fuel by modification and redesigning the reactor core. In the current design, the reactor primary and secondary cooling loops are under pressure about 0.28 MPa. The residual heat is to be removed by natural convection of the primary cooling loop. There are two independent nuclear safety systems: shutdown rods and emergency light water channels. Four beam tubes are provided in this reactor for medical and industrial applications. Eight vertical channels are provided for radioisotope production, irradiation, and activation. The IHWRR core consists of 150 fuel assemblies and the central channel is in a triangular lattice with a pitch of 265 mm. Sixteen fuel assemblies have neutron flux detectors. There are 27 control and protection channels, including three control rod channels, 12 shimming rod channels, six emergency rods (ER), six emergency channels (EC) for light water and one channel for reference specimen (Hashemi-Tilehnoee, Pazirandeh, & Tashakor, 2010). A LOCA which was initiated by a break or leak in the coolant system is considered as a case study of this research. In other words, a rupture of a 40 cm head pipeline of the primary coolant system is considered. According to the preliminary safety analysis report of IR-40, the safety systems that are designed to perform following such an accident are consisting of Reactor Protection System (RPS), Electric Power Supply System (EPSS), Emergency Core Cooling System (ECCS), Containment Isolation (CI), Containment Spray System (CSS), and Emergency Ventilation System (EVS). Fig.4 shows the event tree developed for the occurrence of a large type of LOCA. The end-state sequences or final core damage status (CDS) can be classified into three types, including safe, abnormal and core meltdown conditions. If the reactor shutdown takes place successfully and EPSS and ECCS systems operate timely, the core of the reactor will be in a safe condition. Otherwise, the sequences lead to abnormal or core damage situations. In abnormal situations, the core will not meltdown, but serious damages are expected. The worst core damage conditions from radioactivity release quantity are end-states 10 and 11, in which the RPS fails to operate and CI integrity is lost. In order to calculate the unavailability or the failure probability of the safety systems pertaining to LOCA prevention, the respective fault trees must be developed and analyzed. As an example, for demonstrating the application of the proposed approach, the EPSS fault tree is constructed (Fig. 5). The rest of the related safety system fault tree and their importance measures that applied to reactor components can be found in appendix A.

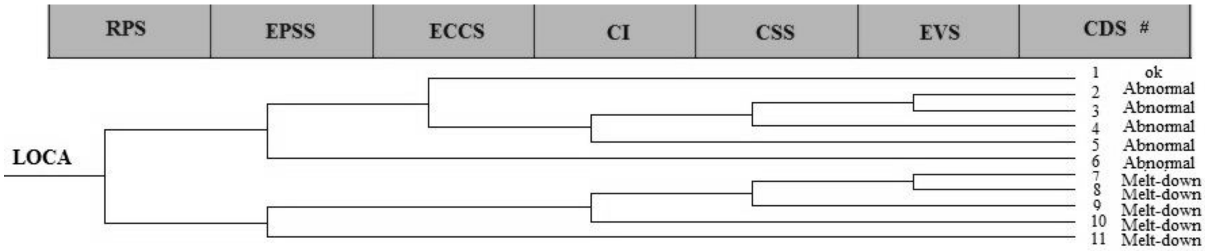


Fig. 4. IR-40 LOCA event tree

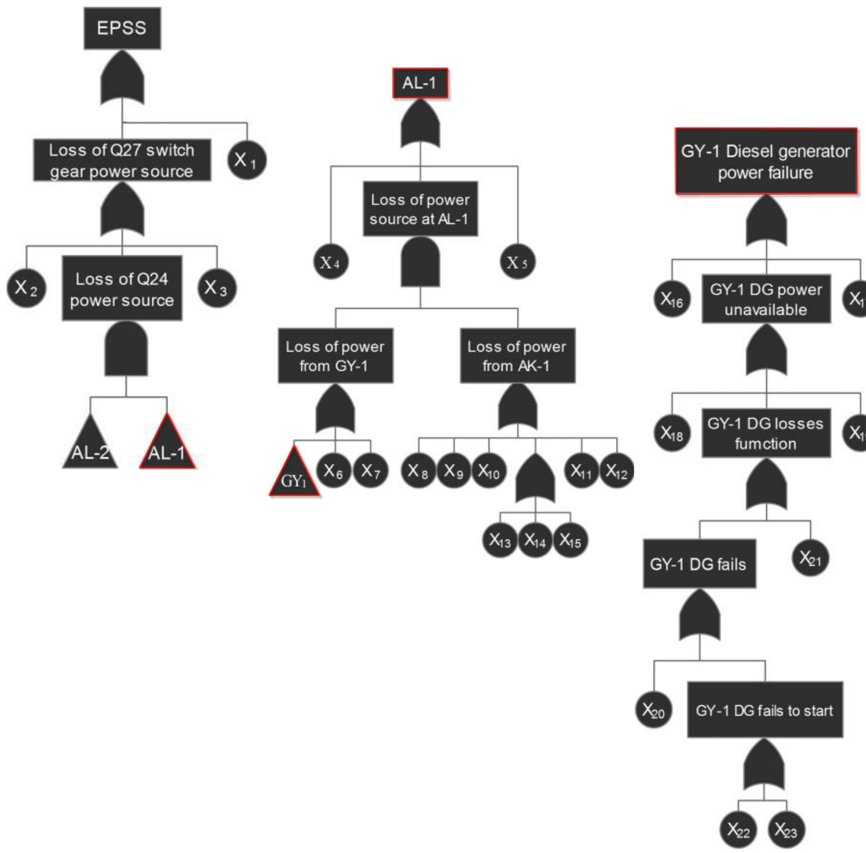


Fig. 5. EPSS fault tree

4. Results and Discussion

4.1. Fuzzy fault tree analysis

As discussed in Section 2, due to the aleatory and epistemic uncertainties existing in component failure data, two separate strategies were applied. For overcoming the aleatory uncertainty, by using Eqs. (4-6) and the values of EF, the fuzzy failure probabilities of BEs with known failure rates are evaluated. Table 3 represents the BEs of EPSS and their corresponding fuzzy failure probabilities.

Table 3
The failure probabilities, FII and FFUI that applied to EPPS components (and their subsets, AL-1 and GY-1)

Component	Description	Failure probabilities			FFII	FFUI
		Lower bound	Median point	Upper bound		
X1	Q27 switch gear loses function	3.6E-8	3.6E-7	3.6E-6	15.56	2.21E-5
X2	Q24 Vacuum Circuit Breaker (VCB) failure	3.2E-8	3.2E-7	3.2E-6	15.56	2.02E-5
X3	CT3 transformer failure	4.6E-8	4.6E-7	4.6E-6	15.56	2.65E-5
X4	S3 load breaker switch failure	3.2E-8	3.2E-7	3.2E-6	0.243	1.18E-5
X5	Q18 VCB loses function	3.2E-8	3.2E-7	3.2E-6	0.243	1.18E-5
X6	Q12 VCB loses function	3.2E-8	3.2E-7	3.2E-6	5.22E-3	1.18E-5
X7	Q12 VCB not available due to maintenance	6.9E-5	6.9E-4	6.9E-3	5.22E-3	3.59E-5
X8	Q6 VCB loses function	1.0E-7	1.0E-6	1.0E-5	3.13E-2	1.18E-5
X9	Q6 VCB not available due to maintenance	6.9E-5	6.9E-4	6.9E-3	3.12E-2	1.94E-4
X10	Q11 VCB loses function	3.2E-8	3.2E-7	3.2E-6	3.13E-2	1.18E-5
X11	Q11 VCB not available due to maintenance	6.9E-5	6.9E-4	6.9E-3	3.12E-2	1.94E-4
X12	AY-1 transformer failure	1.3E-7	1.3E-6	1.3E-5	3.13E-2	1.18E-5
X13	Q1 VCB loses function	1.0E-7	1.0E-6	1.0E-5	3.13E-2	1.18E-5
X14	Loss of offsite power	1.0E-5	1.0E-4	1.0E-3	3.13E-2	2.81E-5
X15	Q1 VCB not available due to maintenance	6.9E-5	6.9E-4	6.9E-3	3.13E-2	1.94E-4
X16	GY-1 VCB loses function	2.5E-8	2.5E-7	2.5E-6	5.22E-3	1.18E-5
X17	GY-1 VCB not available due to maintenance	2.3E-3	7.0E-3	3.5E-2	5.22E-3	7.32E-5
X18	Q12 normally open VCB fails to close	1.0E-7	1.0E-6	1.0E-5	5.22E-3	1.18E-5
X19	Common cause failure of diesel generators (DG)	3.6E-3	1.8E-2	9.0E-2	5.22E-3	2.82E-4
X20	GY-1 DG fails to run	2.0E-3	6.0E-3	3.0E-2	5.22E-3	6.27E-5
X21	GY-1 DG not available due to maintenance	8.0E-4	2.4E-3	1.2E-2	5.22E-3	2.53E-5
X22	GY-1 fails to start manually	4.6E-5	4.6E-4	4.6E-3	5.22E-3	2.20E-5
X23	GY-1 fails to start automatically	6.0E-6	6.0E-5	6.0E-4	5.22E-3	2.75E-5

In addition, the required error factor used in Section. 2.4 and Section 2.5 for fuzzy-based fault and event tree analysis are shown in Table 4.

Table 4
General guidelines for estimating uncertainty (bounds for error factor)

Failure probability	P<0.001	0.001<P<0.01	P>0.01
Error Factor	10	3-5	5

The rest of BEs related to other safety systems and their fuzzy failure probabilities are shown in Table B.1 (Appendix B). In order to tackle the epistemic uncertainty, a group of 12 experts have been invited to express their own opinions linguistically about the failure probabilities of 15 BEs in which their reliability data were unknown. Table 5 shows the experts' specifications, including their professional position, age, educational level, and experience. By considering the values in Table 3, any expert gets a weighted score. Table 6 represents the experts' justifications about the 15 mentioned BEs and their corresponding fuzzy failure probabilities. The descriptions of the above BEs are given in Table B.1. Table 7 shows the fuzzy values of all safety system top event failure probabilities. In the case of fuzzy representation, considering the values in table 3, the total possible range of EPSS failure probability extends from 1.14E-7 to 1.35E-4, which shows a considerable difference in quantity. Thus, it can be seen that the use of generic data as a crisp value might have led to high uncertainty in final results. Hence, uncertainty analysis and determining the most important components which have a greater effect on the uncertainty level is vital. Furthermore, identifying the critical components which are of great importance to the failure probability of the top event is needed. With respect to FFII and FFUI of BEs in the EPSS fault tree which illustrated in table 4, it is obvious that the components X_1- X_5 are the most critical ones in the EPSS system due to their high value of FFII. Therefore, special attention for design modification or applying strict maintenance programs is necessary. As an example, Figs 6 demonstrates the top event fuzzy failure probabilities, with component X_4 fully available or U = 0 in Fig. 6(a) and fully unavailable, U = 1, in Fig. 6(b). From uncertainty point of view, considering the FFUI values of the BEs, the component X_{19} has the most effect on the total top event uncertainty and the components X_9, X_{11} and X_{15} are placed in the second matter of importance. The results of FFUI indicate the importance of precise reliability data gathering process on the reduction of the total uncertainty. As an example, Fig. 7 shows the FFUI α-cuts values of component X_1.

Table 5
Experts weighting

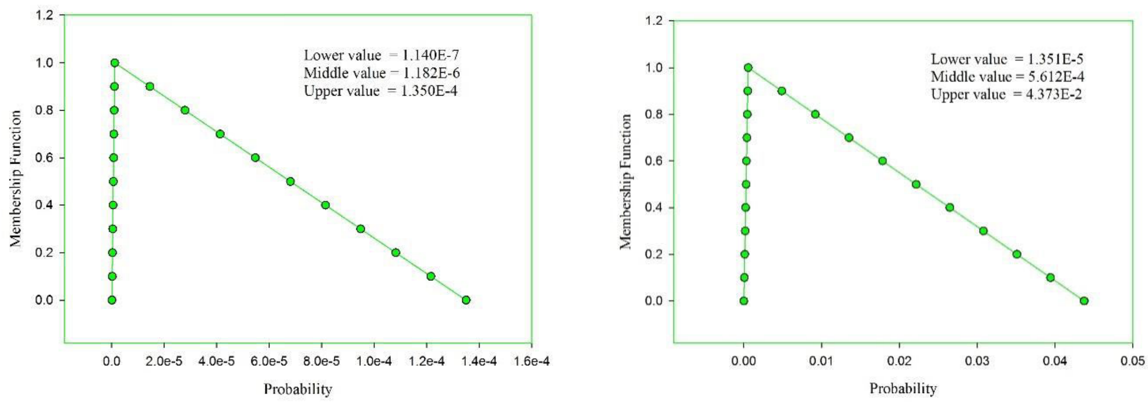
No.	Position	Educational level	Experience	Age	Weight factor	Weight score
1	Academician	PHD	22	51	17	0.12
2	Academician	PHD	18	48	15	0.11
3	Operations manager	PHD	12	45	13	0.09
4	Operations manager	Master	25	50	15	0.11
5	Chief engineer	Master	22	47	13	0.09
6	Chief engineer	Master	18	45	12	0.08
7	Engineer	Master	12	37	9	0.06
8	Engineer	Master	10	38	9	0.06
9	Engineer	Master	10	39	9	0.06
10	Engineer	Bachelor	16	42	10	0.07
11	Engineer	Bachelor	18	42	10	0.07
12	Engineer	Bachelor	16	40	10	0.07

Table 6
Experts justification results.

BEs	BEs qualitative data assessment by expert group												Generated failure probabilities		
	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}	Lower Bound	Best Estimate	Upper Bound
B_1	M	M	FH	M	FL	M	FL	M	FH	M	FH	FH	4.37E-06	8.85E-05	3.44E-04
B_{14}	FL	L	FL	L	FL	L	VL	FL	L	VL	L	L	6.35E-13	3.75E-07	4.37E-06
B_{19}	M	FL	M	M	FL	M	M	FL	FL	M	M	FL	4.37E-06	2.88E-05	6.43E-05
B_{26}	FL	FL	L	FL	L	FL	L	FL	FL	FL	L	FL	8.47E-08	1.77E-06	4.37E-06
B_{27}	L	L	VL	L	FL	VL	VL	L	FL	VL	L	L	6.35E-13	4.33E-08	4.37E-06
B_{28}	L	L	VL	L	FL	VL	VL	L	FL	VL	L	L	6.35E-13	4.33E-08	4.37E-06
B_{29}	FL	FL	L	FL	L	FL	L	FL	FL	FL	L	FL	8.47E-08	1.77E-06	4.37E-06
B_{50}	FL	M	M	FL	FL	M	FL	L	FL	M	FL	L	8.47E-08	1.13E-05	6.43E-05
B_{102}	L	VL	L	FL	VL	L	VL	L	FL	L	FL	VL	6.35E-13	9.62E-08	4.37E-06
B_{112}	M	FL	FL	M	FL	FL	M	M	FL	FL	M	M	4.37E-06	2.08E-05	6.43E-05
B_{117}	FL	M	FL	FL	M	L	L	FL	FL	M	FL	L	8.47E-08	7.38E-06	6.43E-05
B_{118}	L	L	FL	L	VL	VL	L	L	FL	FL	L	FL	6.35E-13	2.31E-07	4.37E-06
B_{119}	FL	FL	FL	L	FL	L	L	FL	L	FL	FL	FL	8.47E-08	1.77E-06	4.37E-06
B_{123}	FL	L	FL	FL	FL	VL	L	L	FL	VL	L	L	6.35E-13	5.78E-07	4.37E-06
B_{125}	L	FL	FL	FL	L	FL	L	FL	L	L	FL	L	8.47E-08	1.04E-06	4.37E-06

Table 7
Fuzzy values of safety system top event failure probabilities.

Safety Systems	Triangular Fuzzy Number
RPS	(2.89E-7,3.18E-6,5.45E-5)
EPSS	(1.14E-7,1.18E-6,1.35E-4)
ECCS	(2.06E-6,2.33E-5,6.58E-4)
CI	(1.41E-7,1.77E-6,2.17E-5)
CSS	(4.36E-6,5.78E-5,7.11E-4)
EVS	(1.45E-5,1.24E-4,1.75E-3)



(a) (b)

Fig. 6 Component X4 EPSS top event fuzzy failure probabilities a) U = 0, b) U = 1

DOI: 10.22094/JOIE.2020.575925.1590

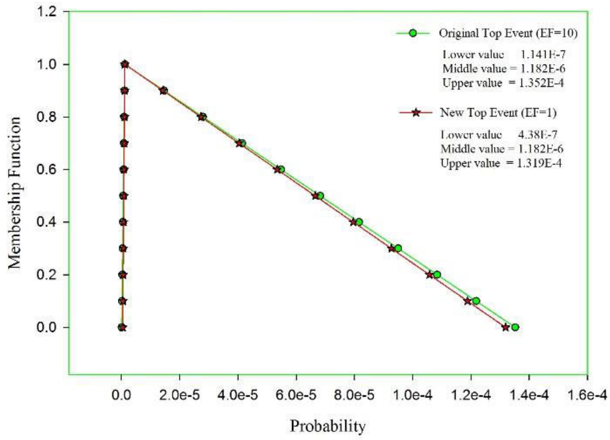


Fig. 7. FFUI α-cuts values of component X_1 in EPSS

4.2. Fuzzy event tree analysis

Since the fuzzy failure probabilities of different safety systems are obtained, we can determine the fuzzy frequency of damage to the IR-40 reactor in the scenario of LOCA. The reference value of LOCA occurrence is extracted from a generic database pertaining to research reactors (IAEA, 1997) (IAEA, 1998). Using the Eqs. (4-6) and the values in Table 4, the lower bound and upper bound of the LOCA occurrence probability was calculated. So the fuzzy numbers of initiating events are (6.32E-6, 6.32E-5, 6.32E-4). By substituting the fuzzy values of each safety system and performing the fuzzy logic operations, the fuzzy end-state sequences of the event tree are obtained. Among all sequences, some of them (CDS7-11) will result in the core meltdown. The summation of these sequences gives the core damage frequency which is (1.826E-12, 2.01E-10, 3.456E-8). Sequences 2-6 will not lead to a core meltdown, but we consider them as an abnormal condition and the summation results are (1.374E-11, 1.544E-9, 5.024E-7). For a proper interpretation of the event tree results, FEII and FEUI indexes are employed to determine the most important causes of a core meltdown, so that some revisions and modifications could be applied to reduce the probability occurrence of severe accidents. Table 8 shows the values of fuzzy indexes of the six safety systems which prevent or mitigate the consequences of LOCA.

Table 8
Fuzzy importance and uncertainty indexes of safety systems.

Safety Systems	Damage Status			Abnormal Status		
	FEII (U=0)	FEII (U=1)	FEUI	FEII (U=0)	FEII (U=1)	FEUI
RPS	1.91E-7	3.89E-3	1.89E-7	1.68E-8	2.77E-6	0
EPSS	5.50E-11	6.60E-10	2.44E-11	4.71E-7	3.88E-3	4.66E-7
ECCS	No-effect	No-effect	No-effect	2.30E-6	3.88E-3	2.71E-6
CI	5.50E-11	6.21E-10	5.47E-10	5.21E-11	5.92E-9	4.84E-11
CSS	2.70E-10	6.31E-10	6.35E-10	1.63E-9	5.87E-9	1.50E-9
EVS	3.90E-10	1.90E-7	7.18E-10	4.01E-9	4.25E-9	3.76E-9

As can be seen, the reactor protection system (RPS) has the largest quantity of FEII and FEUI in sequences which leads to the core meltdown. On the other hand, the ECCS large values of FEII and FUII indicate the importance and critical role of this system in preventing the occurrence of abnormal conditions. These useful information gathering in table 8, help the analysts find the imperfections and defects so that they are able to apply the proper modifications and make necessary revisions.

5. Conclusions

In the current research, we have investigated the application of fuzzy set theory as a new methodology to overcome the uncertainty raised in the conventional probabilistic safety assessment of nuclear reactors. In conventional fault and event tree analyses, the input variables are treated as crisp values and consequently the outcome data will be received as an exact value which contains high uncertainty. In the fuzzy method, all variables are replaced by fuzzy numbers. By utilization of the fuzzification process and fuzzy arithmetic, the top event fuzzy probabilities of fault trees and accident sequence fuzzy frequencies of event trees are obtained. In addition, for the identification of critical components, some fuzzy importance measures are developed. As an initiating event, the LOCA accident was supposed to occur in the IR-40 research reactor. The fault trees of all safety systems pertaining to this event were constructed and for the sake of uncertainty analysis, all failure probability data were represented by a triangular fuzzy number. Thereafter, by applying the obtained results of fault tree analysis, the fuzzy event tree was developed. Among all sequences, some of them (CDS 7-11) resulted in core meltdown, which their fuzzy end-state probability summation gave the core damage frequency by the value of (1.82E-12, 2.01E-10, 3.456E-8). With the assistance of fuzzy importance indexes, it was possible to determine the most important components which have greater or lesser relevance to the unavailability of the system as a whole in FTA and to provide valuable information about how much the total frequency of severe accidents were reduced or increased after eliminating or ensuring the occurrence of any event, respectively. Using fuzzy uncertainty indexes helped us measure the level of uncertainty contribution of the components to the fault trees and various events to the final sequences in event trees. On the basis of the obtained results, it can be concluded that the fuzzy approach could be a useful methodology in dealing with the safety analysis of nuclear reactors.

References

Aldemir, T. (2013). A survey of dynamic methodologies for probabilistic safety assessment of nuclear power plants, Annals of Nuclear Energy 52:113–124.

Ferdous, R., Khan, F., Sadiq, R., Amyotte, P., & Veitch, B. (2001). Fault and Event Tree Analyses for Process Systems Risk Analysis: Uncertainty Handling Formulations. Risk Analysis 31(1): 86-107.

Guimarães, A.C.F., Lapa, C.M.F., & Moreira, M.L. (2011a). Fuzzy methodology applied to Probabilistic Safety Assessment for digital system in nuclear power plants, Nuclear Engineering and Design 241:3967– 3976.

Guimarães, A.C.F., Lapa, C.M.F., Simões Filho, F.F.L., & Cabral, D.C. (2011b) Fuzzy uncertainty modeling applied to AP1000 nuclear power plant LOCA. Annals of Nuclear Energy 38(8):1775-1786.

Gupta, S., Bhattacharya, J. (2007). Reliability analysis of a conveyor system using hybrid data. Qual Reliab Eng Int 23(7):867.

Hasannejad, H., Seyyedi, S.M., & Hashemi-Tilehnoee, M. (2019). Utilizing an auxiliary portable lube oil heating system in Aliabad Katoul-Iran V94. 2 gas turbine during standstill mode: a case study. Propulsion and Power Research. 8(4):320-328.

Hashemi-Tilehnoee, M., Pazirandeh, A., & Tashakor, S. (2010). HAZOP-study on heavy water research reactor primary cooling system. Annals of Nuclear Energy 37:428–433.

Hryniewicz, O. (2007). Fuzzy Sets in the Evaluation of Reliability. In: Levitin, G. (Editor). Computational Intelligence in Reliability Engineering. New Metaheuristics, Neural and Fuzzy Techniques in Reliability. Springer-Verlag. Berlin Heidelberg. pp. 363-386.

Huang, D., Chen, T., & Wang, M.J.J. (2001). A fuzzy set approach for event tree analysis, Fuzzy Sets and Systems 118:153-165.

IAEA-International Atomic Energy Agency (1992) Procedure for conducting probabilistic safety assessment of nuclear power plants (level 1). Safety series no. 50-P-4. Vienna.

IAEA-TECDOC-930 (1997) Generic component reliability data for research reactor PSA. Vienna: International Atomic Energy Agency.

IAEA-TECDOC-478 (1998) Component reliability data for use in probabilistic safety assessment. Vienna: International Atomic Energy Agency.

Kančev, D., Čepin, M., & Gjorgiev, B. (2014). Development and application of a living probabilistic safety assessment tool: Multi-objective multi-dimensional optimization of surveillance requirements in NPPs considering their ageing, Reliability Engineering and System Safety131:135–147.

Keller, M., & Modarres, M. (2005). A historical overview of probabilistic risk assessment development and its use in the nuclear power industry: a tribute to the late professor Norman Carl Rassmussen. Reliability Engineering & System Safety 89:271-285.

Klir, G.J., & Folger, T.A. (1988). Fuzzy Sets, Uncertainty and Information. Prentice Hall; 1st Edition; ISBN 13: 978-0133459845.

Lee, W.S., Grosh, D.L., Tillman, F.A., & Lie, C.H. (1985). Fault tree analysis, methods, and applications-a review. IEEE Reliab Trans R-34:194-203.

Lee, J., & McCormick, N. (2012). Risk and Safety Analysis of Nuclear Systems, 1st edition. Wiley, ISBN-13: 978-0470907566.

Liang, G., & Wang, M. (1993). Evaluating human reliability using fuzzy relation. Microelectronics Reliability 33(1): 63–80.

Mahmood, Y.A., Ahmadi, A., Verma, A.K., Srividya, A., Kumar, U. (2013). Fuzzy fault tree analysis: a review of concept and application, Int J Syst Assur Eng Manag 4(1):19–32.

Markowski, A., & Mannan, M. (2008). Fuzzy risk matrix. Journal of Hazardous Materials 159(1): 152-157.

Martorell, S., Carlos, A., Sanchez, A., & Serradell, V. (2000). Constrained optimization of test intervals using steady-state genetic algorithm. Reliability Engineering and System Safety 67: 215-232.

Miller, G. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. The psychological review 63:81-97.

Misra, K.B., Weber, G.G. (1990). Use of fuzzy set theory for level-I studies in probabilistic risk assessment, Fuzzy Sets and Systems 37:139-160.

Modarres, M., Kaminskiy, M.P., & Krivtsov, V. (2009). Reliability Engineering and Risk Analysis: A Practical Guide. CRC Press; 2nd Ed 2009. ISBN-13: 978-0849392474.

Onisawa T (1988) An approach to human reliability in man-machine systems using error possibility. Fuzzy Sets and Systems 27(2): 87-103.

Journal of Optimization in Industrial Engineering
Vol.13, Issue 2, Summer & Autumn 2020, ?- ?
DOI: 10.22094/JOIE.2020.575925.1590

Onisawa ,T. (1989). Fuzzy theory in reliability analysis. Fuzzy Sets Syst 30(3):361–363.

Onisawa T (1990) An application of fuzzy concepts to modelling of reliability analysis. Fuzzy Sets and Systems 37(3): 267-286.

Purba, J.H., Lu, J., Ruan, D., & Zhang, G. (2012). An area defuzzification technique to assess nuclear event reliability data from failure possibilities. International Journal of Computational Intelligence and Applications 11(4): 1250022.

Purba, J.H., Lu, J., Zhang, G. (2014). An intelligent system by fuzzy reliability algorithm in fault tree analysis for nuclear power plant probabilistic safety assessment, International Journal of Computational Intelligence and Applications 13(3):1450017.

Purba, J.H. (2014a). Fuzzy probability on reliability study of nuclear power plant probabilistic safety assessment: A review, Progress in Nuclear Energy 76:73-80.

Purba, J.H. (2014b). A fuzzy-based reliability approach to evaluate basic events of fault tree analysis for nuclear power plant probabilistic safety assessment, Annals of Nuclear Energy 70:21–29.

Purba, J.H., Lu, J., Zhang, G., & Pedrycz, W. (2014). A fuzzy reliability assessment of basic events of fault trees through qualitative data processing. Fuzzy Sets and Systems 243:50-69.

Purba, J.H., Tjahyani, D.T.S., Ekariansyah, A.S., & Tjahjono, H. (2015). Fuzzy probability based fault tree analysis to propagate and quantify epistemic uncertainty, Annals of Nuclear Energy 85:1189–1199.

Rao K.D., Kushwaha, H.S., Verma, A.K., & Srividya, A. (2007). Quantification of epistemic and aleatory uncertainties in level-1 probabilistic safety assessment studies, Reliability Engineering and System Safety 92: 947–956.

Ross, T.J. (2004). Development of Membership Functions. In: Fuzzy Logic with Engineering Applications. John Wiley & Sons, pp. 197-212.

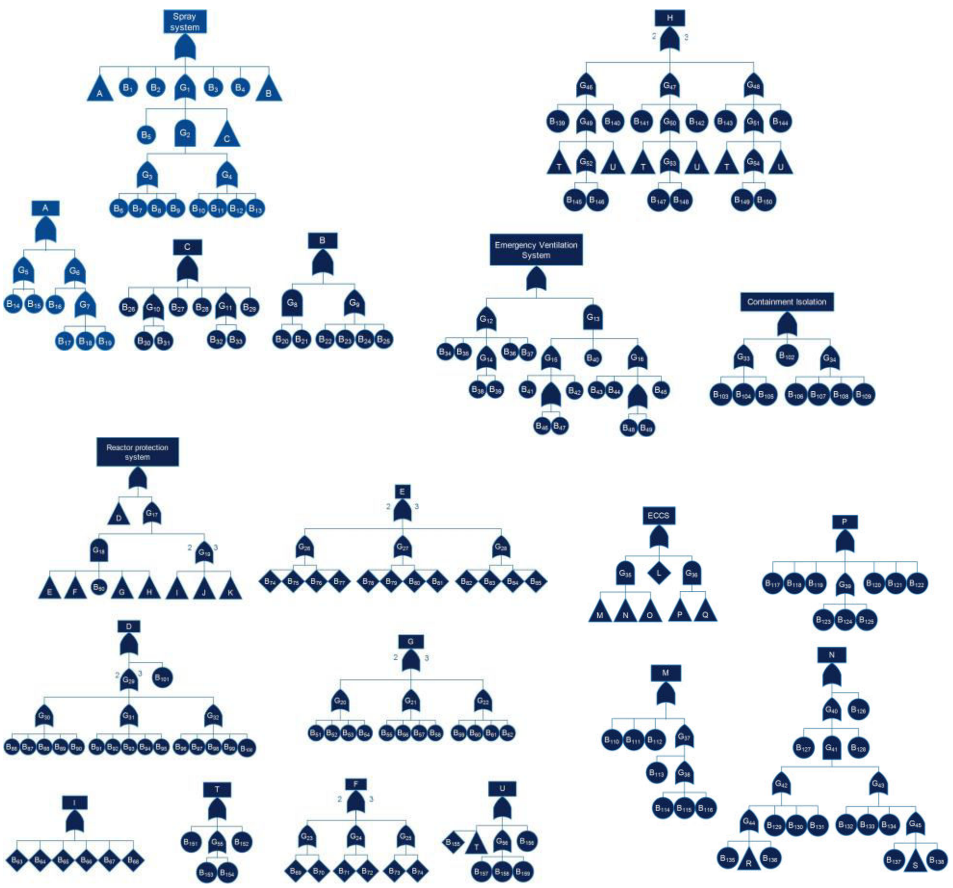
Wolkenhauer, O. (2001). Fuzzy mathematics. In: Data Engineering: Fuzzy Mathematics in Systems Theory and Data Analysis. John Wiley & Sons, pp. 197-212.

Woo, T.H., Noh, S.W., Kim, T.W., Kang, K.M., & Kim, Y.I. (2014). A fuzzy set safety assessment for a core falling failure accident (CFFA) in a spherical isotropic power reactor (SIPR), Energy Sources, Part A, 36:2338–2346.

Zadeh, L.A. (1965). Fuzzy sets. Information and control 8(3): 338–353.

Zimmermann, H.J., (1991). Fuzzy set theory and its applications, 2nd. Ed, Kluwer academic publishers, Boston.

Appendix A:



Appendix B

Table B.1
Basic events and their fuzzy probabilities

BEs	Description	Failure probabilities		
		Lower bound	Median point	Upper bound
B1	No operator action to start/stop of the pump	4.37E-06	8.85E-05	3.44E-04
B2	Switch fail to change position	1.00E-07	1.00E-06	1.00E-05
B3	Pressure sensor of the containment spray system fails to function	1.80E-08	1.80E-07	1.80E-06
B4	Spray nozzles fail modes	5.40E-07	5.40E-06	5.40E-05
B5	Alarm device (Level detector failure)	6.70E-08	6.70E-07	6.70E-06
B7	Check valve fails to remain in position	1.00E-09	1.00E-08	1.00E-07
B8	TY00-D001 pump fails to start	5.40E-08	5.40E-07	5.40E-06
B9	TY00-D001 pump fails to run	7.10E-07	7.10E-06	7.10E-05
B10	TY00-D002 pump fails to run	7.10E-07	7.10E-06	7.10E-05
B11	TY00-D002 pump fails to start	5.40E-08	5.40E-07	5.40E-06
B12	Check valve fails to remain in position	1.00E-09	1.00E-08	1.00E-07
B13	No operator action to start/stop of the pump	4.37E-06	8.85E-05	3.44E-04
B14	VR60-B002 water tank empty	6.35E-13	3.75E-07	4.37E-06
B15	Alarm device (Level detector failure)	6.70E-08	6.70E-07	6.70E-06
B16	Check valve fails to open	2.00E-08	2.00E-07	2.00E-06
B17	Motor operated valve fails to open on demand	1.00E-07	1.00E-06	1.00E-05
B18	Motor operated valve fails to remain open	5.30E-09	5.30E-08	5.30E-07
B19	The operator fails to correct actions	4.37E-06	2.88E-05	6.43E-05
B20	TY00-D002 pump fails to start	5.40E-08	5.40E-07	5.40E-06
B21	TY00-D002 pump fails to run	7.10E-07	7.10E-06	7.10E-05
B22	Check valve fails to remain in position	1.00E-09	1.00E-08	1.00E-07
B23	The operator fails to correct actions	4.37E-06	2.88E-05	6.43E-05
B24	VR60-B002 water tank empty	2.60E-09	2.60E-08	2.60E-07
B25	Alarm device (Level detector failure)	8.70E-07	8.70E-06	8.70E-05
B26	TJ00-B002 heat exchanger leakage (Shell)	8.47E-08	1.77E-06	4.37E-06
B27	TJ00-B002 heat exchanger leakage (Tube)	6.35E-13	4.33E-08	4.37E-06
B28	TJ00-B001 heat exchanger leakage (Tube)	6.35E-13	4.33E-08	4.37E-06
B29	TJ00-B001 heat exchanger leakage (Shell)	8.47E-08	1.77E-06	4.37E-06
B30	TJ00-02 Motor operated valve fails to open	5.30E-09	5.30E-08	5.30E-07
B31	Motor operated valve fails to remain in position	5.30E-09	5.30E-08	5.30E-07
B32	Motor operated valve fails to remain open	5.30E-09	5.30E-08	5.30E-07
B33	Motor operated valve fails to open	2.00E-08	2.00E-07	2.00E-06
B34	Pre-filter outdoor of intake ventilation system unavailable	3.00E-06	3.00E-05	3.00E-04
B35	Aerosol filter plug REVS	3.00E-06	3.00E-05	3.00E-04
B36	Intake ventilation system control valve fails to change position	1.00E-06	1.00E-05	1.00E-04
B37	One-way valve fails to open	2.00E-08	2.00E-07	2.00E-06
B38	Fan fails to start	1.40E-06	1.40E-05	1.40E-04
B39	Fan fails to run	6.00E-07	6.00E-06	6.00E-05
B40	Common cause failure EVSS (Active and reverse)	1.00E-06	1.00E-05	1.00E-04
B41	REVS pressure valve fails to remain open	1.10E-08	1.10E-07	1.10E-06

B42	AEVS aerosol filter plug	3.00E-06	3.00E-05	3.00E-04
B43	No signal for activation	1.80E-07	1.80E-06	1.80E-05
B44	REVS pressure valve fails to remain open	1.10E-08	1.10E-07	1.10E-06
B45	REVS aerosol filter plug	3.00E-06	3.00E-05	3.00E-04
B46	Fan fails to start	1.40E-06	1.40E-05	1.40E-04
B47	Fan fails to run	6.00E-07	6.00E-06	6.00E-05
B48	Fan fails to start on demand	1.40E-06	1.40E-05	1.40E-04
B49	Fan fails to run	6.00E-07	6.00E-06	6.00E-05
B50	The operator fails to manually shutdown the reactor	8.47E-08	1.13E-05	6.43E-05
B51	Temperature sensor TCP-01 type1 fails to function	1.70E-07	1.70E-06	1.70E-05
B52	Thermocouple1 fail to function	7.10E-08	7.10E-07	7.10E-06
B53	Normalizing convertors IPM 0399/m2A1 fail to function	4.20E-09	4.20E-08	4.20E-07
B54	Normalizing convertors IPM 0399/m3A1 fail to function	4.20E-09	4.20E-08	4.20E-07
B55	Temperature sensor TCP-01 type2 fails to function	1.70E-07	1.70E-06	1.70E-05
B56	Thermocouple2 fail to function	7.10E-08	7.10E-07	7.10E-06
B57	Normalizing convertors IPM 0399/m2A2 fail to function	4.20E-09	4.20E-08	4.20E-07
B58	Normalizing convertors IPM 0399/m3A2 fail to function	4.20E-09	4.20E-08	4.20E-07
B59	Temperature sensor TCP-01 type3 fails to function	1.70E-07	1.70E-06	1.70E-05
B60	Thermocouple3 fail to function	7.10E-08	7.10E-07	7.10E-06
B61	Normalizing convertors IPM 0399/m2A3 fail to function	4.20E-09	4.20E-08	4.20E-07
B62	Normalizing convertors IPM 0399/m3A3 fail to function	4.20E-09	4.20E-08	4.20E-07
B63	OR element failure	1.20E-09	1.20E-08	1.20E-07
B64	2 from 3 element (Multiplexer) failure	1.20E-09	1.20E-08	1.20E-07
B65	24V DC source fails to function	4.20E-09	4.20E-08	4.20E-07
B66	RS flip-flop fails to function	1.20E-09	1.20E-08	1.20E-07
B67	EPCM 1 related relays fail to remain in position	1.00E-09	1.00E-08	1.00E-07
B68	Emergency protection diagnostic controller fails to function	4.90E-09	4.90E-08	4.90E-07
B69	Pressure gage FIR-22MT1 fails to function	1.80E-08	1.80E-07	1.80E-06
B70	Normalizing convertor1 fails to function	4.20E-09	4.20E-08	4.20E-07
B71	Pressure gage FIR-22MT2 fails to function	1.80E-08	1.80E-07	1.80E-06
B72	Normalizing convertor2 fails to function	4.20E-09	4.20E-08	4.20E-07
B73	Pressure gage FIR-22MT3 fails to function	1.80E-08	1.80E-07	1.80E-06
B74	Normalizing convertor3 fails to function	4.20E-09	4.20E-08	4.20E-07
B75	DUE-1 type level sensors fail to function	6.70E-08	6.70E-07	6.70E-06
B76	Pressure gage FIR-22MT G1 fails to function	1.80E-08	1.80E-07	1.80E-06
B77	ROS-101 type1 level switches fail to function	2.70E-09	2.70E-08	2.70E-07
B78	Normalizing convertor G2 fails to function	4.20E-09	4.20E-08	4.20E-07
B79	DUE-2 type level sensors fail to function	6.70E-08	6.70E-07	6.70E-06
B80	Pressure gage FIR-22MT G2 fails to function	1.80E-08	1.80E-07	1.80E-06
B81	ROS-101 type2 level switches fail to function	2.70E-09	2.70E-08	2.70E-07
B82	Normalizing convertor G3 fails to function	4.20E-09	4.20E-08	4.20E-07

B83	DUE-3 type level sensors fail to function	6.70E-08	6.70E-07	6.70E-06
B84	Pressure gage FIR-22MT G3 fails to function	1.80E-08	1.80E-07	1.80E-06
B85	ROS-101 type3 level switches fail to function	2.70E-09	2.70E-08	2.70E-07
B86	Control rod and drive mechanism improper movement(1)	3.90E-08	3.90E-07	3.90E-06
B87	Failure of related ERs electromagnets disengage(1)	3.90E-08	3.90E-07	3.90E-06
B88	Failure of related SRs electromagnets disengage(1)	3.90E-08	3.90E-07	3.90E-06
B89	Related ERs fail to drop(1)	4.60E-08	4.60E-07	4.60E-06
B90	Related SRs fail to drop(1)	9.20E-08	9.20E-07	9.20E-06
B91	Control rod and drive mechanism improper movement(2)	3.90E-08	3.90E-07	3.90E-06
B92	Failure of related ERs electromagnets disengage(2)	3.90E-08	3.90E-07	3.90E-06
B93	Failure of related SRs electromagnets disengage(2)	3.90E-08	3.90E-07	3.90E-06
B94	Related ERs fail to drop(2)	4.60E-08	4.60E-07	4.60E-06
B95	Related SRs fail to drop(2)	9.20E-08	9.20E-07	9.20E-06
B96	Control rod and drive mechanism improper movement(3)	3.90E-08	3.90E-07	3.90E-06
B97	Failure of related ERs electromagnets disengage(3)	3.90E-08	3.90E-07	3.90E-06
B98	Failure of related SRs electromagnets disengage(3)	3.90E-08	3.90E-07	3.90E-06
B99	Related ERs fail to drop(3)	4.60E-08	4.60E-07	4.60E-06
B100	Related SRs fail to drop(3)	9.20E-08	9.20E-07	9.20E-06
B101	Common cause failure of scram rod channel	1.90E-08	1.90E-07	1.90E-06
B102	Doors fail to remain closed	6.35E-13	9.62E-08	4.37E-06
B103	Containment sealing related valve V1 fails to close	7.10E-07	7.10E-06	7.10E-05
B104	Containment sealing related valve V2 fails to close	7.10E-07	7.10E-06	7.10E-05
B105	Containment sealing related valve V3 fails to close	7.10E-07	7.10E-06	7.10E-05
B106	Containment sealing related valve V4 fails to close	7.10E-07	7.10E-06	7.10E-05
B107	Containment sealing related valve V5 fails to close	7.10E-07	7.10E-06	7.10E-05
B108	Containment sealing related valve V6 fails to close	7.10E-07	7.10E-06	7.10E-05
B109	Containment sealing related valve V7 fails to close	7.10E-07	7.10E-06	7.10E-05
B110	YT10-S005 check valve fails to open	2.00E-08	2.00E-07	2.00E-06
B111	TT10-S004 check valve fails to open	2.00E-08	2.00E-07	2.00E-06
B112	Pre-accident human error	4.37E-06	2.08E-05	6.43E-05
B113	YT10-D001 pump fails to run	7.10E-07	7.10E-06	7.10E-05
B114	YT10-S003 check valve fails to open	1.00E-08	1.00E-07	1.00E-06
B115	YT10-S002 check valve fails to open	1.00E-08	1.00E-07	1.00E-06
B116	YT10-S001 check valve fails to open	1.00E-08	1.00E-07	1.00E-06
B117	YT10-B001 heat exchanger leakage (Shell)	8.47E-08	7.38E-06	6.43E-05
B118	YT10-B001 heat exchanger leakage (Tube)	6.35E-13	2.31E-07	4.37E-06
B119	YT10-B001 heat exchanger external leakage (Shell)	8.47E-08	1.77E-06	4.37E-06
B120	Operator fails to correct actions	4.37E-06	2.88E-05	6.43E-05

Journal of Optimization in Industrial Engineering
Vol.13, Issue 2, Summer & Autumn 2020, ?- ?
DOI: 10.22094/JOIE.2020.575925.1590

B121	YT10-S001 motor operated valve fails to close	2.00E-08	2.00E-07	2.00E-06
B122	YT10-S002 motor operated valve fails to close	2.00E-08	2.00E-07	2.00E-06
B123	Leakage internal leak	6.35E-13	5.78E-07	4.37E-06
B124	Butterfly valve fails to change position	2.60E-07	2.60E-06	2.60E-05
B125	Leakage external leak	8.47E-08	1.04E-06	4.37E-06
B126	Q-27 switch gear losses function	3.60E-08	3.60E-07	3.60E-06
B127	CT3 transformer failure	4.60E-08	4.60E-07	4.60E-06
B128	Q-24 vacuum circuit breaker(VCB) failure	3.20E-08	3.20E-07	3.20E-06
B129	S3 load breaker switch failure	3.20E-08	3.20E-07	3.20E-06
B130	Q-18 VCB losses function	3.20E-08	3.20E-07	3.20E-06
B131	Q-18 VCB not available due to maintenance	6.90E-05	6.90E-04	6.90E-03
B132	Q-20 VCB not available due to maintenance	6.90E-05	6.90E-04	6.90E-03
B133	Q-20 VCB losses function	3.20E-08	3.20E-07	3.20E-06
B134	S4 load breaker switch failure	3.20E-08	3.20E-07	3.20E-06
B135	Q-12 VCB losses function	3.20E-08	3.20E-07	3.20E-06
B136	Q-12 VCB not available due to maintenance	6.90E-05	6.90E-04	6.90E-03
B137	Q-13 VCB losses function	3.20E-08	3.20E-07	3.20E-06
B138	Q-13 VCB not available due to maintenance	6.90E-05	6.90E-04	6.90E-03
B139	Operative display(digital & analog) fails to function(1)	7.70E-08	7.70E-07	7.70E-06
B140	Digital display fails to function(1)	7.70E-08	7.70E-07	7.70E-06
B141	Operative display(digital & analog) fails to function(2)	7.70E-08	7.70E-07	7.70E-06
B142	Digital display fails to function(2)	7.70E-08	7.70E-07	7.70E-06
B143	Operative display(digital & analog) fails to function(3)	7.70E-08	7.70E-07	7.70E-06
B144	Digital display fails to function(3)	7.70E-08	7.70E-07	7.70E-06
B145	KNK 15 ionization chamber fails to function(1)	8.20E-09	8.20E-08	8.20E-07
B146	KNK 17 ionization chamber fails to function(1)	8.20E-09	8.20E-08	8.20E-07
B147	KNK 15 ionization chamber fails to function(2)	8.20E-09	8.20E-08	8.20E-07
B148	KNK 17 ionization chamber fails to function(2)	8.20E-09	8.20E-08	8.20E-07
B149	KNK 15 ionization chamber fails to function(3)	8.20E-09	8.20E-08	8.20E-07
B150	KNK 17 ionization chamber fails to function(3)	8.20E-09	8.20E-08	8.20E-07
B151	Self-testing means of DSCM failure	3.00E-10	3.00E-09	3.00E-08
B152	Micro-processor controller failure	4.90E-09	4.90E-08	4.90E-07
B153	KNK 15 ionization chamber fails to function	8.20E-09	8.20E-08	8.20E-07
B154	KNK 17 ionization chamber fails to function	8.20E-09	8.20E-08	8.20E-07
B155	Self-testing means of NVPM failure	3.00E-10	3.00E-09	3.00E-08
B156	Micro-processor controller failure	4.90E-09	4.90E-08	4.90E-07
B157	Self-point digital indicator display failure	7.70E-08	7.70E-07	7.70E-06
B158	Micro-processor controller failure	4.90E-09	4.90E-08	4.90E-07
B159	Control buttons failure	4.50E-10	4.50E-09	4.50E-08

Table B.2
Gates and Transfer gates descriptions.

Symbol	Description	Symbol	Description
A	Feed water from fire-fighting system unavailable	B	Feed water from chemical system unavailable
C	Discharge line failure	D	Scram rods fail to enter the core
E	Level measuring channel failure	F	Flow rate measuring channel failure
G	Temperature measuring channel failure	H	In-core monitoring system failure
I	Emergency protection control module1 failure	J	Emergency protection control module2 failure
K	Emergency protection control module3 failure	L	ECCS pressurizer supply unavailable
M	YT10-D001 pump failure	N	No emergency electric power supply system
O	YT20-D001 pump failure	P	YT10-B001 heat exchanger failure
Q	YT20-B001 heat exchanger failure	R	GY-1 diesel generator power unavailable
S	GY-2 diesel generator power unavailable	T	Detectors supply and conversion modules
U	Neutron variables processing modules		
G1	Recirculation line failure	G2	Drainage system pumps failure
G3	TY00-D001 pump failure	G4	TY00-D002 pump failure
G5	Failure of water supply	G6	Delivery system failure
G7	TJ00-01 motor operated valve failure	G8	Failure of circulation system
G9	Failure of water supply	G10	TJ00-02 motor operated valve failure
G11	TJ00-03 motor operated valve failure	G12	Intake ventilation system unavailable
G13	Exhaust ventilation system unavailable	G14	Intake ventilation system fan failure
G15	Active exhaust ventilation system unavailable	G16	Reserve's exhaust ventilation system fan failure
G17	No scram signal in case of LOCA	G18	Instrumentation channels for local failure
G19	Emergency protection control modules failure	G20	Temperature channel 1 failure
G21	Temperature channel 3 failure	G22	Temperature channel 2 failure
G23	Flow rate measuring channel 1 failure	G24	Flow rate measuring channel 2 failure
G25	Flow rate measuring channel 3 failure	G26	Level measuring channel 1 failure
G27	Level measuring channel 2 failure	G28	Level measuring channel 3 failure
G29	Scram rod channels failure	G30	Channel 1 related scram rods fail to enter the core
G31	Channel 2 related scram rods fail to enter the core	G32	Channel 3 related scram rods fail to enter the core
G33	Containment sealing related intake valves failure	G34	Containment sealing related exhaust valves failure
G35	ECCS pump failure	G36	ECCS discharge line failure
G37	YT10-D001 pump fails to run	G38	Failure of related valves
G39	Butterfly valve failure	G40	Loss of Q-27 switch gear power source
G41	Loss of Q-14 power source	G42	Loss of power from AL-1
G43	Loss of power from AL-1	G44	Loss of power from GY-1
G45	Loss of power from GY-2	G46	Emergency protection channel 1 failure
G47	Emergency protection channel 2 failure	G48	Emergency protection channel 3 failure
G49	Power and period meter fails to function	G50	Power and period meter fails to function
G51	Power and period meter fails to function	G52	Neutron flux detection devices failure
G53	Neutron flux detection devices failure	G54	Neutron flux detection devices failure
G55	Neutron flux detection devices failure	G56	Loss of set point (ESPD failure)

This article can be cited: Mohsendokht, M. & Hashemi-Tilehnoee, M. (2021). Overcoming the Uncertainty in a Research Reactor LOCA in Level-1 PSA; Fuzzy Based Fault-tree/event-tree Analysis. Journal of Optimization in Industrial Engineering. 13 (2), 249-266.

http://www.qjie.ir/article_674014.html

DOI: 10.22094/JOIE.2020.575925.1590