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Reliability measures for liquefied natural gas receiving terminal based on the failure information of emergency shutdown system

Bi-Min Hsu^a, Ming-Hung Shu^{b*}, and Min Tsao^c

^aDepartment of Industrial Engineering & Management
Cheng Shiu University, Kaohsiung County 833, Taiwan

^bDepartment of Industrial Engineering & Management
National Kaohsiung University of Applied Sciences, Kaohsiung 807, Taiwan

^cDepartment of Mathematics & Statistics
University of Victoria, British Columbia, Canada

Abstract

Natural Gas (NG), one of the cleanest, most efficient and useful of all energy sources, is a vital component of the world's energy supply. To make the NG more convenient for storage and transportation, it is refined and condensed into a liquid called liquefied natural gas (LNG). In an LNG site, safety is a long-term critical issue. The emergency shutdown system (ESS) in the LNG receiving terminal is used to automatically stop the pumps and isolate the leakage section. Fault tree analysis (FTA) has been widely used to characterize the logical functional relationships among components and subsystems of a system, and to identify the root causes of failures in a system. In the conventional FTA for the ESS, we assume that exact failure probabilities of events are available. However, in real applications the FTA for the ESS needs to be done at an early design or manufacturing stage at which certain new components may have to be used without failure data. Also, sometimes due to environmental changes in the ESS during the operation periods, it is difficult to gather past exact failures data for the FTA. Hence there may not be sufficient information for a conventional FTA. In this research, we propose an intuitionistic fuzzy (IF) sets theory based approach for the FTA which can be used when the conventional FTA cannot. We generate the IF fault-tree interval and the IF reliability interval for the ESS. Based on IF-FTA, we also present an algorithm for finding the critical components and determining weak paths in the ESS for which the key improvement event must be made.

Keywords: Liquefied natural gas, Emergency shutdown system, Fault-tree analysis, Intuitionistic fuzzy sets

*corresponding author with e-mail: workman@cc.kuas.edu.tw

1. Introduction

The natural gas (NG), one of the cleanest, most efficient and useful of all energy sources for residential and industrial customers, is a vital element of the world's energy supply. It is a combustible mixture of hydrocarbon gases and its composition can vary a great deal. Table 1 shows the main ingredients and their percentages; the primary ingredient is the methane (CH_4) but heavier gaseous hydrocarbons such as ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}) and trace gases are also present.

| Component | Typical Weight % |
|---|------------------|
| Methane CH_4 | 70-90 |
| Ethane C_2H_6 | 5-15 |
| Propane (C_3H_8) and Butane (C_4H_{10}) | < 5 |
| CO_2, N_2, H_2S , etc. | Balance |

Table 1. Typical composition of natural gas

To make the NG more convenient in further storage and transportation, it is refined to remove impurities such as water, hydrogen sulfide and other compounds which could cause problems for downstream conveyance or environmental pollution. After refining, the clean NG at nearly atmospheric pressure is condensed by cooling it to approximately -162 degrees Celsius into a liquid form, resulting in the liquefied natural gas (LNG). The LNG is about 1/600th the volume of that of the NG at standard temperature and pressure. It can be delivered by specially designed cryogenic vessels and cryogenic tankers over long distances. It is returned to the gas form through gasification at end-use facilities.

Generally, mass volumes of the LNG are conveyed and stored often in the proximity of densely populated area. Due to its highly flammable and explosive nature, accidents involving LNG can lead to loss of human lives and serious damages to industrial facilities and the natural environment. Because of these, high reliability and safety is a long-term crucial issue for the LNG industry. The reliability of a huge quantity of the LNG stockpiled in a conveying system (which mostly consists of pipes and storage tanks) is a major issue affecting the LNG receiving terminal safety. During the LNG processing process, even a small amount of the LNG leakage may cause considerable contamination, fire accidents or explosions. Consequently, to prevent leakage, an emergency shutdown system (ESS) in the LNG receiving terminal is implemented to automatically stop the LNG pumping and isolate the leakage condition.

For the reliability of equipments and operational procedures at the LNG receiving terminals, the failure information provided by the ESS is considered to be the most vital resources for the safety and thus deserves particular attention. A typical LNG plant devotes a substantial amount of manpower and capital towards the monitoring and investigation of failure events which trigger off the ESS in order to learn the underlying causes of these failure events. In order to understand the LNG receiving terminal reliability, an effective analysis and performance measure based on the failure information gathered by the ESS is required. The fault tree analysis (FTA) has been widely employed in variety of systems for providing logical functional relationships among components and subsystems of a system, and identifying root causes of the undesired system failures (9; 12).

In this research, we first describe the detailed LNG receiving procedure and then its FTA on the basis of the failure information from the ESS. For this description of the FTA, we assume that all the malfunction events provided by the ESS are fully understood; that is, exact data of their failure probability collected from normal operations of the LNG receiving terminal are

available. We then present the traditional reliability measure of the FTA for the LNG receiving terminal based on the failure information of the ESS.

However, collecting precise failures data for the FTA requires substantial amount of time and knowledge of operations and maintenance on the LNG receiving terminal. In real operations, the following scenarios often occur:

- FTA for the ESS needs to be done at an early design or manufacturing stage at which certain new components may have to be used without prior failure data, and
- due to environmental changes in the ESS during the operation periods, it may be difficult to gather past exact failures data for the FTA.

Under these uncertain situations, traditionally system engineers usually omit ambiguous failure events of the ESS when they construct or analyze the fault tree. But such omitted events may actually be critical, and the measure of reliability of the LNG receiving terminal that does not take into consideration such events may be unreliable.

In order to handle inevitable imprecise failure information in diversified real applications, many research works have taken the uncertain situations into consideration. Chen (7) and Mon et al. (15; 16) carried out system reliability analysis by using the fuzzy set theory. Suresh et al. (17), Antonio et al. (1), Tanaka et al. (20), and Huang et al. (11) proposed the fuzzy FTA for certain systems applications. The concept of an intuitionistic fuzzy (IF) sets can be viewed as an alternative approach to define a fuzzy set in cases where available information is not sufficient for the definition of an imprecise concept by means of a conventional fuzzy set (2; 3). Bustince and Burillo (6) showed that the notion of vague sets coincides with that of IF sets; that is, fuzzy sets are IF sets, but the converse is not necessarily true (2; 3). IF sets theory has been widely applied in different areas such as logic programming (4; 5), decision making problems (13; 18; 19) in medical diagnosis (8), and pattern recognition (14).

In this research, with imprecise failure information from the ESS, we apply fuzzy fault tree (20) and Posbist fault tree (11) methods to construct fuzzy reliability measures for the LNG receiving terminal and provide the corresponding IF fault-tree interval and the IF reliability interval. We also compare the results of these proposed reliability measures for the FTA methods. Further, we will discuss identification of the most critical component of the LNG receiving terminal which is essential for determining weak paths and areas where the key improvements must be made.

2. LNG-ESS Fault Diagnosis

2.1 The Operation Process of the LNG Receiving Terminal

Most LNG is imported from exporters such as Indonesia, Malaysia and Qatar by long-term contract carriers. In this paper, we investigate an LNG receiving terminal located in Asia, Taiwan. When the LNG vessels arrive at the LNG terminal, the LNG they carry is discharged and stored at about -160°C and $0.2\text{kg}/\text{cm}^2$ in storage tanks. Through an open rack vaporizer, the stored LNG is reheated and gasified into natural gas. The open rack vaporizer is connected to a storage and trunk-line distribution network through which the natural gas is transported to local distribution companies, independent power plants and households. A typical process diagram of the LNG receiving terminal is given in Figure 1 which shows the receiving, storage, vaporization and distribution components of a receiving terminal and how these components are connected.

Normally, the LNG must be kept cold in order to remain in liquid form. However, because of heat coming from the outside ambient atmosphere, there is inevitably a certain amount

of boil-off gas (BOG). The BOG can be re-liquefied through a BOG compressor and a recondenser. The recondenser has an emergency isolation valve to keep the liquid level from falling too low or raising too high to prevent the internal pressure from rising abnormally. It has two primary functions. First, it recycles BOG when the LNG is stored and transported through pipelines. Second, through secondary stage pumps which are submerged high-pressure centrifugal pumps, it provides buffer control to LNG which is flammable even at ultra-low temperatures. The secondary stage pumps are used to collect the LNG from the recondenser, and then pressurize and pump the LNG to the open rack vaporizer. The open rack vaporizer consists of finned tubes submerged in seawater. When the LNG flows through the tubes, heat exchange between the seawater outside of the tubes and the LNG inside takes place, and the LNG is re-gasified and return to its original gaseous state. Before leaving the receiving terminal, the natural gas is measured for its quantities through a measure station. Other related systems such as the cold power generator (CPG), pressure power generator (PPG) and air separation plant (ASP) are set up for the purposes that achieve the goals of energy conservation and energy recycling.

In case of a LNG leakage, the emergency shutdown system (ESS) in the LNG receiving terminal can be automatically invoked to isolate the leakage pipe section in the unloaded dock district and the tank district and to stop the primary pumps.

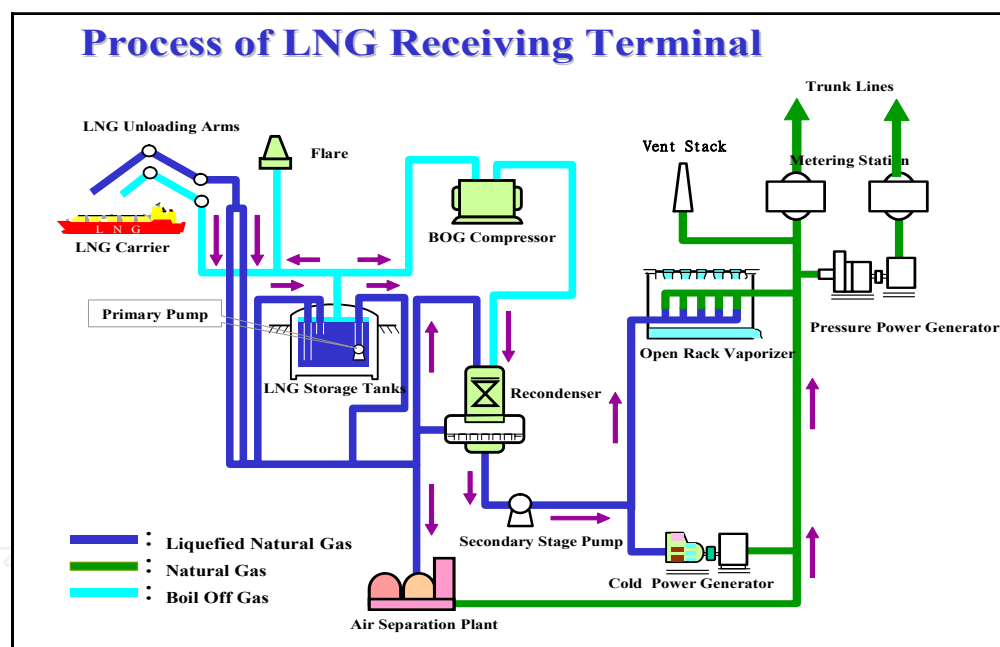


Fig. 1. The operation process of the LNG receiving terminal.

2.2 Fault-Tree Analysis of the ESS

Prior to the actual construction of the ESS fault tree, it is essential to have an in-depth understanding about related equipments involved in the ESS. Incidents related to the LNG facilities are generally classified into two classes, namely internal events and external events. The former include equipment failures, miss-operation and other incidents resulted from internal causes within a site. The latter include the device breakdown and the pipe leakage due to typhoon or earthquake. In this paper, we make the following assumptions which are necessary for the construction of the fault-tree analysis (FTA) of the ESS.

- Our primary concern is focused on internal events with the ESS.
- We consider only the isolating valve closest to the point of leakage; in other word, only the first level of isolating mechanism was taken into account.
- The entire isolation procedure is considered to have failed if the isolating device did not function correctly.
- All failures are independent events.

Based on the descriptions in Sections 2.1 and 2.2, the fault tree of the ESS is developed and shown in Figure 2, whose subevents and bottom events are listed in Tables 2 and 3.

| Code | Fault |
|------|---|
| I | Emergency process isolation of the ESS fails |
| II | Primary pump shut-down of the ESS fails |
| A | Isolation valve of tank inlet fails to close |
| B | Isolation valve of tank outlet fails to close |
| C | Isolation valve of BOG pipe fails to close |
| D | Isolation valve of ICD (Initial Cooling Down) pipe fails to close |
| E | Circuit breaker of pump fails to open |
| F | Pump S/D control logic failure |
| G | Loss of pump stopping signal |

Table 2. Descriptions of sub-events of the ESS fault

2.3 Traditional Reliability Measure of FTA

Traditionally, the reliability measure of the FTA of the “ESS Fault” can be obtained as follows:

$$\begin{aligned}
 \text{ESS Fault} &= I \cup II \\
 &= (A \cup B \cup C \cup D) \cup (E \cup F \cup G) \\
 &= (A_1 \cup A_2 \cup A_3 \cup A_4 \cup A_5 \cup A_6) \cup (B_1 \cup B_2 \cup B_3 \cup B_4 \cup B_5 \cup B_6) \cup \\
 &\quad (C_1 \cup C_2 \cup C_3 \cup C_4 \cup C_5 \cup C_6) \cup [D_1 \cup (C_{21} \cup D_{22})] \cup \\
 &\quad \{E \cup (F_1 \cup F_2 \cup F_3 \cup F_4) \cup [(G_{11} \cup G_{12}) \cap (G_{11} \cap G_{12}) \cap G_3]\}, \quad (1)
 \end{aligned}$$

where \cap means relation of parallel “and” operation) and \cup means series (“or” operation). Let f_i represent the crisp (precise) failure rate of event i . Then the crisp failure probability of the “ESS Fault”, denoted by f_T , can be computed as follows

$$\begin{aligned}
 f_T &= 1 - [(1 - f_{A_1})(1 - f_{A_2})(1 - f_{A_3})(1 - f_{A_4})(1 - f_{A_5})(1 - f_{A_6})] \\
 &\quad [(1 - f_{B_1})(1 - f_{B_2})(1 - f_{B_3})(1 - f_{B_4})(1 - f_{B_5})(1 - f_{B_6})] \\
 &\quad [(1 - f_{C_1})(1 - f_{C_2})(1 - f_{C_3})(1 - f_{C_4})(1 - f_{C_5})(1 - f_{C_6})] \\
 &\quad [(1 - f_{D_1})(1 - f_{D_{21}})(1 - f_{D_{22}})][(1 - f_E)] \\
 &\quad [(1 - f_{F_1})(1 - f_{F_2})(1 - f_{F_3})(1 - f_{F_4})] \\
 &\quad \{[1 - (1 - f_{G_{11}})(1 - f_{G_{12}})](f_{G_{21}}f_{G_{22}}f_{G_3})\}. \quad (2)
 \end{aligned}$$

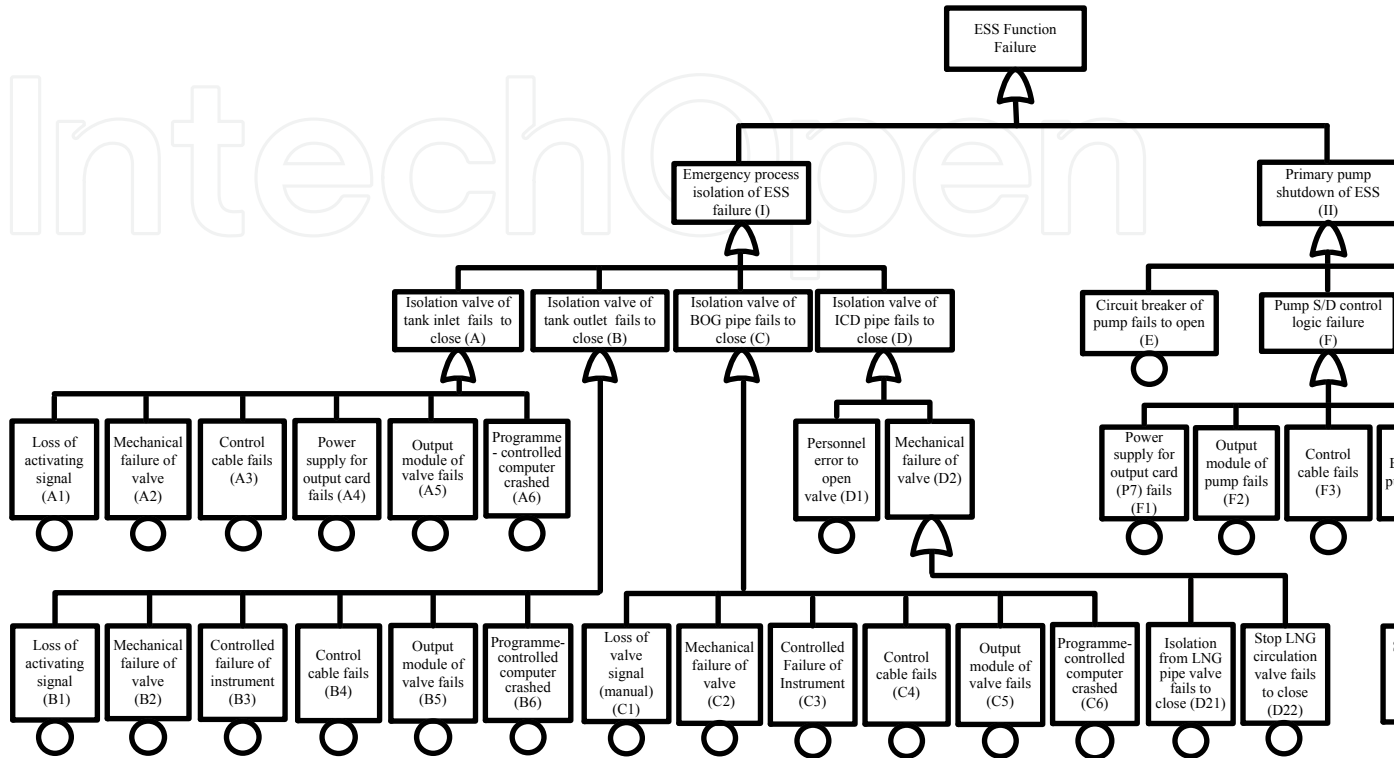


Fig. 2. The fault tree of the ESS.

| Code | Fault | Bottom events of the ESS fault |
|-----------------|--|--------------------------------|
| C ₅ | Output module of valve fails | activating signal |
| C ₆ | Program-controlled computer crashed | ical failure of valve |
| D ₁ | Personnel error to open valve | cable fails |
| D ₂₁ | Isolation from shore LNG pipe valve fails to close | upply for output card fails |
| D ₂₂ | Stop LNG circulation valve fails to close | odule of valve fails |
| E | Circuit breaker of pump fails to open | n-controlled computer crashed |
| F ₁ | Power supply for output card fails | activating signal |
| F ₂ | Output module of pump fails | ical failure of valve |
| F ₃ | Control cable fails | ed failure of instrument |
| F ₄ | Circuit breaker of pump MCC fails | cable fails |
| G ₁₁ | Stop pump by WLT logic | odule of valve fails |
| G ₁₂ | WLT fails | n-controlled computer crashed |
| G ₂₁ | UV/IR fire detector fails (ESSII) | activating signal(manual) |
| G ₂₂ | High temperature fire detector fails (ESSII) | ical failure of valve |
| G ₃ | Lose pump stopping signal from CCR (manual) | ed failure of instrument |
| | | cable fails |

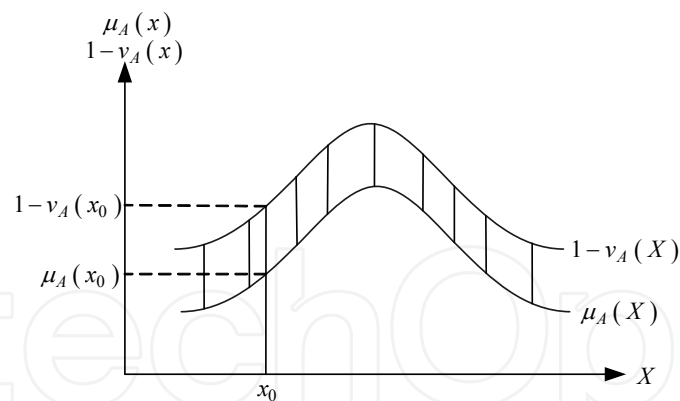


Fig. 3. IF set of a real number R .

3. Intuitionistic Fuzzy Reliability Measure of FTA

In the conventional FTA for the ESS of the LNG terminal, we must fully understand the ESS. Usually, we assume that exact failure probabilities of events are available. However, collecting failures data for the FTA is a challenging task requiring extensive human expertise and knowledge of operations and maintenance on the system. In real operations, this may not even be possible as the FTA for the ESS of the LNG receiving terminal needs to be made at an early design or manufacturing stage at which we have no failure data on new components. Furthermore, sometimes the environmental change in the system during the operation periods can also make it more difficult to gather past exact failures data for the FTA. In such uncertain situations, traditionally system engineers usually omit some ambiguous failure events of the ESS when measuring the reliability of the LNG receiving terminal. But the missing events or probability information might be critical and thus omitting these may lead to unreliable decision results. In order to handle inevitable imprecise failure information of the ESS, which has been recognized as one of the uncertainties in the real world, a possible solution is to use intuitionistic fuzzy (IF) sets, defined by Atanassov (2; 3).

3.1 IF-FTA on the ESS

Definition 3.1. Let a set U be fixed. An intuitionistic fuzzy (IF) set \tilde{a} of U is an object having the form, $\tilde{a} = \{x, u(x), v(x) | x \in U\}$ where the function $u_{\tilde{a}} : U \rightarrow [0, 1]$ and $v_{\tilde{a}} : U \rightarrow [0, 1]$ measure the degree of membership and the degree of non-membership, respectively, of an $x \in U$ as a potential member of set $\tilde{a} \subset U$, and $0 \leq u(x) + v(x) \leq 1$ for $x \in U$.

Clearly, the IF set uses a degree of truth membership function $\mu_{\tilde{a}}(x)$ and a degree of falsity membership function $v_{\tilde{a}}(x)$ to represent lower bound $\mu_{\tilde{a}}(x)$ and upper bound $1 - v_{\tilde{a}}(x)$ such that $\mu_{\tilde{a}}(x) + v_{\tilde{a}}(x) \leq 1$. By complementing the membership degree with a non-membership degree that expresses to what extent the element does not belong to the IF set, the interval $[\mu_{\tilde{a}}(x), 1 - v_{\tilde{a}}(x)]$ can extend the fuzzy set of membership function. The uncertainty or hesitation can be quantified for each x in \tilde{a} by the length of the interval $\pi_{\tilde{a}}(x) = 1 - v_{\tilde{a}}(x) - \mu_{\tilde{a}}(x)$. A small $\pi_{\tilde{a}}(x)$ represents that we are more decisive about x , and a large $\pi_{\tilde{a}}(x)$ represents that we are more uncertain about x . Obviously, when $\mu_{\tilde{a}}(x) = 1 - v_{\tilde{a}}(x)$ for all elements of the universe, the traditional fuzzy set concept is recovered. As an example, Figure 3 shows an IF set of a real number R .

Note that when $a_1 = a'_1$, $c_1 = c'_1$ and $a_2 = a'_2$, $c_2 = c'_2$, the IF set is changed from Figure 4 to Figure 5, and its four arithmetic operations become much more easy.

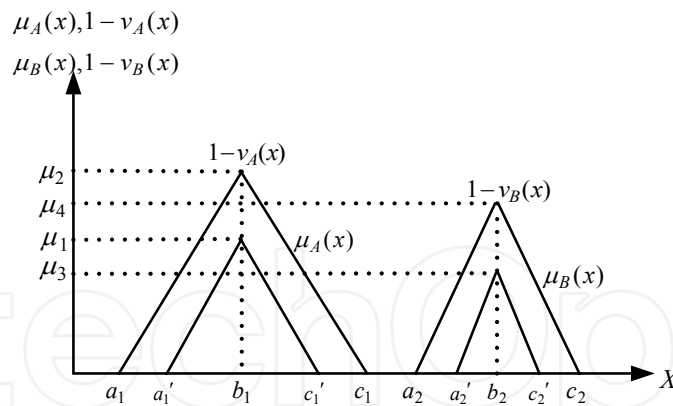


Fig. 4. A triangle IF set.

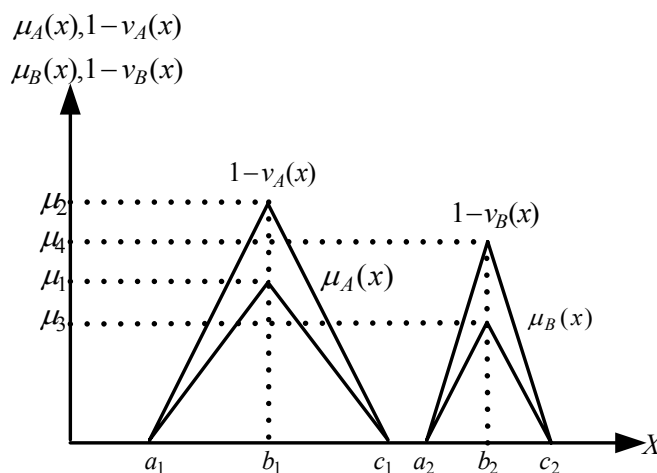


Fig. 5. A triangle IF set.

Based on definition of a triangle IF set shown in Figure 4, we propose failure possibility operations for the FTA on the ESS as follows. Let \tilde{f}_A and \tilde{f}_B be failure possibilities of two triangular IF sets, truly, $\tilde{f}_A > 0$ and $\tilde{f}_B > 0$:

$$\begin{aligned} \tilde{f}_A &= \{(a'_1, b_1, c'_1); \mu_A, (a_1, b_1, c_1); 1 - v_A\}, \\ \tilde{f}_B &= \{(a'_2, b_1, c'_2); \mu_A, (a_2, b_2, c_2); 1 - v_B\}. \end{aligned}$$

Let \oplus , \ominus and \otimes be binary operations between two IF sets \tilde{f}_A and \tilde{f}_B corresponding to the operations $\circ = +, -, \text{ and } \times$, respectively. Then we have the following useful results of operations on the IF set (2).

Proposition 3.1. Let \tilde{f}_A and \tilde{f}_B be two triangular IF set numbers. Then $\tilde{f}_A \oplus \tilde{f}_B$, $\tilde{f}_A \ominus \tilde{f}_B$, $\tilde{f}_A \otimes_{\text{product}} \tilde{f}_B$, and $\tilde{f}_A \otimes_{\text{min}} \tilde{f}_B$ are also triangular IF set numbers. They have the following operations.

$$\begin{aligned}
\tilde{f}_A \oplus \tilde{f}_B &= \{(a'_1 + a'_2, b_1 + b_2, c'_1 + c'_2); \min(\mu_A, \mu_B), \\
&\quad (a_1 + a_2, b_1 + b_2, c_1 + c_2); \min(1 - v_A, 1 - v_B)\} \\
\tilde{f}_A \ominus \tilde{f}_B &= \{(a'_1 - c'_2, b_1 - b_2, c'_1 + a'_2); \min(\mu_A, \mu_B), \\
&\quad (a_1 - c_2, b_1 - b_2, c_1 - a_2); \min(1 - v_A, 1 - v_B)\} \\
\tilde{f}_A \otimes_{\text{product}} \tilde{f}_B &= \{(a'_1 a'_2, b_1 b_2, c'_1 c'_2); \min(\mu_A, \mu_B), \\
&\quad (a_1 a_2, b_1 b_2, c_1 c_2); \min(1 - v_A, 1 - v_B)\} \\
\tilde{f}_A \otimes_{\text{min}} \tilde{f}_B &= \{(\min(a'_1, a'_2), \min(b_1, b_2), \min(c'_1, c'_2)); \min(\mu_A, \mu_B), \\
&\quad (\min(a'_1, a'_2), \min(b_1, b_2), \min(c'_1, c'_2)); \min(1 - v_A, 1 - v_B)\}
\end{aligned}$$

\tilde{a} is a crisp number with value m if its membership function is defined by

$$u_{\tilde{a}}(x) = \begin{cases} 1 & \text{if } x = m \\ 0 & \text{if } x \neq m, \end{cases}$$

which is also denoted by $\tilde{1}_{\{m\}}$.

According to equation (2), the IF set failure possibility of the "ESS Fault", denoted by \tilde{f}_T , can be computed by

$$\begin{aligned}
\tilde{f}_T &= \tilde{1}_{\{m\}} \ominus [(\tilde{1}_{\{m\}} \ominus \tilde{f}_{A_1}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{A_2}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{A_3}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{A_4}) \otimes \\
&\quad (\tilde{1}_{\{m\}} \ominus \tilde{f}_{A_5}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{A_6})] \otimes \\
&\quad [(\tilde{1}_{\{m\}} \ominus \tilde{f}_{B_1}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{B_2}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{B_3}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{B_4}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{B_5}) \otimes \\
&\quad (\tilde{1}_{\{m\}} \ominus \tilde{f}_{B_6})] \otimes \\
&\quad [(\tilde{1}_{\{m\}} \ominus \tilde{f}_{C_1}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{C_2}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{C_3}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{C_4}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{C_5}) \otimes \\
&\quad (\tilde{1}_{\{m\}} \ominus \tilde{f}_{C_6})] \otimes \\
&\quad [(\tilde{1}_{\{m\}} \ominus \tilde{f}_{D_1}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{D_{21}}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{D_{22}})] \times [(\tilde{1}_{\{m\}} \ominus \tilde{f}_E)] \otimes \\
&\quad [(\tilde{1}_{\{m\}} \ominus \tilde{f}_{E_1}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{E_2}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{E_3}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{E_4})] \otimes \\
&\quad \{[\tilde{1}_{\{m\}} \ominus (\tilde{1}_{\{m\}} \ominus \tilde{f}_{G_{11}}) \otimes (\tilde{1}_{\{m\}} \ominus \tilde{f}_{G_{12}})] (\tilde{f}_{G_{21}} \otimes \tilde{f}_{G_{22}} \otimes \tilde{f}_{G_3})\}. \quad (3)
\end{aligned}$$

It should be noted that $\tilde{f}_A \otimes \tilde{f}_B$ is represented by either $\tilde{f}_A \otimes_{\text{product}} \tilde{f}_B$ or $\tilde{f}_A \otimes_{\text{min}} \tilde{f}_B$, whose operations are described in Proposition 3.1. The collected data of IF failure interval are listed in Table 4, which is based on the representation of the triangle IF set. The IF reliability interval for the ESS results are

$$\tilde{f}_{\text{ESS Fault}} = \tilde{f}_{T\text{product}} = \{(0.0619, 0.0746, 0.0816); 0.6, (0.0440, 0.0746, 0.0966); 0.7\} \quad (4)$$

$$\tilde{f}_{\text{ESS Fault}} = \tilde{f}_{T\text{min}} = \{(0.0650, 0.0772, 0.0836); 0.6, (0.0478, 0.0772, 0.0980); 0.7\} \quad (5)$$

3.2 The Critical Components on the ESS

In order to find the critical components in the system based on IF-FTA and determine weak paths in the ESS where key improvement event must be made, we expand Tanaka et al's (20) fuzzy-FTA definition and redefine the influence degree of every bottom event through implementing four arithmetic operations of the triangle IF set as shown in Proposition 3.1.

Definition 3.2. Denote by \tilde{f}_{T_i} the computation result that the i th bottom event of failure interval (delete the i th bottom event) is not included in the \tilde{f}_T shown in equation (3), and denote by $\mathcal{V}(\tilde{f}_T, \tilde{f}_{T_i})$ the difference between \tilde{f}_T and \tilde{f}_{T_i} ; that is,

$$\mathcal{V}(\tilde{f}_T, \tilde{f}_{T_i}) = (a'_T - a'_{T_i}) + (a_T - a_{T_i}) + (b_T - b_{T_i}) + (c'_T - c'_{T_i}) + (c_T - c_{T_i}). \quad (6)$$

A larger value of $\mathcal{V}(\tilde{f}_T, \tilde{f}_{T_i})$ represents the i th bottom event has a greater influence on \tilde{f}_T .

Therefore, according to Definition 3.2, we can calculate $\mathcal{V}(\tilde{f}_T, \tilde{f}_{T_i})$ for $i = A, B, \dots, G$, the IF failure difference between overall and partial (with second level nodes deleted) fault-tree, for obtaining the most critical system event of the "ESS Fault". Table 5 shows the ranks of such differences. Based on these results, the failure of BOG (Boil Off Gas) pipes and isolation valve of BOG pipe failing to close (event "C") and ICD pipes and isolation valve of ICD pipe failing to close (event "D") are the first and second significant events leading to ESD failure. Because of this, the components involved in these events require particular attention in daily maintenance. From the well known 80/20 rule, we can effectively reduce 80% of risk if we can have 20% of critical equipments under our control. Daily monitoring of such critical components will help to significantly reduce the change of failure.

Finally, for ease of implementation in real applications, we provide a step-by-step procedure of the IF-FTA on the ESS as follows:

- Step 1. Construct fault-tree logic diagram, fault-tree logical symbols such as "AND" gate and "OR" gate, for all the faults under the top level event shown in Figure 2. Use these to represent the sequence of faults and causes and trace back whole process from top to bottom events.
- Step 2. Obtain the possible failure intervals of bottom events shown in Table 4 based on the aggregation of the ESS information and expert's knowledge and experience.
- Step 3. calculate the "ESS Fault" reliability result by using equation (3).
- Step 4. Find the influential bottom events of the system reliability by using equation (6).
- Step 5. Discuss the results and make suggestions.

4. Reliability Measures Methods for FTA

In this section, we briefly review existing reliability measures for the FTA within reliability theory and compare the results of the existing approaches and our proposed methods.

Traditionally, probability method is the method for dealing with the heterogeneous problems, and probability can only show the randomness of success or failure events. The usage of this method depends on the availability of a large amount of sample data and complete knowledge of all event outcomes. We calculated the failure possibility of the top event "ESS Fault" based on equation (2) using the crisp failure probabilities, b_i , in Table 4 and obtained $f_T = 7.4631 \times 10^{-2}$.

Posbist reliability theory, developed by Cai (10), is one of the forms of fuzzy reliability theories that have been proposed. It uses the possibility assumption and the fuzzy state assumption in place of the probability assumption or the binary state assumption. For systems with extremely small failure probabilities or when necessary statistical data are scarce, the posbist reliability theory has certain advantages for evaluating system reliability and safety (11). Based on the fault tree of failure of the ESS shown in Figure 3 and the corresponding failure possibility of every basic event listed in Table 4, we have identified the failure possibility of the top event by using the Posbist reliability theory and this value is $f_T = 3.95 \times 10^{-2}$.

The results of the existing approaches and our proposed methods are shown in Figure 6 and Table 6. For comparisons, we find that the failure possibilities of Posbist under different α -level are the same with crisp failure possibility of event "C₄". This is because the Posbist select the maximal failure possibility of bottom events. In this case, this simple assessment could possibly overlook the potential risk on the ESS reliability and safety. The results of the proposed "and-by-product" or "and-by-min" method could cover both the results of the crisp failure possibility and the fuzzy FTA approach (20). The differences between proposed two "and" operations are that "and-by-product" gives more consistent results because the center of its estimated result is the same with the crisp failure possibility and the fuzzy FTA approach. Also, "and-by-min" can give the more safety results because it selects the least possibility in each event connected by the "and" gate without underestimating the failure interval.

5. Conclusions

Traditionally, we assume that exact probabilities of failure events are available and fully understood. However, in real applications for various reasons it is often difficult to obtain the past exact failures data. In this paper, to handle uncertain situations and inevitable imprecise information occurring in the liquefied natural gas (LNG) terminal emergency shut-down system (ESS), we propose a new approach which integrates intuitionistic fuzzy (IF) set operations on fault-tree analysis (FTA) to compute the IF fault-tree interval, traditional reliability and IF reliability interval based on the failure information gathered by the ESS. Moreover, based on IF-FTA, we present an algorithm to find the critical components and determine weak paths in the ESS where key improvement events must be made. The failures of BOG (Boil Off Gas) pipes, isolation valve of BOG pipe failing to close (event "C") and ICD pipes, isolation valve of ICD pipe failing to close (event "D"), are the first and second significant events leading to ESD failure. As such, particular attention must be paid to the related components in the daily maintenance to effectively reduce risk; 80% of the risk can be removed when 20% of critical equipments are under our control. A step-by-step procedure of the IF-FTA on the ESS is also presented for easy implementation in real applications. Finally, the result of this proposed methodology is briefly compared with the existing FTA approaches.

| Bottom Event | a_i | a'_i | b_i | c'_i | c_i | u_i | $1 - v_i$ |
|--------------|----------|----------|----------|----------|----------|-------|-----------|
| A_1 | 2.26E-05 | 2.59E-05 | 3.37E-05 | 3.67E-05 | 4.11E-05 | 0.60 | 0.70 |
| A_2 | 4.86E-04 | 6.23E-04 | 7.16E-04 | 7.88E-04 | 9.45E-04 | 0.70 | 0.90 |
| A_3 | 3.58E-05 | 4.36E-05 | 5.52E-05 | 6.29E-05 | 6.99E-05 | 0.80 | 0.90 |
| A_4 | 2.43E-05 | 2.76E-05 | 3.10E-05 | 3.35E-05 | 3.62E-05 | 0.90 | 0.95 |
| A_5 | 1.97E-05 | 2.85E-05 | 3.10E-05 | 3.63E-05 | 4.28E-05 | 0.65 | 0.85 |
| A_6 | 1.71E-05 | 2.01E-05 | 2.28E-05 | 2.74E-05 | 2.98E-05 | 0.80 | 0.85 |
| B_1 | 1.78E-05 | 2.34E-05 | 3.39E-05 | 3.90E-05 | 4.37E-05 | 0.85 | 0.90 |
| B_2 | 4.11E-04 | 6.23E-04 | 7.16E-04 | 8.09E-04 | 9.87E-04 | 0.70 | 0.90 |
| B_3 | 1.17E-03 | 1.41E-03 | 1.70E-03 | 1.85E-03 | 2.37E-03 | 0.60 | 0.75 |
| B_4 | 3.27E-05 | 4.36E-05 | 5.52E-05 | 6.29E-05 | 7.80E-05 | 0.75 | 0.85 |
| B_5 | 1.88E-05 | 2.73E-05 | 3.10E-05 | 3.63E-05 | 4.79E-05 | 0.80 | 0.90 |
| B_6 | 1.74E-05 | 1.92E-05 | 2.28E-05 | 2.76E-05 | 3.70E-05 | 0.85 | 0.90 |
| C_1 | 2.00E-03 | 2.28E-03 | 2.68E-03 | 3.11E-03 | 3.79E-03 | 0.70 | 0.80 |
| C_2 | 4.41E-04 | 5.44E-04 | 7.16E-04 | 8.02E-04 | 9.86E-04 | 0.80 | 0.95 |
| C_3 | 1.12E-03 | 1.51E-03 | 1.70E-03 | 1.84E-03 | 2.39E-03 | 0.60 | 0.75 |
| C_4 | 2.22E-02 | 3.12E-02 | 3.95E-02 | 4.31E-02 | 5.30E-02 | 0.75 | 0.90 |
| C_5 | 1.24E-02 | 1.94E-02 | 2.23E-02 | 2.36E-02 | 2.58E-02 | 0.60 | 0.80 |
| C_6 | 1.30E-05 | 1.92E-05 | 2.28E-05 | 2.67E-05 | 3.15E-05 | 0.65 | 0.90 |
| D_1 | 7.70E-05 | 8.55E-05 | 1.14E-05 | 1.38E-04 | 1.53E-04 | 0.90 | 1.00 |
| D_{21} | 1.98E-03 | 2.39E-03 | 2.57E-03 | 3.16E-03 | 3.95E-03 | 0.80 | 1.00 |
| D_{22} | 1.60E-03 | 2.10E-03 | 2.53E-03 | 3.14E-03 | 3.76E-03 | 0.90 | 0.95 |
| E | 2.33E-04 | 3.38E-04 | 3.98E-04 | 4.86E-04 | 5.68E-04 | 0.85 | 1.00 |
| F_1 | 1.62E-05 | 2.45E-05 | 3.98E-04 | 3.57E-05 | 3.89E-05 | 0.75 | 0.90 |
| F_2 | 2.10E-05 | 2.39E-05 | 3.10E-05 | 3.35E-05 | 3.95E-05 | 0.90 | 1.00 |
| F_3 | 4.32E-05 | 5.02E-05 | 5.52E-05 | 6.57E-05 | 8.21E-05 | 0.70 | 0.85 |
| F_4 | 2.76E-04 | 3.54E-04 | 3.98E-04 | 4.86E-04 | 5.63E-04 | 0.65 | 0.80 |
| G_{11} | 1.85E-02 | 2.13E-02 | 3.09E-02 | 3.83E-02 | 4.52E-02 | 0.80 | 0.90 |
| G_{12} | 8.42E-04 | 9.90E-04 | 1.32E-03 | 1.53E-03 | 1.67E-03 | 0.70 | 0.90 |
| G_{21} | 2.54E-02 | 3.02E-02 | 3.64E-02 | 4.33E-02 | 5.24E-02 | 0.85 | 0.90 |
| G_{22} | 1.46E-03 | 2.24E-03 | 2.73E-03 | 3.25E-03 | 4.00E-03 | 0.85 | 1.00 |
| G_3 | 1.00E-02 | 1.28E-02 | 1.44E-02 | 1.74E-02 | 1.90E-02 | 0.80 | 0.90 |

Table 4. The possible ranges of bottom events of ESS failures

| | "and" operation type | |
|-----------------------------------|----------------------|----------------------|
| | and-by-product | and-by-min |
| $V(\tilde{f}_T, \tilde{f}_{T_A})$ | 4.0824E-03(4) | 4.0720E-03(4) |
| $V(\tilde{f}_T, \tilde{f}_{T_B})$ | 1.1820E-02(3) | 3.2951E-03(5) |
| $V(\tilde{f}_T, \tilde{f}_{T_C})$ | 3.0936E-01(1) | 3.0858E-01(1) |
| $V(\tilde{f}_T, \tilde{f}_{T_D})$ | 2.5745E-02(2) | 2.5680E-02(2) |
| $V(\tilde{f}_T, \tilde{f}_{T_E})$ | 1.8688E-03(6) | 1.8641E-03(7) |
| $V(\tilde{f}_T, \tilde{f}_{T_F})$ | 2.4672E-03(5) | 2.4609E-03(6) |
| $V(\tilde{f}_T, \tilde{f}_{T_G})$ | 2.1484E-07(7) | 1.2764E-02(3) |

Table 5. The failure difference between deleting any fault-tree node in level 2

| α -level | Fuzzy fault tree | | | Crisp | Posbist | Proposed intuitionistic fuzzy fault tree analysis | | | | | | | | | |
|-----------------|------------------|--------------|-----------------|----------|----------|---|----------|----------|------------|----------|----------|----------|----------|----------|----------|
| | Left point | Middle point | Right end point | | | and-by-product | | | and-by-min | | | | | | |
| | | | | | | a | a' | b | c' | c | a | a' | b | c' | c |
| 1.0 | 7.46E-02 | 7.46E-02 | 7.46E-02 | 7.46E-02 | 3.95E-02 | | | | | | | | | | |
| 0.9 | 7.34E-02 | 7.46E-02 | 7.53E-02 | 7.46E-02 | 3.95E-02 | | | | | | | | | | |
| 0.8 | 7.21E-02 | 7.46E-02 | 7.60E-02 | 7.46E-02 | 3.95E-02 | | | | | | | | | | |
| 0.7 | 7.08E-02 | 7.46E-02 | 7.67E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | | | | | | | | | |
| 0.6 | 6.96E-02 | 7.46E-02 | 7.74E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 7.46E-02 | | | | | | | | |
| 0.5 | 6.83E-02 | 7.46E-02 | 7.81E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 7.25E-02 | 7.46E-02 | | | | | | | |
| 0.4 | 6.70E-02 | 7.46E-02 | 7.88E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 7.04E-02 | 7.46E-02 | 7.69E-02 | | | | | | |
| 0.3 | 6.57E-02 | 7.46E-02 | 7.95E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 6.83E-02 | 7.46E-02 | 7.81E-02 | 8.72E-02 | | | | | |
| 0.2 | 6.45E-02 | 7.46E-02 | 8.02E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 6.62E-02 | 7.46E-02 | 7.93E-02 | 9.04E-02 | 5.62E-02 | | | | |
| 0.1 | 6.32E-02 | 7.46E-02 | 8.09E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 6.41E-02 | 7.46E-02 | 8.04E-02 | 9.35E-02 | 5.20E-02 | 6.70E-02 | | | |
| 0.0 | 6.19E-02 | 7.46E-02 | 8.16E-02 | 7.46E-02 | 3.95E-02 | 7.46E-02 | 6.19E-02 | 7.46E-02 | 8.16E-02 | 9.66E-02 | 4.78E-02 | 6.50E-02 | 7.72E-02 | 8.36E-02 | 9.80E-02 |

Table 6. Comparisons with other fault analysis methods

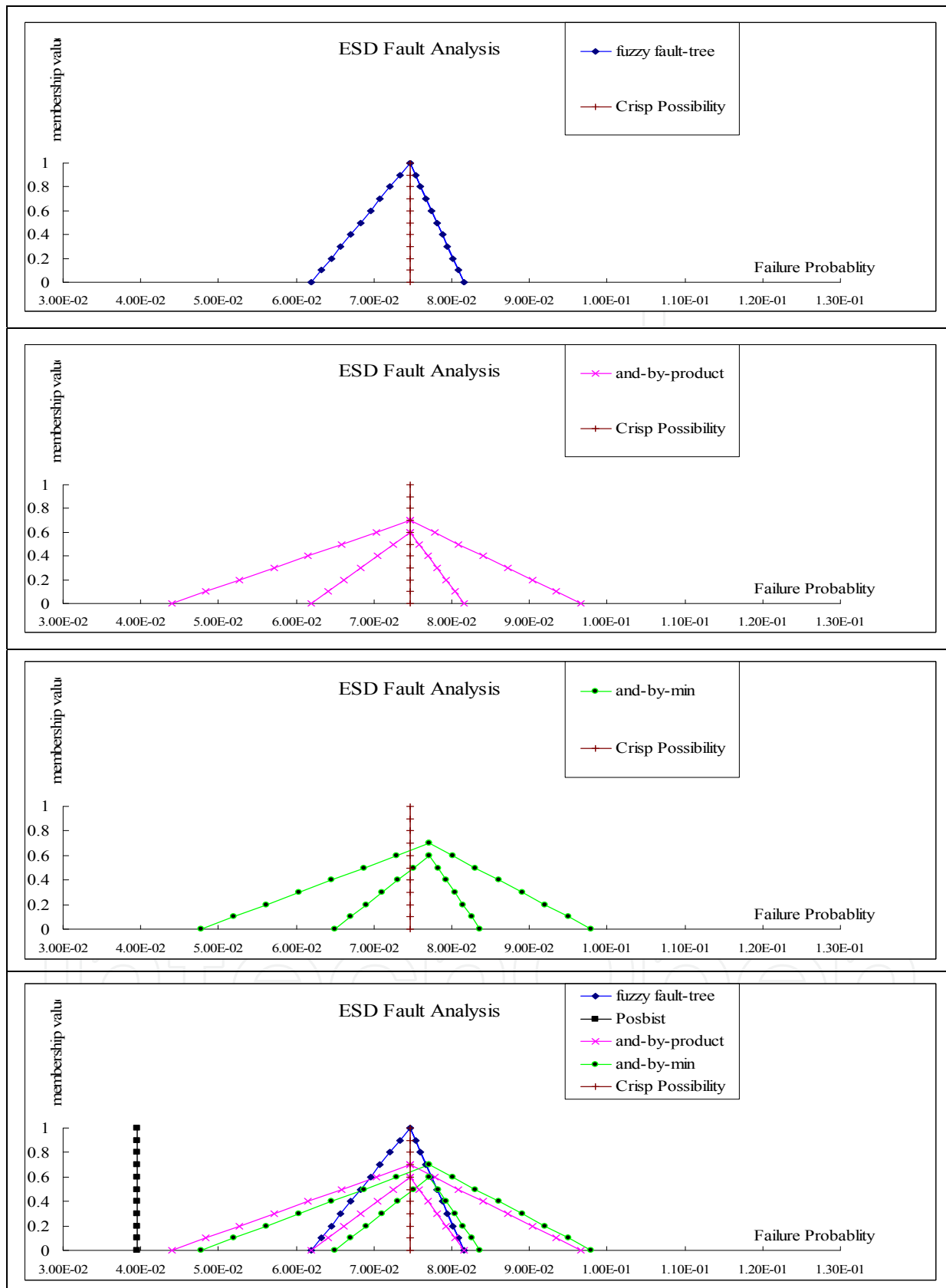
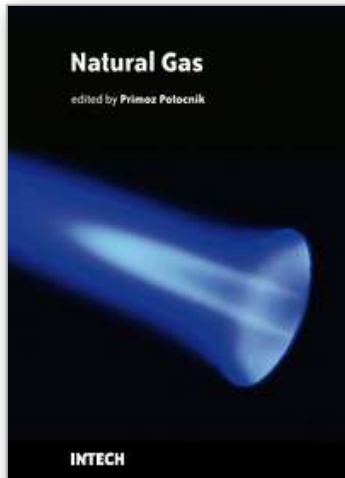


Fig. 6. Membership function for top event of ESS fault.

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The contributions in this book present an overview of cutting edge research on natural gas which is a vital component of world's supply of energy. Natural gas is a combustible mixture of hydrocarbon gases, primarily methane but also heavier gaseous hydrocarbons such as ethane, propane and butane. Unlike other fossil fuels, natural gas is clean burning and emits lower levels of potentially harmful by-products into the air. Therefore, it is considered as one of the cleanest, safest, and most useful of all energy sources applied in variety of residential, commercial and industrial fields. The book is organized in 25 chapters that cover various aspects of natural gas research: technology, applications, forecasting, numerical simulations, transport and risk assessment.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Unit 405, Office Block, Hotel Equatorial Shanghai
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中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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