Fuzzy Fault Tree Analysis with Natural Language

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ABSTRACT

This paper mentions a fault tree analysis using not probability but natural language and fuzzy theory. Reliability estimate of each basic event and dependence level estimate among subsystems are expressed by linguistic terms. Analysis results are also expressed by natural language. The meaning of linguistic terms is expressed by a fuzzy set. In the presented analysis approach parametrized operations of fuzzy sets are considered so that analyst's subjectivity can be introduced into the analysis. This paper gives the analysis of the Chernobyl accident as an example of the fuzzy fault tree analysis using linguistic terms.

I. Introduction

The WASH-1400[1] is famous for the fault tree analysis of a nuclear power plant by the use of the probabilistic method. The conventional quantitative fault tree analysis uses the probabilistic method. However reliability of each basic event of a fault tree cannot be necessarily estimated by probability. And the probability of a top event is usually very small from the viewpoint of our daily life. The top event probability is usually compared with probabilities of rare events based on expert's experienced and engineering judgement. The construction of a fault tree is also based on expert's experienced and engineering judgement. It is said that expert's judgement holds a central position in system reliability assessment[2]. Subjectivity, which is closely related to fuzziness, is observed from all parts of the analysis of system reliability[3]. Therefore, it is necessary to introduce fuzziness into the system reliability analysis[4]. Applications of fuzzy set theory to the system reliability analysis have been performed recently[5]-[14].

This paper is based on the non-probabilistic method, and focuses on the introduction of natural language expressions and analyst's subjectivity into the system reliability analysis[12]-[14]. The meaning of linguistic terms about reliability information is expressed by the use of a fuzzy set. This paper also considers parametrized operations of the fuzzy sets in the analysis. The parameters reflect analyst's subjectivity towards the analyzed system. Finally the analysis of the Chernobly accident is shown as an example of the analysis.

II. Fuzzy Fault Tree Analysis and Natural Language Expressions

2.1 Natural Language Expressions

System reliability is estimated through system component reliability estimate and system functional relation. In the conventional quantitative reliability analysis, numerical values, e.g., accident probability, error probability, play an important role. However, as is often the case, numerical values cannot be always

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Table 1. Natural language expressions of reliability estimate and corresponding parameter x_0

Class	Expressions of Reliability Estimate	Parameter x_0 (Representative Value)
	(Hardware or human operator has)	
1	no reliability	-
2	very low reliability	0.9-1.0(0.95)
3	low reliability	0.7-0.9(0.8)
4	rather low reliability	0.55-0.7(0.625)
5	standard reliability	0.45-0.55(0.5)
6	rather high reliability	0.3-0.45(0.375)
7	high reliability	0.2-0.3(0.25)
8	quite high reliability	0.1-0.2(0.15)
9	extremely high reliability	0.05-0.1(0.075)
	(Accident, failure or human error is)	
10	next to impossible	0.0-0.05(0.025)
11	impossible	-

obtained objectively and are little better than guesses when we have not enough amount of data. In this case natural language expressions are more appropriate for reliability estimation than numerical values [15]. The construction of a fault tree is also based on expert's experienced and engineering judgement. Information on system functional relation including a fault tree is need for the analysis of system reliability. This kind of information is expressed more easily with linguistic terms than numerical values. In this paper hardware and human reliabilities are expressed by natural language in the form of reliability estimate and its fuzziness. Table 1 shows natural language expressions of reliability estimate and Table 2 shows expressions of fuzziness of reliability estimate.

The dependence level, which is related to information on system functional relation, is also expressed by natural language in the form of dependence level estimate and its fuzziness as shown in Table 3 and Table 4, where Table 3 is referred to [16], and Table 4 is the same as Table 2 for simplicity.

Table 2. Natural language expressions of fuzziness of reliability estimate and corresponding parameter m

Class	Expressions of Fuzziness	Parameter m
1	Low Fuzziness	2.0
2	Medium Fuzziness	2.5
3	Rather High Fuzziness	3.0
4	High Fuzziness	3.5

Table 3. Natural language expressions of dependence level estimate

Level	Expressions of Dependence Level Estimate
1	Complete Dependence
2	High Dependence
3	Moderate Dependence
4	Low Dependence
5	Zero Dependence

Table 4. Natural language expressions of fuzziness of dependence level estimate and corresponding parameter m_r

Class	Expressions of Fuzziness	Parameter m_r
1	Low Fuzziness	2.0
2	Medium Fuzziness	2.5
3	Rather High Fuzziness	3.0
4	High Fuzziness	3.5

2.2 Fuzzy Set Representation

The meaning of linguistic terms is represented by a fuzzy set better than a numerical value. This paper employs a fuzzy set with a membership function (1) in order to express the meaning of linguistic terms of reliability estimate.

$$F(x)=\frac{1}{1+20\times|x-x_0|^m}, \qquad (1)$$

where x_0 and m are parameters and $0\leq x,\ x_0\leq 1$. The parameter x_0 gives the maximal grade of membership and the parameter m is related to fuzziness. The unit interval [0, 1] on which the fuzzy set (1) is defined means not probability but subjective evaluation of reliability. The value 0.5 in [0, 1] means the subjective standard evaluation of reliability. The value 1 means subjective evaluation of no reliability. On the other hand the value 0 means subjective evaluation of completely high reliability. The smaller the value in [0, 1], the higher the subjective evaluation of reliability. Therefore, the fuzzy set (1) is a subjective and non-probabilistic measure of reliability in the sense that the fuzzy set (1) does not necessarily satisfy axiomatic laws of probability.

The membership function (1) has the following properties. (i)The fuzzy set with the membership function is normal[17] and convex[17]. Therefore, it is easy to express reliability estimate with simple linguistic terms. (ii)$F(1)\neq 0$ and $F(0)\neq 0$. The former means that there is also a possibility that hardware does not always work or a human operator does not always perform task without error even if the subjective evaluation of reliability is high. The latter means that there is a possibility that hardware does not necessarily fail or a human operator does not necessarily make an error even if the subjective evaluation of reliability is low.

The parameters x_0 and m correspond to natural language expressions of reliability estimate and its fuzziness, respectively, as shown in Tables 1 and 2. Especially, the fuzzy sets corresponding to the class 1 and the class 11 are defined as follows, respectively:

$$F(x)=\begin{cases}1, & x=1\\ 0, & x\neq 1\end{cases}, \qquad (2)$$

$$F(x)=\begin{cases}0, & x\neq 0\\ 1, & x=0\end{cases}, \qquad (3)$$

With respect to linguistic terms of dependence level evaluation, the same membership function as Equation (1) is employed in order to express the meaning of the linguistic terms of dependence.

$$R(r)=\frac{1}{1+20\times|r-r_0|^{m_r}}, \qquad (4)$$

where r_0 and m_r are parameters and $0\leq r,\ r_0\leq 1$. The parameter m_r corresponds to the linguistic terms of fuzziness of dependence level evaluation as shown in Table 4. The determination of the parameter r_0 is mentioned later.

2.3 *And* Operation and *Or* Operation

Basic operations of fuzzy sets in this paper are the *and* operation and the *or* operation, which correspond to the *and* gate and to the *or* gate in a fault tree, respectively. In this paper the following operations are used as the *and* and the *or* operations.

$$H(x,\ y)=\frac{1}{1+(((1-x)/x)^{1/nH}+((1-y)/y)^{1/nH})^{nH}}, \qquad (5)$$

where $0<x,\ x_0\leq 1$, $H(0,\ y)=H(x,\ 0)=0$ and nH is a

non-negative parameter, and

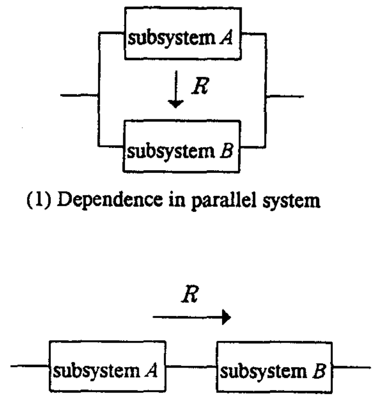
$$G(x, y)=\frac{((x/(1-x))^{nG}+(y/(1-y))^{nG})^{1/nG}}{1+((x/(1-x))^{nG}+(y/(1-y))^{nG})^{1/nG}}, \quad (6)$$

where $0 \leq x,\ y<1$, $G(1,\ y)=G(x,\ 1)=1$ and nG is a non-negative parameter. The operation H is used when reliability of a parallel system is estimated, and the operation G is used when reliability of a series system is estimated, where subsystems are assumed to be independent of each other functionally. The extension principle[17] is employed in the operations H and G of fuzzy sets. The operations H and G are the so called Dombi t-norm and Dombi t-conorm[18]. These operations have the following properties according to the parameters nH and nG. When nH is infinite, the operation H becomes the *drastic product*[18]. The operation H becomes the *min* operation when the parameter nH is zero[18]. The operation G becomes the *drastic sum* when the parameter nG is zero[18]. When the parameter nG is infinite, the operation G becomes the *max* operation[18].

From the viewpoint of the fault tree analysis with natural language expressions, the operations with above properties can cover the range of reliability estimate from the most pessimistic estimate through the most optimistic estimate. This means that analyst's subjectivity towards an analyzed system can be reflected by the parametrized operations (5) and (6), whether reliability of the analyzed system is evaluated optimistically or not. The larger the values of the parameters nH and nG are, the more optimistic the reliability estimate is. The determination of the parameters nH and nG are mentioned later.

2.4 Dependence Analysis

In a practical complex system the dependence among subsystems often exists as shown in Fig. 1. The dependence in this paper means that the failure of subsystem A(or human error in task A) has an influence on the failure of subsystem B(or human error in task B). In this paper the dependence as shown in Fig. 1(2) is not considered since the failure of at least one of subsystems leads to the failure of the series system whether the dependence exists or not.



(1) Dependence in parallel system

(2) Dependence in series system

Fig. 1 Dependence

Reliability of the parallel system with the dependence as shown in Fig. 1(1) is analyzed according to the following processes. Let F_A and F_B be fuzzy sets representing reliability of subsystems A and B in Fig. 1(1), respectively. And let R be a fuzzy set with the membership function (4) representing the dependence level.

(i)Let us consider the case in which the failure of subsystem A is assumed to have an influence on the failure of subsystem B. The fuzzy set F_B' representing reliability of the whole system in this case is estimated by

$$F_B'=H(F_A,\ R), \quad (7)$$

where the extension principle is employed in this and the following operations.

(ii)Let us consider the case in which the failure of subsystem A is assumed not to have an influence on the failure of subsystem B. As far as the dependence level is not complete dependence, the failure of subsystem A does not always have an influence on the failure of subsystem B. The portion of F_A, which does not have an influence on the failure of subsystem B, is estimated by

$$F_A = G(F_A', F_B'), \tag{8}$$

where F_A' is this portion. Equation (8) implies that the failure of subsystem A has an influence on the failure of subsystem B or does not have any influence on the failure of subsystem B. Reliability of whole system in this case is estimated by

$$F' = H(F_A', F_B). \tag{9}$$

Equation (9) implies that the failure of whole system occurs when the failure of subsystem A and the failure of subsystem B occur without influence.

Reliability of whole system considering the above two cases is estimated by

$$F = H(F_B', F'). \tag{10}$$

Equation (10) implies that the failure of whole system occurs when the failure of subsystem A has an influence on the failure of subsystem B, or when subsystem A fails and subsystem B fails without influence by the failure of subsystem A.

2.5 Natural Language Expressions of Analysis Results

The results of the fuzzy fault tree analysis are expressed by linguistic terms in the form of reliability estimate and its fuzziness. Let F_R be a fuzzy set obtained by the fuzzy fault tree analysis, and F_S be a fuzzy set with the membership function (1). Let *α-cut* of F_R and F_S be $(F_R)_\alpha = (x_{1R}(\alpha), x_{2R}(\alpha))$ and $(F_S)_\alpha = (x_{1S}(\alpha), x_{2S}(\alpha))$, respectively. Let us define the distance between F_R and F_S by

$$d = \int_0^1 \sqrt{(x_{1R}(\alpha) - x_{1S}(\alpha))^2 + (x_{2R}(\alpha) - x_{2S}(\alpha))^2}\, d\alpha. \tag{11}$$

The parameters x_0 $(0 \leq x_0 \leq 1)$ and m (2.0, 2.5, 3.0, 3.5) are selected so that the distance d is minimized. The analysis results are expressed by linguistic terms referring to Tables 1 and 2.

2.6 Criticality Importance of Basic Event

In the conventional fault tree analysis the criticality importance of a basic event[19] is considered. The criticality importance considers the fact that it is more difficult to improve the more reliable basic event than to improve the less reliable event[19]. The criticality importance is defined by the following equation[19].

$$CI(i) = \frac{pr(i) \times (pr(1_i) - pr(0_i))}{pr(q)}, \tag{12}$$

where $pr(i)$ is probability of basic event i, $pr(q)$ is probability of the top event, $pr(1_i)$ is probability of the top event assuming that probability of basic event i is equal to 1, and $pr(0_i)$ is probability of the top event assuming that probability of basic event i is equal to 0. In this paper the criticality importance is defined by extending the consideration of Equation (12).

$$\tilde{CI}(i) = \frac{F_i \times (F(1_i) - F(0_i))}{x_0}, \tag{13}$$

where F_i is the fuzzy set representing the reliability estimate of basic event i, $F(1_i)$ is the fuzzy set representing the reliability estimate of the top event assuming that basic event i is certain(the fuzzy set has the membership function (2)), $F(0_i)$ is the fuzzy set representing the reliability estimate of the top event assuming that basic event i is impossible(the fuzzy set has the membership function (3)), and the x_0 is the value of the parameter x_0 of the fuzzy set F_S representing the reliability estimate of the top event obtained by the analysis. The operation in Equation (13) is performed by the use of the extension principle. The $\tilde{CI}(i)$ is a fuzzy set defined on [0, 1]. In this paper the 1-cut of $\tilde{CI}(i)$ is given as information of the criticality improtance.

2.7 Determination of Parameters nH, nG and r_0

2.7.1 Parameters nH and nG

Let us consider the parallel system and the series system which consist of two subsystems, where subsystems are independent of each other functionally. Let the reliability estimate of each subsystem and its fuzziness be ***standard reliability*** and ***medium***, respectively. The parameters nH and nG are determined depending on analyst's reliability estimates of the parallel system and the series system, respectively. This means that the parameters nH and nG reflect analyst's subjectivity towards an analyzed system.

2.7.2. Parameter r_0

Let us consider the parallel system as shown in Fig. 1(1), where the reliability estimate of each subsystem and its fuzziness are ***standard*** and ***medium***, respectively. When the dependence level is estimated to be ***complete***, the reliability estimate of the parallel system is ***standard*** and its fuzziness is ***medium***. When the dependence level is estimated to be ***zero***, the reliability is estimated by the operation H with the determined parameter nH. Let x_{0i} be the parameter x_0 of the fuzzy set F_S with the membership function (1), where F_S represents the reliability estimate of the parallel system with the dependence level i($i=1$: *complete dependence*, $i=2$: *high dependence*, $i=3$: *moderate dependence*, $i=4$: *low dependence*, $i=5$: *zero dependence*). The value of x_{01} is equal to 0.5. The x_{05} value is obtained by the operation H, the extension principle and Equation (11). Let r_{0i} be the parameter r_0 of the fuzzy set (4) representing the dependence level i. The parameters r_{0i} ($i=2$, 3, 4) are determined so that the Equation (14) holds. The parameters r_{0i} ($i=2$, 3, 4) are dependent on nH and nG.

$$(x_{0i}-x_{05}):(x_{01}-x_{0i})=\begin{cases} 3:1 & (i=2) \\ 1:1 & (i=3) \\ 1:3 & (i=4) \end{cases} \qquad (14)$$

Ⅲ. Analysis of the Chernobyl Accident

In this paper an analysis of the Chernobyl accident is performed as an example of the fault tree analysis by the use of natural language. In the analysis the following are assumed as in [20]. (ⅰ)Only human errors are considered for discussion. All nuclear power plant personnel act in a manner they believe to be in the best interests of the plant. (ⅱ)The disfunction of the system results from human errors. An inherent defect of the system is not considered in this analysis. (ⅲ) The operation crew are dependent on each other completely.

3.1 Task Analysis

Six links of human errors are considered in the analysis[20]. They contributed to the accident as follows. **Action A**: During the reduction of reactor power, the operator did not enter a 'hold power' request at the required level in transferring unit power control from the local to the global auto-regulating system, so that the reactor power ran down rapidly to 30MW instead of the hoped-for target level of 700-1000MW. **Action B**: After the reactor fell into the 'iodine well', the operator withdrew many of the control rods, with the motive of conducting the test program, to retrieve the power to 200MW, despite it being forbidden to operate the reactor at such low level by normal safety procedure. **Action C**: Under the low power operational condition, in meeting the requirements of the planned test, two standby main circulation pumps were connected to the core, which resulted in violating the thermo-hydraulic balance in the core coolant system and some individual pump discharges exceeding the permissible levels specified in the regulation. This operational mode was a violation of normal station procedures. **Action D**: In order to continue the test without interruption, the operator blocked the trip signals associated with steamdrum water level and pressure regardless the unstable reactor condition. Hence the reactor protection system triggered by heat transfer parameters was completely cut off. **Action E**: The operator regulated the steam-drum level with difficulty by means of raising the feedwater flow(there is no such function in the design of the steam-drum) for stabilizing the pressure and water level in the drum and creating the adequate condition to begin the test. Meanwhile, more control rods had to be withdrawn to compensate the negative reactivity introduced by the above action. At that time, the number of the control rods remaining in the core was far less than the minimal number according to the safety principle. **Action F**: In order to be able to repeat the test if necessary, the operator blocked the reactor protection system relying on shut-down signals from both turbo-generators. Consequently, the last possibility of automatic shutdown of the reactor was lost.

3.2 Effect of Performance Shaping Factor

The dependence between the actions is usually assumed as shown in Fig. 2(1). However in accordance with the background of the Chernobyl accident, the relationship between the actions is changed, that is, the dependence tends to the higher level. The dependence in the Chernobyl accident is assumed as shown in Fig. 2(2). Fig. 3 shows fault trees in the situations of Fig. 2(1) and Fig. 2(2).

A---------- B ---------- C ---------- D ---------- E ---------- F

ZD HD LD LD LD

(1)

A ---------- B ---------- C ---------- D ---------- E ---------- F

ZD CD HD HD HD

(2)

Fig. 2 Dependence between actions

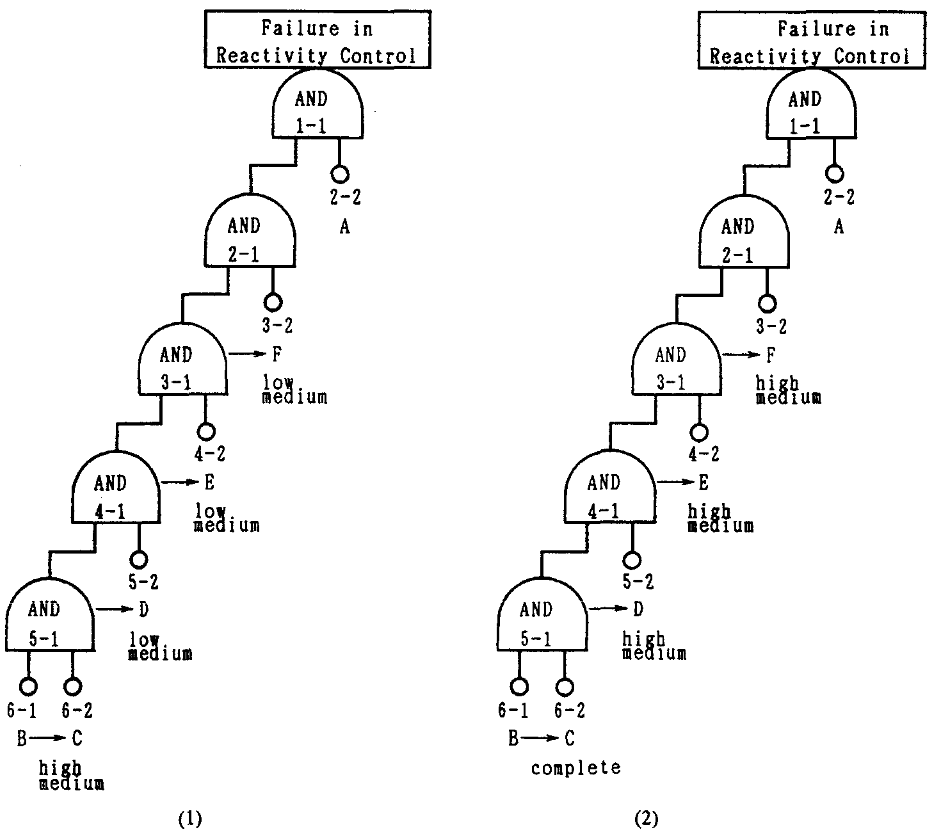


Fig. 3 Fault trees

3.3 Analysis Results

Table 5. Reliability estimate of basic events and parameters *nH* and *nG*

Situation	Analysts	Reliability Estimate of Basic Event (estimate, fuzziness)	*nH*	*nG*
Fig. 3(1)	I	standard reliability, medium	0.4	1.0
	II	standard reliability, medium	1.0	2.5
Fig. 3(2)	I	rather low reliability, high (event (2-2)) low reliability, high (except (2-2))	0.4	1.0
	II	rather low reliability, high (event (2-2)) low reliability, high (except (2-2))	1.0	2.5

In the analysis the following are assumed: Two analysts analyze two fault trees shown in Fig. 3. One is rather pessimistic and the other is rather optimistic. Table 5 shows the reliability estimate of each basic event and the parameters *nH* and *nG* by two analysts. In this analysis example two analysts estimate reliability of each basic event to be ***standard reliability*** in the situation Fig. 3(1) and to be ***rather low reliability*** (basic event (2-2)) and ***low reliability***(except basic event (2-2)) in the situation Fig. 3(2). In the practical analysis the reliability estimate of each basic event may be usually different from each other. But in this example the reliability estimate of each basic event is assumed to be the same for simplicity.

The analyst I estimates reliabilities of the parallel system and the series system to be ***standard reliability*** and ***rather low reliability***, respectively. On the other hand the analyst II estimates reliabilities of the parallel system and the series system to be ***rather high reliability*** and ***standard reliability***, respectively. Fig. 4 shows the results of the analysis in the situation Fig. 3(1) by the two analysts. Table 6 shows natural language expressions of the analysis results.

Table 6. Natural language expressions of analysis results in the situation Fig. 3(1)

Analyst	Reliability Estimate	Fuzziness
I	rather high reliability	medium
II	high reliability	low

Fig. 5 shows the results of the analysis in the situation Fig. 3(2) by the two analysts. Table 7 shows natural language expressions of the analysis results.

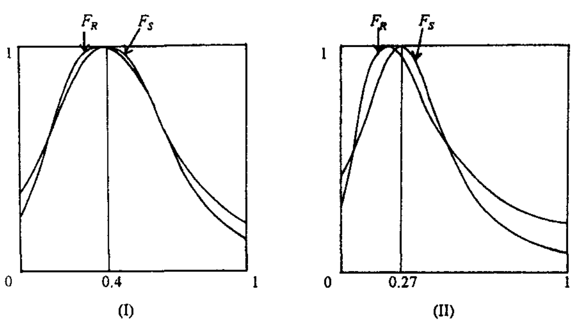


Fig. 4 Analysis results in the situation Fig. 3(1)

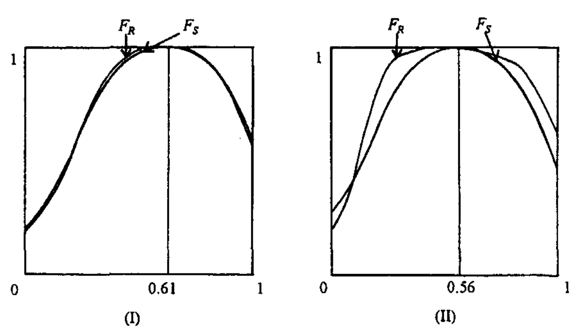
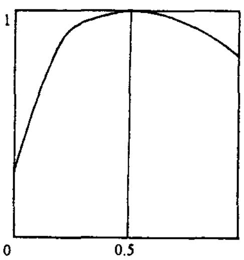


Fig. 5 Analysis results in the situation Fig. 3(2)

Table 7. Natural language expressions of analysis results in the situation Fig. 3(2)

Analyst	Reliability Estimate	Fuzziness
I	rather low reliability	high
II	rather low reliability	high

As a matter of course, reliability estimate in the situation Fig. 3(2) is lower than the one in the situation Fig. 3(1). Comparing the analysis results by the two analysts the analyst I estimates reliability of the actions to be more pessimisitc than the analyst II. These results reflect their subjectivity towards reliability of the actions at the Chernobyl nuclear power station in both situations Fig. 3(1) and Fig. 3(2).



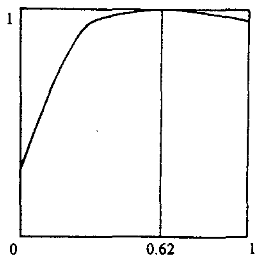


Fig. 6 Examples of criticality importance of basic event (2-2) by analyst I

Fig. 6 shows examples of the criticality importance of basic event (2-2) in the situations Fig. 3(1) and Fig. 3(2) by the analyst I. Table 8 shows 1-cut of the criticality importance of each basic event. It is found that in both cases criticality importances of event (2-2) and event (6-1) are high since event (2-2) leads to the top event directly and the failure of event (6-1) has a high influence on the failure of event (6-2).

In the presented method analyst's subjectivity can be reflected. In this example, as mentioned before, the reliability estimate of each basic event is assumed to be the same for simplicity. If analyst's subjectivity in the reliability estimate of each basic event is more reflected, analyst's subjectivity towards the analyzed system is more reflected in the analysis.

IV. Conclusions

This paper mentions the fault tree analysis with natural language. The reliability estimate of each basic event, the dependence level between some subsystems and the analysis results are expressed by linguistic terms. The meaning of linguistic terms is represented by a fuzzy set. The parametrized operations are used as the *and* and the *or* operations in the fault tree analysis. The parameters are determined depending on analys's subjectivity. The present analysis reflects analyst's subjectivity towards the analyzed system. The reliability estimation also reflects the analyst's subjectivity. This paper also defines the criticality importance of an basic event in the fuzzy fault tree analysis, which is an extended concept of the conventional criticality importance.

The analysis of the Chernobyl accident is shown as an example of the presented analysis method. In this example the reliability estimation of each basic event

Table 8. Criticality importance of basic event

Analyst	Situation	Criticality Imporatnce (1-cut)					
		(2-2)	(3-2)	(4-2)	(5-2)	(6-1)	(6-2)
I	Fig. 3(1)	0.50	0.37	0.37	0.37	0.49	0.07
	Fig. 3(2)	0.62	0.24	0.24	0.24	0.66	0.0
II	Fig. 3(1)	0.48	0.10	0.09	0.08	0.43	0.02
	Fig. 3(2)	0.65	0.10	0.09	0.08	0.66	0.0

is assumed to be same, e.g., ***standard reliability***, for simplicity. In the practical analysis the reliability of each basic event is estimated subjectively. The present paper compares the results of the presented approach with the results of the probabilistic analysis method. It is found that the presented approach reflects the analyst's subjectivity well.

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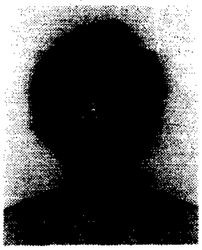

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Takehisa Onisawa received the B.S. and the M.S. in Control Engineering in 1975 and 1977, respectively, and the Dr. Eng. in Systems Science in 1986, all from the Tokyo Institute of Technology. He served as Research Associate in the Department of Systems Science, Tokyo Institute of Technology from 1977 to 1986. From 1986 to 1989, he was a Lecturer and from 1989 to 1991 an Associate Professor in the Department of Basic Engineering at Kumamoto University. Then he joined the University of Tsukuba. Currently, he is an Associate Professor in the Institute of Engineering Mechanics. He received the Hashimoto Award from Japan Ergonomics Association in 1987. His research interests include applications of fuzzy theory and soft computing technology to human interface, human intelligent behavior modelling, emotional engineering as well as reliability engineering. He is a member of IEEE, IFSA and SOFT.