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Establishing the Method of Risk Assessment Analysis for Prevention of Marine Accidents Based on Human Factors: Application to Safe Evacuation System

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Abstract

For the prevention of marine accidents based on human factor, the risk assessment analysis procedure is proposed which consists of (1) the structural analysis of marine accident, (2) the estimation of incidence probability based on the Fault Tree analysis, (3) the prediction of effectiveness to reduce the accident risk by suitable countermeasures in the specified functional system, and (4) the risk assessment by means of minimizing of the total cost expectation and the background risk. As a practical example, the risk assessment analysis for preventing "deaths in the marine fire" is investigated using the proposed method.

Keywords: risk assessment, marine accidents, human factors, reliability analysis, cost-benefit, psychological intelligence process, Safe evacuation system

1 Introduction

With the deterioration in the technical ability of ship operators without enough navigation training to achieve low transportation cost, the marine accidents such as collisions, running aground or ship fires also tend to increase gradually. It may be considerably difficult to establish the methodology for a safety measures system by originating in the human factors without uniformity. The suitable safety measures have to be taken to cope with the existence of the ambiguity of human behavioral patterns. The development of a methodology for the risk assessment analysis for the prevention of marine accidents based on human factors is becoming highly desirable in recent years.

The methodology of risk assessment analysis for prevention of marine accidents based on human factors is described in this paper. Furthermore, the safe evacuation system for preventing the deaths in the marine fire is investigated by using the proposed method. However, it may be hard to put perfectly the evacuation system on a safety, by originating in the intricacies of the fire spread phenomena and the uncertain human behaviors of evacuation. Herein, the evacuation movement can be simulated in consideration of the decrease of walking speed and the occurrence of self-isolation in psychological action by using the mathematical model of the intelligence process in an emergency. Then, the evacuation exercises may be verified to be one of effective measures for risk avoidance.

2 Reliability and risk analyses on man-machine systems

The analytical process of reliability and risk assessment is divided into three stages as shown in Figure 1. In *the structural analysis procedure*, the hierarchical analysis on the reliability of the functional system is carried out using the fault tree(*FT*). Next, the accident probability is estimated by using the probability of human error and frequency of device failure in the functional systems in the *probability calculation procedure*. In third stage as the risk assessment procedure, the countermeasures for selecting the improved items are decided in accordance with the prediction of those effectiveness.

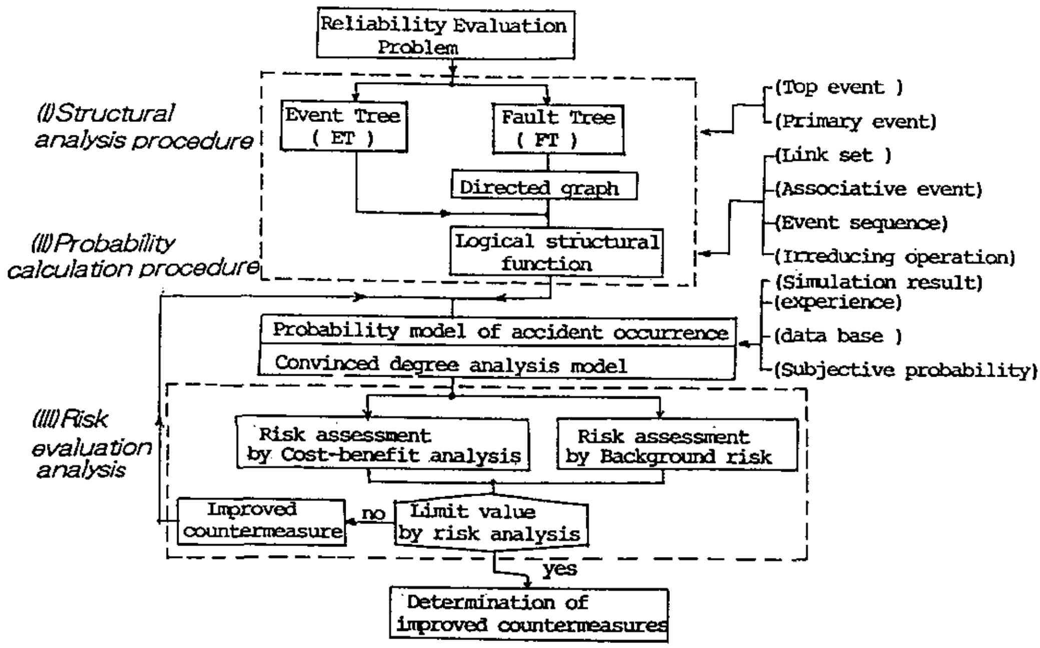

Figure 1: Flow chart of risk assessment analysis

2.1 Reliability analysis on functional systems

(1) Fault tree and logical structural function

For the sake of the hierarchical analysis on the reliability of the functional systems, the logical structure of possible accident has to be grasped entirely using a fault tree(Hayashi 1984, Rasmussen 1981) which expresses the relation between causes and effects of an accident. A fault tree is consisted in the relationship where top event is connected to independent primary events using logical *AND*-gate and *OR*-gate of Boolian function.

The fault tree of "Death in the marine fire" accident is shown in Figure 2(b) that signifies to prevent human life from lost by means of first staged fire fighting and evacuation.

As the logical structural function $\phi(x)$ can be expressed as follows:

$$\phi(x) = (x_1 \bullet x_2 \bullet x_3) \vee (x_4 \bullet x_5 \bullet (x_6 \bullet x_7)) \bullet (x_8 \bullet (x_9 \vee x_{10})) \qquad (1)$$

in which symbols "•"and "∨" denote logical *AND*-gate and *OR*-gate respectively.

(2) Probability estimation of event occurrence(Hayashi 1984, Rasmussen 1981)

For estimating the incidence probability of top event, it is necessary to ir-reduce a logical structural function in order to reject overlapped effect of the primary events being twice or more times in a function $\phi(x)$. The ir-reducing a structural function is operated to apply following laws.

a) Identical law:

$$x_i \bullet x_i = x_i, \;\; x_i \vee x_i = x_i \tag{2}$$

b) Absorptive law:

$$x_i \vee x_i \bullet x_j = x_i, \;\; x_i \bullet (x_i \vee x_j) = x_i \tag{3}$$

A logical operation should be transformed to an arithmetic calculation for estimating the probability of top event.

a) Logical sum:

$$x_i \vee x_j = 1 - (1 - x_i)(1 - x_j) \tag{4}$$

b) Logical product:

$$x_i \bullet x_j = x_i x_j \tag{5}$$

Transforming (1) by use of (4) and (5), the calculation formula $\phi_E(x)$ can be obtained as follows:

$$\phi_E(x) = (1 - (1 - x_1 x_2 x_3)(1 - x_4 x_5 x_6)) \cdot x_8 \cdot (1 - (1 - x_9)(1 - x_{10})) \tag{6}$$

In the case of considering ten primary events to be divided into two similar groups as $x_1 = x_2 = x_4 = x_6 = x_7 = x_8 = x_9$ (*Abnormal mental state, Panic*) and $x_3 = x_5 = x_{10}$ (*Existance of smoky material*), $\phi_E(x)$ is expressed to be following contraction form by identical law and absorptive law.

$$\phi_E(x) = x_1 \cdot x_3 \tag{7}$$

In general, it is difficult to find the probability of primary event originating from human error. The probability of after-mentioned example are mainly decided to refer to the data of human-reliability on Nuclear Power Plant applications(Swain and Guttmann 1983). Besides, the interview for ship operative expert may be one of effective methods for the purpose of getting the probability of primary events for an accident.

2.2 Risk assessment analysis

(1) Analytical procedure on risk assessment

The analytical process of risk assessment is divided into following four stages.

[1] The selection of governing risk factor: After the reliability analysis is carried out using Fault Tree, the distinguished primary events can be selected to be as latent dangerous factors.

[2] The quantitative analysis on accident damage by governing risk factors: The accident damage of human life, substance and environment may be predicted quantitatively for each risky factor.

[3] Estimating a degree of safety level for a countermeasure: The relation between the measures for governing risk factor and its assumed effect against risk has to be clarified.

[4] The risk assessment: The intensity of countermeasures for improved items are decided by the judgments of cost-benefit and background risk.

(2) The methods for risk assessment

In the case of executing a risk assessment, it needs to determine the limit of financial load for safety, especially securing human life, regardless of value judgement of human life, by following ways.

[1] Cost-benefit assessment

The safety level may be decided to seek the minimum of expectance total loss(E) as follow:

$$E = p_H U_H + U_S + C \tag{8}$$

in which, p_H, U_H are respectively the probability of human loss and valuation of human life. Also, U_S is the physical loss and $C$is the cost of safety measures.

[2] Assessment based on background risk

The method of cost-benefit assessment by expectance total loss contains unfavorably the hard problems on the value of human life. In order to avoid this judgement, the permissible probability of human life loss is decided using a background risk that means the probability of a dangerous affair in daily life, and also minimum economical load.

Following items and probability are usually applied to background risk in Japan: *Unexpected accident*(2.1×10^{-4}), *Traffic accident*(0.85×10^{-4}), *Automobile accident*(0.68×10^{-4})

3 An applied example: Safe evacuation system

3.1 Reliability analysis on safe evacuation system

(1) The fault tree and distinguished primary events

The fault tree of "*death in marine fire*" accident may be expressed minutely as Figure 2(a) in which the estimated incidence probabilities(Hayashi 1984, Swain and Guttmann 1983) are respectively put down with every events and the probability of top event is 0.352. By using high incident probability events only, the fault tree is simplified to be Figure 2(b) that is the tree consisted of extreme distinguished primary events "*Abnormal mental state*"(incident probability: 0.5) and "*Existence* *of smoky material*"(0.7). And these events can be seen as decisive factors by the fact that logical product of two extreme events is calculated to be 0.350. Accordingly, the safe evacuation system can be effectively established by working out measures to two distinguished primary events.

(2) The measures to the distinguished primary events

The measures to two distinguished primary events may be taken as follows:

[1] Event "*Abnormal mental state*": Education and training on fire fighting and evacuation are rather useful to avoid the panic state as mental self-isolation(Ikeda 1986, Kugihara 1995) (described minutely in 3.2).

[2] Event "*Existence of smoky material*": It is to be desired that floor, ceiling, wall and furnishings are made by non-smoky or non-inflammable material.

3.2 Necessity of training based on psychological intelligence process in an emergency

(1) The psychological intelligence process model

The psychological intelligence process in emergency conditions, such as marine fires and ship sinking accidents, is assumed as the flow chart(Ikeda 1986) shown in Figure 3(a) that is composed of *the recognition of circumstance, the judgement of situation, the action with comprehend and the correspondence.* During a dangerous condition, *the comprehending script* and *the action script* are activated for redefinition of circumstance and producing action expectancy. These scripts are the fixed form of individual knowledge about judgement of specified situation and normative action that depends on the quantity of education and training taken in the concerned person's life.

In a case of severe expectancy of circumstance, *the mental self-isolation* like as panic state occurs in consequence of the emotional reaction beyond the threshold of fear. For keeping away from the self-isolation occurrence, it will need to increase the quality and quantity of both scripts by undergoing train and education.

(2) A mathematical model of the intelligence process(Fukuchi et al 1999)

A block diagram of the psychological intelligence process in an emergency is expressed in Figure 3(b) as a mathematical model of control engineering in which u is the stimulus by an accident (input), y is the reaction of emotion and action (output), A is the coefficient of action script, B is the coefficient of monitoring ability and $1/s$ means integral operation.

The transfer function of this arithmetic model can be expressed as follows:

$$\frac{Y(s)}{U(s)} = \frac{C}{s^2 + As + B} \tag{9}$$

Also, the state equation is given as following form.

$$\frac{d^2y}{dt^2} + A\frac{dy}{dt} + By = Cu \tag{10}$$

Table 1: Magnitudes of stimuius by an accident and personal capacity

(a) Input of Stimulus

	Stimulus by an accident
Grade-I	0.25
Grade-II	0.5
Grade-III	1.0
Grade-IV	2.0

(b) Set up of Ability

	High	Low
Action script "B"	13.0	9.0
Monitoring ability "C"	0.34	0.25

Magnitude of "C": 20.0
(comprehending Script)

in which t denotes time and C is a constant governed by comprehending script. The emotional reaction for input stimulus can be simulated as time proceeds in the condition of given magnitudes of coefficients A, B, C.

(3) The control factors for psychological model(Fukuchi et al 1999)

The control factors for psychological model are determined as under-mentioned by the analytical results of psychological experiments(Kugihara 1995) and case study(Ikeda 1986) on accident instances.

[1] The grades of accident stimulus: The magnitude of stimulus is classified as grades I IV and the input values are shown in Table 1(a). For an example, the grades for the case of marine fire are decided based on several case studies as follows:

Grade-I: Hearing the emergency fire alarm and the warning broadcast

Grade-II: Exposing in the smoke layer under 1.5m height.

Grade-III: Exposing in the smoke layer under 0.9m height.

Grade-IV: Exposing in the smoke layer under 0.9m height and perceiving a fire flame.

[2] Comprehensive script: The degree of comprehensive script is classified into three levels as *high, middle, low* with following operations.

Level-*high*: Lowering input stimulus down as one grade

Level-*middle*: Keeping input stimulus

Level-*low*: Raising input stimulus up as one grade

[3] Action script: The level of action script is classified as *high* and *low* and the input values are shown in Table 1(b).

[4] Monitoring ability: This ability is a capacity on recognition and expectation of circumstance. The level of monitoring ability is classified as *high* and *low* shown in Table 1(b).

(4) Mental self-isolation

An accident stimulus going beyond terror threshold, outbreak of the self-isolation occurs and various kinds of human capacity are reduced extremely. In this calculation, it takes an assumption

Table 2: Occurrence states of self-isolation according to various stimulus grades

comprehending script	High				Middle				Low			
Action script	High		Low		High		Low		High		Low	
Monitoring ability	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Grade-I	n	n	n	n	n	n	n	n	n	n	n	n
Grade-II	n	n	n	n	n	n	n	n	n	n	o	o
Grade-III	n	n	n	n	n	n	o	o	o	o	o	o
Grade-IV	n	n	o	o	o	o	o	o	o	o	o	o

based on the results of MFF-test and many case studies(Ikeda 1986, Kugihara 1995) that human capacity is drastically decreasing as so far as 10 percents during outbreak of the self-isolation. Further, the incidence probability of human error is still known to be about 50 percents at a panic state.

The occurrence states of self-isolation according to various stimulus grades and personal capacity is shown in Table 2. From this table, It can find out from this table that increasing comprehensive and action scripts by undergoing training and education is effectively in anticipation of avoiding an occurrence of self-isolation.

(5) A simulation of evacuation in marine fire(Fukuchi et al 1999)

In order to verify the effectiveness of proposed psychological model, the evacuation state in fire accident of a cruising ship (refer to Figure 4(a)) is numerically simulated. The walking tracks of evacuees are predicted in Figure 4(b) that locations of evacuees are shown as mark(◯) at one second interval and crammed marks mean the outbreak of the self-isolation.

The reducing rates of walking speed are respectively varied with time in Figure 5 according to personal properties and Figure 6 denotes evacuation times toward walking distances for a various stimulus and evacuee abilities.

3.3 Risk assessment for the selected countermeasures

(1) The incidence probability of accident corresponding to measures level

A degree of measures is set up three levels as { Level-N,n: no measures}, { Level-A,a: moderate measures},{Level-B,b: high-degree measures}.

[1] The measures for event "*Abnormal mental state*" are assumed concretely by the basis of 3.2 and a behavioral learning theory, as level-N: no training, level-A: once training and level-B: three times training.

[2] The measures for event "*Existence of smoky material*" are assumed the furnishings made by non-smoky material, as level-n: no execution, level-a: one third of whole area of practicable material control and level-b: two third of whole area of practicable material control.

The ambiguity effects of the measures for "*death in marine fire*" accident may be respectively expressed membership functions to three levels like as Figure 7(a). After taking the measures for two distinguished primary events, the probabilities of accident are estimated as shown in Figure 7(b) and the value of executing two kinds of measures simultaneously can be obtained by the product of two probabilities.

(2) Quantifying risk and safety level

A {risk on human life: R_H} can be predicted by the product {probability of fire accident with human loss: p_F} and {number of human loss: N_L}, in which N_L consists of {probability of "*death in marine fire*"} ×{number of embarkation}.

The safety level: S_i is defined to be the inverse of risk decisive factor p_i and the safety level consisted of n-decisive factors S can be represent as follows:

$$S = \prod_{i=1}^{n}(1/p_i) \tag{11}$$

(3) Selecting the degree of measures by risk assessment

A numerical example is carried out by using the following calculation conditions:

[a] Subject: Cruising passenger ship (77,000GT, Passenger: 1780 persons, Crew: 860 persons)

[b] The cabin crews only have to go through eight hours evacuation training at one time and the expense of special paid for training is 2000Yen (about 20US dollars)/hour/person.

[c] The difference cost between smoky material and non-smoky material is 2000Yen/m^2.

The results of risk assessment by a cost-benefit analysis of measures for two distinguished events is shown in Figure 8. It denotes that the reasonable number of training time is once a year (level-A) and the rational area using non-smoky material is one third of whole area of practicable material control (level-b).

Furthermore, the results of risk assessment analysis based on a background risk for two measures is shown in Figure 9(a) and (b). It means that the number of training time is desirable to be twice a year (level-$A \sim B$) and the suitable area using non-smoky material is two third of whole area of practicable material control (level-$a \sim b$), according to judge by using the probability of automobile accident.

4 Conclusions

The methodology of risk assessment analysis based on human factors is established to prevent marine accidents and a validity of this procedural method can be verified fairly by applying to the safe evacuation system. Moreover, it can be clarified the availability of training and education for avoiding the mental self-isolation occurrence in case of severe circumstance at accident, by using the mathematical model of the intelligence process.

For applying the proposed method to practical safety problems, it is necessary to accumulate hereafter the data of case studies on accident instances and the results of psychological experiments.

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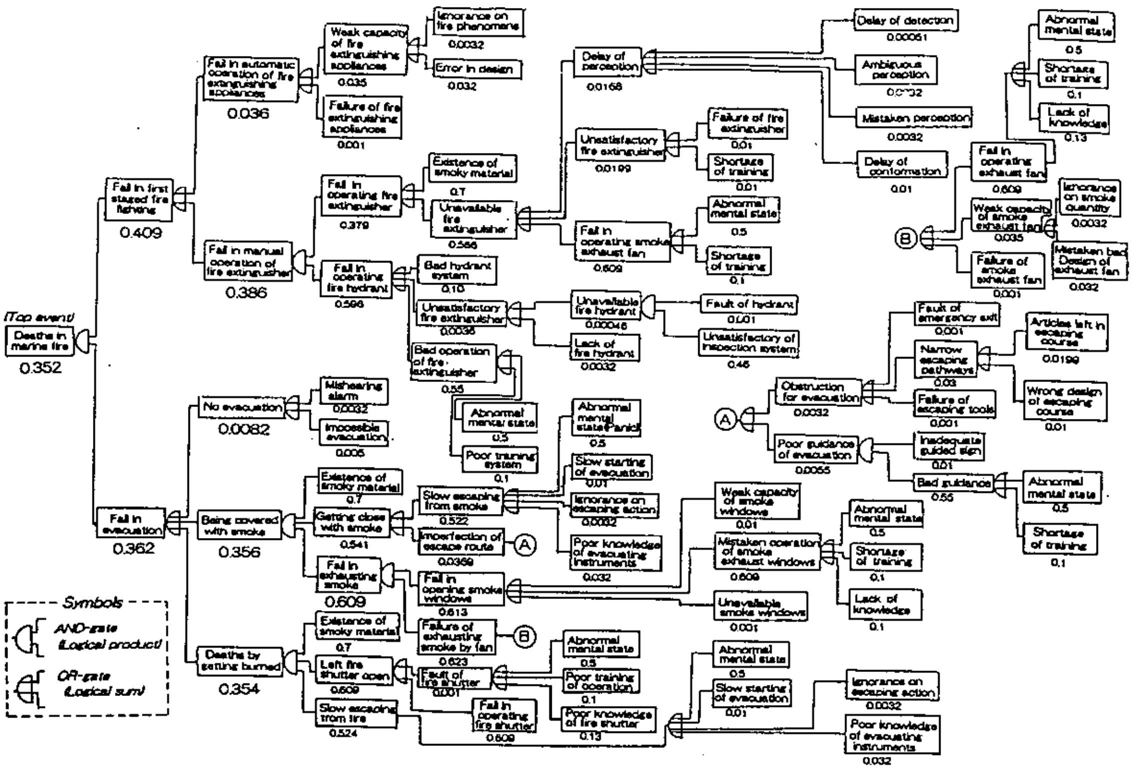
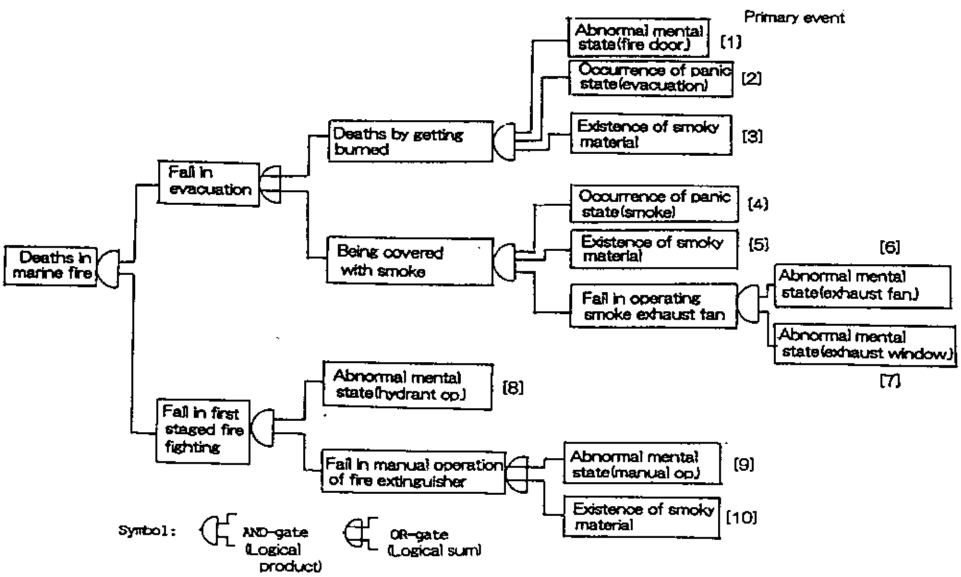
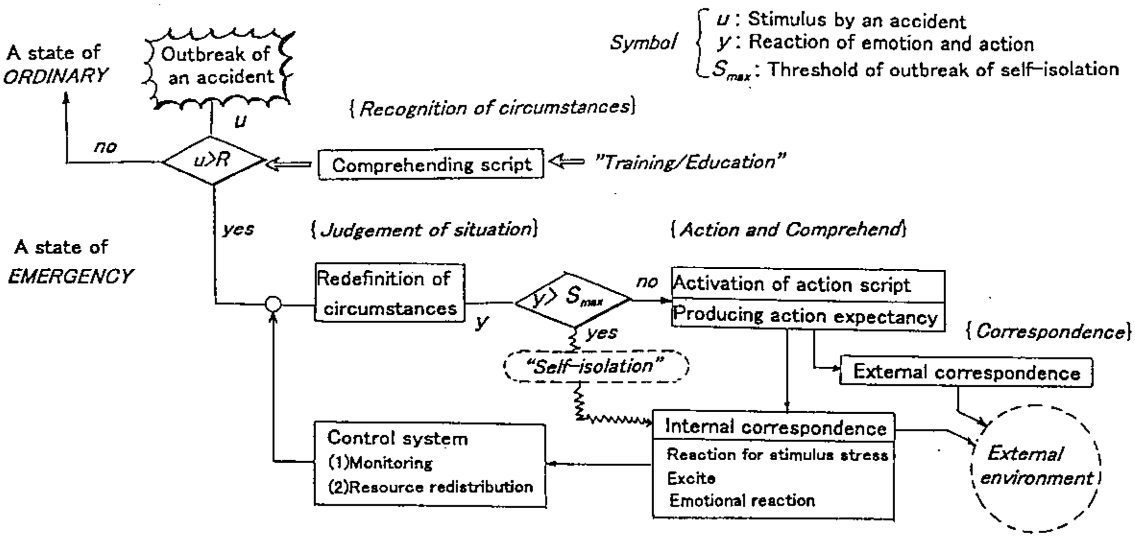


(a) Using whole primary events

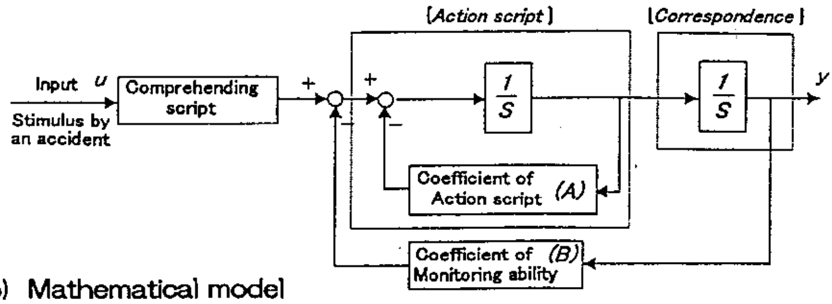


(b) Using only distinguished primary events

Figure 2: Fault tree on "Deaths in marine fire" accident

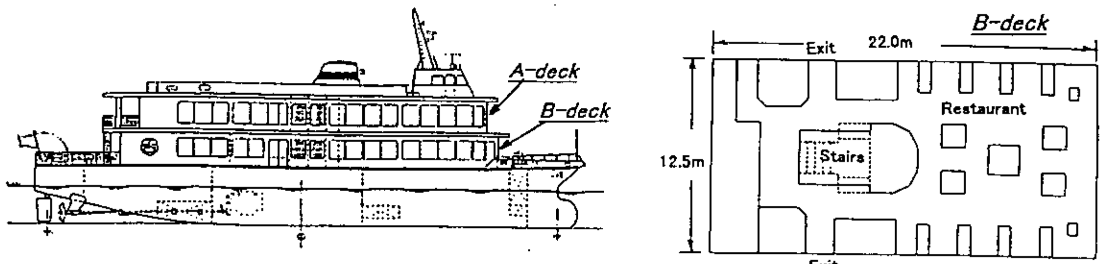


(a) Flow chart of intelligent process

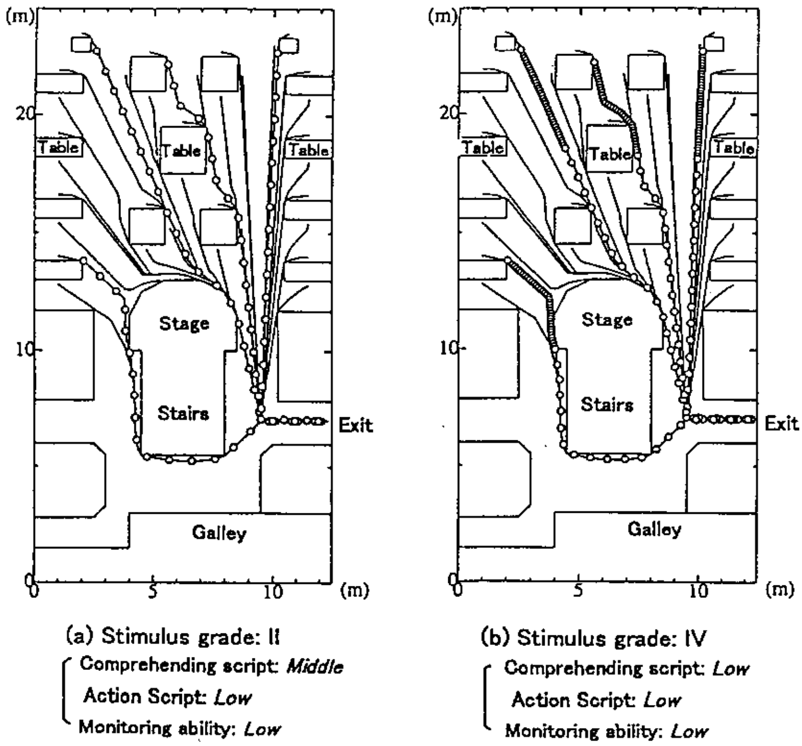


(b) Mathematical model

Figure 3: Modeling paychological intelligent process in a state of emergency



(a) Cruising ship "A" for simulation



(b) Walking tracks of evacuee with constant ability from B-deck

Figure 4: Evacuation behavior on a cruising ship

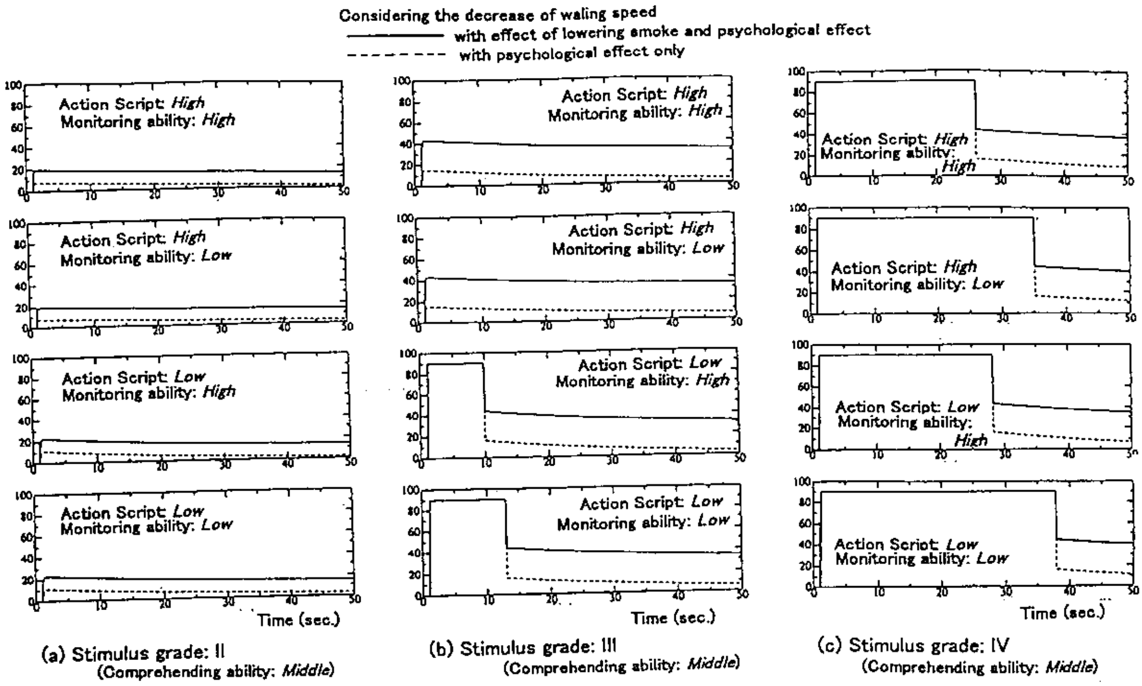


Figure 5: Reducing rate of walking speed by smoke and psychological effect

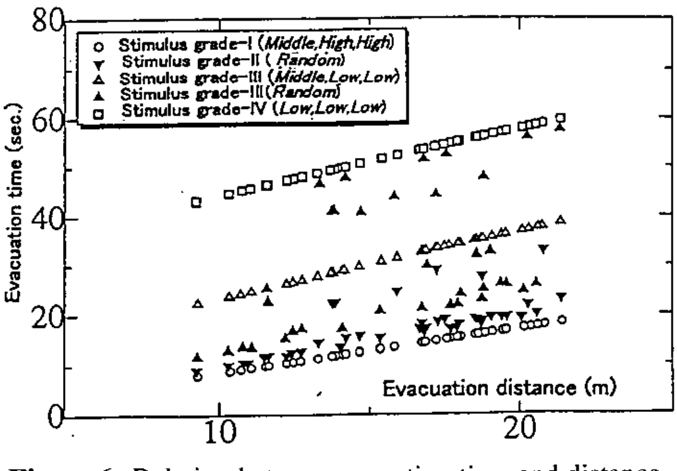


Figure 6: Relation between evacution time and distance

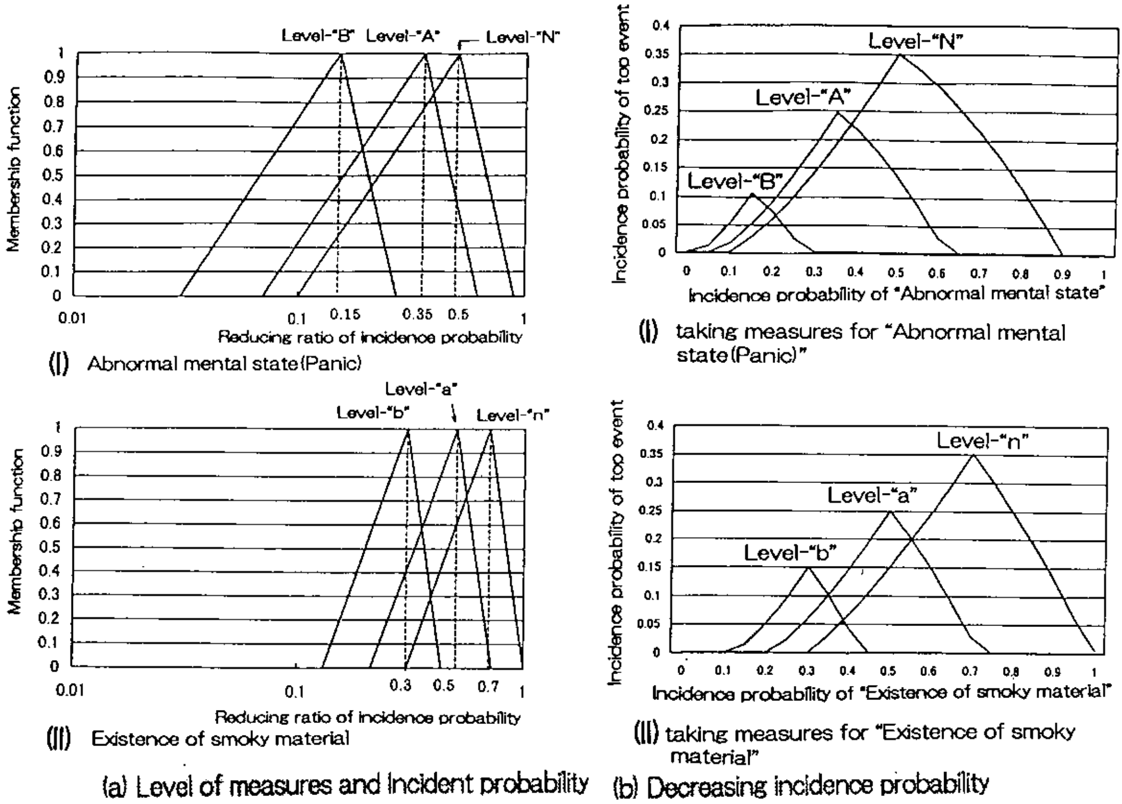


Figure 7: Assumed effect of the measures for two distinguished primary events

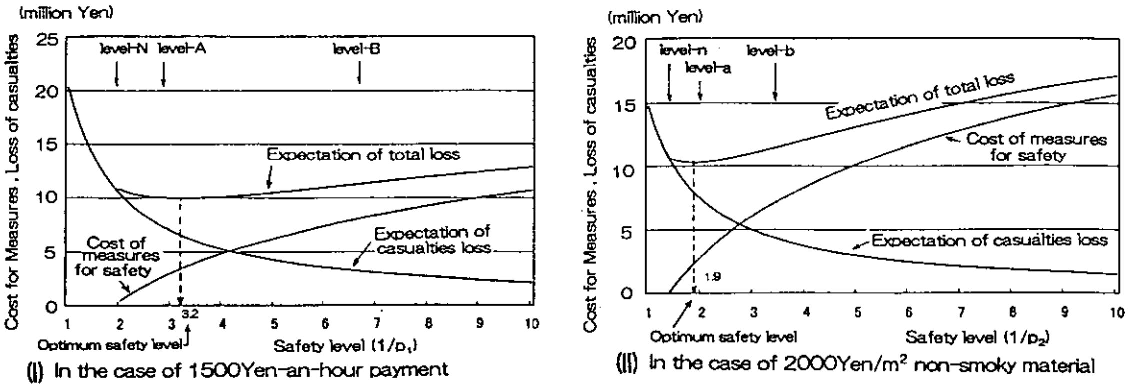


Figure 8: Risk assessment based on cost-benefit analysis for the measures

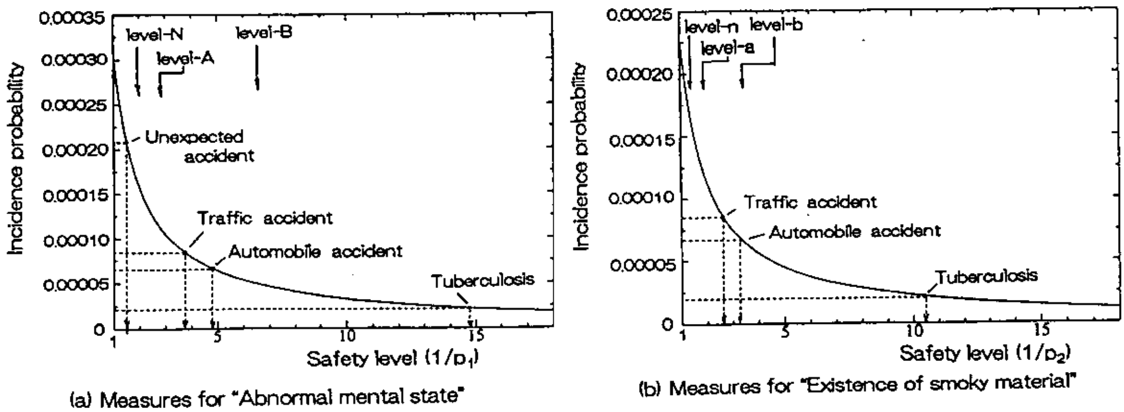


Figure 9: Risk assessment based on background risk for the measures