A technique to prioritize plausible counter operation procedures in an accidental situation of plants

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Abstract: For accomplishing the safety of a large-scale engineering plant, the common approach is to suppose various emergency situations and prepare in advance effective measures. However, there may happen an unanticipated event. Therefore, it is very important to generate support information for operators to take responsive actions. The previous study developed a technique to generate plausible operation procedures for an emergency situation based on a functional model. Although the algorithm produces some plausible counter operation procedures, it does not indicate which counter operation procedure is suitable. It is desirable for operators that the technique can prioritize the counter operation procedures produced. This study proposes a technique to prioritize plausible counter operation procedures considering the accidental situation happened and the strategy of counter operation decided by operators. The counter operation procedures are evaluated by several evaluation indices such as the effect for achieving the objective, the required time of executing a counter operation procedure, the influence on the environment, and so on. These indices are investigated from the viewpoint of risk assessment. The weights to evaluate the priority of a counter operation procedure are adjusted according to the counter operation strategy decided by operators. The priorities of counter operation procedures are finally determined by the weighted values of evaluation indices. The applicability of the proposed prioritizing technique is confirmed by several priority evaluating examples for the plausible operation counter procedures produced for the LOCA cases.
Keyword: functional model; Multilevel Flow Modeling; counter operation procedure; prioritization

1 Introduction

It is important to suppose various accidents and to prepare in advance efficient measures in order to minimize the damage in the happening of an accident. Basically operators are asked to take counter measures following operation procedures. However, there might happen an abnormal situation that is not supposed due to the troubles of safety systems. Therefore, it is desirable to support operators in such a situation as well as to suppose abnormal situations and to prepare counter measures for them as many as possible.

There is a study [1] that proposed a technique to find plausible responsive actions against an emergency situation. However, the technique cannot produce operation procedures that are composed of several actions. The previous study [2] developed an algorithm to generate counter operation procedures based on the functional model by the Multilevel Flow Modeling (MFM) [3] [4] in order to keep a safe condition of a large plant system from unexpected situations caused by a devastating earthquake, *etc.* The Pressurized Water Reactor (PWR) was selected as a target plant because a nuclear power plant is a large-scale safety critical system that mainly circulates water and heat to produce electric energy. The MFM model and proposed algorithm enable to represent not only whole flows of mass and energy but also to find the way of responsive actions in an emergency situation. In other words, it substantiates to find an appropriate method of accident managements (AMs).

The previous study [5] does not consider to determine the priority of a counter operation procedure derived.

A decision making by operators in an accidental situation will be supported by showing the priority of a procedure. This paper investigates the indices to evaluate counter operation procedures by the viewpoint of risk assessment. Moreover, this paper

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considers the weights of the indices by the viewpoint of "defense in depth". The applicability of the method to prioritize the procedures is also studied for an example case of accidental situations.

2 Concepts of the safety protection and related works

2.1 Defense in depth

"Defense in depth" [6] is one of the safety ensuring concepts for designing nuclear power plants. It is one of the fundamental principles of the safety in nuclear power technology, and it is important to achieve the principle for safety study and safety design in nuclear power plants.

Generally, "Defense in depth" protects nuclear power plants by five layers [6]:

First layer: Preparing to prevent occurrences of disturbance.

Second layer: Preparing to reduce the influence of disturbances to equipment.

Third layer: Preparing to avoid the release of radioactive substances even if serious failures have occurred in equipment

Fourth layer: Preparing to avoid the considerable release of radioactive substances even if core damage has happened.

Fifth layer: Preparing to suppress public exposure of radioactivity even if serious release of radioactive substances happens.

"Defense in depth" is composed of multiple layers for the case when several layers don't work well [7]. These layers enable to respond to an anomaly and failure if some layers have broken and to reduce the influence of an accident. We expect that the proposed technique to generate plausible operation procedure for an emergency situation can strengthen the third and fourth layers of "Defense in depth".

2.2 Resilience engineering

Applying the concept of resilience engineering [8] will contribute to realize "defense in depth". Resilience engineering focuses on how humans respond to a thread flexibly and how humans recover the damaged system in an early stage of disturbance happening.
The system generates operation procedures by using the component that has the same function as that of failed component. By the support of the computer system, human operators will take suitable counter actions resiliently.

2.3 Related works

The related study [1] proposes a selection method of plausible counter action. The related study derives counter action when an oil refinery plant becomes to an anomalous situation and selects the most suitable counter action by the operational knowledge about components, effect knowledge of each counter action, and effect influence knowledge based on plant structure and physical behavior of components.

The operational knowledge represents the operability and availability of each counter action. The effect knowledge is the explicit representation of knowledge about the effect of an operation on plant behavior which operators acquire empirically from their operation experience. The effect influence knowledge is derived based on physical behavior of engineering systems.

However, the related study did not consider the effect on environment. The effect on environment by executing the operation procedures has to be considered because this paper deals with a nuclear power plant that may give serious influence on the environment at an accident as the target plant. Therefore, this paper considers more indices to prioritize the counter operation procedure.

For various types of accidental situations, there are symptom-based operation procedures [9] to take counter measures according to the decision made using the plant parameters that can directly be measured. The procedures are the complementary procedures of the event-based operation procedures for specific events [10]. Owing to the symptom-based operation procedures, operators can take suitable counter measures without being involved with an accidental scenario when the event happened has not been identified [11]. Moreover, for the case that a safety function is damaged, the safey function-based operation procesures are also prepared to recover the safety function damaged and to maintain the function in order not to develop to a catastrophic accident [12].

The generation technique of operation procedures that this study deals with can generate online symptom-based operation procedures if the objective of counter measure is specified as a desirable value change of a plant parameter. It can also generate safety function-based operation procedures if the objective is specified as the safety function to be recovered.

3 Multilevel Flow Modeling

3.1 Functions and functional modeling

We modeled a target plant by focusing on functions of it. The characteristics of functions are as follows:

(1) functions are in high abstraction level, and

(2) a function explains that why a component exists in a system [13].

A function may be realized by different components. Furthermore, a component may have behaviors that are not recognized as functions in the original design but may be recognized as functions in abnormal conditions [14].

3.2 Multilevel Flow Modeling

MFM [3] [4] [15] is one of the functional modeling method. MFM makes the model of an engineering system from the viewpoints of functions and objectives. MFM expresses sub-flow structures of mass, energy, action, and information by using a set of primitive functions [3] [4]. Figure 1 shows the symbols of MFM.

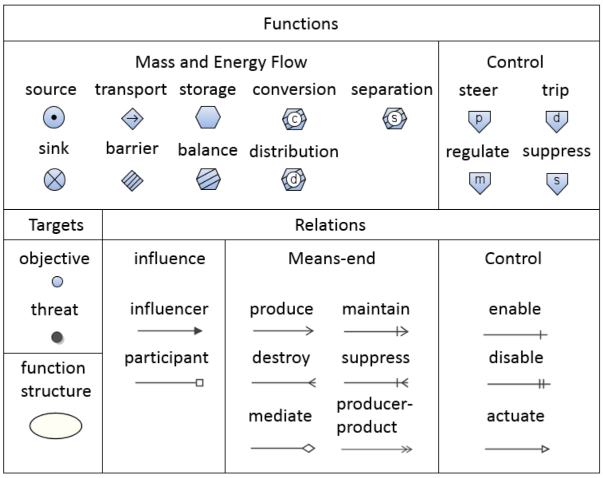


Fig. 1 Symbols of MFM.

The symbols of primitive functions are represented in the "Functions" part of Fig. 1. The roles of systems and components are represented by "objective" and "threat" of the figure. Each function is connected by a relation symbol of the sub-category of "influence". The connected functions form a function flow in a form of graph. These graphs constitute "function structure" and mass and energy sub-flow structures represent energy and mass flows of the target system. Relations between primitive functions and "targets" are represented by a relation symbol in the category of "means-end" and "control".

The states of objective, threat, and each function primitive are defined by referring the literature [16] except for "source" function. Table 1 shows the states for functions and objective/threat. The "True (high)", "True (low)" or "False" state is assigned to "objective" according to the accomplishment of them. The definition of states of "threat" is similar to those of "objective". Because the "source" function is defined as a source with infinite capacity, the state of "source" function is expressed in this study as one of "Normal", "High flow potential", and "Low flow potential" according to the force to flow. The capacity of "sink" function is also treated as infinity in MFM. Therefore, the state of "sink" function is expressed by the input flow. The states of "transport" and "storage" functions are expressed by the flow through the function and the volume in the function, correspondingly. Because the purpose of "barrier" function is to keep not flowing, the state of it can be "Normal" or "Leak". The "balance" function is used to express a component that its input and output flows are balanced, its state can be "Normal", "Unbalance (fill)", or "Unbalance (Leak)".

Table 1 States of the symbols

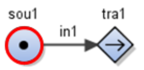
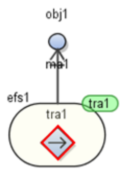
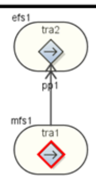
Symbols	The states of the symbols
Source:	Normal, High flow potential, Low flow potential
Sink:	Normal, High input flow, Low input flow
Transport:	Normal, High flow, Low flow
Storage:	Normal, High volume, Low volume
Barrier:	Normal, Leak
Balance:	Normal, Unbalance(fill), Unbalance (leak)
Threat:	Exist(high), Exist(low), Non-exist
Objective:	True(high), True(low), False

3.3 Influence propagation rule

Influence propagation rules are needed to make a causal inference based on an MFM model. Influence propagation rules indicate how the states of the neighboring functions and objectives/threats change when the state of a focusing function or objective/threat changes. By using the rules, we can know how the influence of the state change of a function or objective/threat will propagate in the MFM model.

We have derived influence propagation rules for each combination of MFM function primitives and relations by referring the previous studies [2] [15]. Some of influence propagation rules are shown in Table 2.

Table 2 Examples of the influence propagation rules

Patterns	Cause	Downward consequence
	sou1	tra1
	High flow potential	High flow
	Low flow potential	Low flow
	tra1	obj1
	High flow in state 1	True (high)
	Low flow in state 2	True (low)
	State 2	False
	tra1	tra2
	High flow	High flow
	Low flow	Low flow

4 Generating operation procedures based on an MFM model

4.1 MFM model of a pressurized water reactor plant

The simplified schematic diagram of a PWR plant is shown in Fig. 2. The preceding study [5] constructs an MFM model for the major systems and some safety systems of a PWR plant such as the primary system, the secondary system, the turbine bypass system, the residual heat removal system, the internal spray system, and the fire protection system.

Figure 3 shows the constructed MFM model. In this MFM model, there are two large mass flow structures (MFSs) in the center of the figure. The left MFS represents the water flow of the primary system, the residual heat removal system, and the fire protection system. On the other hand, the right MFS represents the steam/water flow of the secondary system and the turbine bypass system. These MFSs are connected with the objectives that represent the primary flow and the secondary flow. Furthermore, these objectives are also connected with energy flow structure (EFS) that represents heat transfer from primary side to secondary side because the continuous flows in primary and secondary flows are necessary for the heat transfer.

4.2 Considered accidental situations

In this study, three severe accidental situations of a PWR plant are considered. They are loss of coolant accident (LOCA) cases after the detection of partial core damage with the conditions such that (A) the emergency core cooling system (ECCS) and main steam relief valve fail to initiate, (B) the residual heat removal system does not work, and (C) internal spray system fails to initiate. The real Japanese PWRs prepare counter procedures what are called the accident managements (AMs) for the situations using suitable components that are originally equipped for other purposes: "usage of turbine bypass system" for the case A, "alternative recirculation" for the case B and "water injection into a reactor containment" for the case C [17].

4.3 Derived operation procedures

Table 3 shows the derived operation procedures and AMs. As shown in the table, the same procedure as AM for each case is successfully derived by the proposed algorithm based on the constructed MFM model. Moreover, the proposed algorithm derives some other candidates of operation procedures than the AM for each case. These operation procedures are considered to be effective to reduce the negative influence due to the accidental situations. However, the degree of effectiveness of each operation is not estimated because the proposed algorithm uses qualitative reasoning.

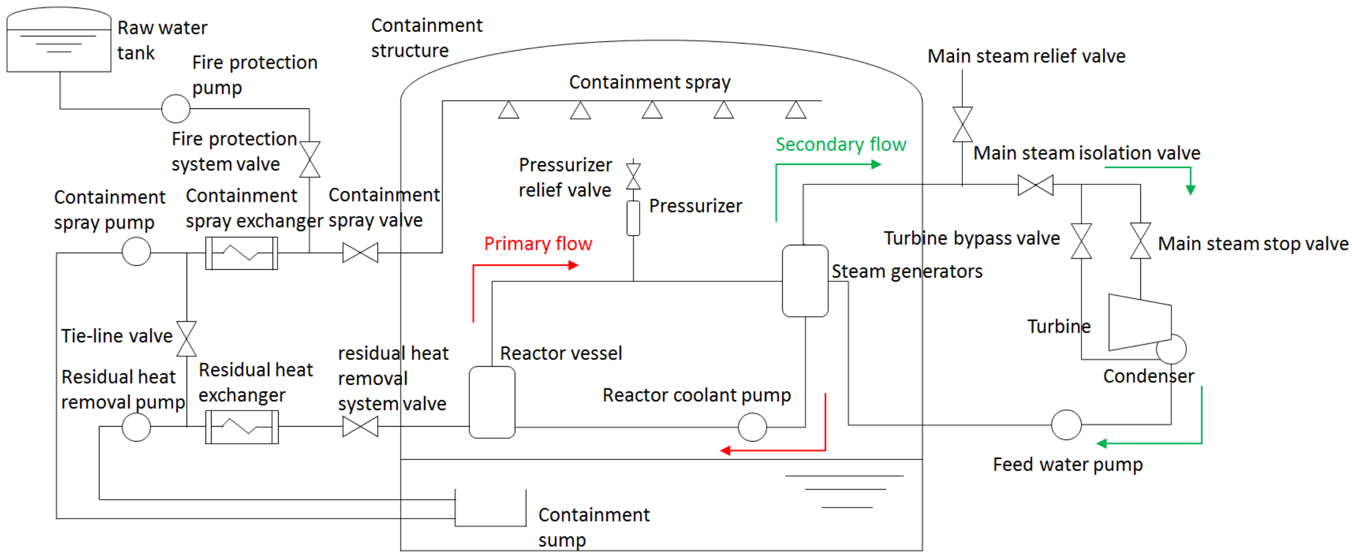


Fig. 2 Schematic diagram of the PWR plant.

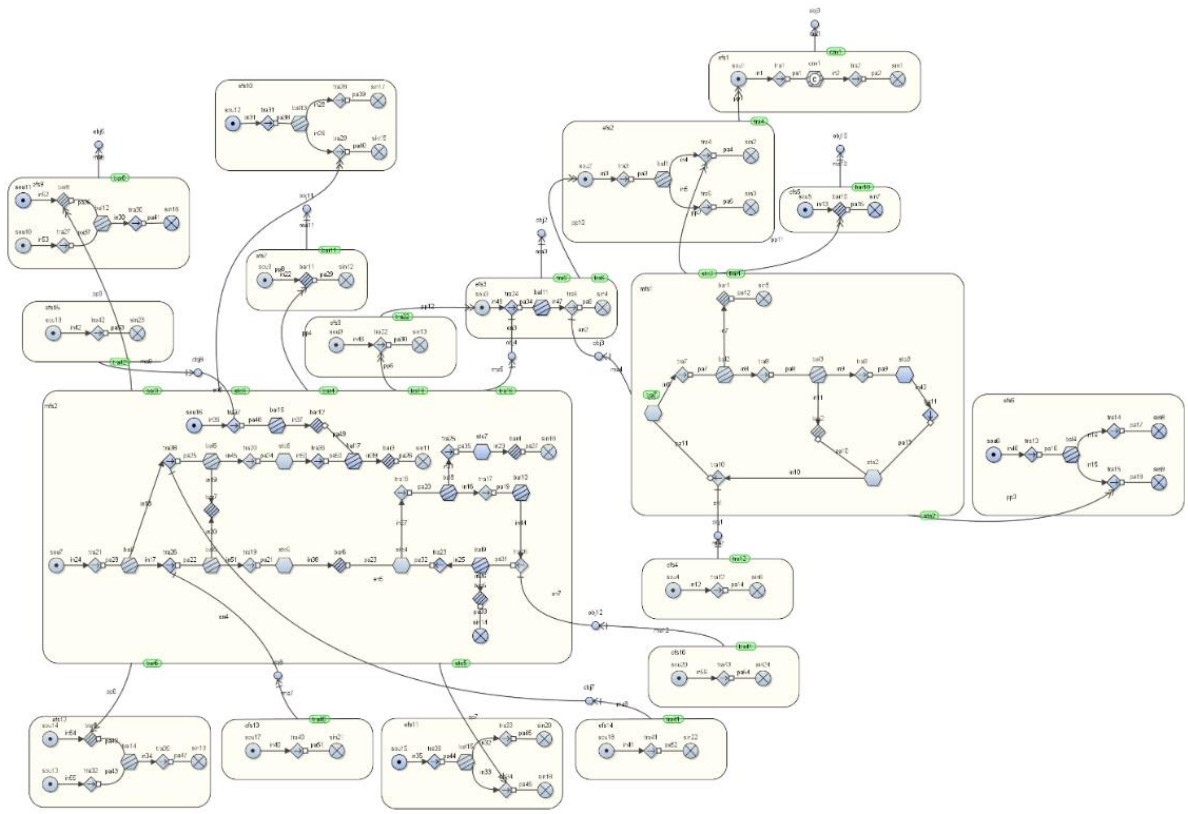


Fig.3 MFM model of a PWR plant.

Table 3 Comparison between derived operation procedures and AMs

Generated procedures			AMs
A	a	1. Opening MSIV 2. Opening TBV	1. Opening MSIV 2. Opening TBV (Using turbine bypass system)
	b	1. Opening pressurizer relief valve	
B	a	1. Opening MSIV 2. Opening TBV	
	b	1. Opening tie-line valve 2. Opening residual heat removal valve	1. Opening tie-line valve, 2. Opening residual heat removal system valve (Alternative recirculation)
	c	1. Opening pressurizer relief valve	
	d	1. Opening main stream relief valve	
C	a	1. Opening pressurizer relief valve	
	b	1. Opening main stream relief valve	
	c	1. Opening MSIV 2. Opening TBV	
	d	1. Opening residual heat removal valve	
	e	1. Opening fire protection system valve 2. Opening containment spray valve	1. Opening residual heat removal valve 2. Opening containment spray valve (Water injection into a reactor containment)

5 Prioritization of counter operation procedures produced

5.1 Investigation of the indices to prioritize derived operation procedures

The indices to prioritize the counter operation procedures are investigated and the selected indices are shown in Fig. 4.

The risk in engineering is defined as the function of effects and probabilities. In the safety studies of the nuclear power plants, probabilistic risk assessment (PRA) [18] defines the risk by the impact of the damage of undesirable events and the occurrence frequency of the events. Therefore, the indices should be selected by the viewpoint of risk assessment.

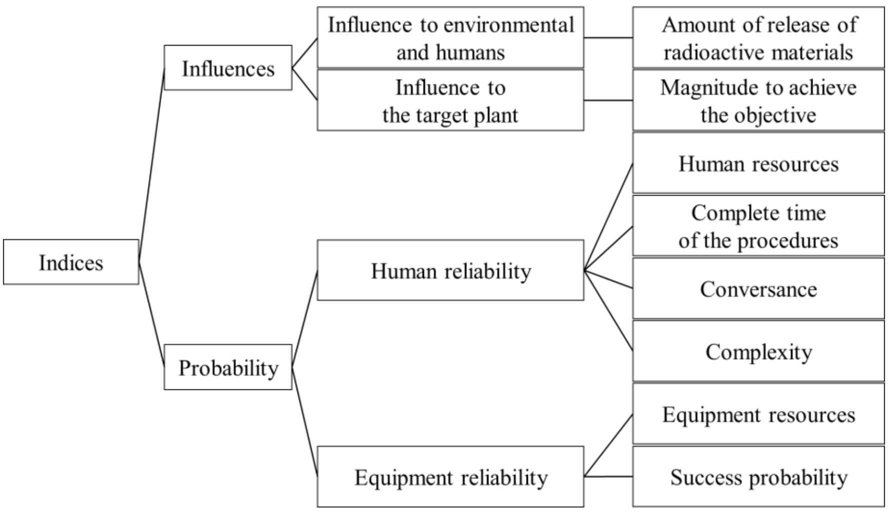


Fig. 4 The indices of the operation procedures.

First, we consider the effect by executing the procedure. The influence is divided into two types of the influence to environment and the influence to the target plant. The influence to environment means the release of the radioactive materials, and the influence to the target plant means the damage protection by the achievement of the objective of procedures.

Next, we consider the reliability. The reliability of the procedures is also divided into two types, that is, reliability of equipments and reliability of operators. The reliability of an equipment depends on whether the target plant has alternative equipments and the failure rates of the equipment.

The human reliability is considered by human reliability analysis (HRA) [18] that gives some factor for shaping human's performances (performance shaping factors: PSFs). PSFs include factors such as the time pressure, physical and/or mental workload, extent of training, plausibility of the procedures, complexity of the tasks, and the culture of the organizations.

This paper selects the complete time of the procedures, human resources, conversance of the procedures, and complexity of the procedures as the indices of the human reliability from the viewpoint of HRA. The indices selected in this study are compared with those listed in the literature [1]. The four indices of "Magnitude to achieve the objective", "Conversance", "Complexity", and "Success probability" are selected by both studies. This study newly derives four indices of "Amount of release of radioactive materials", "Human resources", "Complete time of the procedures", and "Equipment resources". A counter operation procedure will be more strictly evaluated by considering the new four indices selected in this study as well as the four ones listed in the literature.

5.2 Weighting and scoring of counter operation procedures

This paper prioritizes the counter operation procedures derived for accidental situation B as an example. The scores for an operation procedure generated and weights of indices for the two viewpoints predetermined in this study are shown in Table 4.

The score of an index is expressed between -1 and 1. The higher value is better. On the other hand, the weight of an index is given to one of among 1 to 8 as the ordinal scale. The values of scores and indices are artificially determined by considering plant structure and the viewpoint of "defense in depth" by the authors and should be tuned properly based on expert opinions and simulation results in a real application. When a small accident happens, the operators will execute the operation procedures that have no influence on environment. On the other hand, if a severe accident happens, the operators may execute the operation procedures that have large effect to cooling primary flow. Therefore, this study calculates the score of counter operation procedures by some weighting patterns of the indices.

The weights are determined by the approach of "defense in depth" [6]. The first layer, second layer, and the third layer of "defense in depth" are supposed for the accident that doesn't exceed design criteria, and the forth layer and fifth layer are considered for the accident that exceeds design criteria. Then, this study considers two patterns of weighting of the indices.

The weighting pattern (viewpoint 1) for the first layer, second layer, and third layer in "defense in depth" is set by considering that the influence of environment, the reliability of equipment, and reliability of human are important. Another weighting pattern (viewpoint 2) for the fourth layer and fifth layer in "defense in depth" (viewpoint 2) is set by considering that the achieving the objective of the counter operation procedures is important. This weighting pattern considers a small amount of release of radioactive materials.

When a more severe accident happens in another plant at the same time, an increase of human resource will not be realized for the plant happening a design-based accident. In addition, there is time to spare for counter actions. From these considerations, the weight for the index of "Complete time of procedures" is set to a small value. On the contrary, the weight for the index of "Complete time of procedures" is set to a large value and the weight for the index of "human resource" is set to a small value from the consideration that operators will prioritize to make an early convergence of the accidental situation in the case of happening a design extension accident.

Next, this paper explains the scoring of each operation procedures. "Amount of release of radioactive materials" is scored by whether the procedure releases the steam to air. "Magnitude to achieve the objective" is scored by the cooling effect to the primary flow because the procedures are produced to achieve the objective of cooling the primary flow. "Human resources" are scored by the amount of human resources to execute procedures. "Complete time of the procedures" are scored by the number of the operation of the procedures. "Conversance" are scored by whether the procedures include in ordinal operations and operators know well them. "Complexity" is scored by whether the operators can suppose the changeable state of the plant by executing the procedures. "Equipment resource" is scored by whether the target plant has alternative components that is related to procedures. "Success probability of the procedures" is scored by the failure rates of the components that relates with the procedures.

Table 4 The scores and weights

Indices		Score of index				Weight of index	
		Procedure				Viewpoint	
		B-a	B-b	B-c	B-d	Viewpoint 1	Viewpoint 2
Influence to environment	Amount of release of radioactive materials	1	1	1	0	8	1
Influence to the target plant	Magnitude to achieve the objective	0	1	0	0	1	8
Human reliability	Human resources	1	1	1	1	7	4
	Complete time of the procedures	0	0	1	1	4	7
	Conversance	0	-1	0	-1	6	6
	Complexity	0	1	1	0	5	5
Equipment reliability	Equipment resources	0	0	-1	0	2	2
	Success probability of the procedures	1	1	0	0	3	3

5.3 Calculation of the points of each counter operation procedure

The scores of each counter operation procedure is calculated by the following equation.

$$P_{total} = \sum W_i P_i \qquad (1)$$

P_{total} : Total point of the counter operation procedure (recommendation point).

W_i : The weight of the index i

P_i : The score of the index *i*

The weights of the indices may be changed by the accidental situation.

5.4 Result of calculation

The calculation results of the recommendation scores for the counter operation procedures are shown in Table 5. For example, the score of procedure B-b is calculated as 18 by the equation (1) using the data shown in Table 4:

1*8+1*1+1*7+0*4+(-1)*6+1*5+0*2+1*1=18.

Table 5 Recommendation scores

Counter operation procedure	Viewpoint 1	Viewpoint 2
B-a	18	8
B-b	18	15
B-c	22	15
B-d	5	5

Although the score is not strict, the procedure B-c (that means the procedure c for the accidental situation B) is indicated as the most prioritized procedure by the viewpoint 1. On the other hand, the procedures B-b and B-c are indicated as the most prioritized procedures by the viewpoint 2.

The applicability of the method to prioritize the counter operation procedures is confirmed because the procedure B-b that is defined in manuals of a PWR plant and this procedure obtains a high score point.

The setting of weights for indices depending on plant condition by operators will enhance the resilience of counter operation because counter operation procedures are selected under flexible decision-making policy of operators.

6 Conclusions

This paper describes a method to prioritize the counter operation procedures in an accidental plant situation. For the prioritization, this paper investigates the indices to evaluate the operation procedures by the viewpoint of engineering risk assessment. Moreover, this paper evaluates the derived operation procedures by the two patterns of weighting indices by the viewpoint of “defense in depth”. From the results of scoring recommendation points, the applicability of the method is confirmed. However, the values of scores and indices for prioritizing the operation procedures generated are artificially determined considering plant structure and the viewpoint of “defense in depth” by the authors. Moreover, the suitability of the generated operation procedures depends on the accuracy and detailed level of the base MFM model of target plant.

Future works include a development of a method to give the points of counter operation procedures and weights of the indices by NPP experts and to design and develop an interface to show operating support information in an accidental situation. The development of validation technique of MFM model is also a future problem.

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