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# Development of Resilience Evaluation Method for Nuclear Power Plants (Part 3: Study of Evaluation Method and Applicability of Resilience Index)

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**ABSTRACT**

We have developed a new index, called the resilience index, that evaluates the dynamic stability of the system safety of a nuclear power plant during a severe accident by considering the ability to recover system safety functions that have become lost in the situation. In this paper, a detailed evaluation procedure for the resilience index is described. The system safety of a pressurized water reactor plant during a severe accident is then assessed according to the resilience index in order to discuss the applicability of the index. We find that the resilience index successfully represents management capability and, therefore, the resilience capability of a nuclear power plant.

**KEYWORDS**

*System Safety, Safety Assessment, Severe Accident, Accident Management, Resilience, Safety Margin*

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## 1. Introduction

The word "resilience" has a large scope in terms of its definition and meaning, which are dependent on field and context. However, it typically means a system's ability to adapt dynamically to perturbations due to changes inside and outside a system, to maintain normal operations in the functions it must fulfill, and to recover appropriately in the event of a loss of function (e.g., [1][2]). An important representative example of resilience in the field of nuclear power is the ability of a nuclear power plant to respond to situations that exceed its design bases.

When the safety of a nuclear power plant is assessed with regard to its ability to respond to situations that exceed its design bases, in addition to risk assessments, resilience-based assessments are essential to ensuring a plant's safety and that its safety is highly robust. Such evaluations include quantification and assessments of likelihoods and margins (*e.g.*, functional margins, time margins, *etc.*) to determine how large they must be to maintain or recover safety-essential functions, as well as assessments of how likelihoods and margins ("response margins") change in response to elevated hazard intensities and aging.

In this study, we define and evaluate a resilience index as an index of the ability of nuclear power plants to respond to situations that exceed their design bases. The resilience index here is an aggregate of probabilities and margins of functions essential to safety, which have been temporarily lost due to, for example, external hazards, being restored to minimum essential functional levels within the required time through the execution of accident management (AM) strategies [3]. Regarding each measure of AM strategies, probabilistic risk assessment (PRA) binary-logically evaluates whether each measure is success or failure in accordance with the success criteria and does not indicate the

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time required or the response margin explicitly. By contrast, resilience index evaluation is characterized by quantitatively evaluating the required time and response margin in consideration of their accumulation and expressing them explicitly. Therefore, it is possible to evaluate the influence on the response margin due to the change of the AM measures and maintenance activities including education / training of personnel. In this manuscript, we present a specific evaluation procedure for the resilience index, and perform a trial assessment for a simplified model of a pressurized water reactor (PWR) plant in order to demonstrate its applicability.

## 2. Evaluation Method for the Resilience Index

We consider a severe accident in which one or multiple functions critical to system safety are lost due to an external hazard. Nuclear power plants execute AM strategies and take measures to recover the safety functions that they have temporarily lost. The present study adopts the following assumptions about how the recovery capacity for system safety should be evaluated (Fig.1):

- There exists a minimum level of safe functioning necessary to reach a target safety performance (hereafter “minimum safety function level”); moreover, there is usually a margin between safety functional levels during normal operations and the minimum safety function level. Therefore, after a severe accident occurs, it is not strictly necessary in the short term for the safety function level to recover to the same level as during normal operations. We regard a system as having recovered if it reaches the minimum safety function level.
- A system must recover to the minimum safety function level within a certain amount of time. Therefore, there exists a time constraint.
- The success or failure of each measure comprising the AM strategy is probabilistic, being dependent on ambient conditions. Therefore, it is probabilistic which AM sequence (*i.e.*, a progress path to recovery of safety function) takes place.

In this case, the probability of successful recovery of system safety can be evaluated as the integrated value of the occurrence probabilities of all AM sequences that lead to recovery (*i.e.*, the probability of avoiding the “Recovery Impossible” Region in Fig.1). The response margins can be evaluated as the distance of the progress curve of each AM sequence from the “Recovery Impossible” Region. Moreover, we combine the occurrence probability of each AM sequence with the response margins to calculate the statistics of the response margins, and evaluate the reliability of the plant level response capability.

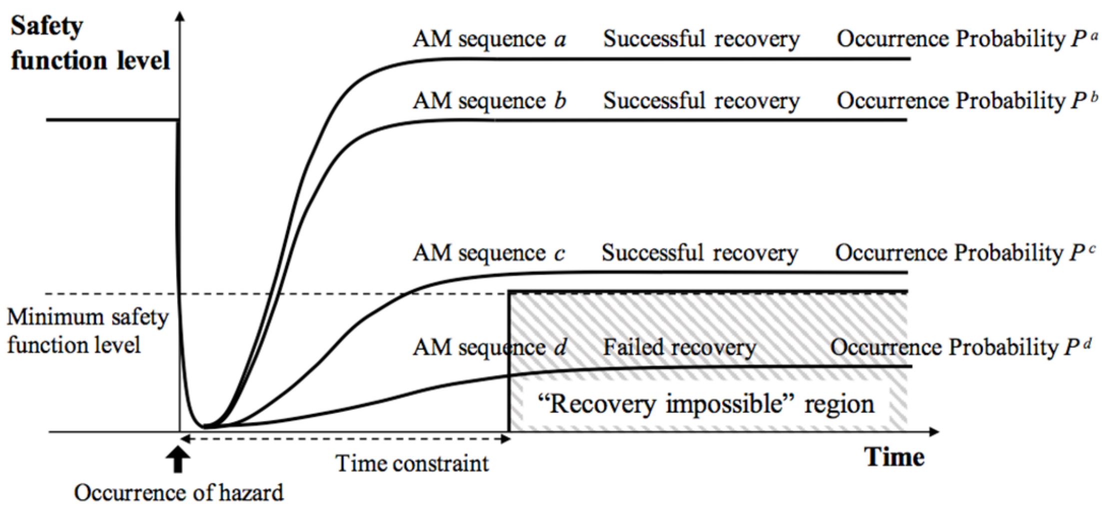



**Fig.1. Recovery of safety function**

### 2.1. Resilience Index Evaluation Procedure

We describe a specific evaluation procedure for the resilience index. During the evaluation, we consider temporal changes in a system's safety function level. The workflow of the evaluation is as follows:

1) Assumption of an Accident Scenario
2) Formulation of AM strategy
3) Analysis of AM sequences
   Creation of AM event tree
4) Evaluation of characteristic values of each AM measure
   Evaluations of execution failure probability, required time, and functional margin
5) Evaluation of Resilience Index
   Evaluation of occurrence probability, cumulative required time, system functional margin, time margin, and recovery success or failure of each AM sequence
6) Extraction of vulnerabilities
   Importance analysis and resistance assessment

### 2.1.1. Assumption of an Accident Scenario

We evaluate and establish assumed hazards and the damage status of the plant under analysis after investigating the plant's structure and characteristics and after identifying an accident sequence deemed important from a risk standpoint. We can apply data from past PRA and AM strategy formulations.

### 2.1.2. Formulation of AM Strategy

With regard to the plant damage status established in Section 2.1.1, we analyze which measures and actions made by operating personnel related to the recovery of safety function are feasible, and establish an AM strategy. In addition, we evaluate and establish a time constraint for the time necessary to reach minimum safety function level. We can apply data from past PRAs and AM strategy formulations.

### 2.1.3. Analysis of AM Sequences (Creation of AM Event Tree)

We model the AM sequence in order to evaluate the progress of system recovery. Based on the plant damage status and AM strategy established through the previous subsection, we create an AM event tree with each AM measure as headings, and identify all AM sequences that could occur.

At this time, we model the generation of functional and temporal margins in successive measures, even for partial recoveries (*i.e.*, when the extent of functional recovery due to a given measure in the AM strategy has not reached the necessary level). In other words, success and failure of a given AM measure (*i.e.*, AM event tree heading) is determined after taking into account the accumulation of partial functional recoveries resulting from preceding AM measures. For example, assume a water supply functional level of 100 [$m^3$/h] is considered necessary. In the event that execution of the first water supply measure is successful, but for some reason the water supply function halts at 60 [$m^3$/h], subsequent water supply measures are executed, while the measure is deemed an "execution success" but a "functional recovery failure". Here, because there is partial functional recovery (60 [$m^3$/h]) from successful execution of the first water supply measure, we judge the second water supply measure to be a "functional recovery success" if it can achieve functioning of 40 [$m^3$/h], in consideration of the cumulative amount.

### 2.1.4. Evaluation of Characteristic Values of Each AM Measure

We consider the execution failure probability, required time, and functional margin described below as quantities that characterize each measure in the AM strategy, and evaluate each individually. Here, we take into account ambient conditions at the time of the accident, including hazard intensities.

(a) Evaluation of Execution Failure Probability

We create a fault tree for each AM measure, the top event of each of which is the execution failure of that measure. The creation of the fault trees takes into account:

- Damage to structures and components due to external forces;
- Deterioration of structures and components due to aging and random failures; and
- Human error.

We perform fragility assessments, aging assessments, and human reliability assessments for the evaluation of each of the above factors, and evaluate the execution failure probability $p_f^i$ of the AM measure in question $i$. In addition, we can utilize the measure of the maintenance index [4] for the aging assessments. Moreover, we take into account ambient conditions at the time of the accident as, for example, the influence of a stressful situation on a human error probability for the human reliability assessments.

(b) Evaluation of Required Time

We evaluate the time $t^i$ required to execute each AM measure $i$. We can utilize data obtained from training results. Moreover, we take into account ambient conditions at the time of the accident as, for example, the influence of workplace accessibility and workability on the required time.

We consider the required time to be $t^i = 0$ in the event that the AM measure in question cannot be executed, owing to, for example, loss of function of equipment whose operation was expected.

(c) Evaluation of Functional Margin

We evaluate the size of the margin between the functional level expected of each AM measure and the minimum safety function level. For this purpose, we evaluate the type and level of the function possessed by each AM measure. (For example, we evaluate the measure *Water injection by high pressure coolant injection system* as a type of *Water supply function* with a level of 150 $m^3$/h. In addition, we calculate the minimum safety function level for each function, *e.g.*, 100 [$m^3$/h]. Here, for each AM measure $i$, we define the functional margin $m^i$ as the ratio of the functional level of the measure to the minimum safety functional level, *e.g.*, 150 [$m^3$/h] / 100 [$m^3$/h] = 1.5. This is essentially the margin with respect to the minimum safety function level.

For realistic assessments, we employ the best estimate from, for example, a safety analysis as the minimum safety function level. A conservative treatment—such as by employing a design value—is also acceptable in the event of an unclear best estimate.

### 2.1.5. Evaluation of Resilience Index (Quantification of AM Sequence, Assessment of AM Effectiveness)

In order to evaluate the cumulative value of the occurrence probabilities in the AM sequence leading to recovery of system safety and response margins, we use the AM event trees created and established through the previous subsection, as well as the characteristic values of each AM measure to evaluate the occurrence probability, the cumulative required time, the system functional margin, time margin, and the recovery success or failure of each AM sequence.

(a) Evaluation of Occurrence Probability for each AM Sequence

From the success and failure probabilities at each heading (AM measure) assessed in Section 2.1.4(a), we derive the conditional occurrence probability $P^j(a, x)$ of each AM sequence $j$ with respect to an hazard intensity $a$ and plant damage status $x$ evaluated and established in Section 2.1.1.

(b) Evaluation of Cumulative Required Time for each AM Sequence

From the required time of each AM measure assessed in Section 2.1.4(b), we derive the cumulative required time $T^j$ for each AM sequence $j$.

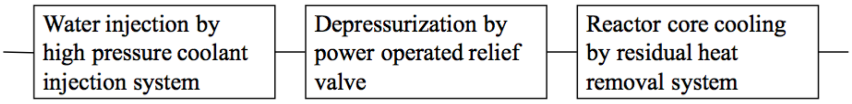
(c) Evaluation of System Functional Margin for each AM Sequence

From the functional margin for each AM measure assessed in Section 2.1.4(c), we derive the system functional margin as described below for each AM sequence $j$ in order to evaluate the extent of recovery of system safety.

For an AM strategy arranged in a series system (*e.g.*, the one shown in Fig.2), the AM strategy in question fails (recovery failure sequence) in the event of the functional level of any measure falling below the minimum safety function level (i.e., having a functional margin of <1). Therefore, we define $M_F^j$ as the system functional margin, and derive it as follows:

$$M_F^j = \min(m^i) \tag{1}$$

where $m^i$ is the functional margin of the $i$ th AM measure. Here, the functional level possessed by each individual AM measure is dependent on hazard intensity (for example, the possibility of functional decline due to partial damage to equipment caused by seismic motion). Accordingly, the functional margin, system functional margin, and system recovery success or failure are also dependent on hazard intensity.



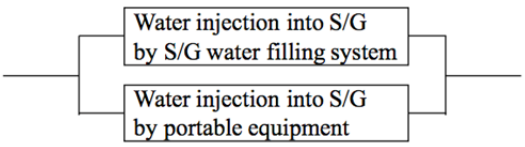

| | (1) High pressure coolant injection system | (2) Power operated relief valve | (3) Residual heat removal system |
|---|---|---|---|
| Minimum safety function level | $L_{Lim}{}^{a)} = 100$ m³/h | $L_{Lim}{}^{b)} = 120$ m³/h | $L_{Lim}{}^{c)} = 5$ MW |
| Function level | $L^{(1)} = 120$ m³/h | $L^{(2)} = 120$ m³/h | $L^{(3)} = 10$ MW |
| Functional margin | $m^{(1)} = 1.2$ | $m^{(2)} = 1.0$ | $m^{(3)} = 2.0$ |
| System functional margin | $M_F = \min[m^*] = 1.0$ | | |

**Fig.2. Example calculation of System functional margin in series system**

For an AM strategy arranged in a parallel system (*e.g.*, the one shown in Fig.3), every measure has a functionally redundant measure, even in the event of the functional level of the measure in question falling below the minimum safety function level (*i.e.*, having a functional margin of <1). Accordingly, we define and derive the system functional margin as:

$$M_F^j = \sum_i m^i \tag{2}$$

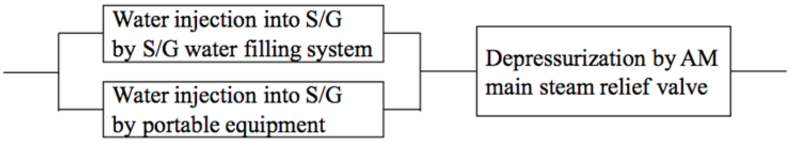
Here, in the event that the best estimate is unclear and a design value is employed as the minimum safety function level, it is acceptable to employ the design value of the measure with the lowest functional value within the measures comprising the parallel system in question as the minimum safety function level.




| | (1) Water injection into S/G by S/G water filling system | (2) Water injection into S/G by portable equipment |
|---|---|---|
| Minimum safety function level | $L_{Lim}{}^{a)} = 100$ m³/h | |
| Function level | $L^{(1)} = 120$ m³/h | $L^{(2)} = 100$ m³/h |
| Functional margin | $m^{(1)} = 1.2$ | $m^{(2)} = 1.0$ |
| System functional margin | $M_F = \Sigma m^* = 2.2$ | |

**Fig.3. Example calculation of System functional margin in parallel system**

For an AM strategy arranged in a series-parallel system (*e.g.*, the one shown in Fig.4), we can combine the above definitions for series systems and parallel systems to derive the system functional margin.




| | (1) Water injection into S/G by S/G water filling system | (2) Water injection into S/G by portable equipment | (3) Depressurization by AM main steam relief valve |
|---|---|---|---|
| Minimum safety function level | $L_{Lim}$[a)] = 100 $m^3$/h | | $L_{Lim}$[b)] = 120 $m^3$/h |
| Function level | $L^{(1)}$ = 120 $m^3$/h | $L^{(2)}$ = 100 $m^3$/h | $L^{(3)}$ = 150 $m^3$/h |
| Functional margin | $m^{(1)} = 1.2$ | $m^{(2)} = 1.0$ | $m^{(3)} = 1.25$ |
| System functional margin | $M_F = \min[m^{(1)}+m^{(2)}, m^{(3)}] = \min[2.2, 1.25] = 1.25$ | | |

**Fig.4. Example calculation of System functional margin in series-parallel system**

(d) Evaluation of Time Margin for each AM Sequence

From the time constraint $T_{Lim}$ evaluated and established in Section 2.1.2 and the cumulative required time $T^j$, we derive the time margin $M_T^j$ as defined below for each AM sequence *j*:

$$M_T^j = T_{Lim}/T^j \tag{3}$$

(e) Evaluation of Recovery Success or Failure for Each AM Sequence

We judge the recovery success or failure of each AM sequence based on the system functional margin (or time margin) for each AM sequence evaluated above. If the system functional margin $M_F^j$ at a time point when the time constraint $T_{Lim}$ has elapsed becomes ≥1 (or, the time margin $M_T^j$ at a time point when the minimum safety function level has achieved becomes ≥1), the recovery progress path does not pass through the "Recovery Impossible" Region, and we consider the AM sequence in question *j* a recovery success.

Based on the results in Subsections 2.1.5(a)–(e) above, we derive the conditional probability of successful system recovery $P_{Recov}(a,x)$ for an assumed hazard intensity *a* and plant damage status *x* using the following equation:

$$P_{Recov}(a,x) = \sum_{j'} P^{j'}(a,x) \tag{4}$$

Here, $P^{j'}(a,x)$ is the conditional occurrence probability of AM sequence *j'* leading to a successful recovery.

In addition, we evaluate the reliability of the plant level response capability. Here, we focus on the probability distribution of the system functional margin at a time point when the time constraint has elapsed and the probability distribution of the time margin at a time point when the minimum safety function level has achieved (Fig.5). From the expectation values $\mu_{M_F}$, $\mu_{M_T}$ and the standard deviations $\sigma_{M_F}$, $\sigma_{M_T}$ of $M_F^j\big|_{T=T_{Lim}}$、$M_T^j\big|_{L=L_{Lim}}$, we derive the plant level response margin $\beta_F$、$\beta_T$ as defined below respectively:

$$\boldsymbol{\mu_{M_F}} = \sum_j \boldsymbol{P^j\, M_F^j}\big|_{T=T_{Lim}} \tag{5}$$

$$\boldsymbol{\mu_{M_T}} = \sum_j \boldsymbol{P^j\, M_T^j}\big|_{L=L_{Lim}} \tag{6}$$

$$\boldsymbol{\sigma_{M_F}} = \left\{\sum_j \boldsymbol{P^j}\left(\boldsymbol{M_F^j}\big|_{T=T_{Lim}} - \boldsymbol{\mu_{M_F}}\right)^2\right\}^{1/2} \quad (7)$$

$$\boldsymbol{\sigma_{M_T}} = \left\{\sum_j \boldsymbol{P^j}\left(\boldsymbol{M_T^j}\big|_{L=L_{Lim}} - \boldsymbol{\mu_{M_T}}\right)^2\right\}^{1/2} \quad (8)$$

$$\boldsymbol{\beta_F} = \boldsymbol{\mu_{M_F}}/\boldsymbol{\sigma_{M_F}} \quad (9)$$

$$\boldsymbol{\beta_T} = \boldsymbol{\mu_{M_T}}/\boldsymbol{\sigma_{M_T}} \quad (10)$$

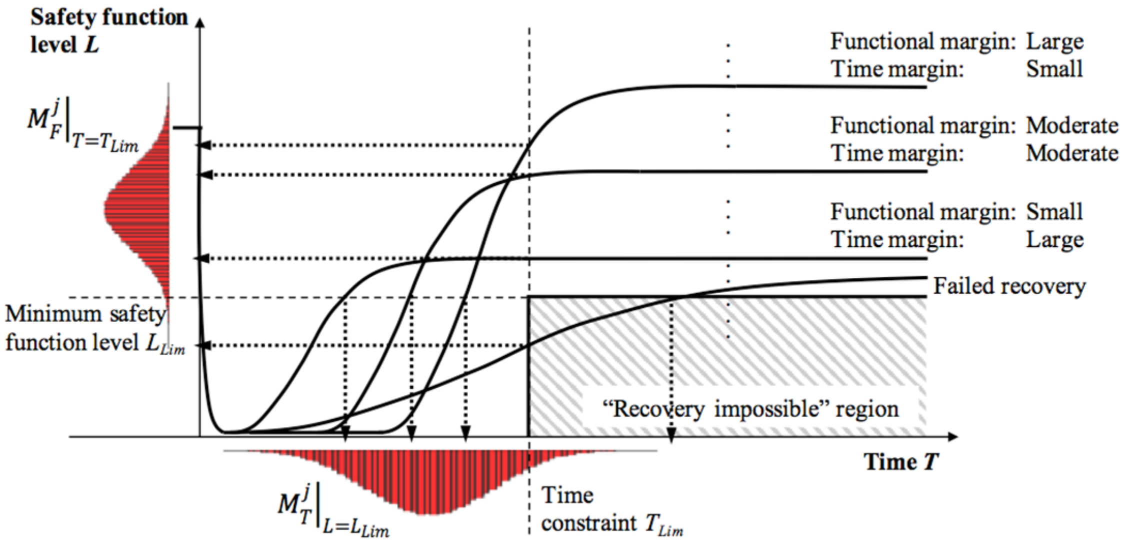



**Fig.5. Schematic illustration of plant level response margin**

### 2.1.6. Extraction of Vulnerabilities (Importance Analysis, Resistance Assessment)

We perform an importance analysis and an assessment of the dependence of the resilience index on hazard intensity. Their purpose is to clarify the relationship of the reliability, availability, and response capacities of each component and essential personnel with the recovery capacity for system safety, as well as to understand latent vulnerabilities.

## 3. Evaluation conditions

As a case study, we performed a trial evaluation of the recovery capacity for system safety based on the concept of the resilience index for two different cases of AM strategies. We applied an accident sequence group defined in the *Screening Guide for Effectiveness Assessments of Core Damage Prevention Measures and Containment Failure Prevention Measures for Commercial Power Reactors* for PWR plants by Japan's Nuclear Regulation Authority.

### 3.1. Assumption of Accident Scenario

We suppose the accident scenario *Loss of heat removal function from the secondary cooling system* from within the screening guide. This scenario comes from an accident sequence group designated as applicable to assessments of the effectiveness of measures for prevention of core damage in PWR plants. This risk-dominant accident sequence assumes the loss of the heat removal function from the secondary cooling system, a function fulfilled by the auxiliary feed water system, and the main steam relief valve or safety valve. In addition, we assume an earthquake as the hazard.

### 3.2. Formulation of AM Strategy

The screening guide shows example strategies of using feed-and-bleed by means of a power operated relief valve and high pressure coolant injection system, and using a steam generator for an alternative method for decay heat removal.

Here, we suppose the two cases of AM strategies below, and compare the results of their trial assessments.

*Case A: Considering Only Heat Removal from the Primary System (Fig.6).* This strategy aims to stably cool the reactor core through the below steps:

1. Water injection by high pressure coolant injection system;
2. Primary system depressurization by power operated relief valve; and
3. Reactor core cooling by residual heat removal system.

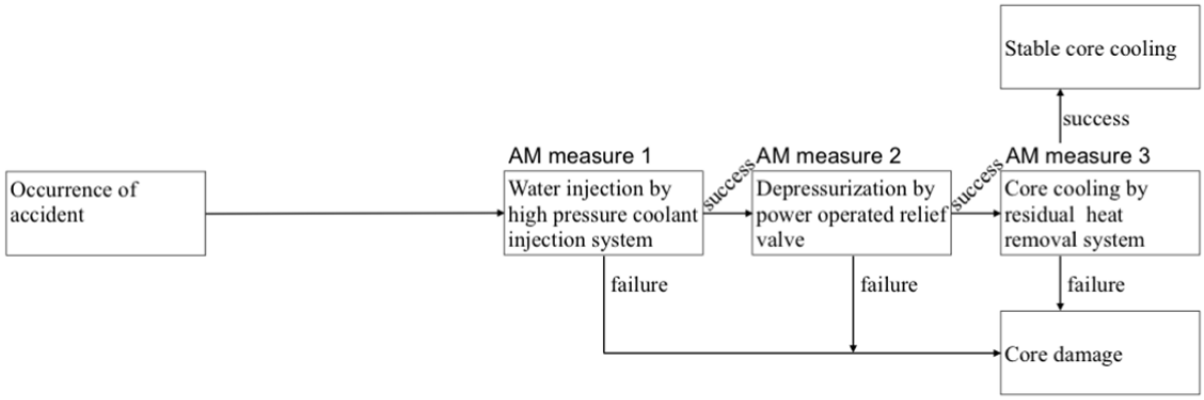



**Fig.6. Accident management procedure: Case A**

*Case B: Considering Heat Removal from Both the Primary and Secondary Systems (Fig.7).* In addition to heat removal from the primary system in Case A above, this strategy takes into account heat removal from the secondary system. Because the heat removal equipment in the safety system of the secondary system has lost functionality, AM equipment must be furnished in the form of heat removal equipment. We provide for the two pieces of equipment below: equipment for water injection into the steam generator (S/G), and equipment for releasing steam.

4. Portable S/G water supply equipment and
5. AM main steam relief valve.

In addition, the following non-safety-system equipment can be utilized during this accident:

6. S/G water filling system.

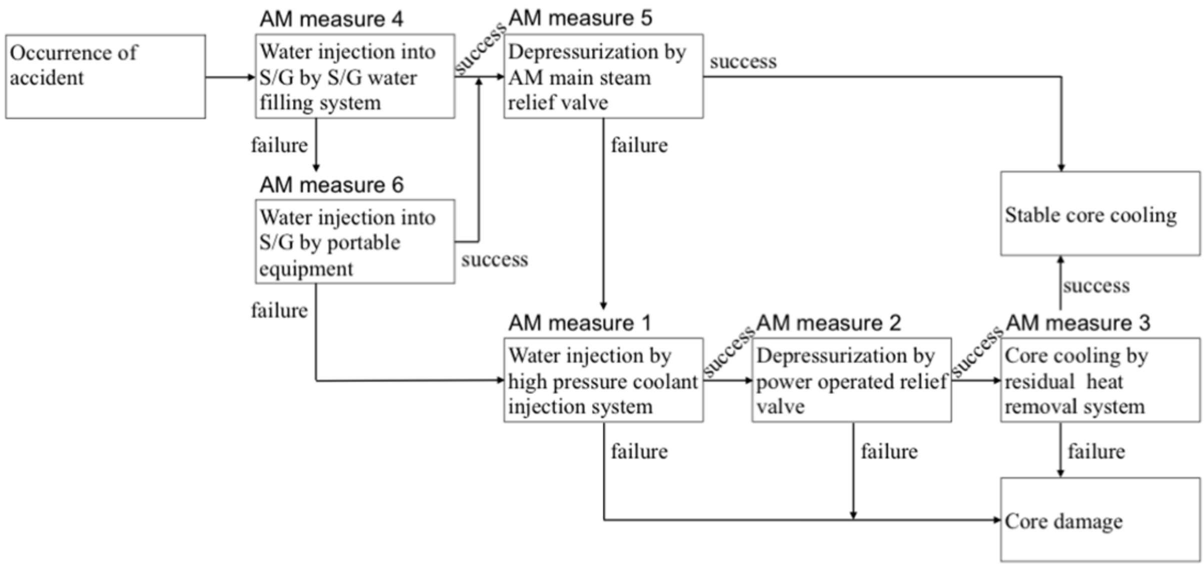



**Fig.7. Accident management procedure: Case B**

In addition, we establish the time constraint as approximately 29 minutes after event occurrence.

This value was chosen with reference to effectiveness assessments of severe accident countermeasures conducted by electric power companies operating PWR plants. However, we subtract 10 minutes for situation assessment, and use 19 minutes as the time constraint for trial assessment calculations.

### 3.3. AM Sequence Analysis (Creation of AM Event Tree)

We create AM event trees for the AM strategies of the two aforementioned cases. The AM strategy for Case A forms the series system shown in Fig.2. This is because the strategy results in recovery failure in the event of the functional level of any of the constituent measures dropping below the minimum safety function level. Four paths constitute the sum of all AM sequences that could occur in Case A. The AM strategy for Case B is a parallel system, since the water supply measure fulfilled by the portable S/G water supply equipment is redundant with the water supply measure fulfilled by the S/G water-filling system. In addition, these water supply measures have a series relationship with the heat emission measure fulfilled by the AM main steam relief valve (*i.e.*, recovery fails if both of the water supply measures fail, or if the heat emission measure fails). Furthermore, the redundancy of the heat removal from the secondary system with the heat removal from the primary system forms a parallel system. Thus, this AM strategy forms a series-parallel system. Thirty-nine paths constitute the sum of all AM sequences that could occur in Case B.

### 3.4. Evaluation of Characteristic Values of each AM Measure

For simplicity, in this manuscript, we consider only the primary equipment among the equipment and facilities expected to operate at each measure, and decide to not take into account human error. (We assume that the essential personnel are ideally trained.)

<u>(a) Evaluation of Execution Failure Probability</u>

*Fragility Assessment:* Because we have assumed earthquakes are the hazard in the trial assessment conditions, we configure the seismic fragility parameters $A_m$, $\beta_R$, and $\beta_U$ for typical equipment in each measure with reference to PRA data from electric power companies operating PWR plants [5], and calculate the fragility curve $f(a)$:

$$f(a) = \Phi\left(\frac{\ln(a/A_m) + \beta_U \cdot \Phi^{-1}(p)}{\beta_R}\right) \tag{11}$$

Here, $p$ is reliability; we set it at 50% in this manuscript.

*Aging Assessment:* We established failure rates by taking into account, in a simplified way, the influence of aging and maintenance activities for typical equipment in each measure. We did this with reference to NUCIA data, and also based on the concept of the maintenance index [4]. The maintenance index is an indicator representing the reliability of safety-critical functions for nuclear power plants, which incorporates the effects of aging and maintenance activities. For the assessment of the failure rate of dynamic equipment within the evaluation procedure for maintenance index, for example, one breaks down the failure rates for each failure mode by grouping them by cause, and then considers time dependence. Then, increases and decreases in failure rate due to a variety of maintenance activities can be evaluated. At this time, we model the differences in effective maintenance activities according to causes of failure. In this trial assessment, for example, we set the start-up failure probability of the electrical pump at 4.3E−05 [1/demand]. Here, we consider the start-up failure-related deterioration factors of immobility of the sliding portion and deterioration of electrical instrumentation and control system. We set the contributions to start-up failure of each (*i.e.*, the proportion of each cause within the number of cases of start-up failure) as 9:1 based on engineering judgment. Here, for simplicity, if we assume that sliding portions are regularly checked by means of periodic tests at appropriate intervals, the only continuous deterioration is of the electrical instrumentation and control system. Therefore, we factor in the above contribution to set the equipment failure rate at 4.3E−05 × 0.1 = 4.3E−06 [1/ Demand].

<u>(b) Evaluation of Required Time</u>

We configure the required times for each measure with reference to the results of effectiveness evaluations of severe accident countermeasures conducted by electric power companies managing PWR plants [6]. We do not take into account the dependence of required time on hazard intensity.

(c) Evaluation of Functional Margin

We establish the functional margins for each measure with reference to equipment design specifications written in establishment license applications. For conservation analysis, we employ design values for minimum safety function levels. We do not take into account the dependence of functional margins on hazard intensity.

The characteristic values for each AM measure used in the trial assessment are shown in Table 1.

**Table 1 Evaluation condition**

| AM measure | | Typical equipment | | Fragility | | | Failure rate [1/Demand/unit] | Required time [min] | Functional margin |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Water injection by high pressure coolant injection system | Electrical pump (150 [$m^3$/h]) | x 2 | $A_m$ = [G] | 4.80 | $b_R = 0.08$ $b_U = 0.17$ | 4.3E-06 | 1.5 | 1 x 2 = 2 |
| 2 | Depressurization by power operated relief valve | Air-operated valve (100 [$m^3$/h]) | x 3 | $A_m$ = [G] | 4.13 | $b_R = 0.21$ $b_U = 0.25$ | 1.5E-06 | 1.5 | 1 x 3 = 3 |
| 3 | Reactor core cooling by residual heat removal system | Electrical pump and valve | x 2 | $A_m$ = [G] | 3.01 | $b_R = 0.13$ $b_U = 0.23$ | 7.7E-06 | 3 | 1 x 2 = 2 |
| 4 | Water injection into S/G by portable equipment | Electrical pump (160 [$m^3$/h]) | x 1 | $A_m$ = [G] | 5.00 | $b_R = 0.15$ $b_U = 0.50$ | 4.3E-06 | 10 | 1.07 |
| 5 | Depressurization by AM main steam relief valve | Air-operated valve (180 [$m^3$/h]) | x 1 | $A_m$ = [G] | 3.03 | $b_R = 0.21$ $b_U = 0.25$ | 1.5E-06 | 3 | 1.8 |
| 6 | Water injection into S/G by S/G water filling system | Electrical pump (160 [$m^3$/h]) | x 1 | $A_m$ = [G] | 1.03 | $b_R = 0.20$ $b_U = 0.19$ | 4.3E-06 | 3 | 1.07 |

## 4. Results and discussion

### 4.1. Resilience Index Assessment (Quantification of AM Sequences, Assessment of AM Effectiveness)

Based on the assessment conditions in the previous chapter, we evaluated the cumulative occurrence probability of each AM sequence leading to recovery of system safety, and the response margins.

*AM Case A: Considering only Heat Removal from the Primary System*. The occurrence probability of each AM sequence obtained for a configured hazard intensity of $a$ = 0.0 [G] is shown in the left side of Fig.8. Sequence 1, in which AM Measures 1, 2, and 3 were all successful, occurred as the dominant path. The right side of Fig.8 is a time history of the system functional margin, and shows the recovery paths of each AM sequence: the large arrow is the recovery path of Seq. 1. The system functional margin $M_F$ reaches 2.0 (>1.0) in a total required time of 6 min (<19 min): the recovery sequence can be seen to be successful because it does not pass through the established "Recovery Impossible" Region (the shaded area in the figure). Sequences other than Seq. 1 are failed recovery sequences: the conditional probability of successful system recovery is $P_{Recov}(a = 0, x) = 1 - 7.78\mathrm{E}{-11}$.

Similarly, the occurrence probability of each AM sequence obtained for a configured hazard intensity of $a$ = 3.0 [G] is shown in the left side of Fig.9. Within the chart, the white portion represents the successful recovery sequences and the shaded portion represents the failed recovery sequences. For $a$ = 3.0 [G], the major sequence Seq. 2 occurs in addition to Seq. 1. In Seq. 2, AM Measure 1 (water injection by high pressure coolant injection system) and AM Measure 2 (depressurization of primary system by power operated relief valve) both succeed, but AM Measure 3 (reactor core cooling by residual heat removal system) fails. The conditional probability of successful system recovery here is $P_{Recov}(a = 3.0, x) = 0.48$. The probability distributions of the response margins can be derived from the occurrence probability of each AM sequence obtained following Section 2.1.5(a) and $M_F^j|_{T=T_{Lim}}$、$M_T^j|_{L=L_{Lim}}$ of each AM sequence as shown in the right side of Fig.9. Using the equations (5)–(10), we obtain the plant level response margins $\beta_F = 0.96$, $\beta_T = 0.96$. For $a$ = 5.0 [G], recovery failure sequences are dominant, including Seq. 4, in which AM Measure 1 fails. Here, the conditional probability of successful system recovery is $P_{Recov}(a = 5.0, x) = 2.62\text{E}{-06}$.

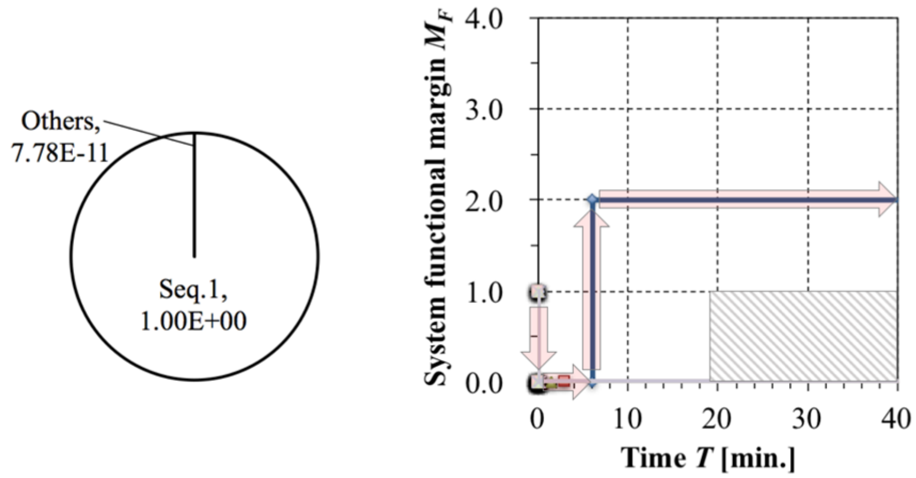



**Fig.8. Occurrence probability of each AM sequence (Left) and time series of system functional margin (Right): AM Case A, *a* = 0.0 [G]**

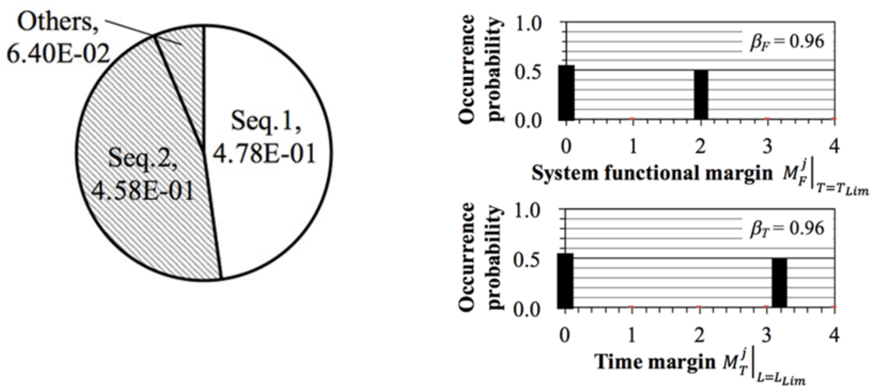



**Fig.9. Occurrence probability of each AM sequence (Left) and probability distribution of response margin (Right): AM Case A, *a* = 3.0 [G]**

*AM Case B: Considering Heat Removal from both the Primary and Secondary Systems*. The occurrence probability of each AM sequence obtained for a configured hazard intensity of $a$ = 0.0 [G] is shown in the left side of Fig.10. Sequence 1 occurs as the dominant path: in it, AM Measure 6 (S/G water supply by S/G water-filling system) and AM Measure 5 (depressurization by AM main steam relief valve) succeed. The right side of Fig.10 shows the recovery paths of each AM sequence: the large arrow is the recovery path for Seq. 1. The system functional margin $M_F$ reaches 1.07 (>1.0) in a total required time of 6 min (<19 min): it can be seen to be a successful recovery sequence. The conditional probability of successful system recovery is $P_{Recov}(a = 0, x) = 1 - 1.17\text{E}{-16}$.

If we compare Fig.10 and Fig.8 (the result of AM Case A), we see that the conditional probabilities of successful system safety recovery are equal at approximately 1. In this trial assessment, AM case B is a strategy in which AM measures with relatively low functional margin are executed first (Fig.7 and Table 1). When the hazard intensity is small and the execution failure probability of each AM measure is sufficiently low, therefore, the response margin of the dominant AM sequence is relatively small. Nonetheless, more sequences having larger latent response margins exist in AM Case B (which provided for a greater variety of AM measures). We successfully visualized this finding quantitatively.

Similarly, the occurrence probability of each AM sequence obtained for a configured hazard intensity of $a$ = 3.0 [G] is shown in the left side of Fig.11. For $a$ = 3.0 [G], the failed recovery sequence Seq. 33 occurred in addition to the successful recovery success sequences Seq. 27 and Seq. 32. In Seq. 33, heat removal from the secondary system fails because of the failure of AM Measures 5 and 6, and, moreover, heat removal from the primary system fails because of the failure of AM Measure 3. Here, the conditional probability of successful system recovery is $P_{Recov}(a = 3.0, x) = 0.75$. The right side of Fig.11 are the probability distributions of the response margins. Using the equations (5)–(10), we obtain the plant level response margins $\beta_F = 1.46$, $\beta_T = 1.70$. Comparing this with the results of AM Case A at the same hazard intensity, $a = 3.0$ G, (Fig.9; $P_{Recov}(a = 3.0, x) = 0.48$; $\beta_F = 0.96$, $\beta_T = 0.96$) revealed that both the probability of successful system recovery $P_{Recov}$ and the plant level response margins rose. We thus achieved a quantitative effectiveness assessment of AM strategy modifications and improvements from both viewpoints of the probability of successful recovery and the margin. For $a$ = 5.0 [G], recovery failure sequences are dominant: the conditional probability of successful system recovery is $P_{Recov}(a = 5.0, x) = 4.27\text{E}{-03}$.

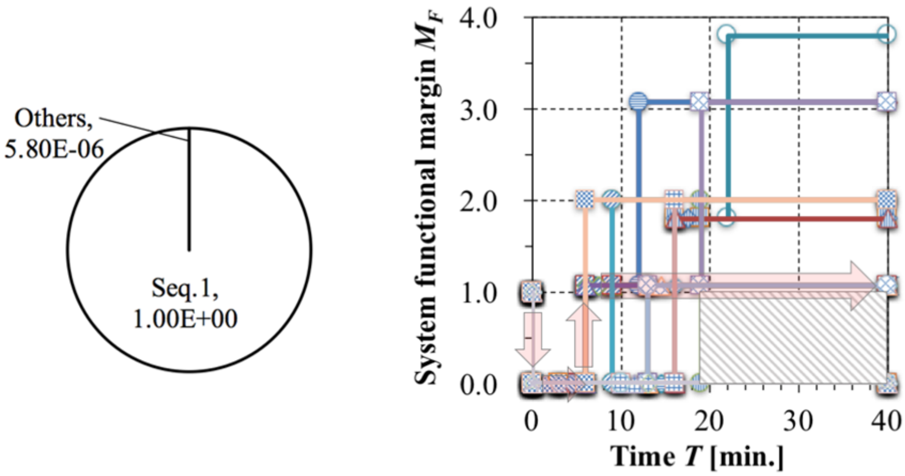



**Fig.10. Occurrence probability of each AM sequence (Left) and time series of system functional margin (Right): AM Case B, $a$ = 0.0 [G]**

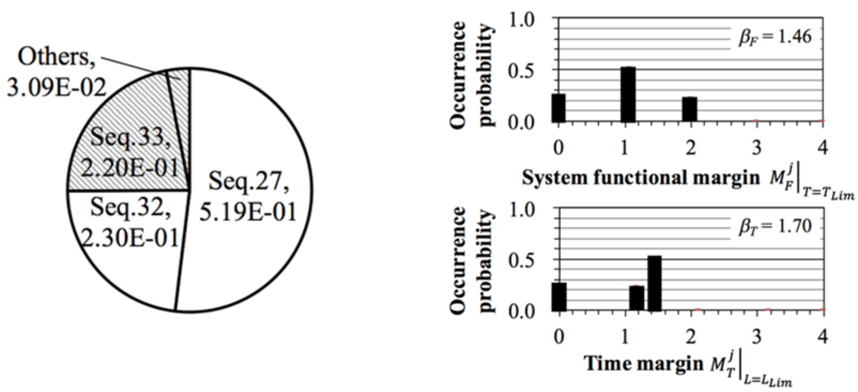



**Fig.11. Occurrence probability of each AM sequence(Left) and probability distribution of response margin (Right): AM Case B, $a$ = 3.0 [G]**

## 4.2. Extraction of Vulnerabilities

### 4.2.1. Importance analysis

In order to quantitatively assess the effects of each AM measure on the recovery capacity for system safety, in this trial assessment we firstly calculate $FV_e$ (equivalent to the Fussell–Vesely measure) and $RAW_e$ (equivalent to risk assessment worth (RAW)) from the conditional probability of successful system recovery, $P_{Recov}(a, x)$, using the following equations respectively:

$$FV_e(a,x) = \frac{\{1 - P_{\mathrm{Recov}}(a,x)\} - \left\{1 - P_{\mathrm{Recov}}(a,x)\Big|_{P_f=0}\right\}}{1 - P_{\mathrm{Recov}}(a,x)} \tag{12}$$

$$RAW_e(a,x) = \frac{\left\{1 - P_{\mathrm{Recov}}(a,x)\Big|_{P_f=1}\right\}}{1 - P_{\mathrm{Recov}}(a,x)} \tag{13}$$

For AM Case B, the calculation results for hazard intensity $a = 3.0$ [G] are shown in Fig.12. Under the conditions of this trial assessment, AM Measure 5 (depressurization by AM main steam relief valve) and AM Measure 3 (reactor core cooling by residual heat removal system) were extracted based on their importance to the probability of successful recovery.

In addition, we evaluate the sensitivity of the plant level response margins to functional margin and required time of each AM measure. For AM Case B, the evaluation results for hazard intensity $a = 3.0$ [G] are shown in Fig.13. Under the conditions of this trial assessment, functional margin of AM measure 4 (water injection into S/G by portable equipment) and AM Measure 5 (depressurization by AM main steam relief valve) were extracted based on its importance to the plant level functional margin. Required time of AM measure 4 (water injection into S/G by portable equipment) was extracted based on its importance to the plant level time margin.

### 4.2.2. Resistance Assessment

We varied hazard intensity from 0.0 to 5.0 [G] at 0.5-G intervals. The results of an assessment of the dependence of conditional probability of successful system recovery on hazard intensity are shown in Fig.14. In the figure, the results corresponding to AM Case A and AM Case B are shown together. As stated before, we find that the probability of successful system recovery has risen for Case B, owing to the increased number of successful recovery sequences, which is a result of incorporating measures for heat removal from the secondary system. Looking at the graph from the perspective of the cliff edge effect, both AM Cases broadly share the trend of the probability of system safety recovery dropping dramatically in the vicinity of $a$ =3.0 [G]. This is because, under the conditions of this trial assessment, the fragility of Measure 5 (depressurization by AM main steam relief valve), which has the smallest seismic resistance margin among the measures for heat removal from the secondary system, is similar to the fragility of Measure 3 (reactor core cooling by residual heat removal system), which has the smallest seismic resistance margin among the measures for heat removal from the primary system ($A_m$ = 3.03 [G] and 3.01 [G], respectively). These results corroborate the results of the importance value analysis in the previous subsection.

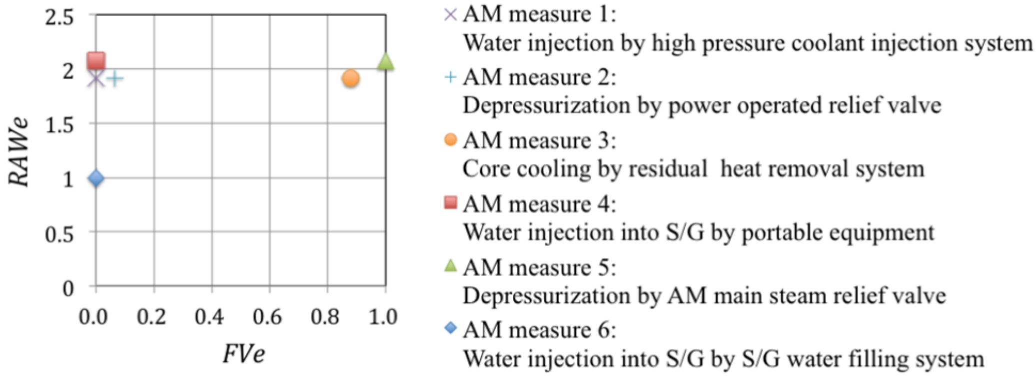


**Fig.12. Importance values equivalent to FV and RAW importance: AM Case B, *a* = 3.0 [G]**

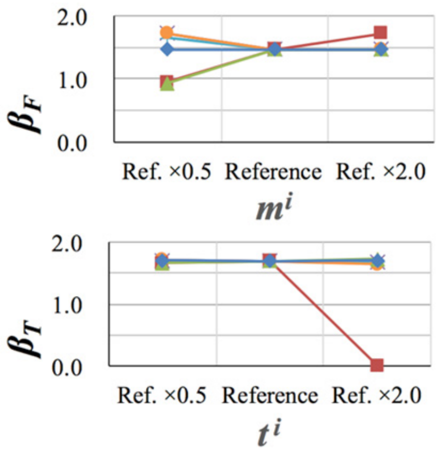



**Fig.13. Sensitivity of plant level response margin to functional margins and required time of each AM measure: AM Case B, *a* = 3.0 [G] (Symbols are in common with those of Fig.12)**

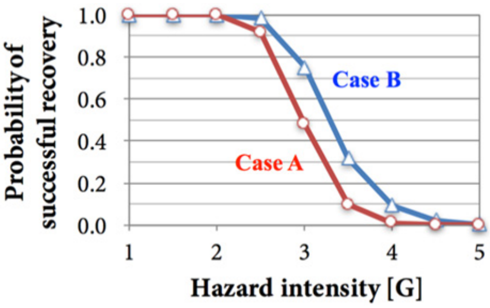



**Fig.14. Hazard intensity dependency of success probability of system recovery**

## 5. Conclusion

We demonstrated a specific evaluation procedure for our proposed resilience index, a measure for use in assessments of system safety in nuclear power plants with respect to situations that exceed their design bases. During the assessment, we considered margins with respect to a minimum safety function level and a time constraint, as well as their temporal changes. In addition, for a simplified PWR plant model, we conducted a trial assessment of the recovery capacity for system safety based on the concept of the resilience index for the accident sequence *Loss of heat removal function from the secondary cooling system*, as defined in a screening guide by the Nuclear Regulation Authority of Japan. Basing our analysis on the concept of the resilience index made possible the following: a quantification of AM sequences leading to recovery of system safety; a quantitative analysis of response margin, response reliability, and successful recovery probabilities resulting from AM strategy modifications and improvements, as well as changes in the successful recovery probabilities' dependences on hazard intensity; and a quantitative evaluation of the effects of each AM measure on recovery capacity for system safety. Trial assessments and investigations that specifically take into account human error are important topics for future research.

## Acknowledgement

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