Application of Dynamic Probabilistic Risk Assessment to Nuclear Power Plant Operation Support - Evaluation of Countermeasure during Multi-unit Operation Considering Operator State -

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ABSTRACT

Dynamic probabilistic risk assessment (PRA) coupled with plant-dynamics analysis is expected to be applied to the establishment of accident management programmes and operation support in addition to conventional safety assessments. In multi-unit operations, scenarios are expected to become complex during simultaneous disasters, making it increasingly difficult to determine the priorities of countermeasures such as response operation and personnel movement. It is possible to generate and evaluate complex scenarios efficiently and exhaustively with a dynamic PRA method, with which multiple scenarios are generated in accordance with changes in plant state. A previous study proposed using the continuous Markov chain Monte Carlo (CMMC) method, a dynamic PRA method, for determining countermeasure priorities to support nuclear-power-plant operations. Scenario generation and evaluation in a single unit using dynamic PRA, with which a uniform distribution was assumed, were carried out. This paper proposes a scenario-generation method for multi-unit operation using the CMMC method that takes into account plant and operator states, and reports preliminary-evaluation results. This method involves the following steps: 1) calculating the states of multi-unit plants on the basis of the water level of the reactor pressure vessel and state of response operations, 2) calculating the stress levels of operators on the basis of the plant states, 3) determining the occurrence of countermeasures such as personnel movement between units, considering the states from 1) and 2), and 4) alternately determining event occurrence and plant-dynamics analysis. The generated scenarios are evaluated on the basis of the plant states at the end of the analysis. The results suggest that it is possible to determine the priority of countermeasures such as personnel movement.

Keywords: Dynamic PRA, Plant Operation Support, Risk-informed Application, Multi-unit Operation, Operator Model

I. INTRODUCTION

Since the Great East Japan Earthquake, the importance of risk assessment and utilization of information has increased to ensure further safety in nuclear power plants. Dynamic probabilistic risk assessment (PRA) coupled with plant-dynamics analysis is expected to be applied to the establishment of accident management (AM) programmes and operation support in addition to conventional safety assessments. Regarding the establishment of AM programmes, it is difficult to determine the priority of countermeasures due to the diversity of accident scenarios, indeterminacy of the order in which events occur, and time dependence of the branching probability. The range of automation for efficiency improvement and precision during plant operation has been expanding in line with technological advances. It is thus considered possible to carry out multi-unit operations in which the scope of responsibility for monitoring and operation per operator is increased. However, it is difficult to rely entirely on automatic operation to respond to events, so intervention, including manual operation in accordance with the situation, using risk information is essential. In particular, in the event of simultaneous incidents during multi-unit operations, the scenario becomes more complicated than during single-unit operations, and the burden of determining the priority of countermeasures, including personnel movements between units, is expected to be higher.

The continuous Markov chain Monte Carlo (CMMC) method was developed as a dynamic PRA method [1–3]. It is possible to efficiently and exhaustively generate and evaluate complex scenarios by repeatedly executing event generation considering

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the ever-changing situation and plant-dynamics analysis. In our previous study, a countermeasure-priority-determination function using the CMMC method was proposed as a support function for safer operation of nuclear power plants [4]. In that study, a simple single-unit plant-dynamics-analysis model was constructed, and the generation and evaluation of scenarios with corresponding operational events using uniform distributions were reported. The results indicated that the CMMC method can be used to evaluate the effectiveness of response operations on the basis of risk information considering uncertainty, and that it can be applied to determine countermeasure priority in complex scenarios.

The objective of this study is to extend that previous study and support the priority determination of countermeasures, including the movement of personnel between units, in a multi-unit-operation situation. As a first step, we propose a scenario-generation method that takes into account multi-unit plant and personnel states. We then report the results of evaluating the effectiveness of the countermeasures, such as personnel movement, by implementing the plant model constructed in the above previous study by extending it to a multi-unit model.

II. DEVELOPMENT OF MULTI-UNIT SIMULATION MODEL

II.A. Overview of Multi-unit Simulation Model

The multi-unit simulation model is constructed using the CMMC method. For the simulation of plant state, a simplified plant-dynamics-analysis model of the primary system of a pressurized water reactor with which a single phase is assumed, is used, which was developed in a previous study [4]. Multiple modules of this single-unit-plant model are operated in parallel, and necessary information is communicated to each other at each time step to represent multi-unit operation.

The scenario-generation procedure in each unit is shown in Fig. 1. At the beginning of each time step, a Monte Carlo state transition probability calculation and plant-dynamics analysis are conducted for a given sample. Next, the value of the evaluation index of the unit situation (unit score; details in II.B), calculated from the plant situation one time step before, is communicated between the units to determine whether personnel movement between units is necessary. The unit score is then updated according to the current situation. Finally, the AM state is analyzed to determine its state transition. This procedure is repeated until an arbitrary analysis end time, and then a unique scenario is created. When the analysis of one scenario is completed, the same procedure is repeated until all predetermined scenarios are generated. A large number of scenarios are thus created.

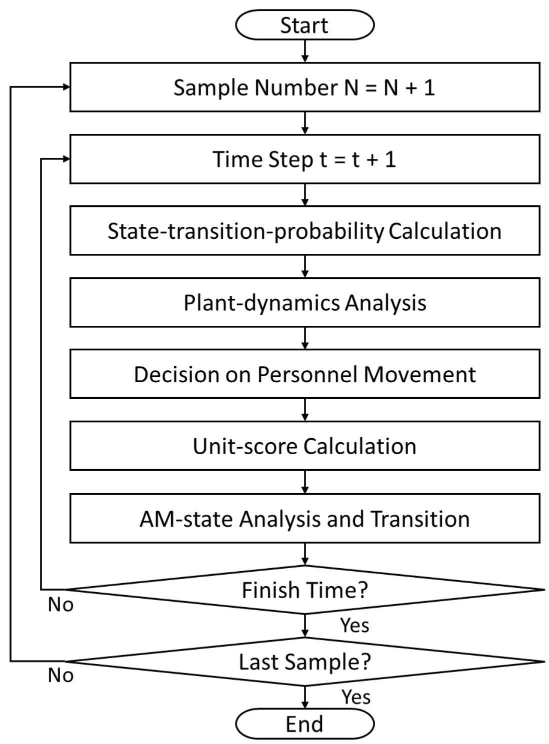

FIGURE 1. Scenario-generation procedure

Details of unit scores, AM states, and personnel movements are given in the following sections.

II.B. Index to Evaluate State of Units (Unit Score)

At nuclear power plants, various values, such as the water level and pressure of reactor pressure vessel (RPV), are monitored. When an event occurs, alarms are triggered in response to a drop in water level, etc. However, it is difficult for operators to determine which unit should be prioritized for response on the basis of numerical values, especially when the event progresses in a complex manner, such as when multiple units are simultaneously involved in an event. Therefore, we introduce a unit score that is based on the water level of the RPV and the prediction of future AM operation effects as an index to determine the implementation of AM operations by dynamically evaluating the state of each unit.

The calculation equation of the unit score $Score_{unit}$ is shown in Eq. (1), and the calculation equations of the base score $Score_{base}$ and the correction score $Score_{cor}$ constituting the $Score_{unit}$ are shown in Eqs. (2) and (3) respectively.

$$Score_{unit} = Score_{base} + Score_{cor} - Score_{fail} \tag{1}$$

$$Score_{base} = \frac{WH_t - WH_{CD}}{WH_{max} - WH_{CD}} \tag{2}$$

$$Score_{cor} = Score_{success} \times \frac{T_{AM_{left}}}{T_{AM_{total}}}. \tag{3}$$

The $Score_{unit}$ represents the unit state, the $Score_{base}$ indicates the margin of water level until core damage and is calculated from the RPV water level WH_t, the RPV water level corresponds to core damage WH_{CD}, and the maximum RPV water level WH_{max} at each time step. $The\ Score_{cor}$ is a correction score, which corrects the $Score_{base}$ by predicting how much the water level is expected to recover in the future according to the AM operation state. It is added to the highest value when the AM operation is successful, i.e., the success score $Score_{success}$, and decreased according to the remaining operating time $T_{AM_{left}}$ of the total operating time of AM $T_{AM_{total}}$. The $Score_{fail}$ is the failure score to reflect the disability of AM operation in the unit state. This value is constant only when AM operation fails and is set to 0 during other periods.

II.C. Construction of Accident-management Model Using Human Reliability Analysis

The number of personnel required for AM operation depends on the AM state. For example, more personnel are generally required when recovering AM from a failed condition than when AM is operating normally. To examine the allocation of personnel according to the AM state, the AM state is divided into seven states (waiting, starting, operating, stopping, cooling down, failed, and recovering). In practice, the probability of equipment failure is low. However, to evaluate the effectiveness of recovery through personnel movement, equipment failure that occurs with a certain probability is considered in addition to an operator's omission errors (e.g., forgetting to operate the equipment). The state transition of AM operation is shown in Fig. 2. AM is executed only during operation. However, a fixed number of operators are assigned from starting process to stopping process and during recovery, and they are not available for other tasks. On the basis of checking the possibility of optimizing AM operations during multi-unit operations by personnel movement, the recovery is designed to start only when the number of personnel required to recover failed AM and the number of personnel required to operate normal AM is secured.

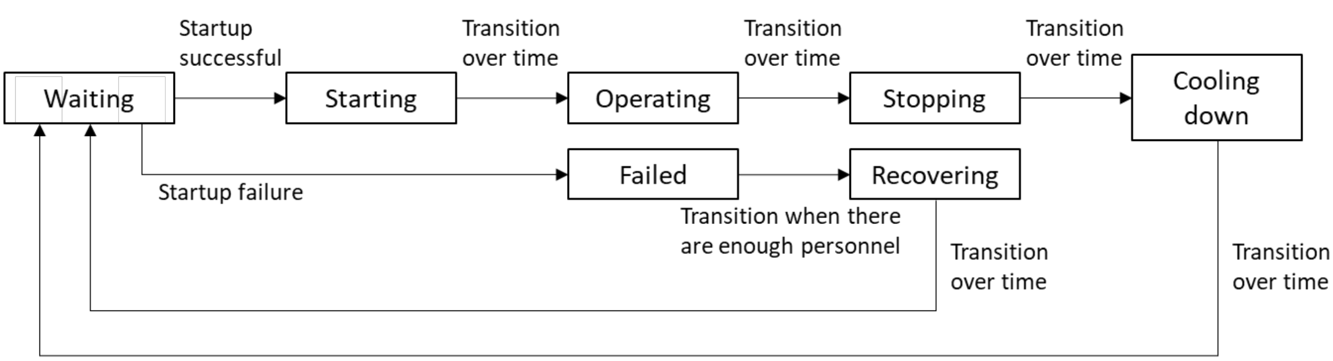

FIGURE 2. State transition of AM operation

To consider omission errors as operator human errors, we developed the following equation for calculating human error probability (HEP) on the basis of technique for human error rate prediction (THERP) [5], a first-generation human reliability analysis (HRA).

$$HEP = BHEP \times PSF \times MAX\left(0.5, \frac{HC_{AM}}{HC_{wait}}\right). \tag{4}$$

This model takes into account the performance-shaping factors (PSFs), which are factors that influence human behavior on the basis of the basic HEP (BHEP), and the impact of personnel margin, which is the ratio of the number of personnel waiting in a unit HC_{wait} to the number of personnel required to execute each AM operation HC_{AM}. However, the decrease in HEP due to an increase in the number of waiting personnel is limited to a maximum of 50%.

There are various types of PSFs. For this study, the effect of stress due to plant conditions is reflected in the HEP as a PSF. In THERP, a PSF is determined for stress levels. We calculated the $Score_{stress}$ from the $Score_{unit}$ of calculation-target unit and other units, and the stress is categorized into four levels on the basis of the $Score_{stress}$ to determine the PSF. The $Score_{stress}$ is calculated as

$$Score_{stress} = SR_{tgt} \times Score_{unit} + \left(1 - SR_{tgt}\right) \times Score_{ave}, \tag{5}$$

where $Score_{ave}$ is the average of $Score_{unit}$ of the other units, and SR_{tgt} is the ratio of the $Score_{unit}$ of the unit to the $Score_{stress}$. Next, the correspondence between $Score_{stress}$, stress level, and PSF is shown in Table 1. The PSFs are determined so that the HEP would not exceed 1.0 when the BHEP is made larger than THERP to allow more simulation patterns to appear in the simulation while reflecting the tendency of THERP.

TABLE 1. Relationship between $Score_{stress}$, stress level, and PSF

$Score_{stress}$ [-]	Stress Level [-]	PSF [-]
More than 1.0	Extremely low	1.5
0.5 to 1.0	Optimal	1.0
0.25 to 0.5	Excessively high	2.0
Less than 0.25	Extremely high	3.0

To evaluate the impact of plant states that change from time to time on the HEP, we constructed an AM model to determine the success or failure of AM operation on the basis of the HEP calculated for each time step and referring to the concept of time-failure rate. The failure rate of a non-recovery system, which is a typical example of time failure, and the equation of variation of failure probability based on the Poisson process used in reliability engineering are used as references. The equation that replaces the failure rate with the success rate is shown in Eq. (6), and the success rate at time t obtained by separating and integrating the failure rate is calculated using Eq. (7). If AM operation is successful, the success probability is reset.

$$\Delta P_s = \left(1 - P_s(t)\right) \times \lambda \Delta t \tag{6}$$

$$P_s(t) = 1 - e^{-\lambda t}, \tag{7}$$

where $P_s(t)$ is the success probability of AM operation from time 0 to t, and λ is the success rate per time step. Since this AM model uses conditional branching by state, $\lambda \Delta t$ is the success probability per time step, and λ is obtained from the HEP in Eqs. (4) and (7). If the probability that AM is not executed from the possible AM start time to core damage is the HEP, then λ is derived from Eqs. (8) and (9).

$$1 - P_s\left(T_{CD} - T_{AM_{st}}\right) = e^{-\lambda\left(T_{CD} - T_{AM_{st}}\right)} = HEP \tag{8}$$

$$\lambda = -\frac{\log(HEP)}{T_{CD} - T_{AM_{st}}}, \tag{9}$$

where T_{CD} is the time at which core damage occurs if AM is not executed, and $T_{AM_{st}}$ is the possible starting time for each AM operation. Thus, AM success or failure is determined at each time step on the basis of the HEP, which varies depending on the situation while AM is in a waiting state.

II.D. Movement of Personnel Between Units

The necessity of personnel movement between units is determined on the basis of the $Score_{unit}$. For simplicity, we assumed personnel movement between two units. The equation for calculating the number of personnel HC_{NM} moved from unit N to unit M is as follows.

$$HC_{NM} = int\left(\frac{Score_{unitN} - Score_{unitM}}{Score_{move}} - \frac{HC_{unitN} - HC_{unitM}}{2}\right), \tag{10}$$

where $Score_{move}$ is the movement score, and HC_{unitN} and HC_{unitM} are the number of personnel in each unit. If the number of personnel in two units is the same, personnel movement is executed if the difference in $Score_{unit}$ is equal to or greater than $Score_{move}$. If the $Score_{unit}$ of the two units are the same, personnel are moved so that the number of personnel becomes equal. When HC_{NM} is negative, the number of personnel is moved from unit M to unit N by the absolute value of HC_{NM}. After HC_{NM} is calculated using Eq. (10), Eqs. (11) and (12) are used to put a limit on HC_{NM}.

$$HC_{NM} = min(HC_{waitN}, HC_{unitN} - HC_{\text{minN}}, HC_{NM}) \tag{11}$$

$$HC_{NM} = max(-HC_{waitM}, -HC_{unitM} + HC_{\text{minM}}, HC_{NM}). \tag{12}$$

These equations are control equations to ensure that the number of moving personnel does not exceed HC_{wait} of the unit from which the personnel are dispatched and the number of personnel in the current unit HC_{unit} minus the minimum number of personnel required of the unit HC_{min}. The minimum number of personnel required is established to avoid the potential risk of dispatching a large number of personnel to other units, i.e., a shortage of personnel when a countermeasure is required in the calculation-target unit. The above control alone may result in an instruction from unit M to unit N to move personnel while in the process of moving personnel from unit N to unit M. Since this would be inefficient, a restriction is added so that no personnel can be dispatched to other units when they are scheduled to receive personnel from other units.

III. ANALYSIS OF MULTI-UNIT SCENARIO

To confirm the effectiveness of the countermeasure of the movement of personnel in multi-unit operations, a preliminary evaluation was conducted using the models introduced in Section II.

III.A. Evaluation Scenario

As in a previous study [4], the failure scenario of steam-generator isolation during steam generator tube rupture (SGTR) was used as the evaluation scenario. It was assumed that the emergency core cooling system (ECCS) would always operate for 1350 s in the initial stage after an SGTR, but would fail to isolate the accident loop, leading to eventual core damage regardless of AM success or failure. Depressurization by opening the pressurizer relief valve (DP) and deheat by opening the main steam relief valve (DSG) were implemented as operator actions for AM. The progression of events and AM operations are shown in Fig. 3.

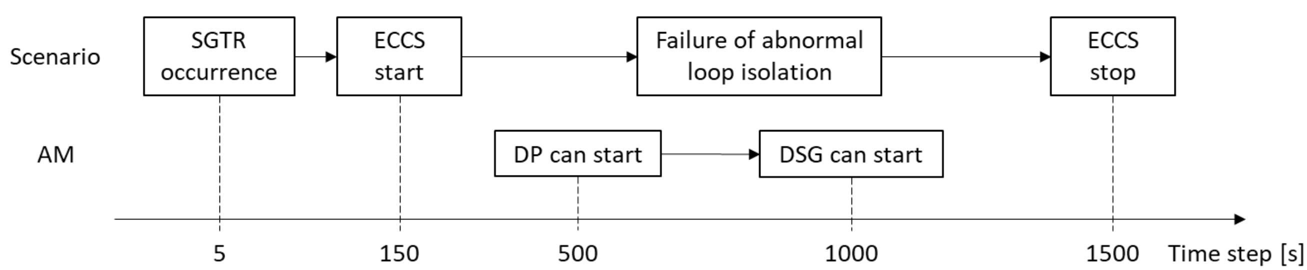

FIGURE 3. Progression of events and AM operations

III.B. Analysis Conditions

Scenarios were generated and evaluated for two cases, one with personnel movement between units and one without. Table 2 lists the analysis conditions.

TABLE 2. Analysis conditions

Item	Setting Value
Analysis period [s]	3600
Number of samples per unit [-]	100
Unit number [-]	3
Initial number of personnel in each unit [-]	3
Movement score [-]	0.2
Movement time between units [s]	0
Minimum number of personnel required for a unit [-]	2
BHEP of DP and DSG [-]	0.1
Number of personnel for DP and DSG implementation [-]	1
Number of personnel for DP and DSG recovery [-]	3
Probability of loss of function of DP and DSG [-]	0.1
Success score of DP and DSG [-]	0.3
Failure score of DP and DSG [-]	0.15
Start time of DP [s]	500
Start time of DSG [s]	1000
Time for starting of DP and DSG [s]	100
Time for operating of DP and DSG [s]	500
Time for stopping of DP and DSG [s]	100
Time for cooling down of DP and DSG [s]	200
Time for recovering of DP and DSG [s]	300

IV. RESULTS AND DISCUSSION

Table 3 lists the occurrences of successes, failures, and recoveries of AM operation for personnel movement based on the analysis conditions and without personnel movement. Without movement, if AM fails, the required number of personnel to meet the recovery start condition cannot be secured. Therefore, AM that has once failed remains in a failed state. With movement, the number of successful AM operations increased because the movement of personnel allowed the recovery of AM and AM become available again.

TABLE 3. Occurrences for each state

	Number of occurrences [-]					
	DP			DSG		
	Success	Failure	Recovery	Success	Failure	Recovery
Without movement	603	77	0	584	73	0
With movement	697	79	60	677	70	49

Tables 4 and 5 respectively list the time percentages for each state after the DP and DSG could be started. The time during failure decreased and that during standby and operation increased with movement compared to without movement.

TABLE 4. Time percentages for each state of DP

DP	Percentages [%]						
	Waiting	Starting	Operating	Stopping	Cooling down	Failed	Recovering
Without movement	57.01	3.25	15.76	3.08	6.09	14.80	0.00
With movement	64.76	3.76	18.36	3.56	6.96	1.61	0.98

TABLE 5. Time percentages for each state of DSG

DSG	Percentages [%]						
	Waiting	Starting	Operating	Stopping	Cooling down	Failed	Recovering
Without movement	52.25	3.75	17.99	3.49	6.89	15.63	0.00
With movement	58.25	4.35	21.00	4.02	7.89	3.54	0.94

The core-damage frequency for each unit is shown in Table 6. This frequency was lower with personnel movement than without personnel movement.

TABLE 6. Core-damage frequency for each unit

	Number of core-damage samples [-]			
	Unit 1	Unit 2	Unit 3	Total
Without movement	50	51	49	150
With movement	38	44	44	126

The average RPV water level for each unit at the end of the analysis is shown in Table 7. This RPV water level was higher with personnel movement than without personnel movement. The distribution of the RPV water level across all units is shown in Table 8. Since a total of 100 samples were generated per unit, the total number of samples for all units for each case was 300. With personnel movement, the number of samples below 5 m decreased and increased above 5 m. Therefore, it was found that the RPV water level, as well as the core-damage frequency, can be improved by personnel movement.

TABLE 7. Average RPV water level for each unit

	Average of RPV water level [m]			
	Unit 1	Unit 2	Unit 3	All units
Without movement	6.42	6.54	6.67	6.54
With movement	7.03	7.08	6.85	6.99

TABLE 8. Distribution of RPV water level across all units

	Number of samples for each RPV water level [-]			
	Below 3 [m]	3 to 5 [m]	5 to 7 [m]	Above 7 [m]
Without movement	21	47	82	150
With movement	10	23	93	174

By applying the CMMC method and creating scenarios that take into account the state-transition probabilities of AM and personnel movement based on plant conditions, it was found that the effectiveness of AM and the impact of personnel movement could be evaluated in complex scenarios involving simultaneous accidents in multiple units. The evaluation results indicate that personnel movement has the advantage of recovering AM operations, and that increasing the number of AM operations improves the core-damage frequency and RPV water level at the end of analysis.

V. CONCLUSION

We proposed a scenario-generation method that takes into account the plant state and operator state during multi-unit operation to support countermeasure determination such as personnel movement between units. The plant model developed in a previous study was extended to a multi-unit simulation model, and the state-transition probabilities of AM, considering the effect of the plant situation on the operator and movement of personnel between units according to the situation, were modeled. Scenario generation and evaluation were carried out for the failure scenario of steam-generator isolation during SGTR in multi-unit operation. The results indicate that the effectiveness of AM and that of personnel movement can be evaluated in complex scenarios considering the changing situation over time.

For future work, we will set various parameters to appropriate values and investigate indices for evaluating the priority of countermeasures during multi-unit operation.

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