Development of Margin Assessment Methodology of Decay Heat Removal Function against External Hazards
(4) Event Sequence Assessment Based on Continuous Markov Chain Monte Carlo Method with Plant Dynamics Analysis

Takashi Takata and Emiko Azuma
Graduate School of Engineering, Osaka University
2-1 Yamadaoka, Suita, Osaka, 565-0871, Japan
takata_t@see.eng.osaka-u.ac.jp, azuma@qe.see.eng.osaka-u.ac.jp

ABSTRACT

Margin assessment of a nuclear power plant against external hazards is one of the most important issues after Fukushima Dai-ichi Nuclear Power Plant Accident. In general, an event tree (ET) method is applied to investigate the margin and the effectiveness of countermeasures against the hazard in which a scenario of the plant status and the timing of the countermeasures are determined and a success or failure probability of each event or countermeasure is assumed mainly based on an engineering judgment. In order to investigate the plant dynamics during the scenario examined in the ET method, a numerical simulation is carried out in accordance to the sequentially-presented events. However, a number of scenarios are depicted potentially in a real situation.
In the present paper, a new approach has been developed to assess the plant status during external hazards and countermeasures against them in operation quantitatively and stochastically by taking possible scenarios into account. For this purpose, a Continuous Markov chain Monte Carlo (CMMC) method is applied. Furthermore, a preliminary event sequence assessment has been carried out under the condition of deep snow in a loop type sodium cooled fast reactor.

KEYWORDS

External hazard, Snow, CMMC, Plant dynamics analysis, Sodium cooled fast reactor

1. INTRODUCTION

On July 8, 2013, Japan Nuclear Regulation Authority (NRA) issued new regulatory requirements for commercial power reactors and countermeasures for nuclear safety against external initiators, such as earthquakes, tsunamis and volcanic eruptions, were decided to be enhanced in the requirements as lesson learned from Fukushima Dai-ichi Nuclear Power Plant Accident [1].

A probabilistic risk assessment (PRA) is quite effective for safety assessment of nuclear power plants against external initiators. In the assessment, an event tree (ET) and a fault tree (FT) models are used generally. In the ET, branches of the event (heading) are determined taking into account the progress of the scenario and their failure probabilities are evaluated by the FT analysis. As a result, the probability of plant state, such as success or failure against the initiating event, is evaluated. In one ET analysis, various scenarios but same occurrence timing (order) of heading is investigated and thus the order of heading is carefully determined by an expected scenario's occurrence with an expert judgment. However, it is noted that an influence of various scenarios on the plant status should be taken into consideration in the risk assessment so as to reduce a complete uncertainty of scenario. It is also noted that a failure probability of each heading is significantly affected by the plant status at that time. Accordingly, a dynamic event tree (DET) method has been developed [2] consider the plant state that includes time history of events. However, it is still not easy to assess all possible scenarios in the ET and FT method.

In the present paper, a continuous Markov chain Monte Carlo (CMMC) method [3] is applied to a plant dynamics analysis so as to evaluate both a variety of scenario and a probability of each plant state statistically at the same time. In the CMMC method, a subsequence plant status is determined by the latest state (Markov chain) and the status is evaluated from a plant dynamics analysis. A failure or recovery of each component is estimated stochastically based on the plant status and consequence of the hazard by Monte Carlo method. In the previous work [3], the CMMC method was applied to investigate the protected loss of heat sink (PLOHS) of sodium cooled fast reactor.

In the present study, the event sequence analysis based on CMMC method has been developed for an external initiator event and a preliminary event sequence assessment has been carried out under the condition of deep snow in a loop type sodium cooled fast reactor.

2. CONTINUOUS MARKOV CHAIN MONTE CARLO METHOD WITH PLANT DYNAMICS ANALYSIS

2.1. Coupling Methodology

Figure 1 shows the schematic of the CMMC method with plant dynamics analysis. As a result of plant dynamics analysis, current parameters such as a temperature and pressure are obtained. Then probabilities of state transitions of components or functions, which correspond to headings of the event tree method, are evaluated based on the parameters as well as an external condition, e.g. snow depth at the plant.

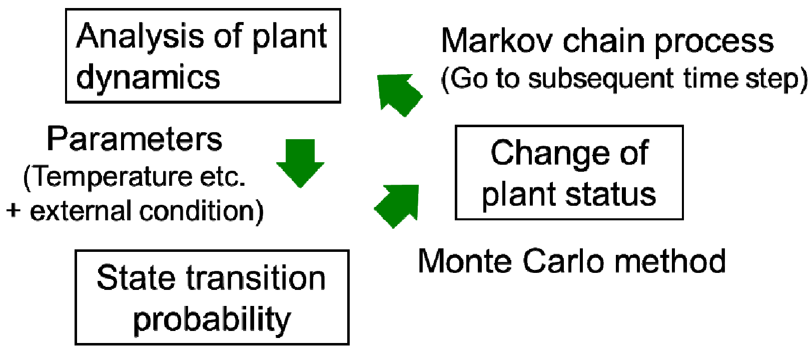


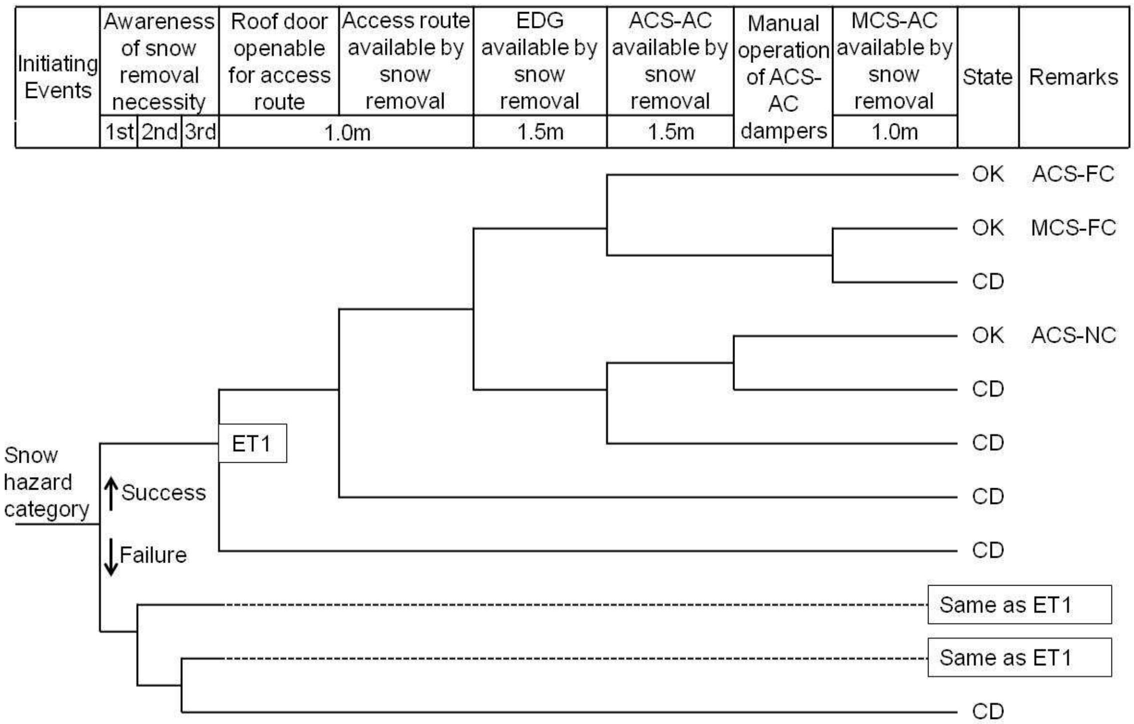
Fig. 1 Schematic of CMMC with Plant Dynamics Analysis.

Next, a Monte Carlo sampling is carried out using the state transition probabilities and the subsequent plant status is determined. Physical models of the components or functions will change due to their state and the subsequent analysis of plant dynamics will be carried out continuously until the end of the analysis. (The Markov chain process is assumed.)

A unique scenario, which means unique order and occurrence time of event, is obtained at one analysis. Accordingly, a number of analyses are examined to investigate the variety of scenario and probabilistic plant assessment statistically.

2.2. Model of State Transition Probability and Conditional Modes

Components or functions where the state transition probabilities are evaluated correspond to the headings of the event tree method. In the present study, categorizations of the probability models and conditional modes are investigated based on the snow PRA for fast reactor as shown in Fig. 2 [4].



NB) CD: Core Damage, EDG: Emergency Diesel Generator, ACS: Auxiliary Cooling System, MCS: Maintenance Cooling System, AC: Air Cooler, FC: Forced Circulation, NC: Natural Circulation

Fig. 2 Main Event Tree for Snow PRA [4].

2.2.1. State transition probability models

Two categories are considered; one is a demand type and the other is a failure rate type. A demand type is applied mainly to manual operations such as the awareness of snow removal necessity and the manual operation of ACS-AC (Auxiliary Cooling System - Air Cooler) dampers as in Fig. 2.

On the other hand, the following equation is applied to the failure rate type as:

$$\frac{\partial p_f}{\partial t} = \lambda_f p_s - \lambda_s p_f \;\; or \;\; p_f = \frac{\lambda_f}{\lambda_f + \lambda_s}\left(1 - e^{-(\lambda_f + \lambda_s)t}\right) \tag{1}$$

Here, p and λ are the probability and the change rate respectively. t is the independent variable. The subscripts s and f means the failure and success. A table format for the independent variable and state probability is also implemented as a failure rate model. Failures of the components, the roof door openable and the access route available follow the failure rate model.

2.2.2. Conditional modes

As concerns the conditional modes, three modes are implemented as: conditional mode, forced mode and common mode. When the roof door cannot open, no access route will be available to remove snow and to operate components manually. This is designated as the conditional mode.

The operation of snow removal will be done regardless of the state of the components or functions (for instance, several times per day). This mode means the forced condition.

In general, multi units of the ACS-AC are implemented in fast reactor plant (one ACS-AC for one loop of heat transport system) and they are placed in the vicinity. Therefore, all ACS-AC can recover when the snow removal is successful. The common mode means that one change of the transition also affects other transition states of components or functions.

3. EVENT SEQUENCE ASSESSMENT OF SNOW IN FAST REACTOR

As a preliminary assessment, the ACS-AC failures due to snow and their recovery by manual snow removal in loop type sodium cooled fast reactor (SFR) is analyzed to investigate the applicability of the present method. With regard to the plant dynamics analysis, the Super-COPD code [5] is applied.

A schematic of heat transport system is shown in Fig. 4. The ACS-AC is located at the secondary transport system. Since liquid sodium has a high boiling temperature at atmospheric condition (approximately 880ºC) and the density varies widely along to the temperature difference rather than that in pressurized water, a natural circulation decay heat removal can be easily achieved by applying the ACS-AC at a higher elevation than the core and the intermediate heat exchanger. In the analysis, independent three heat transport systems are assumed.

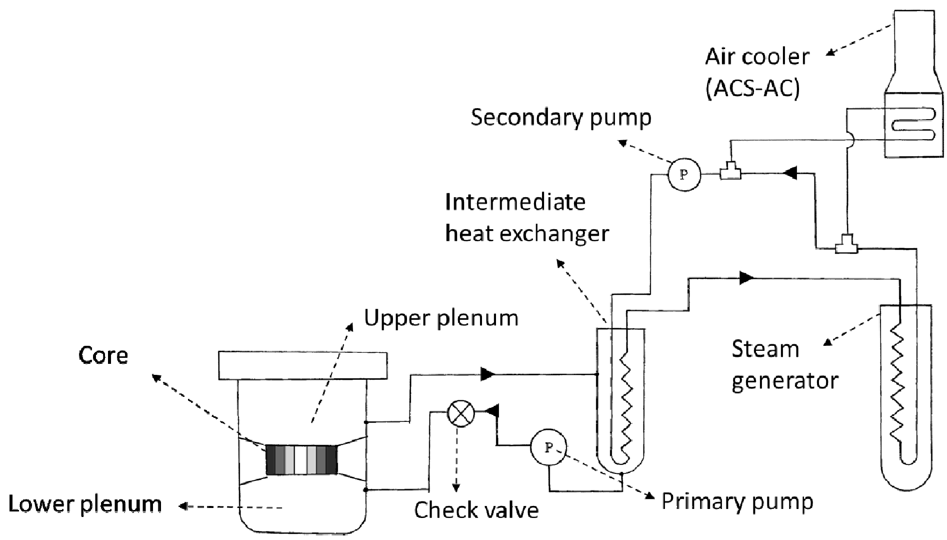


Fig. 3 Schematic of Heat Transport System in SFR.

A station black out (SBO) due to deep snow fall is assumed as an initiating event. It is also assumed that an emergency core shut down is successful. Then the loss of the function of the ACS-AC will take place because of a stack of inlet air opening or a filter clogging at the air inlet caused by snowfall.

In the analysis, the ACS-AC available heading is only taken into account in the analysis for simplicity. Furthermore, the effectiveness of the snow removal operation is numerically investigated.

3.1. Analytical Condition

In the analysis, two state transition probability models are applied to the ACS-AC availability and the snow removal operation. In the ACS-AC availability, the failure rate model is assumed and the failure change rate is set so as to achieve 95% of failure state probability at 2.0m depth of snow as shown in Fig. 4. In the analysis, a constant snowfall rate (0.1m/hr) is assumed. Consequently, a time is the independent variable (t) in Eq. (1) instead of the snow depth and failure rate (λ_f) is set to 4.16×10^{-5}[1/s].

No success change rate is considered in the state probability. Instead, the ACS-AC will recover fully when the snow removal operation is successful. The ACS-AC availability is examined independently at each heat transport system by Monte Carlo sampling.

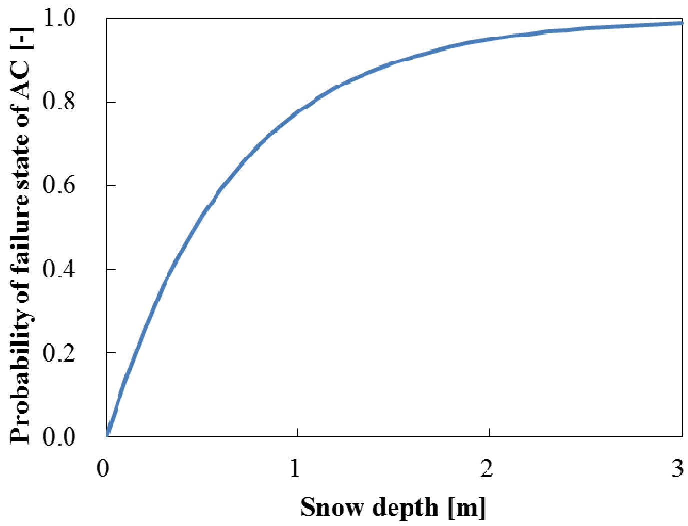


Fig. 4 Probability of Failure State of AC.

When the ACS-AC fails, the heat removal capability reduces to 1% of the rated condition in the plant dynamics simulation.

As concerns the snow removal operation, the demand model is applied and the failure probability per demand is set to 0.5. In the analysis, the ACS-ACs are assumed to be placed in the vicinity. Hence, all ACS-ACs will recover when the snow removal operation is successful and the snow depth at each ACS-AC is set to 0m again. (The common mode is applied in terms of the snow depth.) The interval of the operation is set to 8hr referred by the snow PRA [4]. It is also noted that snow falls continuously during the analysis resulting in probability of repetitive failure although the snow removal is successful.

In each analysis, the time history of 24hr after the initiating event (SBO) occurs and 100 samples are summarized to obtain the statistical result of the core outlet temperature in each case. Table 1 summarizes the analytical condition.

Table 1. Analytical condition

Initiating event	:	Station Black out due to snowfall
Snowfall rate	:	0.1m/hr (2.4m/day)
ACS-AC state transition probability		
	:	Failure rate model (λ_f = 4.16×10^{-5} [1/s])
Snow removal operation		
	:	Demand model (Failure probability per demand: 0.5, interval: 8hr)
Number of sampling	:	100

3.2. Result and Discussion

3.2.1. Time transient of temperature and its statistical distribution

The time transient of the core outlet temperature in case of no snow removal is shown in Fig. 5 (50samples are figured). The analytical result of no ACS-AC failure case is also depicted as a black solid line in the figure. When no ACS-AC recovery is considered, the core outlet temperature will increase gradually in every sample and the variety of temperature history is investigated as in Fig. 5. It is noted that some temperature fluctuations are simulated around 12hr after the initiating event even in case of no ACS-AC recovery shown in Fig. 5. In the present analysis, the heat transport line to the steam generator (see Fig. 3) is closed when the emergency core shut down is operated. However, the isolation valve is assumed to be slightly open in the analysis and thus cold coolant flows into the intermediate heat exchanger gradually resulting in the fluctuations.

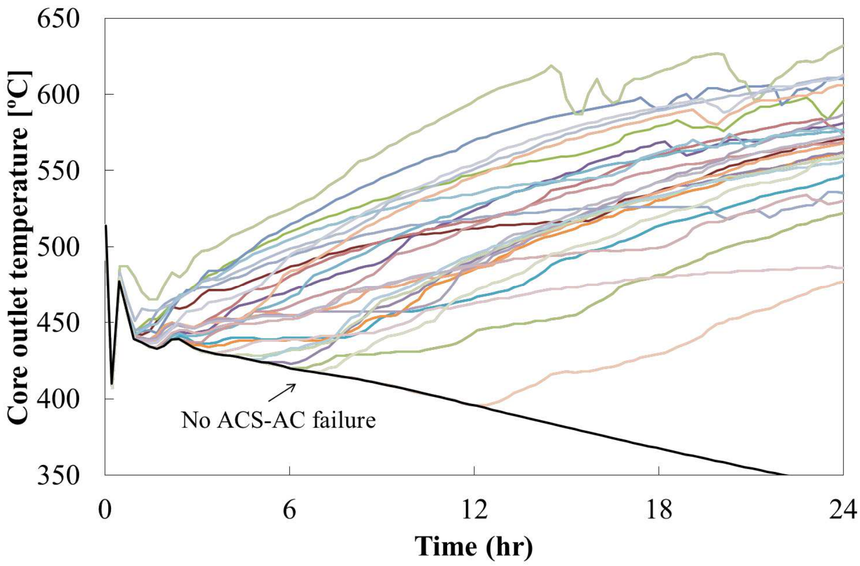


Fig. 5 Time Transient of Core Outlet Temperature in case of No Snow Removal.

When the snow removal operation is taken into consideration, the core outlet temperature tends to decrease after the demands of the snow removal operation as shown in Fig. 6 (dashed blue lines indicate the demand). The maximum core outlet temperature appears almost at the second demand (16hr after the initiating event).

It is apparent that the plant has various statuses though small number of the headings is considered. Hence, the present method has an advantage that one can assess the plant status statistically.

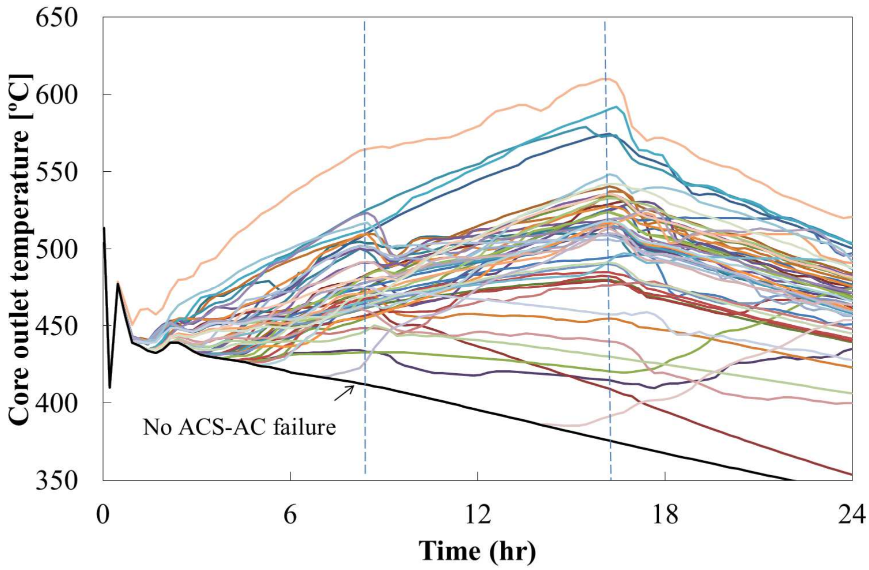


Fig. 6 Time Transient of Core Outlet Temperature with Snow Removal.

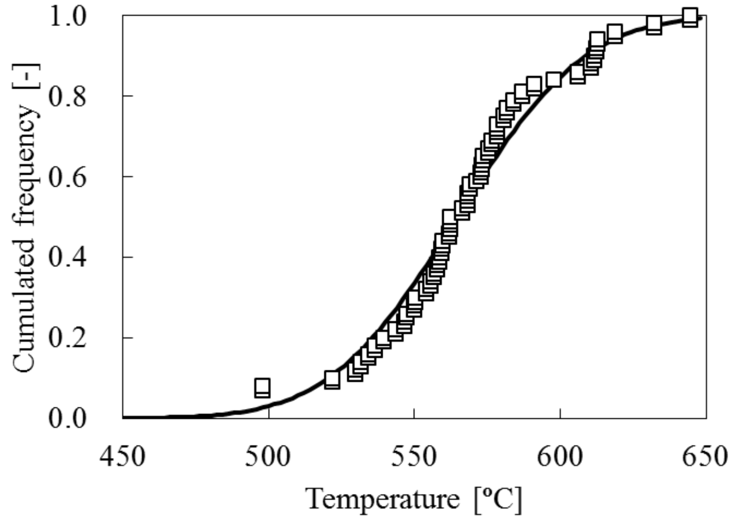
Since a local temperature maximum is investigated within one hour as seen in Figs. 5 and 6, the maximum temperature after one hour is summarized to obtain the statistical data. It is noted that the local maximum will appear because of the temporal difference between the temperature increase and the development of natural circulation.

Figure 7 shows the cumulated frequency of the maximum core outlet temperature after one hour from the initiating event. The solid line is a fitting curve based on a normal distribution. As seen in Fig. 7, the cumulated frequency agrees with the normal distribution although some particularity seems to appear around 600ºC in both cases. Since no phase change of the coolant will happen due to the high boiling temperature, a single phase thermal hydraulics is achieved in the present analysis resulting in the good agreement with the normal distribution. At the same time, the fluctuation caused by the coolant flow from the steam generator mentioned above might affect the particularity as well as the number of the sampling. Those influences on the statistical result will be discussed in a detailed assessment.

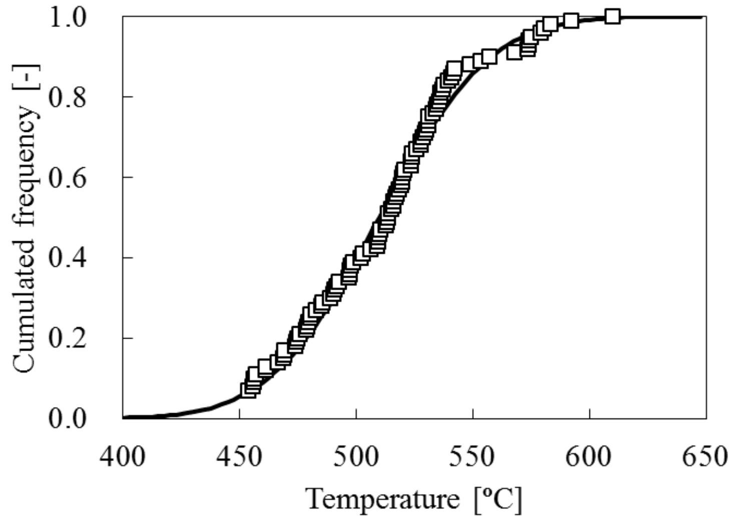
The statistical result of the cumulated frequency is summarized in Table 2.

Table 2. Mean value and standard deviation of maximum core outlet temperature

	Mean value [ºC]	Standard deviation [ºC]
Without recovery	564.6	34.5
With recovery	510.0	37.4



(a) Without recovery by snow removal



(b) With recovery by snow removal

Fig. 7 Cumulated Frequency of Maximum Core Outlet Temperature.

3.2.2. Statistical assessment based on CMMC method

In the present study, the loss of the function of the heat transport system is not considered in the plant dynamics analysis. Instead, the failure probability of the heat transport system is investigated based on the statistical result.

When 650ºC is assumed to be a limiting temperature of the heat transport system, the failure probability within 24 hours after the initiating event is evaluated as 6.6×10^{-3} in case of no recovery based on the fitted curve of normal distribution shown in Fig. 7 and Table 2. Besides, the upper limit of 95% one-sided confidence interval, which is often used in a best estimate plus uncertainty (BEPU) analysis [6], is evaluated to 621.3ºC

The scenario of no recovery corresponds to a loss of ultimate heat sink in the present analysis. However, the comparatively low failure probability is calculated because of high availability of natural circulation decay heat removal and high boiling temperature of coolant. It can also be said that the heat transport system will not be damaged at that time from the viewpoint of the BEPU investigation. It is noted that the heat transport system must be damaged finally in this scenario. However, one has a relatively sufficient time (at least 24 hours) to prepare recovery or mitigation measures against the ACS-AC failure in the present scenario.

When the snow removal operation is taken into account, the failure probability and the upper limit decrease to 9.0×10^{-5} and 571.4ºC respectively. As comparing with the no recovery case, the failure probability reduces almost two orders of magnitude. Consequently, It can be concluded that the snow removal operation is quite effective against the damage of the heat transport system caused by the ACS-AC failure although the failure probability of the operation per demand is comparatively high (0.5) rather than that in the snow PRA [4].

Both a time transient of the plant state and an uncertainty of event (heading) occurrence are coupled in the present event sequence assessment method by applying the CMMC method. Therefore, a quantitative assessment based on a statistical approach can be examined. Furthermore, an optimization in terms of timing and duration and an effectiveness of recovery or mitigation measures are also able to be investigated quantitatively in the present method.

4. CONCLUSIONS

As an event sequence assessment method, a continuous Markov chain Monte Carlo (CMMC) method is applied to a plant dynamics analysis so as to evaluate both a variety of scenario and a probability of each plant state statistically at the same time. The Super-COPD code is used for this purpose. In the coupling, two models of a state transition probability (failure rate and demand models) are three conditional modes (conditional, forced and common modes) are implemented considering with the snow PRA event tree.
Then a preliminary event sequence assessment has been carried out under the condition of deep snow in a loop type sodium cooled fast reactor. In the assessment, failures of three auxiliary cooling system - air coolers (ACS-AC) caused by snow depth and a snow removal recovery operation are taken into account for simplicity.

As a result, it is demonstrated that the comparatively low failure probability of the heat transport system (6.6×10^{-3}) are assessed statistically within 24 hours after the initiating event although no ACS-AC recovery is assumed. It is noted that the heat transport system must be damaged finally in this scenario because it corresponds to a loss of ultimate heat sink scenario in the analysis. However, one has a relatively sufficient time (at least 24 hours) to prepare recovery or mitigation measures against the ACS-AC failure in this scenario. When the snow removal operation is taken into account, the failure probability reduces almost two orders of magnitude (9.0×10^{-5}).

It is concluded that a quantitative assessment based on a statistical approach can be examined in the present method. It is noted that the time transient of plant status can also be assessed in the present method. Consequently, an optimization in terms of timing and duration and an effectiveness of recovery or mitigation measures are able to be investigated quantitatively.

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