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Modeling of the Off-site Power Recovery in the Multi-Unit PSA

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1. Introduction

If the loss of off-site power (LOOP) event occurs in the nuclear power plant, it will be tried to connect the emergency diesel generators (EDGs) and the alternative AC diesel generator (AAC) and to provide AC power. If these power sources cannot be provided either, the off-site power should be recovered by the certain mission time to prevent the core damage. Also, on the condition that core damage occurred already, whether the off-site power can be recovered before the reactor vessel failure or before the containment building failure will affect the operation of the safety systems and the progress of the severe accident.

The LOOP events are categorized as plant-centered LOOP, switchyard-centered LOOP, grid-centered LOOP, and weather-related LOOP, according to the cause. In the previous single unit probabilistic safety assessment (PSA), a single probability curve for the recovery of the off-site power has been used regardless of the cause. However, in the terms of the multi-unit PSA (MU-PSA), the inter-unit dependency for the off-site power recovery will be determined depending on whether the cause of LOOP affects multiple units coincidently. Therefore, it is necessary to reevaluate the probability of the off-site power recovery over time for MU-PSA [1, 2].

In addition, one of the difficulties of modeling the off-site power recovery in the practical MU-PSA is the variety of the mission time according to the plant type, calculated by thermal-hydraulic simulations. Nonsense cut sets which coincidently include the events for the failure of the off-site power recovery with different mission time are generated due to the multiple unit combination. It will be an issue when modeling the domestic situation that the various types of plants exist in the one site. To solve this, in the previous domestic MU-PSA study, the recovery rule to leave only the longest mission time event in the nonsense cut sets was applied [2]. But, it is not in accordance with a present PSA trend trying to minimize the recovery rule. And it is not shown in the fault tree (FT) model.

Therefore, in this study, the probability curve for the off-site power recovery was reevaluated in the view of MU-PSA and the new method to handle the nonsense cut sets from the off-site power recovery was proposed.

2. Methods and Results

2.1 Calculation of Off-site Power Recovery Probability

To reevaluate the probability of off-site power recovery over time for MU-PSA, the domestic experience of multiple units LOOP (MU-LOOP) was investigated. And the duration time for the domestic MU-LOOP events defined by Korea Institute of Nuclear Safety (KINS) is shown in Table I [2, 3]. It was fitted in the lognormal distribution, shown in Fig. 1, using the general method of off-site power recovery probability estimation [4].

Table I: History of domestic MU-LOOP

Units	Date	Cause	Duration
Kori Unit3, 4	86. 08. 28	Typhoon	7 hr 45 min
Kori Unit1, 2, 3, 4	87. 07. 16 / 17	Typhoon	9 hr 36 min
Hanul Unit1, 2	97. 01. 01	Severe Wind	28 min

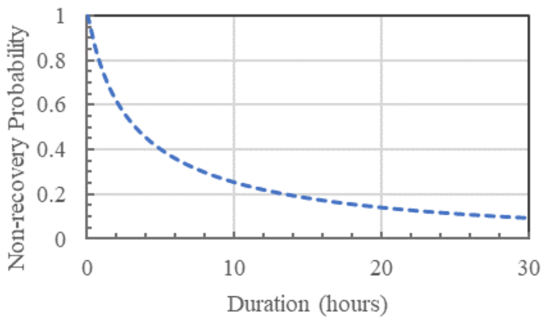

Fig. 1. Probability of exceedance (non-recovery probability) versus duration curve

2.2 Method for Eliminating Nonsense Cut Sets

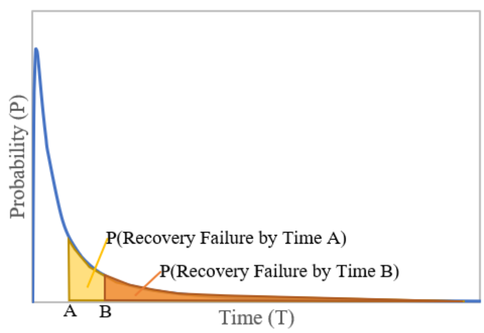

Fig. 2. Example of recovery probability on time after LOOP

When the recovery probability on time is according to lognormal curve like Fig. 2, if each of the mission time of two different units is A and B, the probability for the recovery failure by time A, P(A), and the probability for the recovery failure by time B, P(B), equal the area colored, respectively. Because the area P(B) is included in the area P(A), P(B) can be expressed as follows:

$$P(B) = P(A \cap B) = P(A)P(B|A) \quad (1)$$

In other words, the probability for the failure of the event with longer mission time can be calculated, multiplying the probability for the failure of the event with shorter mission time and the conditional probability at that time. By expanding it, the failure probability with n-th longer mission time, F_n, can be modeled as follow:

$$F_n = F_1 * F_{2|1} * F_{3|2} * \cdots * F_{n|n-1} \quad (2)$$

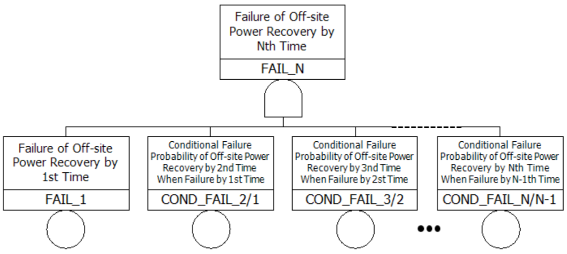

Fig. 3. Method using for eliminating nonsense cut sets in off-site power recovery events.

2.3 Verification with Simplified Model

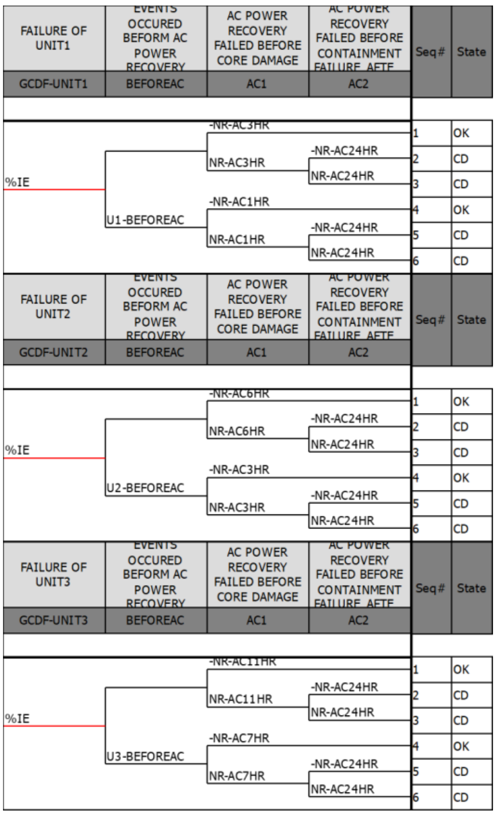

Fig. 4. Simplified event tree model for verification

To verify the method stated above, the simplified multi-unit model regarding the off-site power recovery was implemented. Using this model, these three cases were compared: 1) no nonsense cut set handling, 2) applying the recovery rule, and 3) applying the method using the conditional probability, proposed in this study. The simplified model was composed of three units, of which event tree are shown in Fig. 4. The results of reevaluation of the failure probability for off-site power recovery were put into each event, as shown in Table III. The probability of an initiating event was assumed as 1. It was quantified using the computational codes, FTREX and SiTER [2, 5].

Table III: Basic events for the failure of off-site power recovery

1) & 2)		3)	
Event	Prob.	Event	Prob.
NR-AC1HR	0.758	NR-AC1HR	0.758
NR-AC3HR	0.520	NR-AC-COND(3HR-1HR)	0.686
NR-AC6HR	0.359	NR-AC-COND(6HR-3HR)	0.691
NR-AC7HR	0.325	NR-AC-COND(7HR-6HR)	0.907
NR-AC11HR	0.236	NR-AC-COND(11HR-7HR)	0.724
NR-AC24HR	0.118	NR-AC-COND(24HR-11HR)	0.503

Comparing three results, the number of cut sets was both the same between applying recovery rule and using conditional probability. But, when there was no nonsense cut set handling, it was about twice of that of the other two results. It was caused by that all of the nonsense cut sets regarding off-site power recovery were eliminated in the latter two cases.

However, though nonsense cut sets were excluded in the cut set list in both latter two cases, it was not reflected in FT model when the recovery rule applied. The example of the difference in outcome FT models between 2) and 3) method was shown in Fig. 5 for the cut set that the off-site power recovery by 6 hours failed and then unit 1 and 2 both failed. Therefore, the quantification using Monte-Carlo method that FT models are applicated directly is available to 3), but not to 2).

The total failure probability of the whole logic decreased than that of no nonsense cut set handling case by 0.71 times when the recovery rule applied and by 0.80 times when the conditional probability method applied. The reason for the decrease is considered that the over-estimated failure probability due to the nonsense cut sets is adjusted.

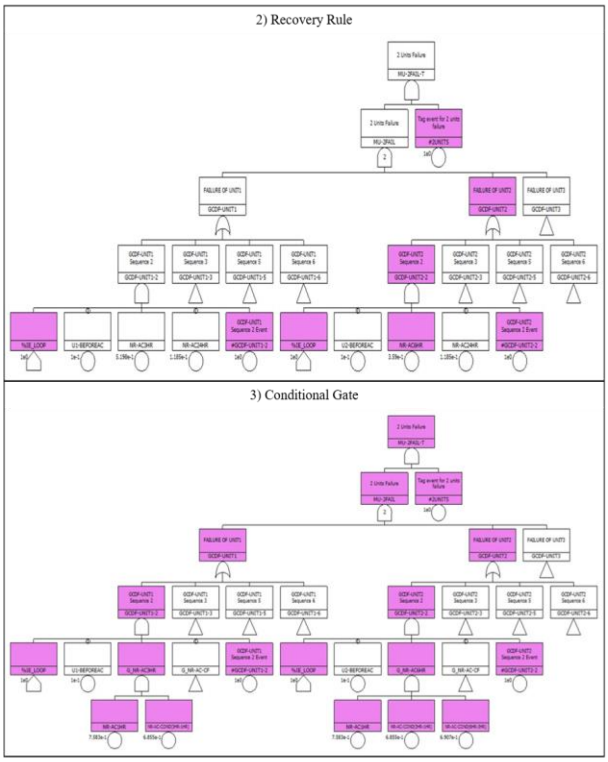

Fig. 5. Example of difference in outcome FT models between recovery rule method and conditional probability method

Table IV: Results of the verification with simplified model

Ratio	1)	2)	3)	
			FTREX +SiTER	FTeMC
No. of Cut Sets	1.00	0.48	0.48	-
Total Failure Probability	1.00	0.71	0.80	0.34

The increase in the results of 3) conditional probability method from 2) recovery rule method is considered to be led by the characteristics of the conditional probability method and quantification tools. In the method proposed in this study, the failure events of off-site power recovery are gates, not a basis event, and non-logic is unavailable for the gates directly. Due to it, using quantification tools that the rare probability events are assumed and the delete term approximation is used, the failure probabilities for the sequences with off-site power recovery success are estimated conservatively.

To find out how much this conservativeness affect the results, the 3) case applying the conditional probability method was re-quantified using FTeMC, the Monte-Carlo quantification computational code. From the results of two quantification methods, it was figured out that the failure probability would be varied from 0.93 times to 3.60 times, upon sequence combination. And the total failure probability quantified by FTeMC was about half of that using the traditional quantification method. The Monte-Carlo approach used in FTeMC can calculate a more realistic value for the events with a high probability than the traditional quantification method used in FTREX. Because it is not affected by the rare probability approximation and the delete term approximation. Thus, the difference in the results with FTeMC can be regarded as the degree of the over-estimation.

3. Conclusions

In this study, the probability curve for the off-site power recovery was reevaluated in the view of MU-PSA and the method using conditional probability to handle the nonsense cut sets from the off-site power recovery was proposed. As a result of verifying it thought a simplified model, it was confirmed that nonsense cut sets for the off-site power recovery was eliminated and it was directly reflected in the FT model. It is expected to contribute to developing multi-unit PSA model in the future.

However, when using the method presented in this study, the quantification tools based on the assumption of rare probability events that are mainly used in previous PSA may lead quite conservative results. Therefore, in the future research, the way to decrease this conservatism such as non-rare events handling, options of quantification software code, and so on, need to be examined.

Acknowledgements

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