How to estimate the inter-unit effects of radioactive releases in multi-unit PSA

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1. Introduction

There have been a lot of researches to assess the multi-unit risk since Fukushima nuclear power plants (NPPs) accident happened. Especially, since there are many multi-unit sites in Korea, Korean research institutes including KAERI have focused on multi-unit probabilistic safety assessment (MUPSA) modeling to evaluate whether multi-unit sites are safe or not. The one of unresolved subjects is the effects of radioactive releases in MUPSA. If the radioactive materials are released from Unit A by an accident that makes a core damage, the adjacent Unit B must be influenced directly or indirectly. To estimate the effects is a quite important subject in multi-unit sites because Fukushima NPPs actually suffered from radioactive releases. Some researches tried to estimate the release effects in PSA [1, 2], however there is no established procedure. The objective of this study is developing how to evaluate the inter-unit radioactive influence in MUPSA. The section 2 gives a detailed explanation of methodology. The section 3 shows the application of the proposed methodology to a multi-unit loss of offsite power (LOOP) accident.

2. Methodology

Prior to explaining the methodology in detail, there are some assumptions to simplify modeling.

- There is no mechanical influence on structures, systems and components. That means the radioactive releases only affects the human performances.
- Dynamic effects are not considered. That means the effects of radioactive releases does not depend on release timing and human performance time. The dynamic effects are certainly not trivial, and therefore it should be regarded as a future work.
- There is a preceding unit which releases radioactive materials before the other units undergo core damages or radioactive releases although initial event (IE) occurs simultaneously at all units in a site.

There are three steps as shown in Fig. 1: Step 1 is to select main core damage scenarios of a preceding unit, Step 2 is to obtain main human failure events (HFEs) of the affected other units, and Step 3 is modeling. Details are following.

Step 1: In order to select main core damage scenarios of a preceding unit, Fussell-Vesely (FV) importance of scenarios for a single-unit is calculated by quantifying minimal cutsets. After that, the main scenarios are selected according to Eq. (1).

$$\mathrm{FV} \times \mathrm{SU\text{-}CDF(by\ target\ IE)} \times \mathrm{LRF} > p_c \qquad (1)$$

where, FV is a Fussell Vesely importance, SU-CDF is a single unit core damage frequency by target IE , LRF is a large release fraction obtained from Level 2 PSA and p_c is a criterion.

The LRF is multiplied because the LR is much more influential on operator action than non-large release (NLR). However, NLR fraction (NLRF) of each scenario as well as LRF is also provided by source term analysis from Level 2 PSA.

Step 2: Main HFEs of the affected other units are obtained from FV importance of basic events. The HFEs having FV importance greater than 0.005 are chosen as main HFEs in accordance with the general rule [3, 4]. Obtained HFEs are classified into two categories: one is an operator action in main control room (MCR) and the other one is a local operator action conducted outside of MCR.

Step 3: The all main scenarios are sub-divided into LR scenario and NLR scenario by using LRF and NLRF, and they are added as AND gates to the HFEs separately in the fault tree (FT), as shown in Fig. 2. The human error probabilities (HEPs) are different whether a scenario is LR or NLR because the amount of radioactive materials mainly affects human performance and habitability of operators in MCR. Therefore, if the operator action is conducted in MCR, a loss of MCR habitability is considered in case of LR. The original HEPs are used for the other scenarios which are not main scenarios.

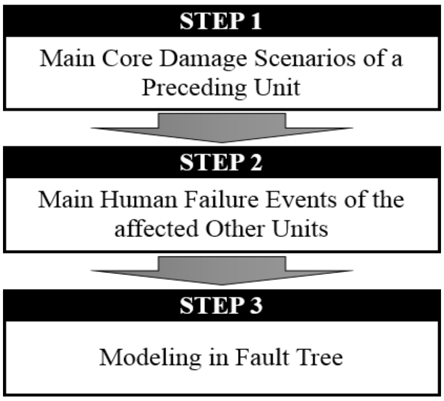

Fig. 1. Schematic flowchart of the methodology to estimate the inter-unit effects of radioactive releases in multi-unit PSA.

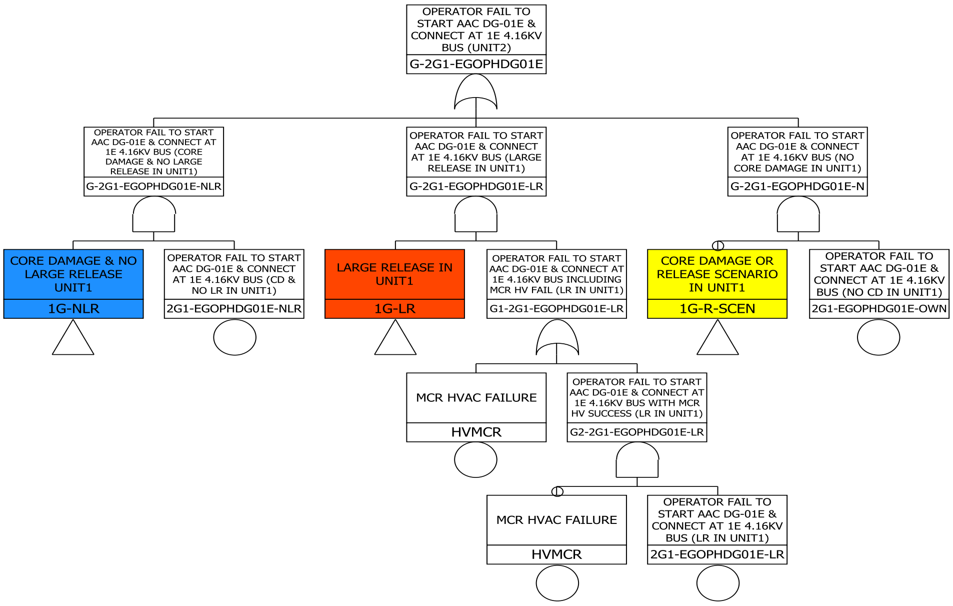

Fig. 2. An example of HFE-FT of the affected unit (Unit 2) when core damage scenario occurs in a preceding unit (Unit 1) during multi-unit IE

3. Case Study: multi-unit LOOP

In order to verify the validation of proposed methodology, multi-unit LOOP IE is selected as a case study. Some prerequisites are needed prior to modeling.

- There are six units with OPR-1000 type in a site, and the model which had been developed by KAERI was used as a base model [5].
- For simplification of modeling, the preceding unit is only Unit 1, and Unit 1 has influence on the other units equally, irrespective of distances between units. The effect of distance between units can be considered differently by employing different HEPs in each units.
- Two alternate alternating current diesel generators (AAC DGs) and two high capacity portable DGs (PDGs) are used during LOOP. PDG is newly added as one of post-Fukushima actions. One pair of AAC DGs and PDGs is used for Unit 1 and Unit 2, the other one pair is used for Unit 3~Unit 6. In order to prevent duplicate use of AAC DG and PDG, a unit with smaller number has a priority on use of AAC-DG, while a unit with larger number has a priority on use of PDG.

Step 1: Total 27 main core damage scenarios were selected in accordance with Eq. (1). Five are LOOP scenarios, seven are station black out start (SBOS) scenarios caused by failure of emergency DG (EDG) startup and fifteen are SBO run (SBOR) scenarios caused by failure of EDG run. The criterion in Eq. (1), p_c, was decided to 1E-10 considering the fact that normal SU-CDF of LOOP is 1E-7 order. The LRF and NLRF of all main scenarios were obtained from 21 source term categories (STC) analyzed in the previous work [5]. According to source term analysis, the scenarios with core damage but containment no-failure are classified as NLR scenarios, while the scenarios with core damage and containment failure are classified as LR scenarios.

Step 2: Five main HFEs were obtained from FV importance analysis of SU-LOOP minimal cutsets as shown in Table I. Only EGOPHPDG, which means operator fails to connect PDG, is an operator action performed outside of MCR.

Table I: Main HFEs obtained in a SU-LOOP model

HFE	HEP	FV	Location
EGOPHPDG	1.00E-01	N/A	LOCAL
EGOPHDG01E	1.53E-02	0.092	MCR
SDOPHLATE	8.52E-03	0.067	MCR
SDOPHEARLY	2.19E-02	0.014	MCR
HIOPHFTS	1.00E-02	0.0074	MCR

Step 3: The HFEs obtained from Step 2 were constructed as modified FTs like Fig. 2. The loss of MCR habitability was added to all HFEs except for EGOPHPDG and its probability was estimated to be 0.1 conservatively. Since there has been no confidence about how to adjust the HEPs in response to whether a core damage scenario is LR or NLR and whether operator actions are conducted in MCR or outside of MCR, sensitivity studies were performed. The conditions were divided into four: a LR/MCR action, a NLR/MCR action, a LR/Local action and a NLR/Local action. Table II shows the results of sensitivity study.

Table II: Results of sensitivity study

No. model	HEP				CDF		
	LR/MCR	NLR/MCR	LR/Local	NLR/Local	Site CDF	MU-CDF	MU-CDF Fraction (%)
1	-	-	-	-	2.30E-06	1.71E-07	7.5
2	x10	x2	No credit	x2	2.30E-06	2.00E-07	8.5
3	x10	x2	No credit	x5	2.30E-06	2.51E-07	10.5
4	x10	x2	No credit	No credit	2.30E-06	3.35-E07	13.6
5	No credit	x2	No credit	x2	2.30E-06	2.07E-07	8.8
6	No credit	x2	No credit	x5	2.30E-06	2.58E-07	10.8
7	No credit	x2	No credit	No credit	2.30E-06	3.43E-07	13.8
8	No credit	x5	No credit	No credit	2.30E-06	3.48E-07	14.0
9	No credit	No credit	No credit	No credit	2.30E-06	5.15E-07	19.4

The CDF was calculated by minimal cutsets obtained from AIMS-PSA software with FTREX engine. The nonsense cutsets all were removed by SiTER. The cutoff is 1E-12/yr. It was judged that local operator actions during LR scenarios have no credit. Some insights were obtained from the results of sensitivity study. First, MU-CDF varies according to conditions, while site CDF is constant. It means a few core damage scenarios that originally occurs in a single unit (Unit 1), are changed to multi-unit core damage scenarios because the radioactive release in Unit 1 affects the other units. Second, the LR scenarios have little influence on CDF because the fraction of LR scenarios is low, compared to the fraction of NLR scenarios. The fraction of LR scenarios is only 9.33%. If the IE is induced by an earthquake, the fraction of LR scenarios will increase, so that MU-CDF also could increase. In addition, the operator actions in MCR also have little relationship with CDF compared to local actions in the range between double and five times HEP, since HEP of MCR is originally smaller than that of local action, as shown in Table I. However, if the MCR actions have no credit when NLR occurs, the results show a remarkable increase of CDF.

4. Conclusions

The methodology to assess the effects of radioactive releases in multi-unit PSA was developed in three steps. Step 1 is to select main core damage scenarios of a preceding unit which releases radioactive materials. Step 2 is to obtain main HFEs of affected other units. Step 3 is a modeling by employing different HEPs according to whether a scenario is LR or NLR. The other scenarios which are not main scenarios employs original HEP used in SU internal PSA. A sensitivity study was conducted for six units with MU-LOOP IE. MU-CDF increase according to higher HEPs, while site CDF is constant. The LR has little influence on CDF because fraction of LR scenario under LOOP IE is quite tiny. In case of seismic IE, the LR must not be negligible because the earthquake makes most scenarios be LR. The operator actions inside of MCR are less effective than the local action in the range between double and five times HEP, while MCR actions are not negligible if they have no credit.

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