The contribution to site core damage frequency from independent occurrences of initiators in two or more units: How low is it?

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1. Introduction

The Fukushima nuclear accident in 2011 highlighted the importance of considering the risks from multi-unit accidents at a site. Since the contribution of common-cause initiators (i.e., initiating events which simultaneously affect two or more unit at a site) to multi-unit or site risk is considered dominant, most studies on multi-unit risks have been concerned with the risk due to common-cause initiators rather than single-unit initiators. In a recent study, Stutzke [1] estimated the site risk by summing the contribution from common-cause initiators and the contribution from single-unit initiators. He considered some kinds of multi-unit accident sequences caused by single-unit initiators. However, the contribution from independent occurrences of initiators in two or more units at a site was not taken into account.

The purpose of this study is to estimate the contribution to site core damage frequency (CDF) from simultaneous occurrences of independent initiators in two or more units at the same site. Some assumptions and methods used in this analysis are firstly described, and the results and conclusions of the analysis are described.

2. Methods and Results

In this section, some of the assumptions and methods used to estimate the contribution to site core damage frequency from independent occurrences of initiators in two or more units at a site are described. A Korean nuclear power plant site with six units (i.e., 6 reactors) was selected as the reference site. The latest revision of the at-power internal events Level 1 PSA model for a specific unit (OPR1000 type) [2] at the reference site was used as the base CDF model.

2.1 Assumptions

This analysis is subject to the following assumptions.

1) All six units at the reference site are identical. SSCs (structure, systems, and components), operating/test/maintenance procedures are the same. Only operators are different. Therefore, for each failure mode of a system or component that is modeled, inter-unit common-cause failure (CCF) can exist.
2) All six units are at full-power operation. Shutdown and low-power modes are not considered. Therefore, the at-power internal events Level 1 PSA model for a specific unit at the site was also used as the single-unit model for the other five units at the site.
3) An initiating event in each unit occurs independently. Therefore, the occurrence of an initiator in a specific unit (i.e., the initiating unit) does not affect the probability that the subsequent unit(s) at the same site experience an initiating event.
4) The "simultaneous" occurrences of independent initiators in two or more units are defined as cases where an initiating event in the subsequent unit(s) occurs within 72 hours after an initiator occurs in the initiating unit.

2.2 Calculation of the Site CDF by Equations

When inter-unit dependencies are completely neglected, the contribution to the site CDF from simultaneous occurrences of initiators in two or more units at a site can be calculated using the following equation:

$$ {}_6P_k \times \left[\sum_{i=1}^{n} f(IE_i) \times CCDP_i \right] \times \left[\sum_{i=1}^{n} Pr(IE_i) \times CCDP_i \right]^{k-1} \quad (1) $$

where $f(IE_i)$ is the frequency of an initiating event in a unit (i.e., the initiating unit), $Pr(IE_i)$ is the conditional probability that an initiating event occurs in the subsequent unit(s) within 72 hours after the occurrence of the initiator in the initiating unit, $CCDP_i$ is the conditional core damage probability, n is the number of initiating events, and k is the number of units that experience core damage.

Table I shows the ratio of the sum of CDF (for k=1, 2, …, 6) to the sum of single-unit CDF. The sum of CDF for each number of units experiencing core damage was calculated by applying Equation (1). As the number of units that experience core damage increases, the sum of CDF dramatically falls.

Table I: Ratio of the sum of CDF for each number of units with core damage to single-unit CDF (without consideration of inter-unit dependencies)

Number of units with core damage	Numr of combinations ($_6P_k$)	Ratio to the sum of single-unit CDF
1	6	1
2	30	1.1E-07
3	120	9.8E-15
4	360	6.5E-22
5	720	2.9E-29
6	720	6.4E-37

The most conservative case for this analysis is to assume that the conditional core damage probability (CCDP) given the occurrence of any initiator in the subsequent unit(s) is 1. In this case, the contribution to the site CDF from simultaneous occurrences of initiators in two or more units at a site can be obtained using the following equation:

$$ {}_6P_k \times \left[\sum_{i=1}^{n} f(IE_i) \times CCDP_i \right] \times \left[\sum_{i=1}^{n} Pr(IE_i) \times 1 \right]^{k-1} \qquad (2) $$

Table II shows the percentage of the sum of CDF (for k=1, 2, … , 6) to the sum of single-unit CDF. This result indicates that even in this unrealistically conservative case, the contribution to the site CDF from independent occurrences of initiators in three or more units at the reference site is negligible (less than 0.1% of the sum of single-unit CDF).

Table II: Ratio of the sum of CDF for each number of units with core damage to single-unit CDF (with the most conservative assumption)

Number of units with core damage	Number of combinations ($_6P_k$)	Ratio to the sum of single-unit CDF
1	6	-
2	30	3.58%
3	120	0.10%
4	360	< 0.01%
5	720	< 0.01%
6	720	< 0.01%

Therefore, in this study, only the contribution of dual-unit CDF was estimated. The actual contribution to the site CDF from independent occurrences of initiators in two units will lie somewhere between the results from Table I and Table II. The ratio of the sum of dual-unit CDF to the sum of single-unit CDF with varying CCDP given any initiator in the subsequent unit is shown in Table III. This result implies that when CCDP of each initiator (except ISLOCA and RVR) in the subsequent unit is lower than 0.03, the contribution to the site CDF from independent occurrences of initiators in two units at the reference unit is negligible (less than about 0.1% of the sum of single-unit CDF).

Table III: Ratio of the sum of dual-unit CDF to the sum of single-unit CDF with varying CCDP

CCDP/IE of the subsequent unit*	Ratio to the sum of single-unit CDF
1.0	3.58%
0.5	1.79%
0.1	0.36%
0.05	0.18%
0.03	0.11%
0.01	0.04%

* The CCDP of ISLOCA and reactor vessel rupture (RVR) was not changed because the CCDP given the initiators was assumed to be 1.

2.3 Development of a Dual-Unit CDF Model

To estimate the contribution to the site CDF from independent occurrences of initiators in two units more realistically, a dual-unit CDF model was developed based on the single-unit Level 1 PSA model. The following inter-unit dependencies were taken into account in the dual-unit CDF model.

1) Shared systems or components between the two units
2) Dependencies between human failure events (HFEs) in different units
3) Inter-unit CCF modeling for risk-significant components

According to a recent study on a multi-unit initiating event analysis for the reference unit [3], the sharing of an alternate AC diesel generator (AAC D/G) between units should be considered for the purpose of this analysis. In this study, it was assumed that in case of simultaneous SBO in both units, the AAC D/G is connected only to the initiating unit (i.e., In the subsequent unit, emergency power supply from the AAC D/G is not credited.)

Although most human actions included in the single-unit Level 1 PSA model are regarded as independent from those in different units, offsite power recovery actions in two units sharing a switchyard should be considered as dependent. In this study, it was assumed that if the offsite power recovery action in the initiating unit fails, the recovery action in the subsequent unit also fails regardless of the allowed time (i.e., The probability of not recovering offsite power in the subsequent unit is 1.)

To find risk-significant components, Fussell-Vesely (FV) importance measure was used. Top 50 basic events that have FV importance greater than 0.01 were selected as significant basic events. Table IV shows the risk-significant CCF basic events for which inter-unit CCFs were modeled. For CCF basic events which CCCG size is less than 4 in the single-unit model (e.g., EGDGK3T-

1A1B1E; “two EDGs and AAC D/G fail to run by CCF”), all combinations of inter-unit CCF events were modeled in the dual-unit model. However, for CCF basic events which CCCG size is 4 or more (e.g., CWCUK4Q-1A2A1B2B; “ECW chiller unit 1A, 2A, 1B & 02B fail to run by CCF”), only CCF basic event with all component failures was added to the existing (single-unit) model.

Table IV: List of CCF Basic Events for which Inter-Unit CCFs were modeled

CCF basic event name	Prob.*	F-V*	CCCG Size
EGDGK3T-1A1B1E	1.10E-04	7.84E-02	3 → 5
EGDGW3T-1A1B1E	3.55E-05	5.66E-02	3 → 5
CWCUK4Q-1A2A1B2B	1.02E-05	3.98E-02	4 → 8
RPRDFCEA12OF28	1.52E-06	1.80E-02	28 → 56
CMPTKPT352ABCD	2.65E-04	1.63E-02	4 → 8
HCCQK2D-HPPAB	7.42E-05	1.60E-02	2 → 4
CSMPW2D-CSMP	7.62E-05	1.52E-02	2 → 4
HCCQK2D-CSPAB	7.42E-05	1.48E-02	2 → 4
CCMVW2D-1412	6.26E-05	1.25E-02	2 → 4
FSXRWX1234S2	4.51E-06	1.22E-02	4 → 8
MSAVW2D-10910	1.29E-04	1.14E-02	2 → 4
AFAVW2D-00910	8.79E-05	7.78E-03	2 → 4

* The probability and FV importance of each basic event are from the single-unit CDF model.

2.4 Quantification Results

As a result of quantification, the total dual-unit CDF due to independent occurrences of initiators in two units at the reference site was about 0.0044% of the sum of single-unit CDF (6 units × single-unit CDF). It can be considered as sufficiently low to be neglected. “SBO * SBO” sequences (i.e., station blackout in both units) accounted for about 83% of the total dual-unit CDF.

3. Conclusions

In this study, the contribution to site core damage frequency (CDF) from simultaneous occurrences of independent initiators in two or more units at the same site was estimated. A Korean six-unit site was selected as the reference site and the at-power internal events Level 1 PSA model for an OPR1000 unit at the reference site was used as the base model, and was modified to deal with some major dependencies between units at the site. Specifically, the availability of the AAC D/G, dependencies between offsite power recovery actions in different unis, and inter-unit CCF modeling for risk-significant components such as diesel generators were taken into account.

As a result, the sum of dual-unit CDF due to independent occurrences of initiators in two units at the reference site was estimated to be sufficiently low to be neglected (less than 0.01% of the sum of single-unit CDF).

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