CONSIDERING DUAL-UNIT LOSS OF OFFSITE POWER INITIATING EVENT IN A SINGLE-UNIT LEVEL 1 PSA

Dong-San Kim[1], Jin Hee Park[2], Ho-Gon Lim[3]

[1-3] Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, Daeduk-daero 989-111, Yuseong-gu, Daejeon, South Korea, 305-353, dongsankim@kaeri.re.kr

The purpose of this study is to add the dual-unit loss of offsite power (LOOP) initiating event to a single-unit internal events Level 1 PSA model and investigate its effect on the core damage frequency. To revise the at-power internal events Level 1 PSA model for an OPR1000 single unit, event trees for single- and dual-unit LOOP were developed separately, and event trees for dual-unit station blackout (SBO), which can be transferred from the dual-unit LOOP event tree, were also developed. Single- and dual-unit LOOP initiating event (IE) frequencies were estimated based on Korean industry data. For CCF modeling, five diesel generators (two emergency DGs in each unit, one alternate AC DG) were grouped into a common cause component group (CCCG=5), and hence 2/5, 3/5, 4/5 and 5/5 CCF basic events were modeled. In addition, the probabilities of not recovering offsite power were estimated separately for single-unit LOOP and dual-unit LOOP. In case of simultaneous SBO occurrence in both units, this study compared two different assumptions on the probability that the AAC D/G is available to a specific unit. As a result, the core damage frequency (CDF) due to SBO sequences increased by about 50 to 60% and the total CDF increased by 11 to 13% depending on the probability that the AAC DG is available to a specific unit in case of simultaneous SBO in both units.

I. INTRODUCTION

The Fukushima nuclear accident in 2011 highlighted the importance of considering the risks from multi-unit accidents at a site. The ASME/ANS probabilistic risk assessment (PRA) standard[1] also includes some requirements related to multi-unit aspects, as shown in TABLE I.

TABLE I. Supporting Requirements Related to Multi-Unit Initiating Events

Index No.	Capability Category I/II/III
IE-A10	For multi-unit sites with shared systems, INCLUDE multi-unit site initiators (e.g., multi-unit LOOP events or total loss of service water) that may impact the model.
IE-B5	For multi-unit sites with shared systems, DO NOT SUBSUME multi-unit initiating events if they impact mitigation capability.

However, many of the existing single-unit PSA models do not explicitly consider multi-unit initiating events and hence systems shared by multiple units (e.g., alternate AC diesel generator) are fully credited for the single unit and ignores the need for shared systems by other units at the same site.[2] This paper describes the results of modeling the dual-unit loss of offsite power (LOOP) initiating event in the at-power internal events Level 1 probabilistic safety assessment (PSA) for an OPR1000 single unit ("reference unit").

II. METHODS

II.A. Multi-Unit IE Analysis for the Reference Unit

A multi-unit IE is an initiating event that leads to reactor trip in multiple units at the same site. For a single-unit PSA, multi-unit IEs should be analyzed because the occurrence of a multi-unit IE can influence the availabilities of the shared systems or components. The reference unit (OPR1000 type) shares the following systems or components with other units at the same site.[3]

- Switchyard
- Intake
- Alternate AC Diesel Generator (AAC D/G)

The switchyard has the capacity of supplying electrical power to two units at the same time, and therefore its availability is not influenced by the states of other units. The intake system is equipped independently for each unit and only the sea water is shared by multiple units. Because the sea water can provide water simultaneously to all units at the same site, the availability of the intake system is also not restricted by the states of other units. Even if the loss of condenser vacuum or loss of essential service water system occurs due to clogging of the intake in two or more units at the same time, the mitigation capability of each unit is not influenced by the states of other units because there is no shared system or component related to those events.

In case of multi-unit station blackout (SBO), however, an AAC D/G can be connected to only one unit at a time, which impacts the availability of AAC D/G for a single unit. The reference unit shares the AAC D/G with other three units at the same site. Therefore, multi-unit (2~4 units) loss of offsite power (LOOP), which is the starting point of multi-unit SBO, and multi-unit SBO initiating events should not be subsumed by single-unit LOOP or single-unit SBO. In this study, only dual-unit LOOP and dual-unit SBO were considered because the probability of triple- or quadruple-unit SBO is much lower than the probability of dual-unit SBO.

II.B. Adding Dual-Unit LOOP and SBO IEs to the Single-Unit PSA Model

Using the results of the multi-unit IE analysis described in the previous section, the dual-unit LOOP initiating event (IE) was added to the existing PSA model for the reference unit. Single- and dual-unit LOOP IE frequencies were estimated using Korean nuclear industry data from 1978 to 2012. Among eight LOOP events (single-unit level) that occurred in critical operations, seven were related to the dual-unit LOOP and the other event was a single-unit LOOP occurrence.[3] The conditional probability of two or more units at a multi-unit site experiencing a LOOP given a LOOP at one of the units at the site was calculated using the same procedure in NUREG/CR-6890 (Ref. 4). Because the risk model used in this study does not distinguish LOOP categories (i.e., plant-centered, switchyard-centered, grid-related, and weather-related LOOP), only the composite conditional probability for critical operation was calculated. The calculated conditional probability is 0.80. Therefore, single-unit LOOP IE frequency and dual-unit LOOP IE frequency were calculated by multiplying the existing LOOP IE frequency by 0.2 and 0.8, respectively.

Fig. 1 shows the event tree developed for the single-unit LOOP initiating event. It has the same logic as the existing event tree for LOOP IE.

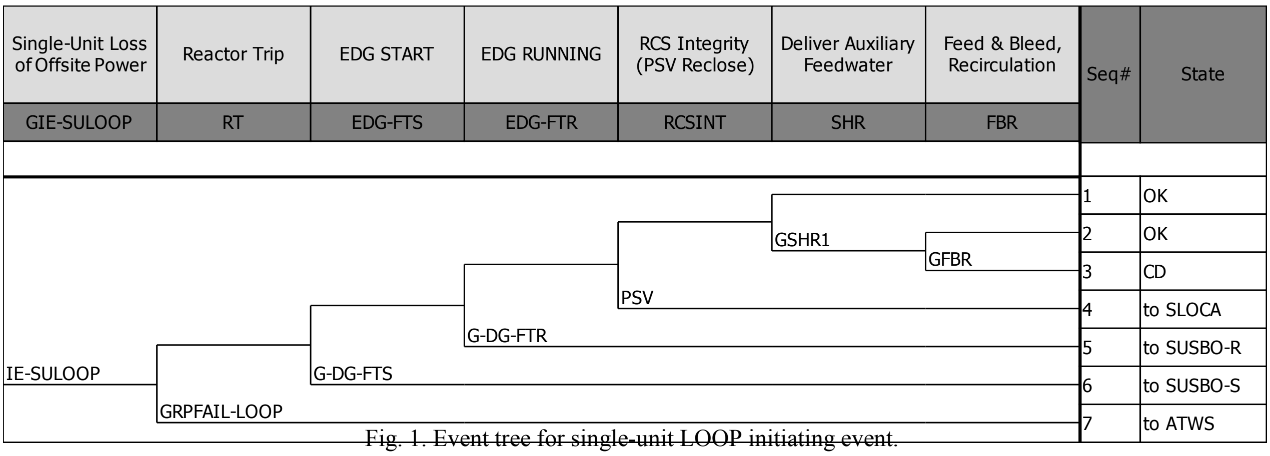

Fig. 1. Event tree for single-unit LOOP initiating event.

Fig. 2 shows the event tree developed for the dual-unit LOOP initiating event. In this event tree, unlike the event tree for single-unit LOOP that considers only emergency diesel generators (EDGs) in the reference unit ("Unit 1"), EDGs in the other unit ("Unit 2") should also be taken into account.

As shown in TABLE II, the dual-unit LOOP IE progresses into different states according to whether the EDGs of each unit succeed or fail to operate. Among the states in TABLE II, the dual-unit SBO-S (two EDGs fail to start after LOOP) and dual-unit SBO-R (two EDG fail but at least one EDG fails to run) are not included in the existing model for the reference unit. Because they influence the availability of AAC D/G for "Unit 1," event trees were newly developed for the dual-unit SBO-S and dual-unit SBO-R.

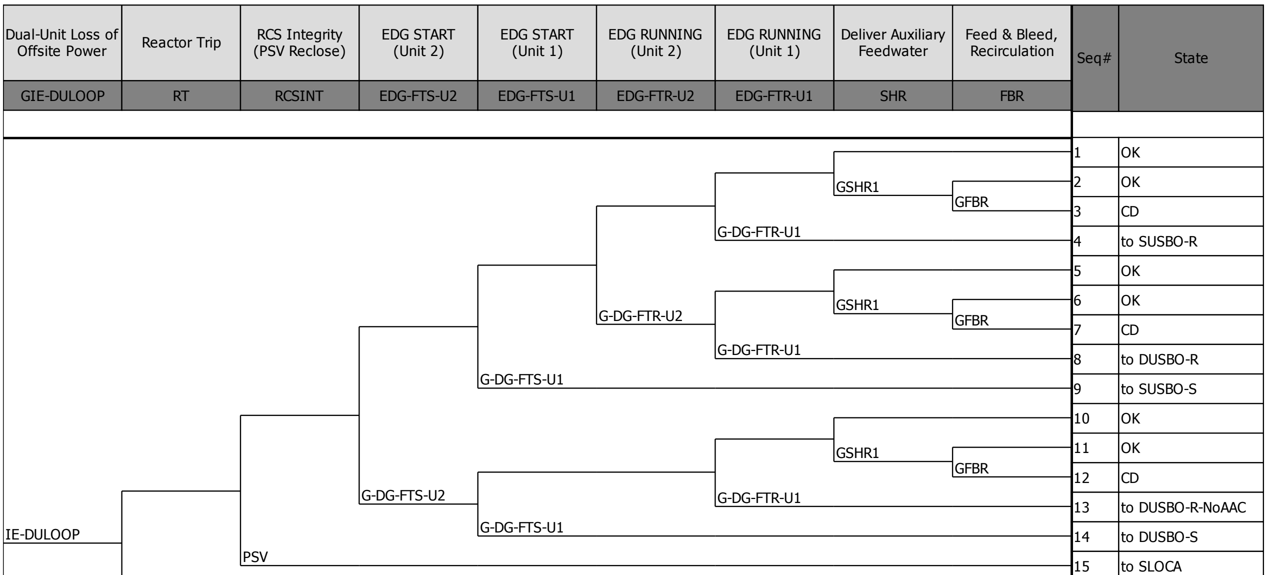

Fig. 2. Event tree for dual-unit LOOP initiating event.

TABLE II. States and AAC D/G Availabilities by EDG Failure Modes of Each Unit after Dual-Unit LOOP

Case	Unit 1	Unit 2	State*	Unit to which AAC D/G is connected
1	At least 1 EDG Succeed to Run	At least 1 EDG Succeed to Run	OK or CD (Core Damage)	N/A
2	At least 1 EDG Succeed to Run	2 EDGs Fail to Start	OK or CD (Core Damage)	Unit 2
3	At least 1 EDG Succeed to Run	2 EDGs Fail (at least 1 EDG fails to run)	OK or CD (Core Damage)	Unit 2
4	2 EDGs Fail to Start	At least 1 EDG Succeed to Run	To Single-Unit SBO-S	Unit 1
5	2 EDGs Fail to Start	2 EDGs Fail to Start	To Dual-Unit SBO-S	Unit 1 or Unit 2
6	2 EDGs Fail to Start	2 EDGs Fail (at least 1 EDG fails to run)	To Dual-Unit SBO-S	Unit 1
7	2 EDGs Fail (at least 1 EDG fails to run)	At least 1 EDG Succeed to Run	To Single-Unit SBO-R	Unit 1
8	2 EDGs Fail (at least 1 EDG fails to run)	2 EDGs Fail to Start	To Dual-Unit SBO-R	Unit 2
9	2 EDGs Fail (at least 1 EDG fails to run)	2 EDGs Fail (at least 1 EDG fails to run)	To Dual-Unit SBO-R	Unit 1 or Unit 2

* States (OK, Core Damage, SBO-S, or SBO-R) are related to "Unit 1".

One of the key issues in considering the dual-unit LOOP is common-cause failure (CCF) modeling for diesel generators. In the existing single-unit model, three diesel generators (i.e., two EDGs in the reference unit and AAC D/G) were grouped into a common cause component group (CCCG) and hence 2-out-of-3 and 3-out-of-3 CCF basic events were modeled. In this study, however, five diesel generators (two EDGs in each unit, and one AAC D/G) were grouped into a CCCG. Therefore, 2-out-of-5, 3-out-of-5, 4-out-of-5, and 5-out-of-5 CCF basic events were modeled. For the CCF data, alpha factors for EDGs from NUREG/CR-5497 (Ref. 5) were used. Because NUREG/CR-5497 does not provide alpha factors for five EDGs (CCCG size = 5), impact vectors for CCCG=5 were obtained using the mapping up technique.[6] In addition, a staggered testing scheme was assumed when calculating the probabilities of DG CCF basic events.

Another important issue is to determine the probability of not recovering offsite power at various times. In the existing PSA model for the reference unit, the non-recovery probabilities were estimated using the Korean nuclear industry data from 1978 to 2012. Among 15 LOOP plant level events that occurred during a critical or shutdown operation, eight were related to the dual-unit LOOP and the other seven were single-unit LOOP events. Because the offsite power restoration times of dual-unit LOOP events are longer than those of single-unit LOOP events, the probability of exceedance versus duration curves were generated separately for single- and dual-unit LOOP.

III. RESULTS

When SBO occur in two units simultaneously and they both need the same AAC D/G (cases 5 and 9 in Table I), the AAC D/G can be connected to only one unit at a time. Because a procedure for this case is not currently available, this study compared two different assumptions: (1) that the probability that the AAC D/G is available to each unit is 0.5; and (2) that the AAC D/G is connected to the other unit ("Unit 2") and is not available to the unit of interest ("Unit 1"). The quantification results for each assumption are presented in Table III.

TABLE III. Comparison of Quantification Results for the Revised PSA Model Considering Dual-Unit LOOP

Assumption used in cases #5 and #9 in Table I	Assumption 1 (AAC D/G availability = 0.5)	Assumption 2 (AAC D/G availability = 0)
Increase of CDF due to SBO	54.4%	61.3%
Increase of Total CDF	11.8%	13.3%

When it is assumed that the probability of the AAC D/G being connected is the same (i.e., on average 0.5 for each unit) for both units in the case of simultaneous SBO occurrences, the core damage frequency (CDF) due to SBO sequences increased by 54.4% and the total CDF increased by 11.8%. However, when it is assumed that the AAC D/G is connected to the other unit and is not available to the unit of interest, the CDF due to the SBO sequences increased by 61.3% and the total CDF increased by 13.3%.

IV. CONCLUSIONS

In this study, a multi-unit initiating event analysis for a single-unit PSA was conducted, and using the results, the dual-unit LOOP initiating event was added to the existing PSA model for the reference unit (OPR1000 type). Event trees were developed for dual-unit LOOP and dual-unit SBO which can be transferred from dual-unit LOOP. Moreover, CCF basic events for five diesel generators were modelled, and the probabilities of not recovering offsite power were estimated separately for single-unit LOOP and dual-unit LOOP. In case of simultaneous SBO occurrences in both units, this study compared two different assumptions on the availability of the AAC D/G. As a result, when the dual-unit LOOP initiating event was added to the existing single-unit PSA model, the core damage frequency (CDF) due to SBO sequences increased by about 50 to 60% and the total CDF increased by 11 to 13% depending on the probability of the AAC D/G being available to a specific unit in the case of simultaneous SBO in both units.

ACKNOWLEDGMENTS

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant, funded by the Korean Government, Ministry of Science, ICT & future Planning (MSIP).

REFERENCES

1. ASME/ANS, Addenda to ASME/ANS RA-S-2008, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME/ANS RA-Sb-2013, The American Society of Mechanical Engineers & American Nuclear Society, New York, U.S., 2013.
2. T. D. LE DUY, D. VASSEUR, and E. SERDET, "Probabilistic Safety Assessment of Twin-Unit Nuclear Sites: Methodological Elements," *Reliability Engineering and System Safety*, **145**, 250-261 (2016).
3. KHNP, At-Power Internal Events Level 1 PSA Report for Hanul Units 3&4: Vol. 1. Initiating Events Analysis, Korea Hydro-Nuclear Power Co., Ltd., 2015.
4. U. S. NRC, Reevaluation of Station Blackout Risk at Nuclear Power Plants, Analysis of Loss of Offsite Power Events: 1986-2004, NUREG/CR-6890, Vol. 1, U.S. Nuclear Regulatory Commission, December 2005.

5. U. S. NRC, CCF Parameter Estimations (2007 Update), http://nrcoe.inl.gov/results/CCF/ParamEst2007/ccfparamest.htm, U.S. Nuclear Regulatory Commission, September 2008.
6. U. S. NRC, Guidelines on Modeling Common-Cause Failures in Probabilistic Safety Assessment, NUREG/CR-5485, U.S. Nuclear Regulatory Commission, November 1998.