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Accident Scenario Analysis for Beyond-design Basis External Hazards Based on the PSA Model

Seunghyun Jang

Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, Republic of Korea. E-mail: jsh872@kaeri.re.kr

Min Kyu Kim

Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute, Republic of Korea. E-mail:minkyu@kaeri.re.kr

Nuclear power plants in Korea are mostly located along the coastal areas, and can be affected by external hazards caused by typhoons such as high wind or external flooding. In addition, the intensity of typhoons in Korea is predicted to increase due to climate change and the possibility of external hazards exceeding design basis is also expected to increase. Therefore, it is necessary to review the plant risk against beyond-design basis external hazards. This study aims to investigate the accident scenarios caused by high wind hazard and external flooding hazard caused by typhoon. In addition, we calculate the conditional probability of core damage for each accident scenario to determine the possibility of core damage resulting from external hazards using the probabilistic safety assessment (PSA) model. By focusing on the derived accident scenarios and their results presented here, it is expected that the plant safety against external hazards can be evaluated more efficiently.

Keywords: Probabilistic safety assessment, beyond-design basis external hazard, high wind, external flooding, accident scenario analysis.

1. Introduction

Nuclear power plant (NPP) sites are exposed to various natural hazards such as earthquakes and typhoons depending on their locations, and NPPs should be designed to withstand external hazards induced by such natural hazards. However, most of these considerations are based on historical observational data, raising concerns about the adequacy of safety margins against external hazards exceeding design basis events, namely beyond-design basis external hazards (hereinafter referred to as BDBE hazards) whose likelihood is increasing due to climate change.

Extensive studies have been conducted on the assessment of BDBE hazards and Natech events (Natural Hazards-Triggered Technological Accidents) affecting industrial facilities. Previous research has addressed risk assessment methodologies, accident progression analysis, and probabilistic approaches for evaluating plant vulnerabilities under external hazard conditions. In particular, Natech studies have highlighted that natural hazards can simultaneously affect multiple safety systems and challenge conventional design assumptions.

Therefore, it is necessary to establish a systematic framework capable of quantitatively evaluating plant safety under BDBE hazard conditions. In this study, the impacts of BDBE hazards on NPPs are evaluated by analyzing accident scenarios induced by high winds and external flooding, which are representative hazards associated with typhoons. For each accident scenario, the conditional core damage probability, defined as the probability of core damage given that a specific accident has occurred, is quantified to assess plant safety under beyond-design basis conditions.

2. Accident Scenarios Induced by BDBE hazards

Probabilistic Safety Assessment (PSA) evaluates the safety of a target plant by identifying all significant accident scenarios that

Table 1. Failure modes and effects due to high wind hazards.

Equipment	Failure mode & effects	Remark
765kV transmission towers and switchyard	(Mode) Structural failure/missile Impact (Effect) Loss of 765kV off-site power	LOOP-causing event (when 154kV off-site power is simultaneously lost)
154kV transmission towers and switchyard	(Mode) Structural failure/missile Impact (Effect) Loss of 154kV off-site power	LOOP-causing event (when 765kV off-site power is simultaneously lost)
Main transformer Unit auxiliary transformer	(Mode) Structural failure/missile Impact (Effect) Loss of 765kV off-site power	LOOP-causing event (when 154kV off-site power is simultaneously lost)
Standby auxiliary transformer	(Mode) Structural failure/missile Impact (Effect) Loss of 154kV off-site power	LOOP-causing event (when 765kV off-site power is simultaneously lost)
Main feed-water pump	(Mode) Unavailable due to turbine building damage(Assumed) (Effect) Loss of main feed-water supply to the steam generator	LOFW-causing event
Main generator and generator circuit breaker (GCB)	(Mode) Unavailable due to turbine building damage(Assumed) (Effect) Loss of 765kV off-site power	LOOP-causing event (when 154kV off-site power is simultaneously lost)

may occur at the plant and probabilistically estimating their impacts. To analyze accident scenarios, it is first necessary to identify and classify initiating events that may affect plant safety, and then to construct event trees for the selected initiating events in order to derive accident scenarios that result in core damage.

As a method for analyzing accident scenarios induced by BDBE hazards, failure modes and their effects were identified for structures and components within the plant that may be damaged by each external hazard.

2.1. High wind hazard

In this study, the impacts on plant were examined and corresponding accident scenarios were analyzed by focusing on high wind and external flooding hazards induced by typhoons among BDBE hazards, using the OPR1000 NPP, as the analysis target. Here, a typhoon refers to a tropical cyclone accompanied by storm conditions with a maximum wind speed near its center of 17 m/s or higher. The OPR1000 is a representative Korean pressurized water reactor with a capacity of 1,000 MWe. Most safety-related structures, such as the reactor building and auxiliary building, are constructed of reinforced concrete, while the turbine building is constructed with a steel frame structure.

In the case of high wind hazards, structures or components may be damaged by wind loads, or damage may be caused when wind-generated missiles strike the relevant equipment.

As a result of identification of failure modes and effects on OPR1000 plant structures and components, it was found that most safety-related structures are reinforced concrete structures designed to Seismic Category I and thus are minimally affected by high wind hazards. However, the turbine building constructed with a steel frame structure and outdoor-installed equipment such as switchyards and transformers may be affected by high wind hazards.

Therefore, based on the results of identification, loss of off-site power (LOOP) due to power system failure and loss of feed-water (LOFW) due to turbine building damage were considered as initiating events defined in the PSA model. Table 1 presents the failure modes and effects due to high wind hazards.

As shown in Figure 1, a primary event tree for high wind hazards was developed, considering damage of structure and component due to such hazards as event tree headings. In this study, primary event tree represent the occurrence of initiating events resulting from hazard-induced failures of plant structures and components. This tree describe how combinations of hazard-induced failures may lead to initiating events such as LOOP or LOFW.

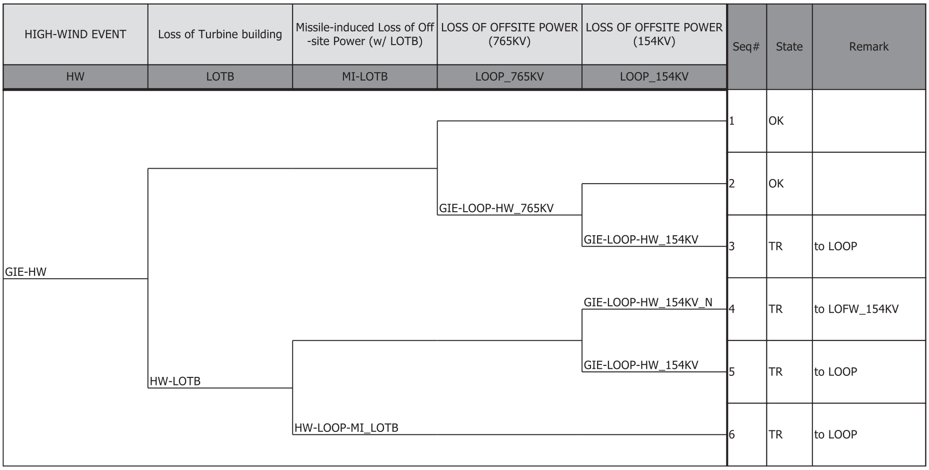

Fig. 1. A primary event tree for high wind hazards.

First, LOTB represents the heading for turbine building damage, while LOOP_765kV and LOOP_154kV represent the headings for loss of the 765 kV and 154 kV off-site power connected to the plant, respectively. In addition, debris generated by turbine building damage may be accompanied by high winds and reaches transformers or equipment related to off-site power located nearby, potentially causing flashover and resulting in loss of off-site power. Therefore, an MI-LOTB heading reflecting this effect was added.

Accordingly, high wind induced LOOP accidents include case caused by debris effects resulting from turbine building damage, case involving turbine/generator loss by turbine building damage and loss of 154 kV off-site power, and case involving loss of both the 765 kV and 154 kV off-site power. When only turbine building damage occurs, the event was classified as a high wind induced LOFW accident, and in this case, the 765 kV off-site power was assumed to be unavailable.

2.2. External flooding hazard

When heavy rainfall accompanies a typhoon passing near the plant site, accumulated rainwater within the plant site may flood structures or components, making them unavailable.

As a result of identification of failure modes and effects on OPR1000 plant structures and components, it was found that most safety-related structures are designed to prevent flooding damage by installing entrances and ventilation openings 40 cm above the site level. In addition, watertight doors are installed in safety-related structures to prevent internal flooding. However, if such watertight equipment fails to function properly, internal flooding may occur, leading to the loss of major safety systems.

Therefore, based on the results of identification, the following initiating events induced by external flooding hazards were considered: loss of essential service water (LOESW) due to flooding of the ESW intake structure, loss of essential power (LEP) due to flooding of the auxiliary building, LOOP due to flooding of outdoor transformers, and LOFW due to flooding of the turbine building or circulating water intake structure. Table 2 presents the failure modes and effects due to external flooding hazards.

A primary event tree for external flooding hazards was developed, as shown in Figure 2. PRE-FLOOD represents the provision of advance warning for expected heavy rainfall due to a typhoon. If additional flood protection measures are successfully implemented following the warning, the likelihood of flooding will be significantly reduced. Therefore, failure of such measures was considered.

Table 2. Failure modes and effects due to external flooding hazards.

Structure	Key compartment	Failure mode & effects	Remarks
Auxiliary building	Class 1E inverter room Class 1E switchgear room	(Mode) Loss of function assumed when internal flooding level reaches 6 in. (Effect) Loss of essential power	LEP-inducing
Emergency diesel generator (EDG) building	Class 1E EDG room EDG control room	(Mode) Loss of function assumed when internal flooding level reaches 4 in. (Effect) Loss of EDGs	-
Essential service water (ESW) intake structure	HVAC room	(Mode) Loss of function assumed when internal flooding level reaches 4 in. (Effect) Loss of ESW pumps	LOESW-inducing
Circulating water (CW) intake structure	Electrical room	(Mode) Loss of function assumed when internal flooding level reaches 4 in. (Effect) Loss of main feed-water	LOFW-inducing
Turbine building	General area Non-class 1E switchgear room	(Mode) Loss of function assumed when internal flooding level reaches 4 in. (Effect) Loss of main feed-water	
Alternate AC diesel generator (AAC DG) building	AAC DG room Switchgear room	(Mode) Loss of function assumed when internal flooding level reaches 4 in. (Effect) Loss of AAC DG	-
Yard	-	(Mode) Loss of all transformers assumed when the flooding level reaches EL. 100 ft-6 in. (Effect) Loss of off-site power	LOOP-inducing

LOESW-LIP represents heading for flooding of the ESW intake structure and LEP-LIP, LOOP-LIP, and LOFW-LIP are headings for internal flooding of the auxiliary building, loss of off-site power due to transformer flooding, and loss of main feed-water due to flooding of the turbine building, respectively. In addition, emergency diesel generator (EDG) building and alternate AC diesel generator (AAC DG) building may be flooded due to external flooding hazards. Since these components are considered after the occurrence of LOOP accident, additional branches representing flooding of these buildings, DG-LIP and AAC-LIP, were added.

3. Plant Impacts According to Accident Scenarios by BDBE hazards

To examine the impacts on the nuclear power plant by accident scenarios due to BDBE hazards, the conditional core damage probability (CCDP) for each accident scenario was evaluated. CCDP refers to the probability that core damage occurs under the assumption that a specific accident has occurred, and represents the likelihood that core damage will be induced due to failures of accident mitigation actions performed after the occurrence of the accident. In this study, since fragility data for each BDBE hazard are under development, the CCDP following the initiating event was calculated based on the failure probabilities of accident mitigations. .The failure probabilities of accident mitigating systems required to derive the conditional core damage probability for each accident scenario were calculated using an internal events PSA model.

Initiating events that may occur due to BDBE hazards include LOOP, LOFW, LOESW, and LEP. Among these, LOESW and LEP induce failures of cooling of safety-related component and loss of essential power, and thus were assumed to lead directly to core damage without additional accident mitigation actions.

In the case of LOOP, power supply through EDGs or AAC DG is possible. However, EDGs and AAC DG may be lost due to external flooding hazards, in which case the event is classified as an extended loss of AC power (ELAP), and core damage was assumed to occur without additional accident mitigation actions. If power supply is successfully restored, heat removal through the steam generators using the auxiliary feed-water system can be performed.

The individual event tree for LOOP due to BDBE hazards is shown in Figure 3.

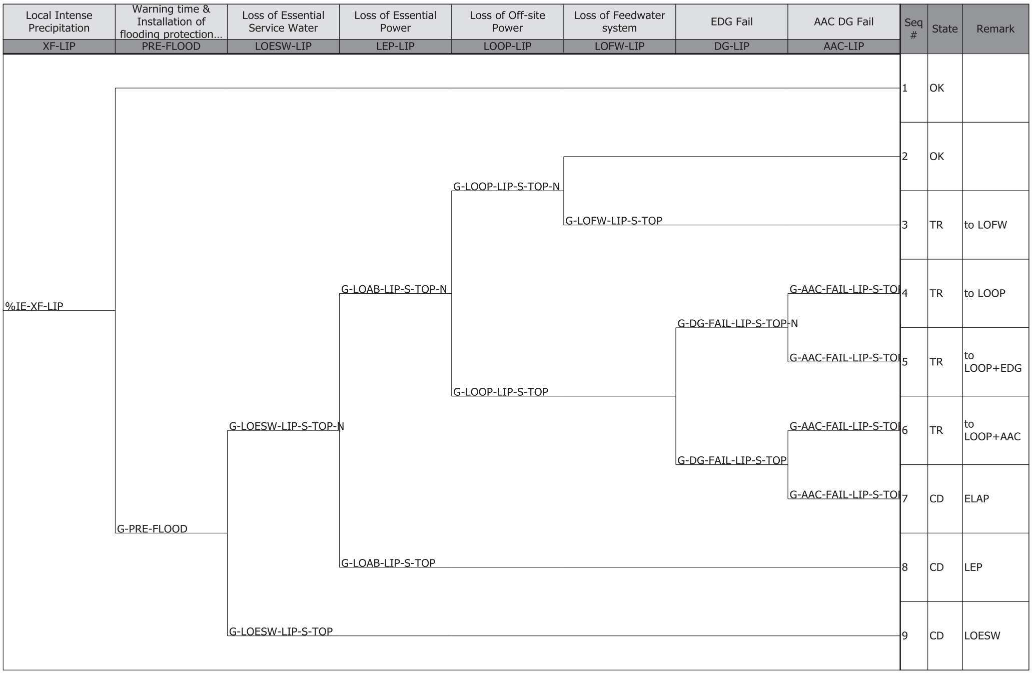

Fig. 2. A primary event tree for external flooding hazards.

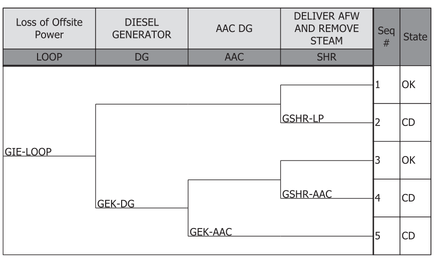

Fig. 3. An individual event tree for LOOP due to BDBE hazards.

Reflecting these considerations, CCDP for LOOP was evaluated as 1.73E-04. As the major core damage accident scenario, failure of EDG and AAC DG operation after LOOP (Seq#5) accounted for most of the total CCDP with a probability of 1.44E-04. And, the case in which EDG operation succeeded after LOOP but heat removal using the steam generators failed (Seq#2) had the second-highest probability, at 2.81E-05.

In addition, flooding of EDG building or AAC DG building may occur concurrently with a LOOP due to external flooding hazard, and in such cases, use of EDGs or AAC DG is not possible. Reflecting this, CCDP for the case of flooding of the EDG building was evaluated as 5.81E-02 and for the case of flooding of AAC DG building, CCDP was evaluated as 2.52E-03.

When LOFW occurs, heat removal through the steam generators can be performed using available power sources. In this case, feed-water supply must be provided through the auxiliary feed-water system. The individual event tree for LOFW due to BDBE hazards is shown in Figure 4.

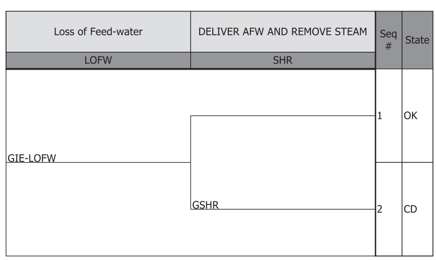

Fig. 4. An individual event tree for LOFW due to BDBE hazards.

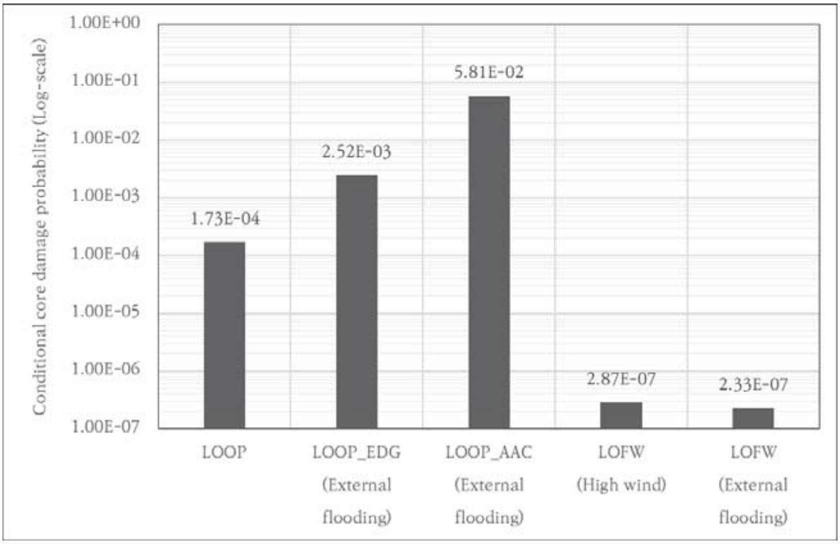

Fig. 5. CCDP results for accident scenarios induced by BDBE hazards.

LOFW due to high wind hazard may occur when the turbine building is damaged, and the 765 kV off-site power supply is unavailable due to damage to the generator and generator circuit breaker by the same cause. Therefore, reflecting this condition, CCDP for LOFW due to high wind hazard was evaluated as 2.87E-07.

In the case of LOFW due to external flooding hazard, since all off-site power sources are available, CCDP was evaluated as 2.33E-07, which is lower than that for high wind induced LOFW. These results are shown in Figure 5.

4. Conclusion

In this study, accident scenarios due to high wind and external flooding hazards, which are representative external hazards that may occur due to typhoons, were analyzed by identifying failure modes and effects of plant structures and components. In addition, to examine the impacts of each accident scenario on the nuclear power plant, the conditional core damage probability for each accident scenario, defined as the probability of core damage under the assumption that a specific accident has occurred, was evaluated.

When the impacts of accident scenarios due to high wind and external flooding hazards on the nuclear power plant are comprehensively reviewed, it is expected that external flooding hazards will have a greater impact on the plant, as only LOOP and LOFW were considered as initiating events for high wind hazards due to the fact that most safety-related structures are constructed of reinforced concrete, whereas LOESW, LEP, LOOP, and LOFW were considered for external flooding hazards. In addition, from the perspective of the considered accident scenarios, external flooding hazard-induced LOESW and LEP are expected to have the greatest accident impacts because no additional accident mitigation actions are possible, and for LOOP and LOFW, the accident impact is expected to be greater for LOOP than for LOFW because fewer available systems exist for LOOP compared to LOFW.

This study has several limitations. First, the analysis was limited to high wind and external flooding hazards associated with typhoons, while other potential external hazards were not considered. Second, the identification of failure modes and effects were based on generic system configurations and may not capture all site-specific vulnerabilities. Finally, hazard intensity and equipment fragility were not considered, and uncertainty associated with accident mitigation system performance were not explicitly quantified. Future studies will address these limitations by incorporating more detailed hazard models and uncertainty analysis.

Through the analysis of accident scenarios induced by BDBE hazards in this manner, major accident combinations affecting the nuclear power plant under accident conditions can be identified. By referring to these results and proposing reinforcement measures that can minimize the occurrence probabilities of major accident scenarios induced by BDBE hazards, it is expected that the safety of nuclear power plants against BDBE hazards can be enhanced.

Acronyms

AAC DG: Alternate AC diesel generator
AFW: Auxiliary feed-water
BDBE: Beyond design-basis event
CCDP: Conditional core damage probability
CW: Circulating water
EDG: Emergency diesel generator
ESW: Essential service water
GCB: Generator circuit breaker
HVAC: Heating, ventilation, and air conditioning
HW: High wind hazard
LEP: Loss of Essential power
LIP: Local intense precipitation
LOAB: Loss of auxiliary building
LOESW: Loss of essential service water
LOFW: Loss of feed-water
LOOP: Loss of off-site power
LOTB: Loss of turbine building
NPP: Nuclear power plant
OK/CD/TR: Core intact/Core damage/Transfer
PSA: Probabilistic safety assessment
SHR: Secondary heat removal
XF: External flooding hazard

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