IMPROVEMENT OF INTERNAL FLOODING PSA BASED ON PLANT-SPECIFIC CONDITIONS FOR WESTINGHOUSE PWRS IN KOREA

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The assessment for the flood event frequencies of flood areas is one of the most important parameters in internal flooding PS(. Internal flood PSA for Westinghouse PWRs in Korea has used generic data in Nuclear Power Experience (NPE) and empirical formula for estimating the flood event frequencies. However, this approach has the weakness in light of the flooding vulnerability in the pipe-concentrated area. To improve these limitations, revised internal flooding PSA was performed with flood area-specific data, which include the pipe characteristics by the flood source, flooding class by the ruptured pipes, actual propagating scenario, and HRA, etc. This paper identified the applicability of improved internal flooding PSA methodology for Westinghouse PWRs in Korea, which is expected to lessen unreasonable conservatism and provide a more realistic analysis.

I. INTRODUCTION

The flooding probabilistic safety assessment (PSA) was used to measure the frequency of internal flooding events reported to the Nuclear Power Experience (NPE) database (Ref. 1, 2). Existing methods did not take into consideration the individual characteristics of the systems and piping present in the flood areas. A quantitative analysis was selected only using the frequency of the flood incident reported to NPE for auxiliary buildings, turbine buildings, etc. This approach has limitations to considering practical plant-specific conditions although the calculation process is simple and the results are conservative. So, in the study, internal flooding PSA in Westinghouse PWRs in Korea was reassessed to apply plant-specific pipe system characteristics and flooding areas' arrangement with operating procedures. Areas which have more impact on core damage frequency (CDF) by internal flooding were properly analyzed and suitable countermeasures were proposed for enhancing the safety of nuclear power plants (NPPs).

II. METHODOLOGY

Basically, internal flooding analysis starts from gathering the plant-specific information and plant walk-down. Gathering the plant-specific information, which includes general arrangement drawing, piping plan drawing, electrical drawing, isometric drawing and plumbing drawing, is needed to determine the location of the equipment and flooding propagation pathways necessary to safety shutdown and accident mitigation.

Plant walk-down is carried out for the purpose of plant familiarization and site survey data. During the walk-down, we have reviewed the major flood sources inducing flood accident and flood protection equipment such as flood proof doors, flood barriers. We have investigated auxiliary building, intermediate building, turbine building, component cooling water (CCW) building, essential sea water (ESW) building, circulating water building and outdoor tank etc.

II.A. Qualitative Analysis

The major outputs of this phase include the screening out of plant flood areas based on criteria associated with flood sources, flood propagation pathways, and potential impacts of flood on structures, systems, and components (SSCs) and the selection of flood areas for quantitative evaluation.

Qualitative screening criteria applied in this task are the following:

- Screen out a flood area with no potential flooding sources present or relevant equipment used in the PSA model.
- Screen out a flood area with no relevant equipment used in the PSA model, but flood sources are present.
- Screen out any area if the postulated flooding area neither causes unavailability of the equipment nor propagate to other area.
- Screen out a flood area with relevant equipment used in the PSA model, but no flooding sources are present. (because flooding does not propagate from other area to this area)
- Screen out the flood area if flood propagation of another flood area to this flood area was previously analyzed for the flooding scenario.

On the basis of the information collected in the criteria, flood areas are screened that consider the potential for flood initiation and propagation, potential for an initiating event or need for immediate plant shutdown, and damage to SSCs that be needed to prevent core damage or large early release in response to the initiating event or plant shutdown.

II.B. Quantitative Analysis

Quantitative analysis, which has not been screened out, is performed by calculating the area CDF. The Area CDF in each flood area was obtained by multiplying the pipe rupture frequency (considering the real pipe system characteristics), the propagation, the initiating event frequency and conditional core damage probability in the screening analysis. The areas whose Area CDF is higher than 1.0E-06/yr were screened for detailed analysis.

In this phase, we changed the flood frequency calculation method used for obtaining the area CDF from the one listed in NPE database to the methodology described in EPRI. Using the new area CDF, quantitative screening analysis was performed.

A quantitative analysis performed by calculating the scenario core damage frequency (CDF) as a function of time, in this case, year, for all flood areas. Then, the area CDF can be obtained by summing the scenario CDF of each flood area. The frequency of flooding events calculated in the "EPRI TR-3002000079 Pipe Rupture Frequencies for Internal Flooding Probabilities Risk Assessment Rev.3" is based on the pipe failure rates per foot by the pipe size and the flood mode (Ref. 3). The flood mode is classified as spray, flood, and major flood. In each flood mode, the pipe rupture frequency is varied. In this paper, we used conservative values which combine all flood modes for frequency of flooding events in the flood areas. In order to apply the EPRI flood area frequency, we investigated the pipe size and length of each system. We used isometric drawings, piping & instrument diagram drawings and piping drawings for a comprehensive pipe survey. This table I shows the example of survey of pipe characteristic by the flooding area.

TABLE I. Example of Survey of Pipe Characteristic by Flooding Area

Flood Area	System	Pipe Diameter (inch)	Total Length (ft)
General Access Area (Auxiliary Building)	CC*	3 ~ 10	~ 300
	CS*	0.75 ~ 4	~ 320
	FP*	2 ~ 6	~ 250
	SI*	1 ~ 2	~ 80
Safety Injection Pump Room A	SI	6 ~ 10	~ 40
	CI*	0.375	~ 1
Component Cooling Water Building	CC	3 ~ 24	~ 3000
	SW*	0.75 ~ 24	~ 1600
	FP	0.25 ~ 6	~ 150
Intermediate Area (Access Area)	AF*	0.75 ~ 6	~ 1000
	CC	3 ~ 12	~ 700
	CZ*	3 ~ 6	~ 500
	FP	0.75 ~ 6	~ 700

*CC: Component Cooling Water System
CS: Chemical and Volume Control System
FP: Fire Protection System
SI: Safety Injection System
CI: Containment Spray System
MS: Main Steam System
SW: Essential Sea Water System
AF: Auxiliary Feed water System
CZ: Essential Chiller Water System

In order to perform a quantitative screening analysis, SAREX, which is commonly used in Korea for quantification of internal PSA modeling, was used to develop flood area modeling and the quantification process. Additionally, the damage terms in the flooding event were developed and combined with partial modification of a fault tree created from the internal PSA modeling.

The flooding frequencies in all areas are much different from the existing ones using NPE data. NPE data considers only frequency, whereas EPRI data consider more in detail, such as systems, modes and pipe diameter. 3 areas were screened out by using NPE data, but general access area of auxiliary building among them were not screened out by using EPRI data. NPE data can underestimate the frequency of the areas with more pipes. This table II shows safety injection (SI) pump room and residual heat removal (RHR) pump room with using the EPRI data gave us the lower area CDF than using NPE data. In other hand, general access areas of auxiliary building with using the EPRI data gave us the higher area CDF than using NPE data. Also, CCW pump building and general access areas of intermediate building with using the EPRI data gave us the higher area CDF than using NPE data.

TABLE II. Example of Screening Analysis

Description	EPRI		NPE	
	Frequency(/yr)	Area CDF(/yr)	Frequency(/yr)	Area CDF(/yr)
SI Pump Room	~ 6×10^{-5}	~ 3×10^{-9}	~ 1.2×10^{-3}	~ 1×10^{-7}
RHR Pump Room	~ 8×10^{-4}	~ 3×10^{-8}	~ 2.4×10^{-3}	~ 1×10^{-7}
CCW Pump Building	~ 9×10^{-3}	~ 5×10^{-4}	~ 1.2×10^{-3}	~ 7×10^{-5}
General Access Area (Aux. Bldg.)	~ 5×10^{-3}	~ 5×10^{-6}		~ 6×10^{-7}
General Access Area (Inter. Bldg.)	~ 4×10^{-2}	~ 5×10^{-2}		~ 3×10^{-4}

II.C. Detailed Analysis

The frequency of flood events is re-evaluated to perform the detailed analysis when additional information of the flood area is collected. First of all, the detail analysis was used to determine the flow rate for breaks in piping systems. This approach is based on the following equation and a few rules for its use. Flow (Q) (gallons per minute) through a leak of equivalent diameter D (inches) from a pipe that is maintained at a pressure P (psig) can be estimated by the equation (Ref. 4)

$$Q = 29.9 \bullet D^2 \bullet \sqrt{P} \qquad (1)$$

To apply this equation, leak rates were estimated, based on system pressure and break size. Break sizes can be estimated as follows:

Spray = ½” equivalent diameter, Flood = 1½” equivalent diameter, and Major Flood= full pipe rupture.

Using the above information, this methodology was applied to determine the maximum flow rates for the three leak categories for the major fluid systems in the detailed analysis area. This figure 1 provides examples to show how the methodology can be performed for some typical fluid systems. And Flow is assessed as the largest value in the group, and frequencies are calculated by summing the frequency of all applicable cells. This figure 2 condenses down to the following:

				Pipe size (inch)																	
System	Pressure (psig)	Pump gpm	Mode	0.25	0.5	0.75	1	1.5	2	2.5	3	4	5	6	8	10	12	16	18	20	24
CC	200	33,200	Spray								106	106		106	106	106	106	106	106	106	106
			Flood								951	951		951	951	951	951	951	951	951	951
			Major								3,806	6,766		15,223	27,062	33,200	33,200	33,200	33,200	33,200	33,200
SW	85	32,800	Spray	17	69	69	69	69	69		69	69	69	69	69	69	69	69	69	69	69
			Flood	17	69	155	276	620	620		620	620	620	620	620	620	620	620	620	620	620
			Major	17	69	155	276	620	1,103		2,481	4,411	6,892	9,924	17,643	27,566	32,800	32,800	32,800	32,800	32,800
FP	125	9,862	Spray	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
			Flood	21	21	188	334	752	752	752	752	752	752	752	752	752	752	752	752	752	752
			Major	21	21	188	334	752	1,337	2,089	3,009	5,349	8,357	9,862	9,862	9,862	9,862	9,862	9,862	9,862	9,862

Fig. 1. Example of Estimated Flow

SYSTEM	Flood Class	
CC	Small	106
	Medium	951
	Large	33,200
SW	Small	69
	Medium	1,103
	Large	32,800
FP	Small	21
	Medium	752
	Large	9,862

Fig. 2. Example of Maximum Leak Flow Rate

Flow is assessed as the largest value in the group, and frequencies are calculated by summing the frequency of all applicable cells. This procedure condenses down to the following:

For the next step, we develop flood scenarios considering the flood sources, location of the equipment (pump, tank, valve, etc.), and intended function required for the flood area. And the damage from the immersion step in the flood scenarios considering flood growth is assessed. Lastly, we calculate the entire core damage frequency due to flood events, considering the frequency of flood damage in each step, conditional core damage probability of flood damage each step, and timing calculations for recovery by operator intervention using human reliability analysis (HRA). The HRA methodology is K-HRA. In the K-HRA, operator action error for flood mitigation can be quantified by assessing two parts separately, a diagnosis part and an action part. The diagnosis part is primarily determined by available time for diagnosing a flood event, and the action part contains operator actions for mitigation strategies based on procedure. For the next step, we develop flood scenarios considering the flood sources, location of equipment (pump, tank, valve, etc.), and intended function required for the flood area. In this paper, a detailed analysis is carried out for two major flood areas.

II.D.1. Detailed analysis about general access area of intermediate building

This general access area of intermediate building is connected to turbine building and series B 480V motor control center (MCC). For the flood accident we consider, flood growth is unmitigated and propagation occurs into the series 'A' battery room, turbine driven pump room, and motor driven pump rooms. Even though demineralization system, condensation storage tank system, and essential chilled water system piping exist, the flooding from rupture of the pipe is estimated to not reach the critical height, leaving the components unaffected. Therefore, the major flooding sources considered are component cooling water system and fire protection system. Therefore, in order to calculate the probability of the flooding event occurring in this area, the pipe length and size existing in the areas were investigated. Using the surveyed pipe information and frequency of flood recorded by EPRI, the pipe rupture frequency in this area is estimated to be 5E-03/yr. And then, we calculate the frequency of flooding event in each flood rating applied to the pipe rupture frequency and operator action probability of flood scenario. For the calculation frequency of flood event and flood damage equipment are considered. This table III shows the detailed analysis of general access area of intermediate building.

TABLE III. Detailed Analysis of General Access Area (Inter. Bldg.)

Flood Area	System	Flood Scenario	Flood Class [gpm]		Pipe Rupture Frequency	IE	Recovery Time(min)	HRA	Scenario Frequency (/yr)
General Access Area (Inter. Bldg.)	CC	Flood Initiation	Small	106	$\sim 8\times10^{-5}$	GTRN	N/A	N/A	$\sim 8\times10^{-5}$
			Medium	951	$\sim 1\times10^{-5}$				$\sim 1\times10^{-5}$
			Large	33,200	$\sim 3\times10^{-6}$				$\sim 3\times10^{-6}$
	FP	Flood Initiation	Small	21	$\sim 4\times10^{-3}$	LODCB	200	$\sim 4\times10^{-3}$	$\sim 2\times10^{-5}$
			Medium	1,137	$\sim 3\times10^{-4}$		4	1	$\sim 3\times10^{-4}$
			Large	9,862	$\sim 1\times10^{-4}$		0	1	$\sim 1\times10^{-4}$
		Propagation (MDP Room)	Small	21	$\sim 4\times10^{-3}$		2000	$\sim 1\times10^{-3}$	$\sim 3\times10^{-9}$
			Medium	1,137	$\sim 3\times10^{-4}$		40	1	$\sim 3\times10^{-5}$
			Large	9,862	$\sim 1\times10^{-4}$		5	1	$\sim 1\times10^{-5}$
		Propagation (battery Room A)	Small	21	$\sim 4\times10^{-3}$		400	$\sim 3\times10^{-3}$	$\sim 1\times10^{-9}$
			Medium	1,137	$\sim 3\times10^{-4}$		8	1	$\sim 7\times10^{-6}$
			Large	9,862	$\sim 1\times10^{-4}$		1	1	$\sim 2\times10^{-6}$

II.D.2. Detailed analysis about component cooling water pump building

The component cooling water building contains component cooling water pump, component cooling heat exchanger and numerous pipes. This flood area is divided into two levels, but the propagation path is established through the stairs and component hatches; therefore, the area is set as one flood area. If flooding growth is unmitigated flood, flooding can propagate into the adjacent essential chiller room. Even though essential chilled water system, chemical & volume control system, fire protection system, demineralization system, condensation storage tank system, and demineralized water system piping exist, the flooding caused by a ruptured pipe is estimated to not reach the critical height, leaving the components unaffected. Therefore, the major flooding sources considered are component cooling system and essential seawater system. Using the surveyed pipe information and frequency of flood recorded by EPRI, the pipe rupture frequency in this area is estimated to be 8E-03/yr. Then, we calculate the frequency of flooding event in each flood rating applied to the pipe rupture frequency and operator action probability of flood scenario. For the calculation, reflect on the frequency of flood event and flood damage equipment.

TABLE IV. Detailed Analysis of Component Cooling Water Pump Building

Flood Area	System	Flood Scenario	Flood Class	[gpm]	Pipe Rupture Frequency	IE	Recovery Time(min)	HRA	Scenario Frequency (/yr)
Component Cooling Water Pump Building	CC	Flood Initiation	Small	106	$\sim 1\times10^{-4}$	GTRN	N/A	N/A	$\sim 1\times10^{-4}$
			Medium	951	$\sim 2\times10^{-5}$				$\sim 2\times10^{-5}$
			Large	33,200	$\sim 5\times10^{-6}$				$\sim 5\times10^{-6}$
		Flood Initiation (More 100.45m)	Small	69	$\sim 7\times10^{-3}$	LOCCW	N/A	N/A	$\sim 9\times10^{-7}$
			Medium	1,103	$\sim 4\times10^{-4}$				$\sim 6\times10^{-8}$
			Large	32,800	$\sim 7\times10^{-5}$				$\sim 7\times10^{-6}$
		Propagation (Essential cooling Room)	Small	69	$\sim 7\times10^{-3}$		N/A	N/A	$\sim 9\times10^{-8}$
			Medium	1,103	$\sim 4\times10^{-4}$				$\sim 6\times10^{-9}$
			Large	32,800	$\sim 7\times10^{-5}$				$\sim 7\times10^{-7}$

III. CONCLUSIONS

The former internal flooding PSA was mainly based on flooding events in NPPs and experience formula for the pipe failure. This approach has limited consideration for practical plant-specific conditions although the calculation process is simple and the results are conservative. In the study, internal flooding PSA in Westinghouse PWRs in Korea was reassessed to apply flood area-specific data, which include the pipe characteristics by the flood source, flooding class by the ruptured pipes, actual propagating scenario, and HRA, etc. The results are shown to be reasonable compared to other internal flooding PSA works. This revised internal flood PSA suggested the safety enhancement such as adopting the water-proof doors in major flood-vulnerable areas, which is expected to lower its CDF by over 50% in sensitivity analysis.

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