FLOODING PSA BY CONSIDERING THE OPERATING EXPERIENCE DATA OF KOREAN PWRs

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The existing flooding Probabilistic Safety Analysis (PSA) was updated to reflect the Korean plant specific operating experience data into the flooding frequency to improve the PSA quality. Both the Nuclear Power Experience (NPE) database and the Korea Nuclear Pipe Failure Database (NuPIPE) databases were used in this study, and from these databases, only the Pressurized Water Reactor (PWR) data were used for the flooding frequencies of the flooding areas in the primary auxiliary building. With these databases and a Bayesian method, the flooding frequencies for the flooding areas were estimated. Subsequently, the Core Damage Frequency (CDF) for the flooding PSA of the Ulchin (UCN) unit 3 and 4 plants based on the Korean Standard Nuclear Power Plant (KSNP) internal full-power PSA model was recalculated. The evaluation results showed that sixteen flooding events are potentially significant according to the screening criterion, while there were two flooding events exceeding the screening criterion of the existing UCN 3 and 4 flooding PSA. The result was compared with two kinds of cases: ① the flooding frequency and CDF from the method of the existing flooding PSA with the PWR and Boiled Water Reactor (BWR) data of the NPE database and the Maximum Likelihood Estimate (MLE) method and ② the flooding frequency and CDF with the NPE database (PWR and BWR data), NuPIPE database, and a Bayesian method. From the comparison, a difference in CDF results was revealed more clearly between the CDF from this study and case ② than between case ① and case ②. That is, the number of flooding events exceeding the screen criterion further increased when only the PWR data were used for the primary auxiliary building than when the Korean specific data were used.

KEYWORDS : Flooding PSA, NuPIPE database, NPE database, Bayesian Analysis, PSA Quality

1. INTRODUCTION

As the interest in Risk-informed Regulation (RIR) is increasing, efforts to improve the quality of the Probabilistic Safety Assessment (PSA) are also increasing. To improve the quality of the Korean PSA model, we evaluated the quality of the Korean Standard Nuclear Power Plant (KSNP) internal full-power PSA model, including an internal flooding PSA model based on the "ASME PRA Standard" [1] and the "NEI PRA Peer Review Process Guidance" [2]. It was found that the overall quality of the KSNP PSA model is between ASME Standard Capability Categories *I* and *II* [3]. We also derived some items to be improved to upgrade the quality of the KSNP PSA to ASME Standard Capability Category *II* [4].

The purpose of this study is to update the flooding PSA with Korean plant specific operating experience data and the appropriate estimation method for the flooding frequency to improve the PSA quality. The existing flooding PSA has used the NPE database [5], of which data was limited to 1985 for the flooding frequency [6,7,8]. The data from the NPE are all based on US nuclear power plant operating experiences. Therefore, an updated flooding frequency using Korean specific plant operation experience has been needed. The existing flooding PSAs have used both Pressurized Water Reactor (PWR) and Boiled Water Reactor (BWR) data for all kinds of plant areas; however, the method proposed in this study for the flooding frequency estimation in the case of the flooding area in the primary auxiliary building uses only the PWR data. We evaluated the Core Damage Frequency (CDF) with the modified flooding frequency and compared the result with that of the existing flooding PSA for UCN plants 3 and 4 [6].

In addition to the NPE database, we used the NuPIPE (Korea Nuclear Pipe Failure Database) database [9], and we selected a Bayesian approach that was done in three steps after reviewing some databases and calculation methods to estimate the flooding frequency for a quantitative screening analysis [10].

The remainder of this paper is organized as follows. We describe some databases, including the NPE, in Section 2. Then, we present the results of the estimation of the flooding frequency using the selected data and the appropriate estimation method in Section 3. Using the estimated flooding frequency, we recalculate the CDF and compare our results with the existing method for the flooding frequency estimation in Section 4. In Section 5, we make our concluding remarks.

2. SELECTION OF THE DATABASE FOR A QUANTITATIVE SCREENING ANALYSIS OF A FLOODING PSA

For existing flooding PSAs for domestic Nuclear Power Plants (NPPs), a screening analysis is performed first and then a detailed analysis is performed for the flooding events not screened out. The screening analysis comprises a qualitative screening analysis and a quantitative screening analysis. For the qualitative screening analysis, the first step is to define various the flooding areas of the plants as independent with respect to an internal flooding. A flooding area is termed independent if the flooding outside the area cannot enter the area without the failure of a flood barrier from the qualitative screening analysis. The second step is to select some of the flooding areas for the quantitative screening analysis. For the quantitative screening analysis, the plant area based flooding frequency taken from the Maximum Likelihood Estimation (MLE) method is used, while the component based flooding frequency is used for the detailed analysis. The plant-area-based flooding frequency and the component-based flooding frequency refer to the flooding frequencies of each flooding area and each major component that are significantly affected by a flooding, respectively [6,7,8].

The quantitative screening analysis for the existing Korean flooding PSA has used the flooding event data from all Light Water Reactors (LWRs), namely, PWRs and a BWRs, for the flooding frequency of all kinds of flooding areas [6,7,8]. In the case of the turbine building, which tends to house similar equipment for major reactor designs, experiences from all LWRs may be applicable. However, we need to be careful in using the data from all LWRs for the primary auxiliary building because of a significant difference in the equipment between the PWR and BWR structures.

In this study, we considered and compared the three databases which are applicable to the quantitative screening analysis: the NPE, NuPIPE, and OPDE (OECD/NEA Pipe Failure Data Exchange) databases [11]. It was convenient to use the NPE database for the flooding PSA, because the flooding event narratives and root causes are described in detail [5]. In addition, the flooding occurrence area and the degree of flooding are analyzed for flooding PSAs of some US NPPs with the NPE [12]. In Korea, however, only a limited amount of flooding event data is available in the NPE database. There is a large amount of NPE data starting from the early 1990’s that describes various plant trips and root causes, including flooding events in Korea. However, detailed analyses of NPE data for the flooding PSA, such as for the flooding occurrence areas and for criticalities, was only performed up to July 1985. Therefore, we needed to consider a database that can cover current plant operation experiences.

The NuPIPE data is a collection of pipe failures which have occurred in Korea since the first commercial operation date of each NPP. The NuPIPE database has a great advantage in that it reflects the real situation about pipe failures that have occurred in domestic NPPs. However, the total plant operating years of Korean NPPs is not sufficient to estimate the flooding frequency using NuPIPE alone. In addition, using only the NuPIPE data, the estimated flooding frequency would provide an optimistic result, because there has been no record of a flooding event in Korea [13].

The purpose of the OPDE database is to apply the pipe failure data from the twelve member countries to various safety analyses, including a PSA, a Risk Informed Application (RIA), and a pipe integrity analysis [11]. To utilize the OPDE data for the quantitative screening analysis of the flooding PSA, a detailed data analysis is required that reveals (1) which failures lead to a flooding event and (2) which areas incur flooding. Even though the OPDE database has an input field from which we can identify if the pipe failure resulted in a flooding area, a large number of piping failure records remain blank in that field.

Table 1 summarizes the merits and demerits of the three databases.

In this study, we selected the NuPIPE data in addition to the NPE data to reflect domestic plant operation experiences for the flooding frequency estimation. We also suggested a method of using only the PWR data for the primary auxiliary building to propose an alternative to estimate the flooding frequency.

3. ESTIMATION OF THE INTERNAL FLOODING FREQUENCY FOR THE SCREENING ANALYSIS

The existing flooding PSAs calculate the flooding frequency with the restricted NPE data and the MLE method for a screening analysis. As mentioned previously, because the NPE data does not include Korean specific plant operation experiences, we utilized the NuPIPE data and the NPE data for an estimation of the flooding frequency as an alternative method. The NPE data has merits in that the data analysis was performed by experts and the NuPIPE data can reflect the plant operation experience of domestic NPPs. We used a Bayesian analysis that was done in three steps to estimate the flooding frequency by considering both the NPE data and the NuPIPE data. We utilized the Bayesian analysis for an evaluation of the frequencies for some initiating events related to piping failures [14][15].

Table 1. NPE, NuPIPE, and OPDE Database for Flooding Frequency

Database	Merit	Demerit
NPE Data	– Detailed event narrative is described – Flooding area and criticality analysis is performed for flooding PSA – PWR & BWR data is available for flooding frequency of turbine building	– To use data after July 1985, it needs additional data analysis by experts
NuPIPE Data	– Safety related piping failures for domestic NPPs by 2004 are collected – Korean specific plant operation is reflected	– Total plant operation year is not sufficient to estimate the flooding frequency – Up to now, there is no recorded event of flooding in domestic NPPs
OPDE Data	– Safety related piping failures are collected from thirteen countries – PWR & BWR data is available for flooding frequency of turbine building – The large number of field data can help various safety issues	– It is difficult to compute total plant operation year – It needs a detail data analysis to define piping failure by flooding

In a similar manner to the evaluation of the initiating event frequencies by US Nuclear Regulation Committee (USNRC), when the available data is insufficient for a frequency evaluation, the Bayesian estimation is preferred [16].

In this paper, we used a Bayesian approach that was done in three steps. The Bayesian analysis can be summarized as follows [17]:

- Step 1: a prior distribution for a parameter is described with engineering knowledge
- Step 2: a posterior distribution is calculated with the first prior distribution from Step 1 and the generic plant experience
- Step 3: a final posterior distribution is calculated with the posterior distribution from Step 2 as a prior distribution and the Korean plant specific data.

In Step 1, we used Jeffrey's noninformative prior, which is based on Fisher's information matrix [18]. By using a noninformative prior, we could avoid a prejudiced prior and obtain a posterior distribution that is more empirical [19]. In this study, we considered a standard Bayesian approach, in which λ the rate of the occurrence of the Poisson distribution, is assumed to have a gamma prior distribution, denoted by gamma(α,β). A recent report for initiating event frequencies used Jeffrey's noninformative prior with a gamma distribution for some cases of initiating events [16]. It is convenient to calculate the posterior distribution when a gamma distribution is used as a prior.

Baye's theorem states that the posterior distribution $f(\lambda/E)$ is related to the prior and sampling models (likelihood distribution) according to

$$f(\lambda/E) = \frac{f(\lambda)L(E/\lambda)}{\int f(\lambda)L(E/\lambda)d\lambda} \tag{1}$$

where $f(\lambda)$ is a prior distribution and $L(E/\lambda)$ is a likelihood function of λ given evidence E .

For the prior distribution, the probability density function of gamma distribution is as follows:

$$f(\lambda) = \frac{\beta^{\alpha}}{\Gamma(\alpha)}\lambda^{\alpha-1}Exp(-\beta\lambda) \tag{2}$$

where $\alpha > 0$ and $\beta > 0$

$$\Gamma(n) = \int_0^{\infty} x^{n-1}e^{-x}dx\text{ , Gamma function}$$

Jeffrey's noninformative prior, which corresponds to taking α=1/2 and β=0 ignoring the normalizing constant at the front part of Equation (2), is proportional to $\lambda^{1/2}$.

In the second step, a posterior distribution is calculated with Jeffrey's noninformative prior with a gamma distribution from Step 1 and the generic plant experience. In this paper, we use the NPE data for the generic plant experience. When the evidence is in the form of n_1 failures over an operational time t_1, the likelihood function given λ_1, the occurrence rate, is a Poisson distribution, as follows:

$$L(E/\lambda_i) = \exp(-\lambda_i t)\frac{(\lambda_i t_1)^{n_1}}{n_1!} \tag{3}$$

With the three equations, the posterior distribution is gamma ($\alpha+n_1$, $\beta+t_1$) when the prior distribution is gamma (α, β) [20]. Therefore, the posterior distribution for λ with Jeffrey's noninformative prior in the second step is gamma (α_{post1}, β_{post1})

$$\alpha_{post1} = n_1 + \frac{1}{2}$$

$$\beta_{post1} = t_1 + 0$$

In Step 3, we perform the Bayesian analysis again using Korean specific plant operation data. In this step, for the prior distribution, we use the posterior distribution from the previous step, gamma (n_1+1/2,t_1). The likelihood function is the same as Equation (2) with n_2 instead of n_1 and t_2 instead of t_1. That is, n_2 is the observed number of events and t_2 is the total time of operating experience in the critical years from the NuPIPE data. With the feature of a gamma distribution, the posterior distribution of the third step is gamma (α_{post2}, β_{post2})

$$\alpha_{post2} = n_1 + n_2 + \frac{1}{2}$$

$$\beta_{post2} = t_1 + t_2 + 0$$

Finally, we compute the mean value of the posterior distribution of the flooding frequency, ($n_1+n_2+0.5$)/ (t_1+t_2), since the mean of gamma (α, β) is α / β. The lower bound (5% percentile) and the upper bound (95% percentile) of the gamma posterior distribution of λ are $\Gamma^{-1}(0.05,\alpha,1/\beta)$ and $\Gamma^{-1}(0.95,\alpha,1/\beta)$ respectively.

Table 2 shows a summary of the flooding frequencies of the flooding areas by the Bayesian analysis that was done in three steps. Among the flooding areas defined for the quantitative analysis, six flooding areas are singled out by the screening criteria for the qualitative screening analysis [6,7,8]. They are the turbine building, the primary auxiliary building, the secondary auxiliary building, the nuclear fuel building, the Emergency Diesel Generator (EDG) room, the Component Cooling Water (CCW) heat exchanger, and the Essential Service Water (ESW) intake building. To calculate the flooding frequency of the primary auxiliary building, the existing flooding PSAs classified the building into three areas: the High Pressure Safety Injection (HPSI) pump room, the Low Pressure Safety Injection (LPSI) pump room, and a general area. The flooding frequencies of the nuclear fuel building, the EDG room, and the CCW heat exchanger and ESW intake building were replaced with that of the general area of the primary auxiliary building [6,7,8]. In the same manner as the existing flooding PSAs, we estimated the flooding frequency for four flooding areas, namely the HPSI pump room, the LPSI pump room, the general area, and the turbine building. As mentioned previously, we selected only the PWR data for the flooding frequency estimation of the primary auxiliary building – the HPSI pump room, the LPSI pump room, and the general area – though the existing flooding PSAs used the PWR and BWR data for the estimation.

A mean flooding frequency and dispersion of the posterior distribution from the Bayesian analysis are shown in Table 2. Reference value 1 is the flooding frequency for the existing flooding PSAs, which used the PWR and BWR data from the NPE database and the MLE method, and reference value 2 is the flooding frequency calculated with the PWR and BWR data for all the flooding areas from the NPE database, the NuPIPE database, and a Bayesian method. The major difference between reference value 1 and reference value 2 is that reference value 2 uses Korean specific plant operation experience data, and a difference between the mean flooding frequency and reference 2 is that the mean flooding frequency only uses the PWR data for the primary auxiliary building, though Korean plant operation data are reflected in both results.

Table 2 shows that the frequencies of the four buildings. The flooding frequency of the HPSI pump room has a lower value in this study than in the existing PSAs, since all the flooding events in the HPSI pump room occurred in BWR plants.

From Table 2, the ratio between the mean flooding frequency and reference value 2 ranges from 0.3 to 1.5, while the ratio between reference 1 and reference 2 ranges from 0.8 to 1.11. The range of ratios has a larger value between the mean flooding frequency and reference value 2 than between reference value 1 and reference value 2. This result shows that the effect of the PWR data alone is more noticeable than that of Korean specific data for a flooding frequency calculation of the primary auxiliary building.

4. CALCULATION OF THE CORE DAMAGE FREQUENCY (CDF)

The risk contribution from a flooding event is evaluated by requantifying the appropriate core melt sequences developed in the internal event study, by taking into account equipment failures due to flood damage as well as random equipment failures. With the modified flooding frequencies, we recalculated the CDF by considering a flooding event. An Event Tree (ET) and a Fault Tree (FT) for the KSNP internal full-power PSA model of which the PSA quality is upgraded are modified to evaluate the effects of a flooding in each flooding area in terms of the resulting accident sequence frequencies [21]. For those flooding areas singled out for the qualitative screening analysis, the sub-flooding areas were defined to be independent with respect to an internal flooding by a safety significant component [6,7,8]. We computed the CDF for the flooding events occurring in those sub-flooding areas with the Conditional Core Damage Probability (CCDP), flooding frequency and the

Table 2. Flooding Frequency for Quantitative Screening Analysis

Flood Area	Mean Flooding Frequency	Percentile		Reference Value 1	Reference Value 2
		5%	95%		
Turbine BLDG	5.4E-3	2.2E-3	9.6E-3	6.0E-3	5.4E-3
General Area	2.2E-3	2.6E-4	5.7E-3	1.2E-3	1.5E-3
HPSI PP Rm.	3.7E-4	1.4E-6	1.4E-3	1.2E-3	1.2E-3
LPSI PP Rm.	1.8E-3	4.2E-4	4.0E-3	2.4E-3	2.2E-3

probability of a flooding barrier failure. For the calculation of the modified CDF, we used the probability of a flooding barrier failure and the designation of the flooding area for the UCN 3 and 4 flooding PSA [6].

$$CDF_i = f_i(\lambda) * BF_i * CCDP_i \tag{4}$$

CDF_i : CDF of the *i*-th flooding event
$f_i(\lambda)$: Flooding frequency of a flooding area related to the *i*-th flooding event
BF_i : Probability of a flooding barrier failure of the *i*-th flooding event
$CCDP_i$: Conditional core damage probability of the *i*-th flooding event

In the UCN 3 and 4 flooding PSA, CDFs of two flooding events exceeded the screening criterion (1.0E-7/yr) to perform a more refined analysis; however, in this study, Table 3 shows that CDFs for sixteen flooding events which occurred in the nine sub-areas of the primary auxiliary building exceeded the screening criterion. In Table 3, Reference CDF 1 is the CDF calculated by using the flooding frequency of the existing flooding PSA, which is from reference value 1 in Table 2. Reference CDF 2 is calculated by using the flooding frequency of reference value 2 in Table 2. Both columns are based on the upgraded KSNP internal full-power PSA model.

Though reference CDF 1 uses the same data and calculation method as the UCN 3 and 4 flooding PSA, it differs from the UCN 3 and 4 flooding PSA CDF results in which only two areas are singled out [6]. The upgraded KSNP PSA model reveals this difference.

Reference CDF 1 and reference CDF 2 show that twelve flooding events in the eight sub-areas are singled out. Accordingly, the effect of the Korean plant operation data is not significant for the CDF change, while the effect

Table 3. CDF and Flooding Events over Screening Criterion

Sub Area	Room No	Flooding Freq.	Propagation Area	BF	CCDP	CDF	Reference CDF 1	Reference CDF2
A-29	100-A06A	2.2E-3	A-27	0.1	4.95E-4	1.09E-7	5.94E-8	7.42E-8
A-34	100-P01	2.2E-3	A-27	0.1	4.95E-4	1.09E-7	5.94E-8	7.42E-8
		2.2E-3	A-30	0.1	1.73E-3	3.81E-7	2.08E-7	2.60E-7
		2.2E-3	A-31	0.1	1.74E-3	3.82E-7	2.08E-7	2.60E-7
A-37	100-A13A	2.2E-3	none	1	6.05E-5	1.33E-7	7.26E-8	9.08E-8
		2.2E-3	A-23	1	1.27E-4	2.80E-7	1.53E-7	1.91E-7
A-38	100-A13B	2.2E-3	none	1	6.05E-5	1.33E-7	7.26E-8	9.08E-8
		2.2E-3	A-24	1	1.27E-4	2.80E-7	1.53E-7	1.91E-7
A-45	125-02A	2.2E-3	A-37	1	1.31E-4	2.89E-7	1.58E-7	1.97E-7
		2.2E-3	A-38	1	1.32E-4	2.89E-7	1.58E-7	1.97E-7
A-51	144-A10	2.2E-3	A-48	0.1	1	2.20E-4	1.20E-4	1.50E-4
		2.2E-3	A-53	0.1	9.36E-3	2.06E-6	1.12E-6	1.40E-6
A-52	144-A11	2.2E-3	A-48	0.1	1	2.20E-4	1.20E-4	1.50E-4
		2.2E-3	A-54	0.1	2.04E-3	4.48E-7	2.44E-7	3.05E-7
A-55	144-A03A	2.2E-3	A-53	0.1	9.36E-3	2.06E-6	1.12E-6	1.40E-6
A-56	144-A03B	2.2E-3	A-54	0.1	2.04E-3	4.48E-7	2.44E-7	3.05E-7

of only using the PWR data for CDFs in the primary auxiliary building is an additional four flooding events exceeding the screening criterion.

5. CONCLUDING REMARKS

We used the Korean specific plant operation experience data and an appropriate flooding frequency estimation method to improve the flooding PSA quality of domestic NPPs. Even though the effect of the Korean specific plant operation data is negligible, since there has been no flooding event in Korean NPPs up to now, the zero event itself is important data. We quantified the modified CDF based on the upgraded KSNP internal full power model. In doing so, the flooding PSA quality can be improved from ASME Standard Capability Category *I* to *II* for a requisite related to a plant specific operation experience.

We utilized the NuPIPE data and the NPE data for an estimation of the flooding frequency. The NPE data has merits in that the data analysis is performed by experts, while the NuPIPE data can reflect the plant operation experience of domestic NPPs. We reduced the data scope of the NPE database to the PWR data alone for the primary auxiliary building by considering the design characteristics. We used a Bayesian analysis that was done in three steps to estimate the flooding frequency by considering both the NPE data and NuPIPE data. The Bayesian analysis that was done in three steps is preferred when there is engineering knowledge, generic plant operation data, and plant specific operation data. We selected Jeffrey's noninformative prior distribution with a gamma distribution. Even if the gamma prior distribution may have some problems when it is used for a prior distribution, it has been applied for an event occurrence frequency since it is very simple to compute the posterior distribution.

Based on the modified flooding frequency, we estimated the CDF. The evaluation results showed that sixteen flooding events are potentially significant according to the screening criterion, while there were two flooding events exceeding the screening criterion of the existing UCN 3 and 4 flooding PSA. Therefore, further analysis is required for the sixteen additional flooding areas.

We compared the CDF results with the results of two cases: (1) the PWR and BWR data from the NPE database with the MLE method and (2) the PWR and BWR data from the NPE and NuPIPE data with the Bayesian method. From this comparison, the effect of the Korean plant operation data is not significant in the CDF change, while the effect of using only the PWR data for the primary auxiliary building causes an additional four flooding events that exceed the screening criterion. This result shows that the number of flooding events exceeding the screen criterion increased further when only the PWR data were used for the primary auxiliary building than when the Korean specific data were used.

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