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THE PRESSURE BOUNDARY DAMAGE PROBABILITY CONSIDERING CORRELATION TOWARD THE SEISMIC-INDUCED FLOODING PROBABILISTIC RISK ASSESSMENT IN NUCLEAR POWER PLANT

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ABSTRACT

In this study, to consider the correlation between damages of pressure boundary of the equipment such as components and piping systems within the virtual compartments, a correlation coefficient was added to the previous method. Because the correlation coefficient was not clear, the correlation coefficient was changed from zero to one as a parameter study, and the damage probabilities of the equipment for each number of damaged points were obtained. Here, the correlation coefficient of zero means no correlation and that of one means complete correlation between damages. As the correlation coefficient increases, the seismic motion at which multiple damage becomes significant decreases. In case of the correlation coefficient of zero, the damage probability to one point of components or piping systems in the unit is dominant as same as the previous study. In case of the correlation coefficient of 0.5, the damage probability to one or more components or piping systems in the unit is about twice the damage probability to two or more components or piping systems. Based on the earthquake damage database in Japanese nuclear power plants, it is thought that it is sufficient to consider a correlation coefficient $r = 0.6$ or less, but further research on the correlation coefficient is considered necessary because the probability of multiple damage differs greatly depending on the correlation coefficient. We also considered a method for applying the obtained damage probability to seismic-induced flooding PRA, and described a simplified assessment method for the seismic-induced flooding risk using the evaluation results of existing seismic probabilistic risk assessment.

INTRODUCTION

The earthquake and tsunami attacking at the Fukushima Daiichi Nuclear Power Station in 2011 caused the cooling and containment functions of the plant to fail, leading to a serious accident. Considering the accident at the Fukushima Daiichi NPP, the Japanese government has reviewed the regulatory framework for NPPs and introduced new regulatory standards that reflect the lessons learned from the accident. In addition to earthquake and tsunami countermeasures, the new regulatory standards strengthen design standards to prepare for a wide range of risks, including natural disasters such as volcanic eruptions and tornadoes, and fires, and add severe accident countermeasures. In studying scenarios for severe accident countermeasures,

the internal, seismic and tsunami probabilistic risk assessments (PRAs) that can currently be used were introduced.

In the final report of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company (2012), it was noted that "comprehensive risk analysis for external events was not conducted, encompassing analysis through seismic PSA (PRA) and safety analysis for tsunami, and fires, volcanoes, and slope collapses, etc. which could cause a disaster." It has been pointed out that a comprehensive risk assessment of nuclear power plants (NPPs) is important for improving the safety of NPPs. For seismic-induced events, the degree of damage to the plant caused by an earthquake has a significant impact on the results of the PRA assessment, and this needs to be given realistically, but it is difficult to analytically assess the realistic degree of damage to the entire plant during an earthquake, and no risk assessment of a real plant has ever been carried out.

In a seismic-induced flooding PRA, the number of points where flooding occurs within a unit during an earthquake and the extent of that flooding are crucially important. If there is only one point of flooding that affects safety function, the possibility of core damage is relatively small because of the countermeasures to prevent flooding affecting the other safety divisions in design. However, if flooding occurs in multiple safety divisions in the unit, the possibility of core damage increases.

In the previous study, the plant-level fragility curve for pressure boundary of equipment such as components and piping systems, developed based on the earthquake damage database in Japanese NPPs, was used for realistically assess the number of flooding points. The unit was divided into m virtual compartments so that the damage probability of pressure boundary of the equipment within each virtual compartment in the event of an earthquake would be equal. For the sake of simplicity, assuming that there is no correlation between equipment damage in the virtual compartments, we set m to infinite and calculated the damage probability of equipment for each number of damaged points in the unit. It was confirmed that the probability of a single damage point was dominant for the entire equipment, and that the damage probability decreased significantly as the number of damage points increased to two or three (Ihara et al. 2023). However, in order to make a more realistic assessment, it is necessary to consider the correlation between damages of the equipment in a unit.

In this study, to consider the correlation between equipment damage in the virtual compartments, a correlation coefficient was added to the previous method. Because the correlation coefficient was not clear, it was changed from zero to one as a parameter study, and the damage probabilities of the equipment for each number of damaged points were obtained. Here, the correlation coefficient of zero means no correlation and that of one means complete correlation between damages.

INTERNAL-FLOODING PROTECTION MEASURES IN JAPANESE NPPs

The new regulatory standards for NPPs, which came into force in the wake of the Fukushima NPP accident, require that internal-flooding occurring in the plant do not affect safety-significant structures, systems, and components (SSCs) of multiple safety divisions (Nuclear Regulatory Authority, 2013). To comply with this requirement, Japanese NPPs have taken measures to prevent internal-flooding, such as the installation of watertight doors and weirs, as shown in the left of Fig.1, to prevent flooded or submerged water from affecting safety-significant SSCs due to damage of equipment, such as pipe breaks, tank failures, etc. These divide the building interior into small flooding protection compartments, as shown in the right of Fig.1, and limit the impact of flooding so that they do not affect safety- significant SSCs in different safety divisions.

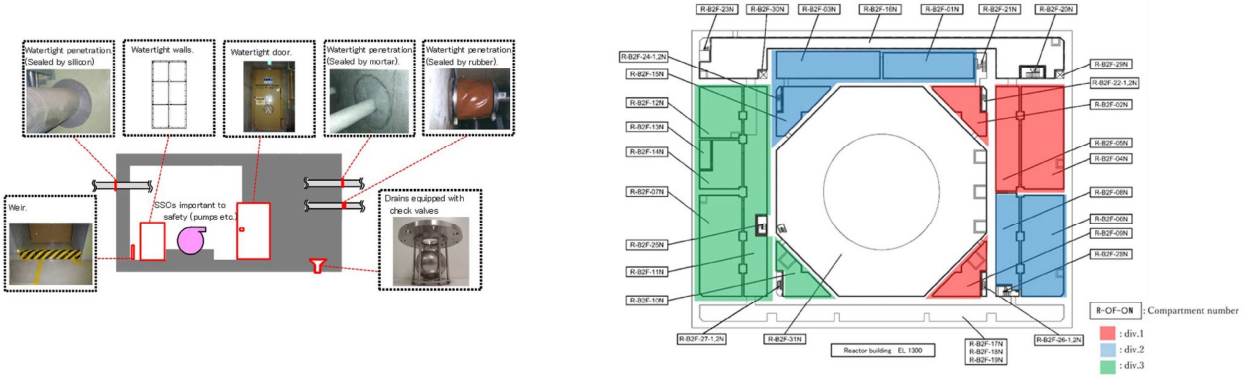

Figure 1. (left) Preventive measures for internal-flooding in Japan and Flooding protection compartments and (right) safety divisions of a reactor building floor.

PLANT-LEVEL FRAGILITY CURVES FOR EQUIPMENT

Plant-level fragility curves for equipment installed on bedrocks are obtained based on the earthquake damage data at Japanese NPPs. The plant-level fragility curve is a curve that expresses the damage probability to one or more equipment within a certain area of a plant due to an earthquake by the seismic motion level, considering the equipment installed within the area as a single unit.

The following two plant-level fragility curves for equipment were estimated based on the earthquake damage data, using the peak base-mat accelerations (PBA) of the reactor building as an indicator of seismic intensity (Miyado et al. 2015).

- Plant-level fragility curve for equipment in the buildings excluding turbine building of one NPP unit (no damage case exists).
- Plant-level fragility curve for equipment in the turbine building of one NPP unit (damage case exists).

There is no damage case to the former equipment, while there is a damage case to the latter equipment in the investigation. Safety-significant SSCs affected by flooding are not installed in turbine buildings. Therefore, for seismic-induced flooding PRA, the plant-level fragility curve for equipment in buildings excluding turbine buildings is used as a plant-level fragility curve for the boundary function of equipment, and is shown in Fig.2.

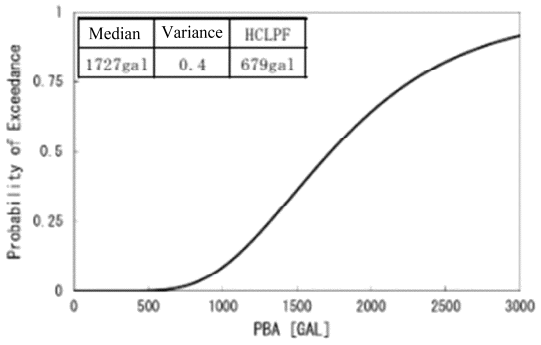

Figure 2. Plant-level fragility curves for equipment in one NPP unit (excluding equipment in the turbine building).

DAMAGE PROBABILITY FOR EACH NUMBER OF DAMAGED POINTS

Methods for calculating the damage probability for each number of damaged points

The probability that an earthquake will damage one or more of the equipment in a NPP unit can be obtained using the seismic hazard curve for each site and the plant-level fragility curve for equipment, as follows:

$$P(A1{:}A2) = \int_{A1}^{A2} -\frac{dH(a)}{da} F_P(a)da \tag{1}$$

where P(A1:A2) is the probability that an earthquake of a PBA from A1 to A2 will damage equipment at one or more points in the unit in one year, and $H(a)$ is the probability of an earthquake of PBA equal to a or greater occurring at the NPP site in one year, and $F_P(a)$ is the damage probability of equipment at one or more points in the unit in the event of an earthquake whose PBA equal to a. $F_P(a)$ is expressed as follows, using the damage probability $F_i(a)$ of equipment at i points in the unit in the event of an earthquake with a PBA equal to a:

$$F_P(a) = \sum_{i=1}^{\infty} F_i(a) \tag{2}$$

The unit is divided into m virtual compartments. As shown in Fig.3, the virtual compartments are divided so that the damage probability of equipment within each virtual compartment in the event of an earthquake is equal, and call this probability Q_m. There is a correlation between the damage to the equipment within the virtual compartments i and j. For simplicity, we assume that the correlation between all the virtual compartments is equal, and call this correlation coefficient r. The damage probability F_i^m of the components and piping system in i of the m virtual compartments can be expressed as a function of Q_m and r as follows:

$$F_i^m = f_i^m(Q_m, r) \tag{3}$$

The damage probability of the equipment will be damaged in one or more of the m virtual compartments in the unit in the event of an earthquake can be expressed as follows:

$$F_p^m = \sum_{i=1}^{m} F_i^m = \sum_{i=1}^{m} f_i^m(Q_m, r) \tag{4}$$

When there is no correlation in the damage of the equipment between the virtual compartments, i.e. when $r = 0$, Equations (3) and (4) are expressed using a binomial distribution ${}_m\boldsymbol{C}_i$ as follows:

$$F_i^m = {}_m\boldsymbol{C}_i \, {Q_m}^i (1 - Q_m)^{m-i} \tag{5}$$

$$F_p^m = 1 - (1 - Q_m)^m \tag{6}$$

From Eq. (4), the damage probability Q_m of the components and piping system within each virtual compartment can be expressed as a function of F_p^m and r as follows:

$$Q_m = q_m\left(F_p^m, r\right) \tag{7}$$

From Eqs. (3) and (7), when an earthquake occurs, the damage probability F_i^m that the equipment will be damaged in i of the m virtual compartments can be expressed as a function of F_p^m and r as follows.

$$F_i^m = g_i^m(F_p^m, r) \tag{8}$$

From Eqs. (2) and (4), if we set $F_P(a) = F_p^m$ and set m to be infinite, the following equation holds. If m is set to be 1000 or more, F_i^m converges to a range that is not problematic in practice (Kuramasu et al., 2014).

$$F_i(a) = F_i^m \quad (1000 < m) \tag{9}$$

At this time, the following equation can be obtained from Eqs. (8) and (9).

$$F_i(a) = g_i^m(F_P(a), r) \quad (1000 < m) \tag{10}$$

The probability $P_m(\mathrm{n}, \mathrm{A1}: \mathrm{A2})$ of n or more damage of equipment in the unit due to an earthquake with a PBA of A1 to A2 in one year (hereinafter referred to as the probability of n or more damage of equipment due to an earthquake from A1 to A2 in one year) can be obtained using the following equation.

$$P_m(n, A1: A2) = \sum_{i=n}^{\infty} \int_{A1}^{A2} -\frac{dH(a)}{da} F_i(a) da = \sum_{i=n}^{m} \int_{A1}^{A2} -\frac{dH(a)}{da} g_i^m(F_P(a), r) da \quad (1000 < m) \tag{11}$$

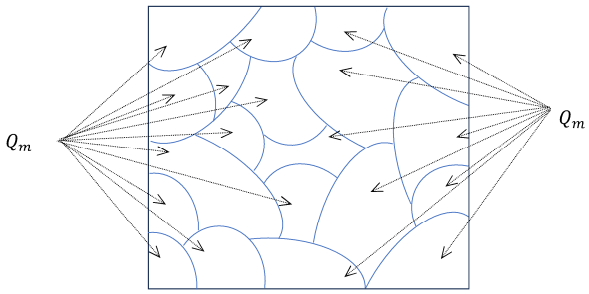

Figure 3. m virtual compartments and the probability Q_m of damage of equipment in the virtual compartments.

Damage probability for each number of damaged points

As a representative of Japanese NPPs, the seismic hazard curve of the Shimane NPP is used to calculate the damage probability of equipment for each number of damaged points in a unit. The seismic hazard curve of Shimane NPP (as of 1 June 2018) is shown in Fig.4. The horizontal axis of this seismic hazard curve is the peak ground acceleration (PGA) of released base surface, which is assumed here to be equal to the PBA because the PBA and PGA are almost equal at Shimane NPP.

The damage probability of equipment for each number of damaged points due to an earthquake in the unit, calculated by Eq. 11, is shown in Fig.5. The horizontal axis is the correlation coefficient r, and the vertical axis is the probability $P(\mathrm{n}, A1: A2)$ of n or more damage in one year from earthquakes of 0 to 2000 gal. Here, the number of the virtual compartments is assumed to be m = 1000. Figure 6 shows the relationship between the correlation coefficient r and damage probability for each number of damaged points in the equipment by seismic motion level. The horizontal axis shows the seismic motion level, and the vertical axis shows the damage probability in one year from n or more points by earthquakes from A gal to B gal.

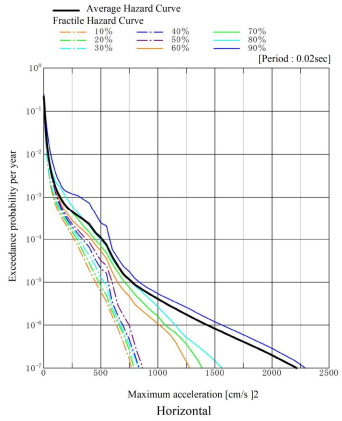

Figure 4. Seismic hazard curve for Shimane Nuclear Power Station (as of 1 June 2018).

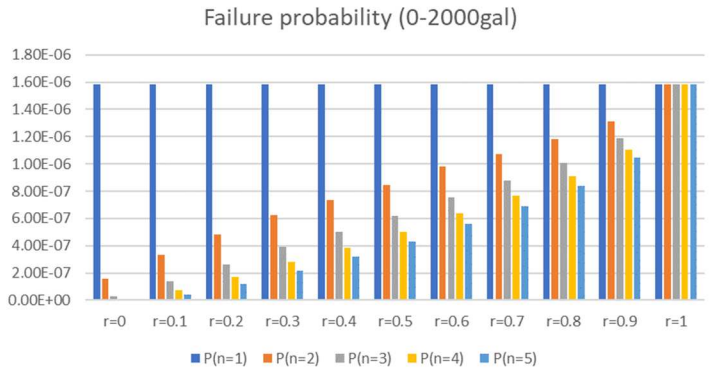

Figure 5. Damage probability to equipment for each number of damaged points; Hazard curve: Shimane Nuclear Power Station.

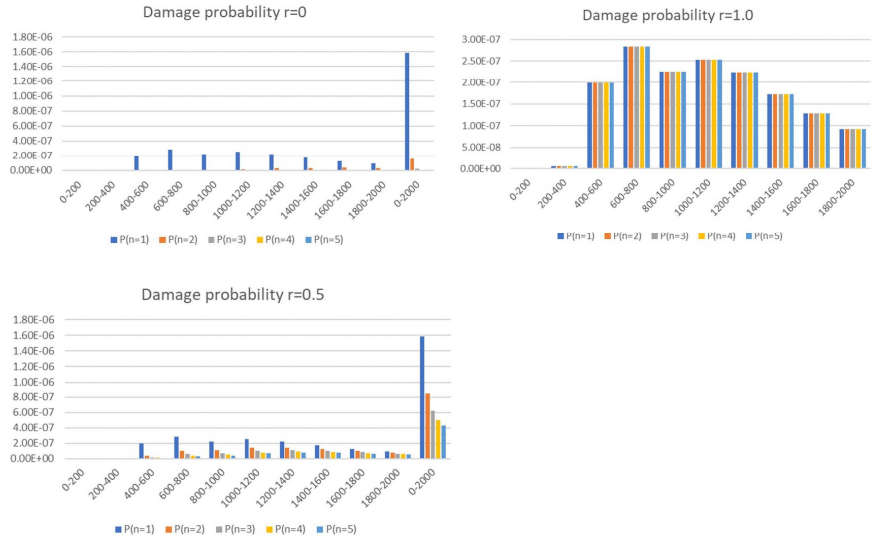

Figure 6. Damage probability to equipment for each number of damaged points by seismic motion level; Hazard curve: Shimane Nuclear Power Station.

From these figures, the following can be seen about the correlation coefficient r and annual damage probability.

- The damage probability of one or more points of the equipment is 1.6E-06/year.
- When $r = 0$, the damage probability to one point of components or piping systems in the unit is dominant, and is about 8 times the damage probability to two or more points. It was confirmed that the damage probability decreases significantly as the number of damaged points increases to two or three.
- When $r = 0.5$, the damage probability to one or more components or piping systems in the unit is about twice the damage probability to two or more components or piping systems.
- When $r = 1$, the damage probability to one or more components or piping systems in the unit is equal to the damage probability to two or more components or piping systems, and the damage probability to three or more components or piping systems, indicating an unrealistic result where all components or piping systems in the unit are damaged when they are damaged.
- As shown in Table 1, as r increases, the seismic motion at which multiple damage becomes significant decreases. Here, "the multiple damage becomes significant" means as the damage probability to two or more points becomes more than half the damage probability to one point or more points, i.e. the damage probability to two or more points becomes equal to the damage probability to one point. In addition, although the seismic motion at which multiple damage becomes significant is not monotonically decreasing, this is thought to be a calculation error.

Table 1 Relationship between correlation coefficient and earthquake motion at which multiple damages become significant

Correlation coefficient	Seismic motion causing significant damage in multiple points
r = 0	Over 2000gal
r = 0.1	Over 1600gal
r = 0.2	Over 1400gal
r = 0.3	Over 1200gal
r = 0.4	Over 1000gal
r = 0.5	Over 1000gal
r = 0.6	Over 800gal
r = 0.7	Over 600gal
r = 0.8	Over 400gal
r = 0.9	Over 200gal
r = 1.0	Over 0gal

DISCUSSION

Considering the following, it is not necessary to think that multiple damage becomes at around 600 gal. Therefore, it is thought that it is sufficient to consider a correlation coefficient $r = 0.6$ or

less, but further research on the correlation coefficient is considered necessary because the probability of multiple damage differs greatly depending on the correlation coefficient.

- The equipment in the plants are undamaged in earthquake damage data with a maximum acceleration of up to 680 gal.
- The HCLPF of the plant-level fragility curve is 679 gal.
- The assumed damage is a phenomenon with a large degree of variation due to fatigue damage and ductile fracture.
- There is a correlation in the response of equipment, but there is no correlation in their capacity.

APPLICATION OF SEISMIC-INDUCED FLOODING TO PRA

We describe a method for performing a simplified for seismic-induced flooding PRA by applying the probability of multiple damages to plant equipment due to earthquakes. In this method, existing seismic PRA evaluation results are used to schematically evaluate the core damage frequency due to seismic-induced flooding. First, the event tree for seismic-induced flooding is described. For example, the published seismic PRA evaluation results for Shimane NPP Unit 2 are referenced as shown in Fig.7

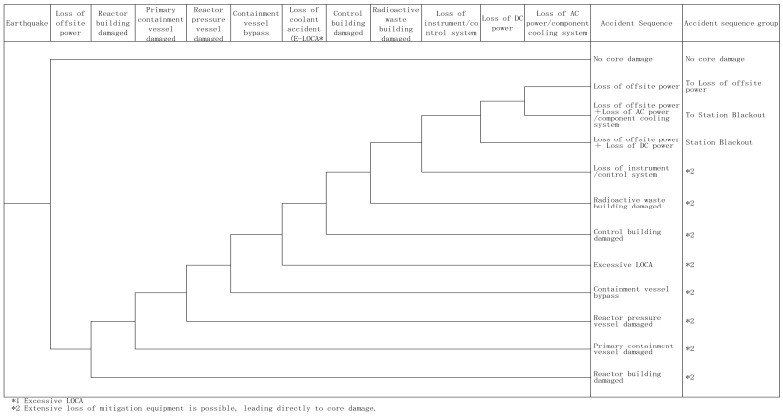

Figure 7. Seismic PRA hierarchical event tree

In this event tree, the sequence leading to core damage caused by an earthquake is developed. When considering seismic-induced flooding, an evaluation can be made by adding an event tree that considers the effects of flooding branched according to the number of equipment damage points in the plant, as shown in Fig.8, to each end of the event tree in Fig.7.

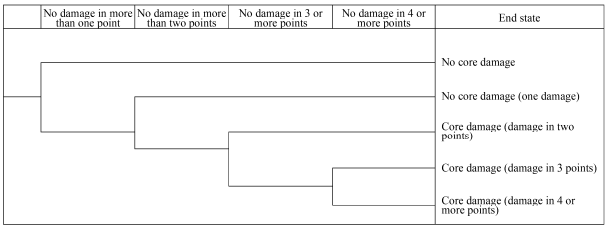

Figure 8. Event tree considering flooding influence

The purpose here is to perform a schematic evaluation using existing PRA results, and the evaluation process is simplified by the following approximations.

- At the end states of the seismic PRA hierarchical event tree shown in Fig.7, all end states other than "no core damage" includes core damage sequence regardless of whether or not there is a flooding effect, and there is no impact from adding the event tree in Fig.8, thus all end states other than "no core damage" was not evaluated in this study.
- The no core damage at the end of the loss of offsite power (LOOP) accident event tree may have possible combinations of equipment damage and human error due to seismic PRA, and a loss of one safety division due to flooding when one point of equipment within the plant is damage. However, this is multiplied by the probability of equipment damage and human error on the order of 1E-03 or less, and is further multiplied by the frequency of LOOP as 1.5E-04/reactor year, and is assumed to be relatively small, so they do not need to be included in this evaluation.
- In response to new regulatory standards, Japanese nuclear power plants have taken measures against internal flooding that separate safety divisions. When considering long term cooling, there are two safety divisions that need to be considered. And as long as one of them is sound, the plant can be shut down stably. Therefore, if there is damage to one equipment, it is assumed that there is no core damage.
- If there are damages to two equipment in the plant, and they are in the same safety division, the impact on the plant is the same as one division damaged, so taking into account combinations, 1/2 of the damage probability to two equipment points is set as the probability for core damage.
- If there are damages to three equipment points in the plant, and they are in the same safety division, the impact on the plant is the same as one division damaged, so taking into account combinations, 6/8 = 3/4 of the damage probability to three equipment points is set as the probability for core damage.

With the above condition settings, the dominant contribution to the core damage frequency can be evaluated by expanding the event tree of the flooding effect for the "no core damage" end state at the top one of the event tree shown in Fig.7. The risk of core damage due to flooding is calculated as follows:

$$\begin{aligned}&(Damage\ Probability\ to\ 4\ or\ more\ points)\\&\quad+\{(Damage\ Probability\ to\ 3\ or\ more\ points)\\&\quad-(Damage\ Probability\ to\ 4\ or\ more\ points)\}\times 3/4\\&\quad+\{(Damage\ Probability\ to\ 2\ or\ more\ points)\\&\quad-(Damage\ Probability\ to\ 3\ or\ more\ points)\}\times 1/2\end{aligned}\tag{12}$$

If we consider the case where the correlation coefficient r is 1, the risk of core damage due to seismic-induced flooding is 1.6E-06/reactor year according to the above formula. If this correlation is a complete correlation, one point damage is equivalent to multiple points damage, so it can be interpreted as an evaluation result assuming a plant state without considering internal flooding measures. If we consider the case where the correlation coefficient r is 0.5, the risk of core damage due to seismic-induced flooding is 5.05E-7+(6.21E-07-5.05E-7)×3/4+(8.47E-07-6.21E-7)×1/2=7.05E-7/reactor year according to the above formula. If we consider the case where the correlation coefficient r is 0, the core damage risk of seismic-induced flooding is 4.15E-09+(2.55E-08-4.15E-09)×3/4+(1.59E-07-2.55E-8)×1/2=8.69E-8/reactor year.

The above results show that the risk of core damage due to seismic-induced flooding changes by changing the correlation coefficient for the number of damaged equipment points in the plant. Setting the correlation coefficient at 1 is highly conservative, and a smaller correlation coefficient reduces the risk. In this way, it is important to appropriately consider the correlation between damaged points.

As mentioned above, the correlation coefficient is expected to be at most 0.6, so if the correlation coefficient is taken as 0.6, the seismic-induced flooding risk will be 8.38E-7/reactor year. Since the core damage frequency in the seismic PRA for Shimane Unit 2 is 7.9E-6/reactor year, the seismic-induced flooding risk will be 10.6% of the seismic risk, which can be estimated as relatively small.

A correlation coefficient of 1.0 means that measures against internal flooding are not taken into consideration, so if the correlation coefficient is 0.6, measures against internal flooding reduce the seismic-induced flooding from 1.6E-6 to 8.38E-7. This evaluation also confirmed that, based on the results of the existing seismic PRA and a risk assessment using the probability of multiple damage points due to plant fragility, measures to prevent internal flooding have reduced the risk of core damage due to seismic-induced flooding.

This shows a schematically evaluation method using the results of the existing seismic PRA, and a detailed evaluation requires the construction of a model that combines the seismic PRA and the flooding PRA. In addition, in the phase of considering the influence of Level 2 PRA and Level 3 PRA, it is necessary to consider not only the frequency but also the influence, and the scale of the core damage frequency alone is insufficient for risk evaluation, so detailed model construction and evaluation are required.

CONCLUSION

The damage probabilities of the equipment for each number of damaged points were obtained changing the correlation coefficient from zero to one as a parameter study. As the correlation coefficient increases, the seismic motion at which multiple damage becomes significant decreases. In case of the correlation coefficient of zero, the damage probability to one point of equipment in the unit is dominant as same as the previous study. In case of the correlation coefficient of 0.5, the damage probability to one or more equipment in the unit is about twice the damage probability to two or more equipment.

Based on the earthquake damage database in Japanese NPPs, it is thought that it is sufficient to consider a correlation coefficient $r = 0.6$ or less, but further research on the correlation coefficient is necessary because the probability of multiple damage differs greatly depending on the correlation coefficient.

We also considered a method for applying the obtained damage probability to seismic-induced flooding PRA, and described a method for simply assessing the risk of earthquake-induced flooding using the evaluation results of existing earthquake PRA. Future challenges include estimating correlation coefficient by expanding actual equipment data.

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