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Outline of Seismic-Induced Flooding Probabilistic Risk Assessment for Nuclear Power Plants

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ABSTRACT

Safety of nuclear power plants (NPPs) against seismic-induced events has gained significant attention following the accident at Fukushima Daiichi nuclear power station. To assess seismic-induced flooding realistically, the number and probability of pressure boundary damage that causes flooding in an earthquake have a significant role to the nuclear safety. The damage probabilities of the pressure boundary versus the seismic intensities in a unit, that is, the plant-level fragility curves of the pressure boundary were proposed based on the earthquake damage database of Japanese NPPs. In this paper, the damage probability of components and piping systems for each number of damaged points in a unit during an earthquake is determined using the plant-level fragility curve, and an existing seismic PRA model is used to study the method of seismic-induced flooding PRA in NPPs. Since the probabilities of one and two damages in the entire plant components and piping systems are dominant here, up to two simultaneous damages are considered. This method allows a simple and rational assessment of the risk of flooding impact considering multiple damages of components and piping systems due to an earthquake.

INTRODUCTION

The earthquake and tsunami at the Fukushima Daiichi Nuclear Power Station 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 Government of Japan 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, earthquake 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 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 an seismic-induced flooding PRA, the number of points where flooding occur in a unit during an earthquake is important, and if there is only one flooding, the possibility of core damage is relatively small due to flooding countermeasures to prevent flooding affecting different the other safety divisions, but if flooding occur in several safety divisions in the unit, the possibility of core damage is larger.

In this study, the plant-level fragility curves for components and piping systems, which were developed based on earthquake damage data from Japanese NPPs, were used to calculate the damage probability of components and piping systems for each number of damaged points during an earthquake. As a result, it was confirmed that the probability of occurrence decreases as the number of damaged points in a unit increases during an earthquake, and that damage at about one point is dominant, and the damage probability decreases significantly as the number of damaged points increases from two to three. Based on these results, a general framework for a seismic-induced flooding PRA was proposed.

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 Fig. 1, to prevent flooded or submerged water from affecting safety-significant SSCs due to damage of components and piping systems, such as pipe breaks, tank failures, etc. These divide the interior of the building into small flooding protection compartments, as shown in Fig. 2, and limit the impact of flooding so that they do not affect safety-significant SSCs in different safety divisions.

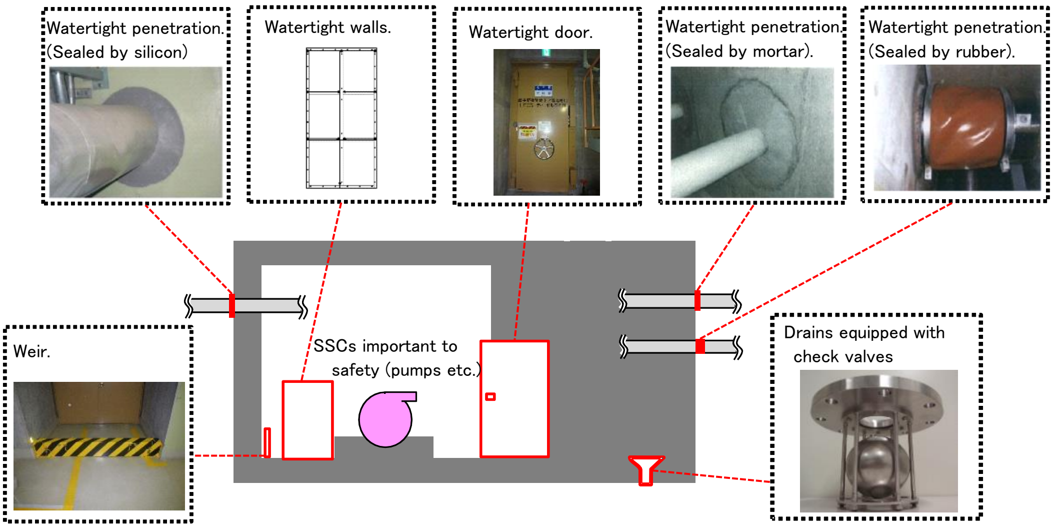

Figure 1. Preventive measures for internal-flooding in Japan

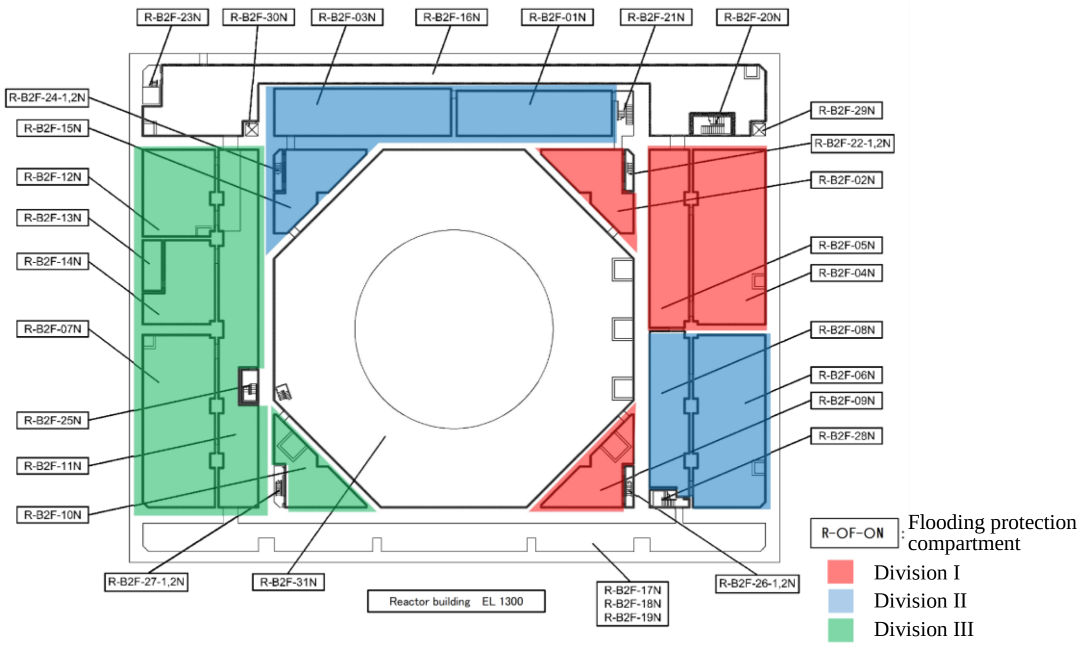

Figure 2. Flooding protection compartments and safety divisions of a reactor building floor.

EARTHQUAKE DAMAGE TO NPPs IN JAPAN

SSCs of NPPs in Japan are classified into three classes of importance (S, B and C) according to the degree of radiological impact on the public caused by the loss of safety functions that could be caused by an earthquake, and are designed to be seismically resistant according to these importance levels. In Japan, six major earthquakes have occurred in the vicinity of NPPs in the eight years from 2003 to 2011, and cases of seismic damage to components and piping systems due to these earthquakes have been investigated based on inspection records and reports (Morita et al. 2014, 2021).

As a result, no damage cases were found in Class S components and piping systems, while damage cases were identified in less critical Classes B and C. The damage cases were classified into damage levels and compiled into a database. The damage cases at the level of deterioration or loss of function for the 28 plants surveyed are listed in Table 1. Considering the total number of components and piping systems surveyed, there are few cases of deterioration or loss of function level damage in components and piping systems in NPPs, indicating that the seismic design is functioning effectively.

Table 1: Components and piping systems with deterioration or loss of functions (Morita et al. 2014).

Function		Boundary						Support					
Components/ Piping		Components			Piping			Components			Piping		
Seismic Class		S	B	C	S	B	C	S	B	C	S	B	C
Indoor (On Bedrock)	Reactor Building	0	0	0	0	0	0	0	0	0	0	0	0
	Turbine Building	0	0	0	0	1	0	0	4	0	0	0	0
	Others	0	0	0	0	0	0	0	0	0	0	0	0
Outdoor	On Bedrock	0	0	0	0	0	0	0	0	0	0	0	0
	Not on Bedrock (on the ground).	0	0	4	0	0	4	0	0	10	0	0	0
	Not on Bedrock (underground).	0	0	0	0	0	6	0	0	0	0	0	0
Total		4			11			14			0		

Focusing on the boundary function of components and piping systems that are critical in the event of flooding, 14 out of a total of 15 cases of deterioration or loss of function level damage occurred in components and piping systems installed in buildings and structures not on bedrocks. Focusing on the cases of components and piping systems installed in buildings and structures on bedrocks that could not maintain their boundary function during an earthquake, damage was identified only in one small-bore drain piping in the turbine building, and no safety-significant SSCs were installed here that would be affected by flooding. The breakage observed at small-bore drain piping connected to a moisture separator hung from the building celling, not bolt-mounted on the floor or wall. Because the separator seemed to be shaken harder than other components owning its hanging structure, the connected piping was broken more easily than normal piping owning to the larger relative displacement (Morita et al. 2021). Therefore, in the components and piping systems in the reactor buildings, control room buildings and other buildings and structures where flooding effects need to be assessed, there are no cases of damage in all 28 plants.

PLANT-LEVEL FRAGILITY CURVES FOR COMPONENTS AND PIPING SYSTEMS

Plant-level fragility curves for components and piping systems 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 components and piping systems within a certain area of a plant due to an earthquake by the seismic motion level, considering the components and piping systems installed within the area as a single unit.

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

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

There is a damage case to the former components and piping systems, while there is no damage case to the latter components and piping systems in the investigation. Safety-significant SSCs affected by flooding are not installed in turbine buildings. Therefore, for earthquake-induced flooding PRA, the plant-level fragility curve for components and piping systems in buildings excluding turbine buildings is used as a plant-level fragility curve for the boundary function of components and piping systems, and is shown in Fig. 3.

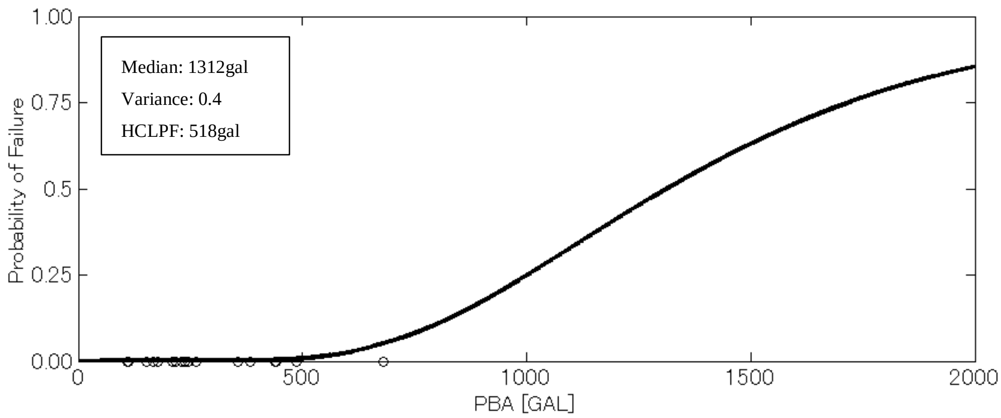

Figure 3. Plant-level fragility curves for components and piping systems in one NPP unit (excluding components and piping systems in the turbine building).

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 components and piping systems in a unit of NPPs can be obtained using the seismic hazard curve for each site and the plant-level fragility curve for components and piping systems, as follows:

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

where P(A1:A2) is the probability that an earthquake of PBA from A1 to A2 will damage components and piping systems 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 components and piping systems at one or more points in the unit in the event of an earthquake whose PBA equal to a.

The damage probability of components and piping systems for each number of damaged points occurring in a unit due to earthquakes can be obtained as follows.

- The plant is divided into m virtual compartments. The virtual compartments are divided so that the damage probabilities of the components and piping systems in the virtual compartments are equal, and this is denoted as $F_m(a)$, as shown in Fig. 4.
- Although there is a possible correlation between the damage of the components and piping systems in the virtual compartments in the unit due to an earthquake, for simplicity, it is assumed here that the damage of components and piping systems in virtual compartments due to an earthquake is an independent event.
- Probability $F_P(a)$ of one or more damages in the unit during an earthquake and the probability $F_m(a)$ of damage of the components and piping system in each virtual compartment is expressed using a binomial distribution as follows:

$$F_P(a) = 1 - \left(1 - F_m(a)\right)^m \quad (2)$$

From this, the following equation is obtained.

$$F_m(a) = 1 - \left(1 - F_P(a)\right)^{\frac{1}{m}} \quad (3)$$

When the unit is divided into m virtual compartments, the probability P_m(n, A1:A2) of n or more damage of components and piping systems due to an earthquakes from A1 to A2 in one year can be expressed using a binomial distribution as follows:

$$P_m(n, A1{:}A2) = \sum_{i=n}^{m} {}_mC_i \int_{A1}^{A2} -\frac{dH(a)}{da} F_m(a)^i \left(1 - F_m(a)\right)^{m-i} da \quad (4)$$

It has been confirmed that if the number m of virtual compartments is sufficiently large (more than 1000), the damage probability of the components and piping systems for each number of damaged points in the unit will converge (Kuramasu et al., 2014), and expressed as follows:

$$P(n, A1{:}A2) \cong P_m(n, A1{:}A2) \quad (1000 < m) \quad (5)$$

where $P(n, A1\colon A2)$ is the probability of n or more damage of components and piping systems due to an earthquake from A1 to A2 in one year.

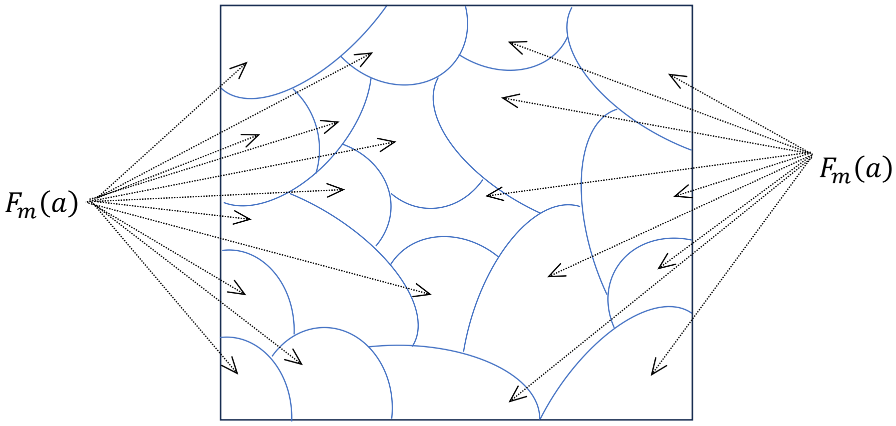

Figure 4. m virtual compartments and the probability $F_m(a)$ of damage of components and piping systems in the virtual compartments.

Damage probability for each number of damaged points

As a representative of Japanese NPPs, the seismic hazard curve of the Shimane Nuclear Power Plant is used to calculate the damage probability of components and piping systems for each number of damaged points in a unit. The seismic hazard curve of Shimane NPP (as of 25 December 2013) is shown in Fig. 5. 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 components and piping systems for each number of damaged points due to an earthquake in the unit, calculated by Eq. 4, is shown in Fig. 6, where the number $m = 1000$ is used. The damage probability of one or more-points of the components and

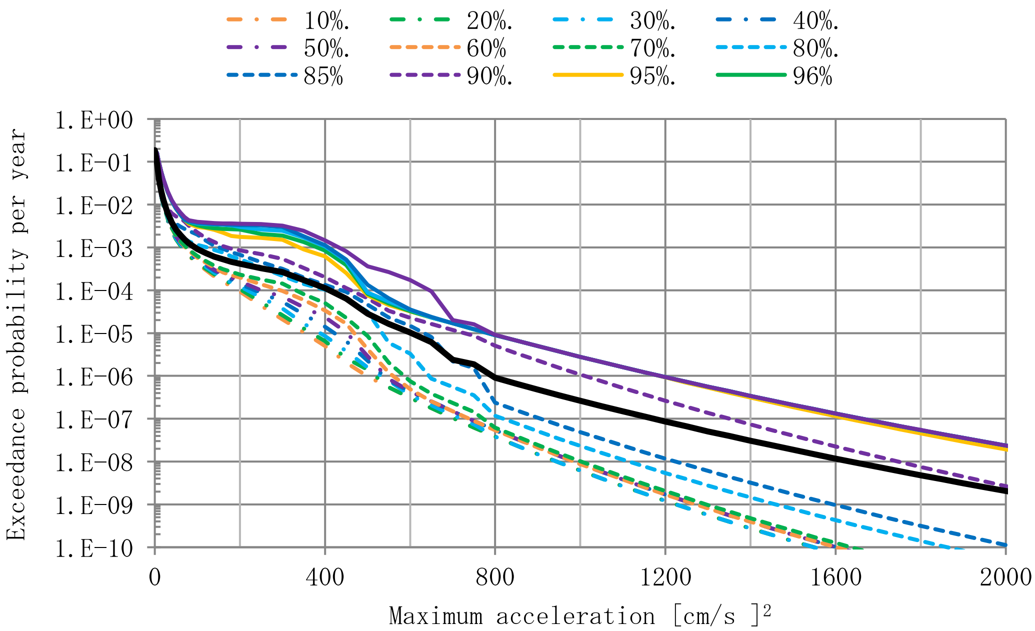

Figure 5. Seismic hazard curve for Shimane Nuclear Power Station (as of 25 December 2013).

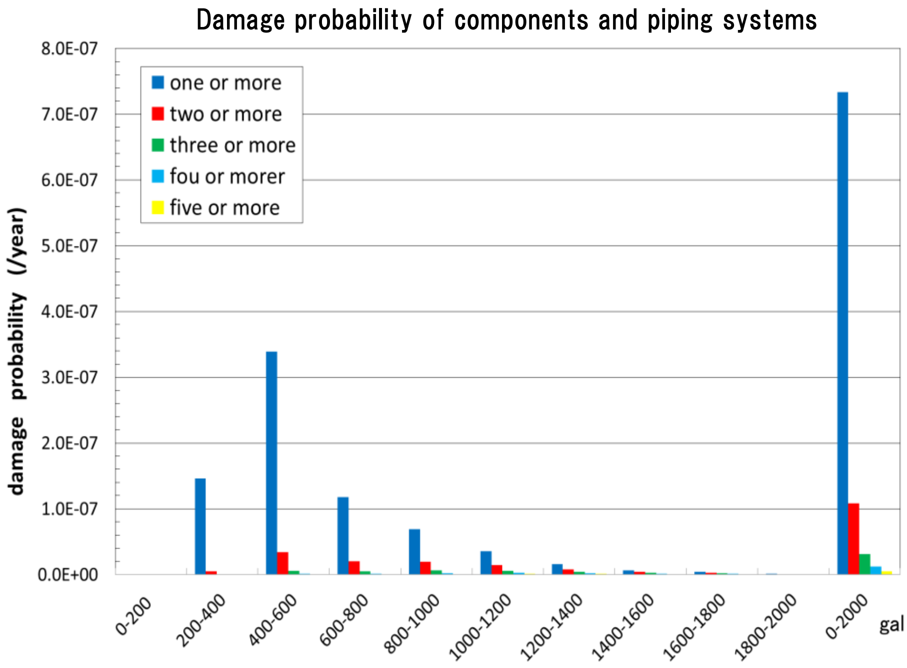

Figure 6. Damage probability to components and piping systems for each number of damaged points; Hazard curve: Shimane Nuclear Power Station.

piping system is 7.3 x 10^{-7} /year and the damage probability of two or more-points is 1.1 x 10^{-7} /year or more, and it was confirmed that the damage probability of one point is dominant in the entire components and piping system in the unit and the damage probability decreases significantly as the number of damaged points increases with two or three.

GENERAL FRAMEWORK OF SEISMIC-INDUCED FLOODING PRA

Using the damage probability of components and piping systems for each number of damaged points in a unit, the risk of flooding effects due to earthquakes at NPPs can be assessed as follows:

(1) The damage probability of components and piping system for each number of damaged points is determined from the plant-level fragility curves of the components and piping systems in the unit.
(2) Establish assessment conditions in the seismic PRA for the impact of flooding in the event of damage to components and piping systems.
(3) Add headings for components and piping system damage to the existing seismic PRA model and quantify them.

The evaluation method is basically based on the seismic PRA, but the following conditions are set to consider flooding effects due to damage to components and piping systems.

Fragility curve

For the components and piping systems considered in the seismic PRA, the fragility curves assessed in the seismic PRA are applied. For the components and piping systems that will be source of flooding, the plant-level fragility curve for the boundary function of components and piping systems, as shown in Fig. 6, is applied to calculate the damage probability of components and piping systems for each number of damaged points in the unit.

Quantification of accident sequences

A way to reflect the effects of multiple damage to components and piping systems in the seismic PRA model is to provide branches based on the number of damaged points of components and piping systems. As mentioned above, the number of damaged points is dominated by damage to one point of the components and piping system in a unit, and the damage probability to three or more points is more than one order of magnitude smaller than the damage probability to one point. Therefore, we think that useful risk information can be obtained even if we develop one point damaged sequences and conservatively treat two or more points damaged sequences as directly core damage.

For the impact of flooding from damaged points during an earthquake, it is necessary to analyse the amount and route of spillage in detail and assess the depth of flooding and the impact on the safety-significant SSCs, but it is assumed that all SSCs within the flooded divisions and the not isolated safety divisions from the flooded division due to flooding protection measures, etc., will lose their function. Although this is a conservative assessment, it is a useful method for the purpose of simply ascertaining the scale of the risk. Therefore, in quantifying the accident sequence, the following assumptions are made.

- In the case of flooding associated with one point damage of the components and piping systems, the mitigation functions of the flooded safety division concerned are lost, but the mitigation functions of the other safety divisions are not lost due to internal-flooding measures.
- Consider seismic damage or random failure for mitigation functions in the other safety divisions that do not lose function due to flooding.
- In the case of flooding associated with two or more-point damages of the components and piping systems, the loss of the mitigation functions of several safety divisions directly leads to core damage in a conservative manner.
- Watertight doors, weirs and other measures to prevent internal-flooding are sufficiently seismic resistant and maintain their function.

The above-mentioned condition set-up allows a simplified assessment of the risk of seismic-induced flooding impacts to be carried out using existing seismic PRAs. An example of a hierarchical event tree that considers damage to components and piping systems as heading in the hierarchical event tree used in the seismic PRA is shown in Figure 7.

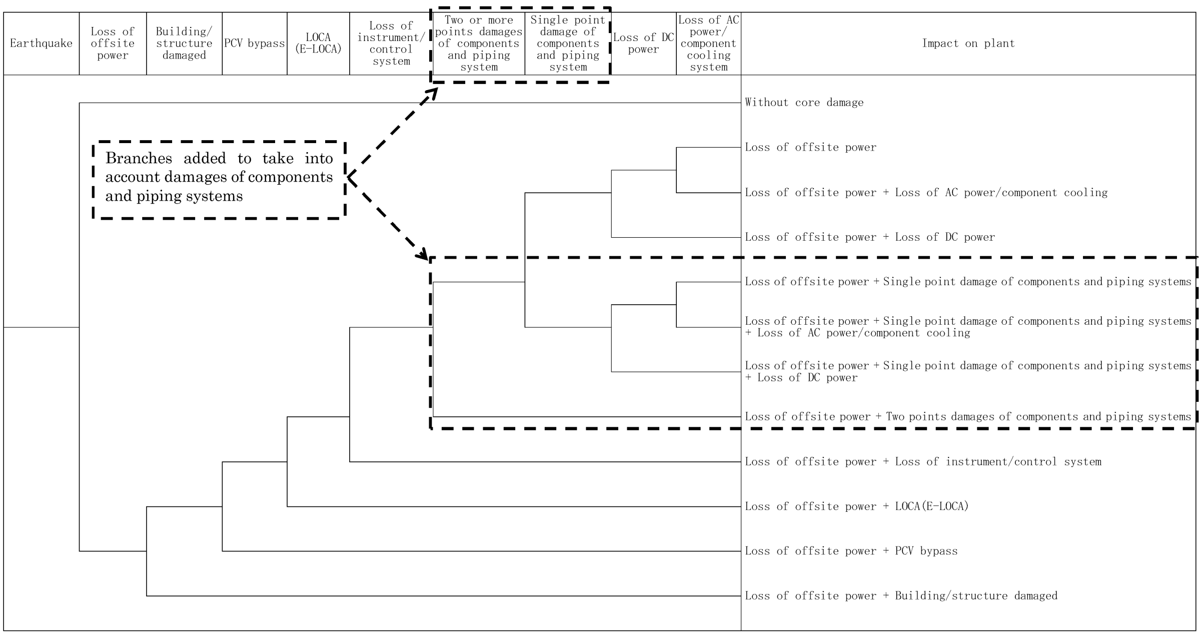

Figure 7. Example of a hierarchical event tree considering damage to components and piping systems as heading.

For the above method, more precisely, it is necessary to consider the elimination of conservatism, such as consideration of the combination of safety divisions where damage to components and piping systems occurs, but in this case, sequences of simultaneous damage to two or more points is directly treated as core damage from the perspective of the damage occurrence frequency and reflected in the hierarchical event tree of the existing seismic PRA model. This evaluation method is considered to be realistic and reasonable, as it enables a simple evaluation of the impact of flooding on multiple components and piping systems using the existing seismic PRA model.

CONCLUSION

In this study, the damage probability of components and piping systems for each number of damaged points in a unit of NPPs was obtained from plant-level fragility curves developed based on earthquake damage cases in Japanese NPPs. It was confirmed that the probability of a single damage point was dominant for the entire components and piping system in the unit, and that the damage probability decreased significantly as the number of damage points increased to two or three. Using these results, an example of seismic-induced flooding PRA is presented using an existing seismic PRA model. According to this method, the risk of flooding impact can be simply and reasonably assessed considering multiple failures of components and piping systems due to earthquakes. For the sake of simplicity, it was assumed in this study that there is no correlation between damages of the components and piping systems in the unit during earthquakes, and it will be necessary to consider the correlation of responses in the future.

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