OECD/NEA Committee on the Safety of Nuclear Installations (CSNI)
International Workshop on PSA of Natural External Hazards including Earthquakes
Prague, Czech Republic, June 17-19th 2013

SEISMIC PRA OF A BWR PLANT

Masahide Nishio
Japan Nuclear Energy Safety Organization (JNES) Tokyo, Japan
Haruo Fujimoto
Japan Nuclear Energy Safety Organization (JNES) Tokyo, Japan

ABSTRACT

Since the occurrence of nuclear power plant accidents in the Fukushima Daichi nuclear power station, the regulatory framework on severe accident (SA) has been discussed in Japan. The basic concept is to typify and identify the accident sequences leading to core/primary containment vessel (PCV) damage and to implement SA measures covering internal and external events extensively. As Japan is an earthquake-prone country and earthquakes and tsunami are important natural external events for nuclear safety of nuclear power plants, JNES performed the seismic probabilistic risk assessment (PRA) on a typical nuclear power plant and evaluated the dominant accident sequences leading to core/PCV damage to discuss dominant scenarios of severe accident (SA).

The analytical models and the results of level-1 seismic PRA on a 1,100MWe BWR-5 plant are shown here.

NOMENCLATURE

AC	Alternate Current
CDF	Core Damage Frequency
DC	Direct Current
DG	Diesel Generator
Gal	1m/s^2
HPCS	High Pressure Core Spray System
ISLOCA	Interface System LOCA
LOSP	Loss of Offsite Power
LPCI	Low Pressure Coolant Injection System
LPCS	Low Pressure Core Spray System

PCS	Power Conversion System
PCV	Primary Containment Vessel
RCIC	Reactor Core Isolation Cooling System
RCW	Reactor Component Cooling Water System
RHR	Residual Heat Removal System
RPV	Reactor Pressure Vessel
SRV	Safety Relief Valve

1. INTRODUCTION

Level-1 seismic PRA was performed for a typical BWR5 plant. The analytical flow is shown in Figure 1. The seismic acceleration range for analysis is 300 -2000gal on the bedrock surface. The lowest acceleration is near the one where reactor scram is initiated to occur in response to the signal of high ground motion. The analysis code used is the one developed mainly by JNES.

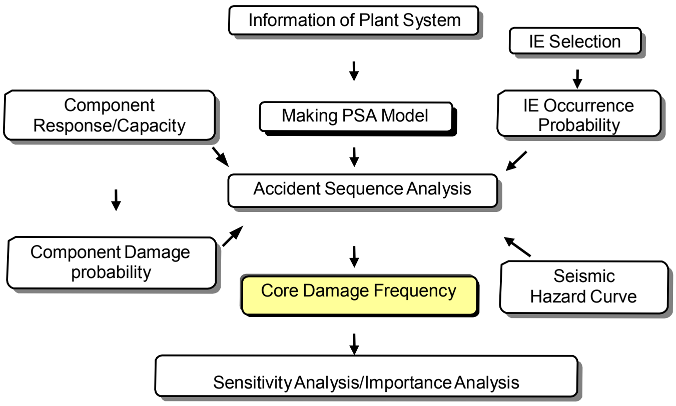

Figure 1. Flow of Seismic PRA

2. ANALYTICAL CONDITION

2.1 SYSTEM CONFIGURATION

The system configuration of a typical BWR5 plant is shown in Figure 2. The typical BWR5 plant system is in principle composed of two safety divisions and has two high pressure injection systems (HPCS, RCIC), two low pressure injection systems (LPCS and LPCI) and two residual heat removal systems (RHR). RCIC is the steam-driven system with DC control and all other systems are motor-driven systems. When loss of offsite power occurs, the power of HPCS is supplied by an exclusive HPCS-DG, and the power of LPCS/LPCI (RHR) is supplied by emergency DG-A or B.

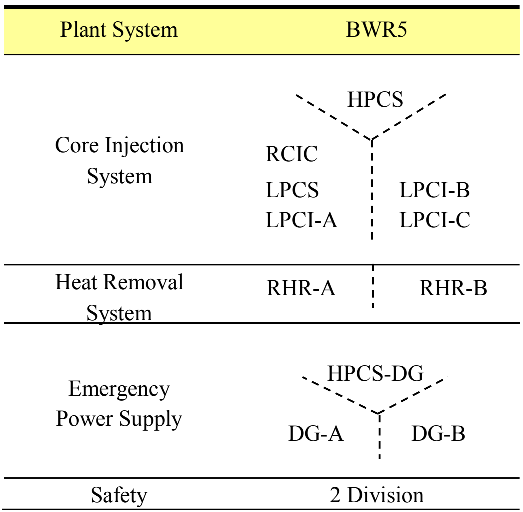

Figure 2. BWR5 Plant System

2.2 SEISMIC HAZARD CURVE

The seismic hazard curve used for analysis is shown in Figure 3. The hazard curve is the annual exceedance probability (1/y). Exceedance Frequency is obtained by ground motion propagation analysis based on historical earthquake data and active fault data.

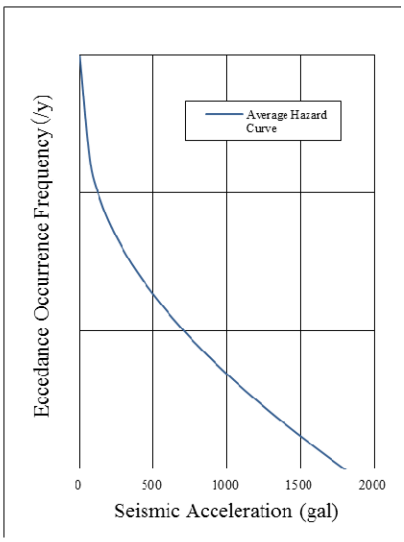

Figure 3. Seismic Hazard Curve

2.3 ANALYSIS PARAMETER

Component seismic responses are calculated from the floor response analysis of the buildings. Dozens of component capacity are evaluated based on equipment shaking test or structure analysis.

Component seismic responses and component capacities are composed of medium values with standard deviations βr of randomness and standard deviations βu of uncertainty of knowledge. Examples of fragility curve calculated by using component seismic responses and capacities are shown in Figure 4.

Component random failure probability and human error probability are set to be the same as internal event PRA though human error probability would be higher than in internal event PRA. Recovery of damaged components with loss of function is not considered in the analysis conservatively because it would be difficult to make repairs under earthquake conditions.

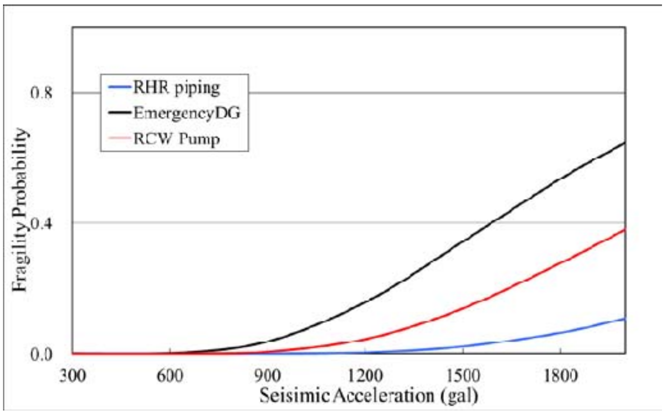

Figure 4. Component Fragility Curve

2.4 INITIATING EVENT

Initiating events for analysis were selected based on possible events under earthquake conditions from initiating events used in internal event PRA. Furthermore, events unique to earthquake were selected which are damages of building or structure, and excessive LOCA with simultaneous damages of multiple piping in PCV. Initiating events selected for seismic PRA are shown below.

- Building damage
- PCV damage
- RPV damage
- Excessive LOCA
- Interface system LOCA
- Large LOCA
- Medium LOCA
- Small LOCA
- Loss of offsite power
- Transient

The occurrence probabilities of initiating events are calculated using the hierarchy tree model because some initiating events occur simultaneously. The hierarchy tree is the method where initiating events are listed in the order of the extent of severity which influences core damage. The occurrence probability of each initiating event is calculated successively using the hierarchy tree model on the condition that any initiating event is supposed to occur surely in earthquake. In this method, initiating events which occur simultaneously are included in more severe initiating event in the upper rank. The occurrence probabilities of initiating events are calculated by multiplying unoccurrence probability of more severe initiating events in the upper rank by the independent occurrence probability of its corresponding initiating event.

The assumed ranking of initiating events for analysis of a BWR plant is shown in Figure 5. The severity order is assumed considering available mitigation systems in earthquake.

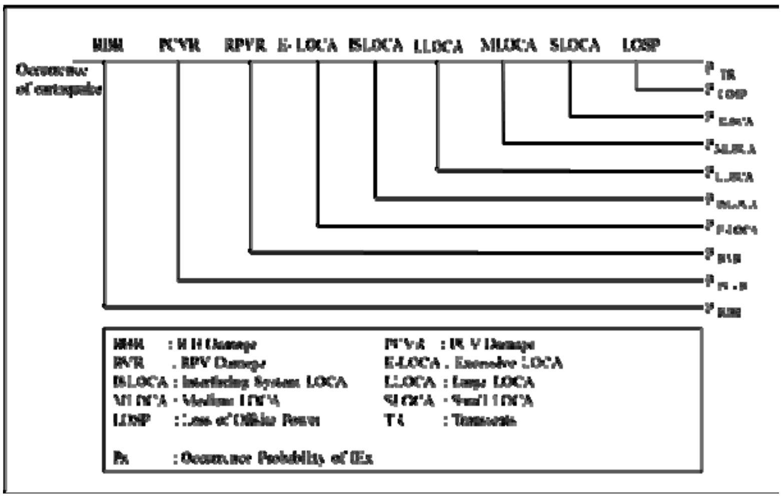

Figure 5. Hierarchy tree model

2.5 ANALYSIS MODEL

The main analysis conditions assumed for accident sequence analysis are as follows.

- Success criteria for the seismic PRA are set up referring to internal event PRA. Low seismic class mitigation systems such as non-safety systems and accident management systems are not considered to be functional in earthquake.
- Damages of building or structure and excessive LOCA which are unique to earthquake lead directly to core damage as they are not mitigated by plant existing systems. These assumptions are considered to have some conservativeness and need to be carefully studied in the future.
- Static components such as piping, piping support, tank are included in the analysis models though they have low random failure probabilities and are not considered in internal event PRA models .

- In case of heat exchangers having boundaries with other systems, there is dependence between systems because the damage of heat exchangers could lead to influence the function of other systems. This dependence is included in the analysis model.
- As the occurrence probability of loss of offsite power (LOSP) is high in earthquake, LOCA and LOSP are considered to occur simultaneously. Scenarios of LOSP are developed in LOCA event trees.
- Recovery of offsite power or emergency DG is not considered because it is accompanied by difficult work in earthquake which was shown in Fukushima Daiichi NPP severe accidents in 2011.
- Human error probability of operator actions is assumed to be set to the same value as in internal event PRA though it may be higher under earthquake circumstances.
- Multiple components of same type could be damaged simultaneously when they receive the same seismic waves. Correlation between simultaneously damaged components is influenced by their natural frequencies and installation locations. As the method of evaluating the correlation, the power of single component fragility probability is used for simultaneous damage probability of multiple components. The correlation is applied to components in the redundant system.

3. ANALYSIS RESULTS

3.1 IE OCCURRENCE PROBABILITY

Initiating event occurrence probabilities after process of the hierarchy tree model are shown in Figure 6. Transient events mostly induced by non-safety component damages and Loss of offsite power are dominant initiating events in the low seismic acceleration range. On the other hand, LOCA becomes the dominant initiating event in the high seismic acceleration range.

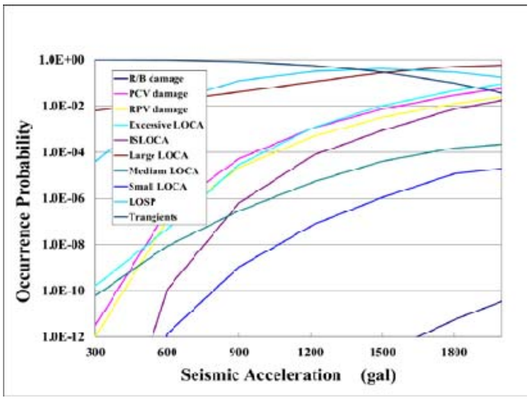

Figure 6. Initiating event occurrence probability
(after process of hierarchy tree model)

3.2 CDF PER SEISMIC ACCELERATION

Conditional core damage probability (CCDP) is the one assuming that an earthquake occurs with probability of 1.0 at individual seismic acceleration. Core damage frequency (CDF) per seismic acceleration which is obtained by multiplying CCDP by earthquake occurrence frequency per seismic acceleration is shown as function of seismic acceleration in Figure 7. Contribution of large LOCA and Loss of offsite power to CDF per seismic acceleration is increasing gradually beyond around 800gal. CDF per seismic acceleration has a mountain shape with a peak of about 1500gal. The mountain shape of CDF per seismic acceleration is made up by multiplying increscent conditional CCDP by decrescent earthquake occurrence frequency per seismic acceleration.

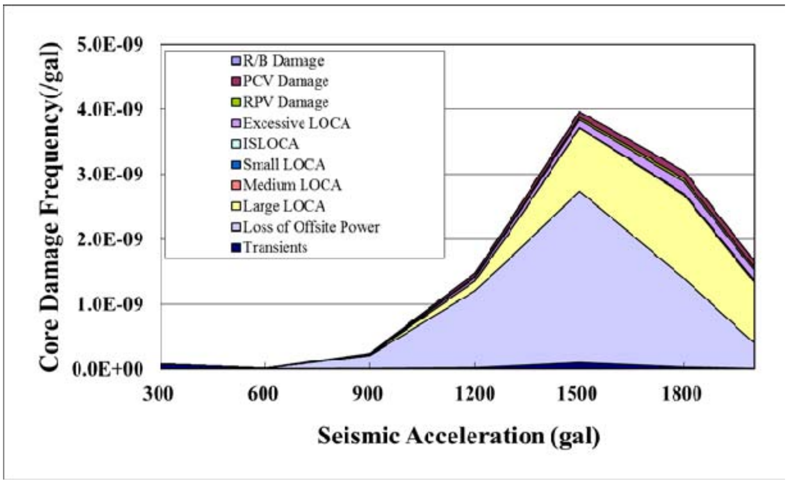

Figure 7. CDF per seismic acceleration

3.3 CORE DAMAGE FREQUENCY

The total core damage frequency is obtained by integrating core damage frequency per seismic acceleration in the previous section over all seismic acceleration ranges.

The contribution of initiating events to the total core damage frequency is shown in the pie chart of Figure 8. The initiating event with largest contribution is LOSP followed by large LOCA. Large LOCA includes simultaneous occurrence of LOSP. The damages of building or structure and the excessive LOCA leading to direct core damage account for several percentages of CDF respectively.

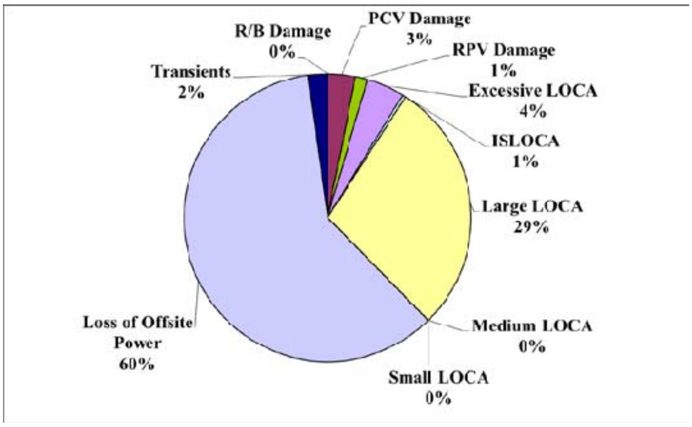

Figure 8. IE contribution to CDF

3.4 DOMINANT ACCIDENT SEQUENCES

Dominant accident sequences are shown in Table 1. The top of dominant sequences is simultaneous occurrence of large LOCA and loss of all AC powers (station blackout). The second and third highest accident sequences are overlapping of failure of steam driven reactor core cooling system RCIC after station blackout. The fourth and fifth highest accident sequences are failures of residual heat removal system RHR after success of core cooling by HPCS after failure of emergency DGs. These accident sequences are all through success paths of reactor shutdown. More than 70% of core damage frequency is occupied by top five accident sequences.

Table 1. Dominant accident sequences

Rank	IE	Scenario	%
1	Large LOCA	LOSP, Loss of DG-A/B/HPCS	21
2	LOSP	Loss of DG-A/B/HPCS, Failure of 1SRV re-closure, Failure of RCIC	16
3	LOSP	Loss of DG-A/B/HPCS, Failure of RCIC	16
4	LOSP	Loss of DG-A/B, Failure of 1SRV re-closure, Success of core cooling by HPCS, Failure of residual heat removal by RHR	15
5	LOSP	Loss of DG-A/B, Success of core cooling by HPCS, Failure of residual heat removal by RHR	5

3.5 IMPORTANCE ANALYSIS

Importance analysis was performed and Fussel-Vesely importance of each component was obtained. Dominant components with high Fussel-Vesely importance are shown in Figure 9. Offsite