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EFFECT OF THE SEISMIC CAPACITY OF EQUIPMENT ON THE CORE DAMAGE FREQUENCY IN NUCLEAR POWER PLANTS

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ABSTRACT

The effects of the seismic capacity of equipment on the core damage frequency (CDF) in nuclear power plants are investigated through a case study for the Younggwang Nuclear Units 5&6, which are operating pressurized water reactors in Korea. A probabilistic safety assessment for a seismic event (seismic PSA) is performed for the plant and then the equipment important for the CDF are selected. Then the seismic PSA is performed using different seismic capacities of the selected equipment for the investigation of the effect of their seismic capacity on the CDF. The results of the case study show that an increase of the seismic capacity of the equipment reduces the CDF significantly. This indicates that the seismic safety of the operating nuclear power plants can be significantly improved by increasing the equipment seismic capacity. When the Diesel Generator or Condensate Storage Tank has an increased seismic capacity, the CDF will decrease significantly, while in the case of the Battery Rack the CDF does not decrease significantly. When all of the selected equipment items have a 25%, 50%, and 75% increased seismic capacity, the core damage frequency will decrease by 45.8%, 64.5%, and 67%, respectively. The effective HCLPF values for the Diesel Generator, Offsite Power, Condensate Storage Tank, and Battery Rack are determined as 0.84g, 0.35g, 0.63g, and 0.63g, respectively.

Keywords: nuclear equipment, seismic capacity, core damage frequency, fragility, effective HCLPF

1. INTRODUCTION

A nuclear power plant is designed to ensure the survival of all the structures and emergency safety systems during a design basis earthquake. Therefore, a seismic analysis for the nuclear power plant must consider all the interrelated factors that determine the release of radioactive material to the public. During an earthquake, since all the facilities of the plant are excited simultaneously, there may be a significant correlation between the component failures. Accordingly, the redundancy of the safety systems in a nuclear power plant is very important. Therefore, all of the safety-related structures, systems and components in a nuclear power plant should be designed to have a sufficient seismic capacity. However, even though the facilities in the plant are designed to be safe during a design basis earthquake, they may be damaged or failed by strong ground motions greater than the design basis earthquake as well as a particular earthquake of which the frequency contents are different from those in the seismic design. Due to these uncertainties in the earthquake ground motions, it is necessary to improve the seismic capacities of the safety facilities enough to ensure the seismic safety of a plant during strong earthquakes.

This study evaluates the seismic safety of a nuclear power plant in the case that the seismic capacities of the equipment are increased. The relations between the seismic capacity of the equipment and the core damage frequency (CDF) in a nuclear power plant are investigated through a case study for the Yonggwang Nuclear Units 5&6, which are operating pressurized water reactors in Korea. The equipment important for the CDF are selected from the results of a probabilistic safety assessment for a seismic event (seismic PSA) for the plant, then the seismic PSA is performed using different seismic capacities of the selected equipment. Finally, the effect of the seismic capacity of the equipment on the CDF is evaluated and the effective seismic capacity of the equipment for the plant is suggested.

2. SEISMIC RISK ANALYSIS PROCEDURES

The seismic risk of core damage for a nuclear power plant can be calculated by the following procedures (Bohn, 1990);

- Determine the local earthquake hazard, for example, hazard curve, site spectra or time histories for each plant site
- Identify accident scenarios induced by an earthquake, for example, initiating events and event trees for the plant which lead to a radioactive release
- Determine the failure modes for the safety and support systems
- Determine the fragilities for the important structures and components
- Determine the responses of all the structures and components for each earthquake level
- Compute the mean values and probability distributions of the accident sequence and core damage frequencies
- Perform sensitivity analysis to identify the dominant contributors to a seismic risk and the relative contributions of the hazard curve, fragility and response uncertainties for the overall uncertainty in the core damage frequency

3. SEISMIC RISK ANALYSIS

This chapter summarizes the results of the seismic PSA for the Yonggwang Nuclear Units 5&6 (KEPCO, 2001).

3.1 Seismic Hazard Curve

The seismic hazard at a given plant site can be characterized by a hazard curve which gives the probability of the exceedance of different peak ground accelerations. The hazard curve is derived from a combination of recorded earthquake data, estimated earthquake magnitudes of known events for which no data is available, local geological investigations, and expert judgments from seismologists and geologists familiar with the region. The region around the site is divided into zones, and each zone has an assumed uniform mean rate of earthquake occurrence. Then, for the region under consideration, an attenuation law is determined which relates the ground

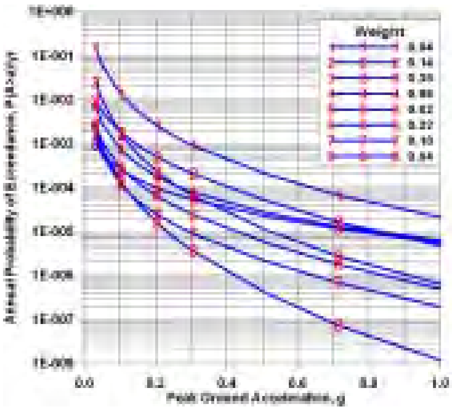

Fig. 1 Seismic hazard curves

acceleration at the site to the ground acceleration at the earthquake source, as a function of the earthquake magnitude. The uncertainty in the attenuation law is specified by the standard deviation of the data regarding the mean attenuation curve. Finally, the hazard curve is computed by a statistical combining of the zonation, mean occurrence rate, magnitude distribution for each zone, and the attenuation law.

At the Yonggwang nuclear plant site, the final eight seismic hazard curves shown in Fig. 1 are derived. These seismic hazard curves are obtained by considering the earthquake activity parameters, seismogenic zone, and the weights for each attenuation law suggested by the experts.

3.2 Initiating Events

In the event of a strong earthquake, the safety system in a nuclear power plant brings the plant to a safe shutdown condition. Since the shutdown is caused through several paths of the system, the possible paths that a plant would follow are identified. These paths involve a seismic induced initiating event that causes a shutdown, and a success or failure designation for plant systems affecting the course of the events. Typically, the minimum set of the initiating events includes both loss of coolant accidents (LOCA) and transient events. In addition, the site-specific failure events, which act as initiating events, may be added to the minimum set.

The initiating events considered in the external event analysis of the Yonggwang Nuclear Units 5&6 are as follows (KEPCO, 2001):

- Loss of essential power (LEP)
- Loss of secondary heat removal (LHR)
- Loss of component cooling water/essential chilled water (LOCCW)
- Small loss of coolant accidents (SLOCA)
- Loss of offsite power (LOOP)
- Seismic induced general transient (GTRN)

In computing the frequency of the initiating events, a hierarchy between them must be established. The order of this hierarchy is defined such that, if one initiating event occurs, the occurrence of other initiating events further down the hierarchy is no significance in terms of the plant response. The seismic event trees should be taken directly from those developed for the internal events analysis, with modifications to include any seismically-induced failures.

The occurrence frequencies for the initiating events are calculated as

$$
\begin{aligned}
&P[IE(LEP)] = LEP \\
&P[IE(LHR)] = \overline{LEP} * LHR \\
&P[IE(LOCCW)] = \overline{LEP} * \overline{LHR} * LOCCW \\
&P[IE(SLOCA)] = \overline{LEP} * \overline{LHR} * \overline{LOCCW} * SLOCA \\
&P[IE(LOOP)] = \overline{LEP} * \overline{LHR} * \overline{LOCCW} * \overline{SLOCA} * LOOP \\
&P[IE(GTRN)] = 1 - P[IE(LEP)] - P[IE(LHR)] - P[IE(LOCCW)] - P[IE(SLOCA)] - P[IE(LOOP)]
\end{aligned}
$$

3.3 Fragility Analysis

To determine the failure modes for the safety systems, fault tree methodology, which can identify all the groups of components in a system that would result in a failure of the plant safety system, is used. The fault trees developed for the internal events analysis may be used directly as the seismic fault trees, with certain modifications. Since the seismic fault trees include failures of basic events due to seismic ground motions, random failures, human error, and test and maintenance outages, the seismic failure modes such as local structural failures and the failure of critical passive components must be added to the internal fault trees. Failure of the plant safety systems due to building structural failures is also considered as a seismic failure mode.

Component seismic fragilities are obtained from a data base of generic fragility functions for seismically-induced failures or developed on a plant-specific basis for components not fitting the generic component descriptions. Fragility functions for the generic categories are developed based on a combination of experimental data, design analysis reports, and an extensive expert opinion survey. A generic fragility for any particular component can be estimated by selecting a suite of site-specific fragilities for that component.

In the case study, eighteen items of equipment, which have HCLPF values lower than 0.65g, are finally selected from the results of the fragility analysis for the failure mode and effect analysis. They are listed in Table 1. HCLPF (High Confidence and Low Probability of Failure) that has a 95% confidence of not exceeding a 5% probability of producing failure indicates the seismic resistance of the equipment in terms of the gravitational acceleration and can be calculated by Eq. (1).

$$HCLPF(g) = A_m(g) \times \exp[-1.65(\beta_R + \beta_U)] \quad (1)$$

where A_m is the median seismic capacity, β_R and β_U are the lognormal standard deviation for the randomness and uncertainty, respectively.

Table 1 Equipment selected through the fragility analysis

Equipment	A_m	β_R	β_U	HCLPF (g)	Failure mode
Offsite Power	0.30	0.22	0.20	0.15	Functional failure
Diesel Generator	1.13	0.36	0.30	0.38	Concrete Coning
ECW Compression Tank	1.00	0.35	0.20	0.40	Anchorage
Battery Charger	1.03	0.28	0.28	0.41	Functional failure
	1.54	0.33	0.33	0.52	Structural failure
Condensate Storage Tank	0.91	0.21	0.27	0.41	Sliding
ECW Chiller	1.08	0.28	0.27	0.44	Structural failure
Regulating Transformer	1.30	0.33	0.30	0.46	Functional failure
ESW Pump	1.20	0.29	0.28	0.47	Anchorage
CCW Surge Tank	2.00	0.41	0.47	0.47	Concrete Coning
4.16kV Switchgear	1.33	0.33	0.29	0.48	Functional failure
Inverter	1.37	0.33	0.30	0.49	Functional failure
Battery Rack	1.46	0.33	0.31	0.51	Structural failure
480V Load Center	1.50	0.32	0.29	0.54	Functional failure
Switch	2.33	0.41	0.45	0.55	Functional failure
Instrumentation Tube	1.50	0.30	0.30	0.56	Pipe Break
125V DC Control Center	1.58	0.33	0.29	0.57	Structural failure
HVAC Ducting and Supports	2.06	0.32	0.41	0.62	Functional failure
ECW Pump	1.85	0.36	0.27	0.65	H.D. Bolt

3.4 Core Damage Frequency

The frequency density of the core damage is calculated by multiplying the conditional probability of the core damage and seismic hazard. Then the total core damage frequency can be calculated by integrating the frequency density of the core damage as in Eq. (2).

$$F_{CD} = \int P_{CD}(PGA) F_{EQ}(PGA) d(PGA) \quad (2)$$

where $P_{CD}(PGA)$ is the cumulative failure probability of the core damage as a function of the peak ground acceleration (PGA), and $F_{EQ}(PGA)$ is the hazard curve.

Total core damage frequency for Younggwang Units 5&6 is calculated as 6.96E-06 as shown in Table 2. The loss of essential power is an important initiating event in calculating the total core damage frequency. The core damage frequency due to the loss of essential power occupies more than a half of the total value.

The loss of essential power, loss of secondary heat removal, and small LOCA directly induce core damage, whereas the loss of component cooling water/essential chilled water, loss of offsite power, and general transient are coupled to the secondary event trees.

Table 2 Occurrence frequency and core damage frequency for the initiating events

Initiating event	Occurrence frequency	CDF
Loss of essential power	3.68E-06	3.68E-06
Loss of secondary heat removal	1.16E-06	1.16E-06
Loss of component cooling water/ essential chilled water	2.48E-06	4.25E-08
Small LOCA	3.82E-08	3.82E-08
Loss of offsite power	1.12E-04	1.20E-06
General transient	2.79E-03	8.73E-07
Total		6.96E-06

4. EFFECT OF THE SEISMIC CAPACITY OF EQUIPMENT ON CDF

4.1 Contribution of Equipment for Core Damage

Figure 2 shows the contribution of an equipment failure for core damage in Younggwang Units 5&6. It is found that the failure of the Diesel Generator contributes about 30% to the core damage for the plant. Based on the contribution shown in Fig.2, there are four high contribution equipment items - Diesel Generator (29.8%), Offsite Power (18.3%), Condensate Storage Tank (17.7%), and Battery Rack (9.3%) – which are selected for a detailed investigation.

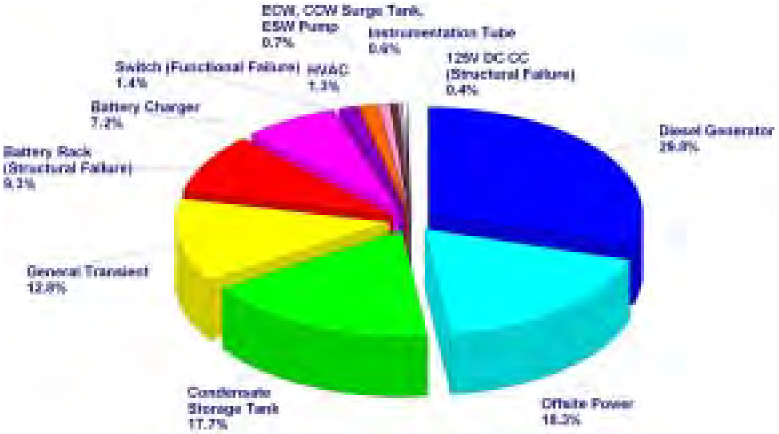

Fig. 2 Contribution of the equipment items for core damage

4.2 Effect of Seismic Capacity on CDF

To investigate the effect of the seismic capacity of the equipment on the core damage frequency, the seismic PSA is performed using different seismic capacities of the four selected equipment items.

When the seismic capacities of the equipment items increase, the plant fragility curve will vary significantly according to their contribution to the initiating events. For instance, in the event of the seismic-induced loss of essential power as shown in Fig. 3, the increase of the seismic capacity of the Diesel Generator can improve the seismic resistance of the plant greatly, while the increase of the seismic capacity of the Offsite Power does not influence the seismic resistance of the plant. In the case of increasing the seismic capacity of all the selected equipment items, the seismic resistance of the plant will be improved significantly.

Figure 4 shows the relation between the cumulative mean frequency of the failure and the peak ground acceleration for the selected equipment items with different increased ratios of 25%, 50%, and 75%. The core damage frequencies and their ratios to the original value 6.96E-06 shown in Table 2 are summarized in Table 3. It is found from Fig. 4 and Table 3 that the failure of the Diesel Generator influences the core damage frequency significantly. In other words, increasing the seismic capacity of the Diesel Generator can improve the seismic safety of the plant remarkably. As shown in Table 3, when the Diesel Generator has a 25% and 50% increased seismic capacity, the core damage frequency will decrease by 16.2% and 22.3% respectively. This indicates that

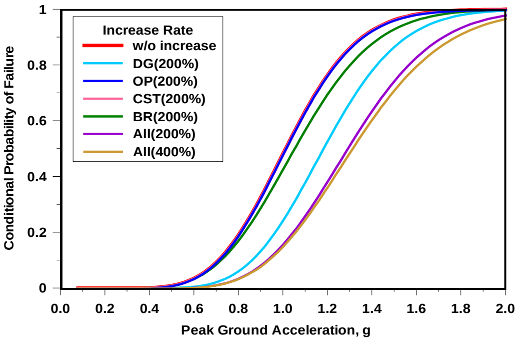

Fig. 3 Plant fragility curves with an increasing seismic capacity of the equipment items for the LEP

an increase of more than 25% in the seismic capacity of the Diesel Generator can improve the seismic safety of the plant by more than 16%. In additions, when the Condensate Storage Tank has an increased seismic capacity, the core damage frequency will decrease significantly. The effect of the seismic capacity of the Battery Rack on the core damage frequency is not significant. When all of the selected equipment items have a 25%, 50%, and 75% increased seismic capacity, the core damage frequency will decrease by 45.8%, 64.5%, and 67%, respectively.

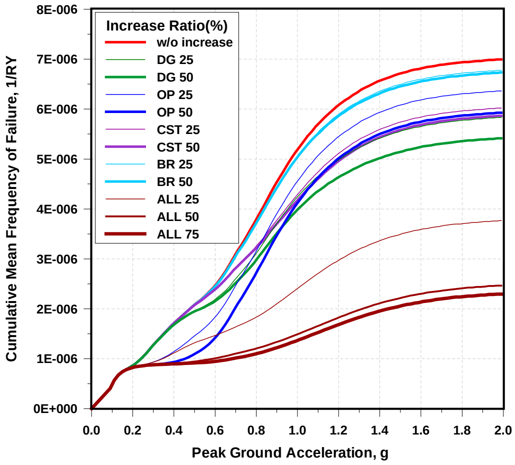

Fig. 4 CDF with increase of seismic capacity

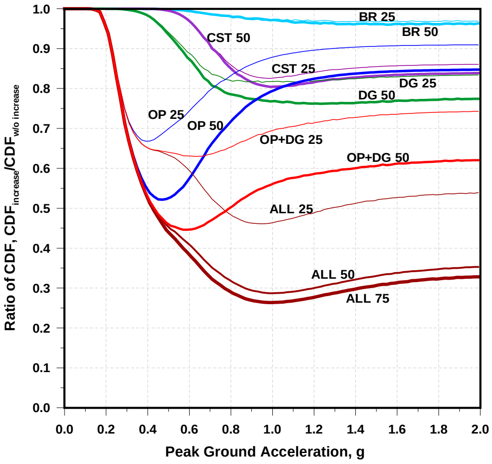

Fig. 5 CDF ratios with increase of seismic capacity

Table 3 Decrease of the CDF with an increase of the equipment seismic capacity

Equipment	Increase ratio of seismic capacity (%)	CDF	CDF decrease ratio (%)
Diesel Generator	25	5.83E-06	16.2
	50	5.41E-06	22.3
Offsite Power	25	6.36E-06	8.6
	50	5.93E-06	14.8
Condensate Storage Tank	25	6.02E-06	13.5
	50	5.86E-06	15.8
Battery Rack	25	6.78E-06	2.6
	50	6.74E-06	3.2
All	25	3.77E-06	45.8
	50	2.47E-06	64.5
	75	2.30E-06	67.0

Figure 5 plots the ratios of the core damage frequency for the equipment with an increased seismic capacity to that with the original capacity according to the peak ground acceleration. It is found that the ratios of the core damage frequency are significantly influenced by the value of the peak ground acceleration, up to 1.0g. The effect of the seismic capacity of the equipment on the core damage frequency is remarkable in the PGA range of 0.3g to 0.5g. If the seismic capacities of all the selected equipment items are improved, the core damage frequencies may be decreased by about 5% and 30% at 0.2g and 0.3g, respectively. At 0.4g, increasing the seismic capacity of the Offsite Power will be more effective, and, under 0.6g, increasing both of the seismic capacities of the Offsite Power and the Diesel Generator will be more effective. In the case of the Offsite Power, at 0.4g, an increase of its seismic capacity of 25% and 50% leads to a reduction of 33% and 45% in the core damage frequency, respectively.

Figure 6 shows the relations between the HCLPF of the equipment and the core damage frequency according to the median value of the seismic capacity, and Table 4 summarizes the core damage frequency for the different HCLPF values of the selected equipment. From Fig. 6 and Table 4, the effective HCLPF values for the Diesel Generator, Offsite Power, Condensate Storage Tank, and Battery Rack are determined as 0.84g, 0.35g, 0.63g, and 0.63g, respectively. For the larger HCLPF value than the effective value, even though the seismic capacity increases, the core damage frequency does not decrease any more. In the case that all the four selected equipment items have an increased seismic capacity, the core damage frequency decreases to 2.30E-06 from 6.96E-06.

5. CONCLUSIONS

This study evaluates the effects of the seismic capacity of nuclear equipment on the core damage frequency of a nuclear power plant through a case study. The following are drawn from the results of a case study for the Yonggwang Nuclear Units 5&6:

- Seismic capacities of the Diesel Generator, Offsite Power, Condensate Storage Tank, and Battery Rack contribute to the core damage frequency of a nuclear power plant remarkably.
- When the Diesel Generator or Condensate Storage Tank has an increased seismic capacity, the CDF will be decreased significantly, while in the case of the Battery Rack the CDF does not decrease significantly.
- Increasing the seismic capacities of the Diesel Generator by more than 25% can improve the seismic safety of the plant by more than 16%. In the case of increasing the seismic capacities of the equipment which exert a high contribution to core damage, the core damage frequency may be decreased by more than 50%.
- In the case that all the four selected equipment items have an increased seismic capacity, the core damage frequency decreases to 2.30E-06 from 6.96E-06.
- The effective HCLPF values for the Diesel Generator, Offsite Power, Condensate Storage Tank, and Battery Rack are determined as 0.84g, 0.35g, 0.63g, and 0.63g, respectively.
- Increase of the seismic capacity of the equipment will improve the seismic safety of a nuclear power plant significantly.

ACKNOWLEDGEMENT

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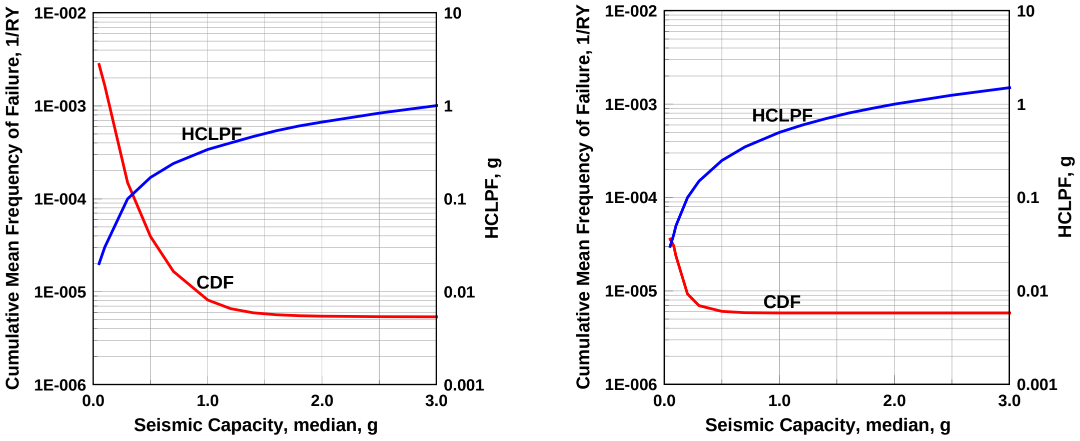
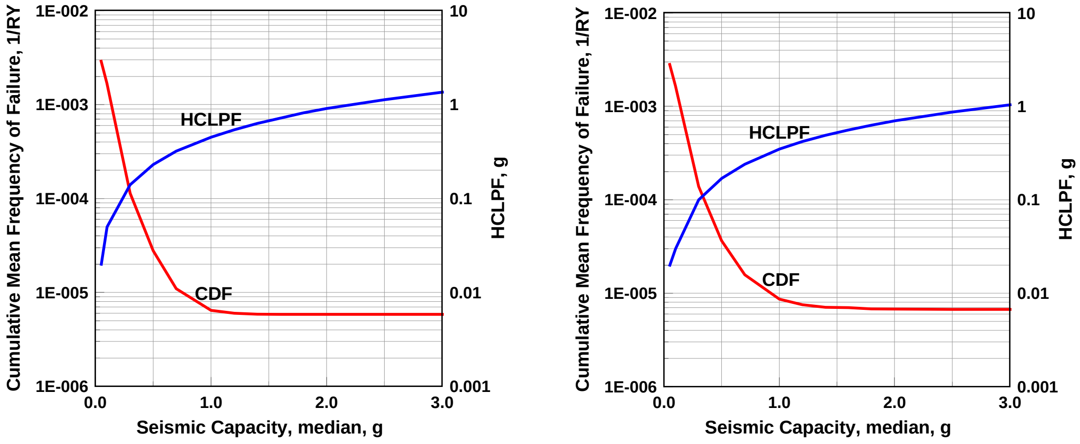


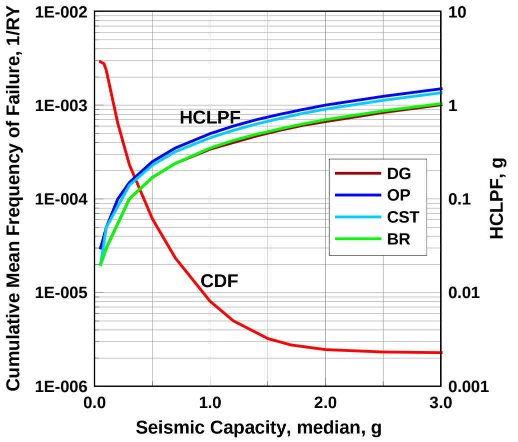
(a) Diesel Generator

(b) Offsite Power



(c) Condensate Storage Tank

(d) Battery Rack



(e) All

Fig. 6 Relations between the HCLPF of the equipment items and the core damage frequency

Table 4 Variation of the core damage frequency for different HCLPF of the equipment items

Seismic capacity (median)	Diesel Generator		Offsite Power		Condensate Storage Tank		Battery Rack		All
	HCLPF	CDF	HCLPF	CDF	HCLPF	CDF	HCLPF	CDF	CDF
0.05	0.02	2.79E-03	0.03	3.58E-05	0.02	2.89E-03	0.02	2.82E-03	2.91E-03
0.1	0.03	1.67E-03	0.05	2.38E-05	0.05	1.68E-03	0.03	1.66E-03	2.39E-03
0.3	0.10	1.49E-04	0.15	6.98E-06	0.14	1.14E-04	0.10	1.39E-04	2.33E-04
0.5	0.17	3.94E-05	0.25	6.04E-06	0.23	2.78E-05	0.17	3.65E-05	6.14E-05
0.7	0.24	1.65E-05	0.35	5.86E-06	0.32	1.10E-05	0.24	1.58E-05	2.34E-05
1.0	0.34	8.13E-06	0.50	5.82E-06	0.45	6.44E-06	0.35	8.67E-06	8.10E-06
1.2	0.40	6.59E-06	0.60	5.82E-06	0.54	5.99E-06	0.42	7.50E-06	5.00E-06
1.4	0.47	5.95E-06	0.70	5.82E-06	0.63	5.88E-06	0.49	7.06E-06	3.76E-06
1.6	0.54	5.65E-06	0.80	5.82E-06	0.72	5.86E-06	0.56	7.02E-06	3.01E-06
1.8	0.61	5.52E-06	0.90	5.82E-06	0.82	5.86E-06	0.63	6.79E-06	2.67E-06
2.0	0.67	5.45E-06	1.00	5.82E-06	0.91	5.85E-06	0.70	6.76E-06	2.48E-06
2.5	0.84	5.39E-06	1.25	5.82E-06	1.13	5.85E-06	0.87	6.73E-06	2.33E-06
3.0	1.01	5.38E-06	1.50	5.82E-06	1.36	5.85E-06	1.04	6.72E-06	2.30E-06