DEVELOPMENT OF A NEW SEISMIC PRA CODE FOR UNCERTAINTY ANALYSIS

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ABSTRACT

The probabilistic risk assessment (PRA) is an important tool for knowing factors that contribute to risks and improving safety of nuclear power plants (NNP). The authors have developed a new computer code SECOM2-DQFM-U for accident sequence quantification in seismic PRAs of NPPs. The important advantage of the code is that it provides uncertainty analysis not only for core damage frequencies but also for importance analysis using FV and RAW measures with consideration of the effect of correlation of failure among components. This capability was made possible by the use of the Direct Quantification of Fault Trees using Monte Carlo (DQFM) method. This paper presents the modeling scheme for uncertainty analysis and some results of applications of the code as well as its advantages.

1. Introduction

After the Fukushima accident, it is widely recognized that the probabilistic risk assessment (PRA) is a powerful and practical approach for searching potential severe accident scenarios to improve our protection against such scenarios as far as reasonably practicable. To support risk-informed decision making by both utilities and regulatory organizations for continuous safety improvement, PRAs should have a good quality and a wide scope. As part of its scope, it should consider the accident scenarios caused by internal and external hazards such as earthquake and tsunami. It is also necessary for PRAs to provide adequate information on the uncertainties in their quantitative outputs.

In this paper, the authors try to show features of the SECOM2-DQFM code[1] and its latest version SECOM-2-DQFM-U developed by the authors and outcomes from past applications in brief, as well as a review of analytical methodologies used for uncertainty analysis by SECOM2-DQFM-U. Then, it shows philosophy and algorism of a newly proposed analytical methodology for consideration of correlation of seismic failures in the process of uncertainty analysis for accident sequence frequencies and importance measures in level 1 seismic PRA. Finally, usefulness of such analysis codes for risk informed applications is discussed.

2. Current status of quantification methods for seismically induced core damage frequency (CDF)

In seismic PRAs, the failure probability of each component of safety systems (fragility) is calculated as a function of the intensity of input seismic motion. This calculation uses information on the uncertainties in the estimation of component strength (seismic capacity) and seismic load (seismic response). Such uncertainties are categorized into those due to lack of knowledge and those due to inherent randomness. The quantification of CDF is made by combining three types of information: (1) the information on the occurrence frequency of earthquake motions at the site (seismic hazard) expressed as a function of the maximum acceleration at bedrock, (2) the information on the fragility, in other words, capacity and response of each component, and (3) the information on system configuration expressed by fault trees (FT) and event trees (ET). For internal event PRAs, many computational tools have been developed and used. But for seismic PRAs, some special considerations were necessary. An important and difficult challenge was the consideration of correlation of failures. There are several analytical method for this problem, such as methods using truth table, methods using minimal cut sets (MCSs), and methods using Monte-Carlo simulation. The DQFM (Direct Quantification of Fault tree using Monte-Carlo simulation) method is one of the methods using Monte-Carlo simulation. A verification calculation by Oikawa et al. [1] showed that the DQFM method gives numerical results very close to that produced by the Boolean Algebra method which was believed to have accuracy close to theoretical solution. In general, methods using MCSs, which are the defact-standards for seismic PRA, have some disadvantages and DQFM method provided a resolution for this disadvantage [1],[2]. The advantage of the DQFM method can be shown by the following comparison of results of calculations with two methods for a hypothetical boiling water reactor (BWR). Figures 1 and 2 show conditional probabilities of various accident sequences as functions of the size of input seismic motion expressed by peak acceleration of bedrock.

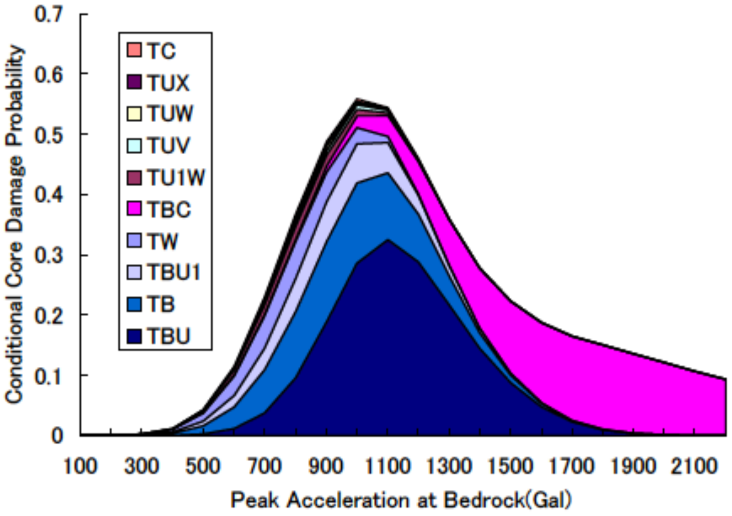

Fig 1 Conditional probability of accident sequences calculated with a method using MCSs

Based on the DQFM method, the result shown in Fig 1 turns to be a different result with the same model and data, as shown below.

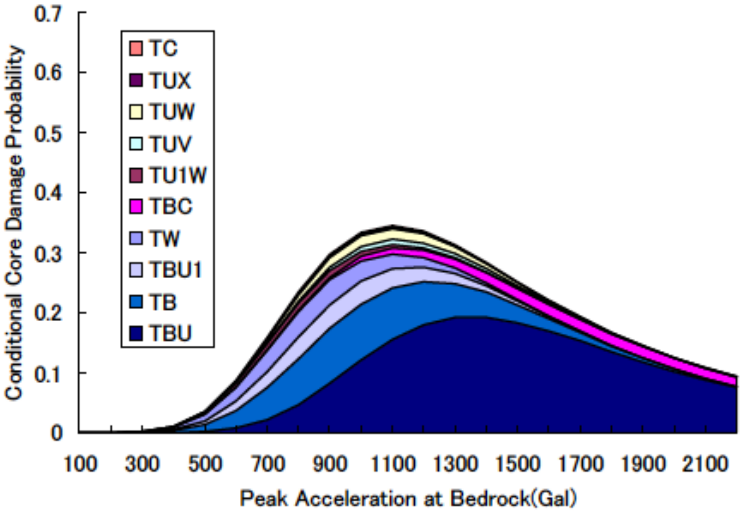

Fig 2 Conditional probability of accident sequences calculated with DQFM method

In general, total probability of core damage sequences with methods using MCSs have tendency to be over estimated, and it makes the difference between the peak probabilities in Fig 1 and Fig 2. If probabilities of accident sequences are uniformly over-estimated by a method, the method can be used to understand relative importance of sequences. But, since the degree of over-estimation is not uniform, Fig 1 shows that there is a possibility that importance of some sequences might be erroneously emphasized [3].

3. Past achievements and current applications by SECOM2-DQFM

The SECOM2 code system was originally developed and verified by Oikawa et al. [1],[2]. An application of the code system to a model plant seismic PRA was conducted by JAEA (Japan Atomic Energy Agency). Then SECOM2-DQFM was extracted from the code system, and was modified and published for use on IBM compatible PCs [4].

Since the code has a feature to treat a wide range of simultaneous seismic failures reasonably, it is used not only for single-unit sites but also for multi-unit sites. It was used to show effectiveness of the accident management strategy by cross-connections of emergency diesel generators (EDGs) for a multi-unit site [5]. An example of results from this application is shown below.

Tab 1 Core damage frequency (CDF) for each case

	Correlations*	Cross-Connections of EDGs	CDF of a Single Unit (/Year)	CDF of This Two-Unit Site** (/Year)	Frequency of Simultaneous Core Damages of Both Unit (/Year)
Base	No	No	2.3×10^{-5}	4.1×10^{-5}	5.5×10^{-6}
Case 1	Yes	No	3.0×10^{-5}	4.8×10^{-5}	1.3×10^{-5}
Case 2	Yes	Yes	2.0×10^{-5}	2.8×10^{-5}	1.1×10^{-5}

[Notes] * Correlations of component responses in the same building are considered using rules of NUREG-1150[6],[7],[8], and component responses between different buildings are also considered to be the same as in the same building, conservatively.

** Frequency of core damages of at least one unit at the same site

In the base case, the CDF of this two-unit site was about 1.8 times higher than that of a single unit instead of 2 times because earthquake was a common cause event that caused simultaneous core damages of both unit. When correlations were considered in Case 1, there was a significant increase of the frequency of simultaneous core damages of both units, which was about 2.3 times higher than that in the base case where correlations were ignored.

On the other hand, when cross-connections of EDGs between the two units were available in Case 2, the CDF of this two unit site was lower than the CDF of a single unit site in Case 1.

SECOM2-DQFM code is based on typical seismic PRA procedures such as that described in the seismic PRA standard published by AESJ (Atomic Energy Society of Japan). Until now, the code has been applied to seismic PRA for light water reactors (BWRs and PWRs), and recently, the code is being applied to seismic PRA for high temperature gas cooled reactors.

4. New development of the uncertainty analysis capability of the SECOM2-DQFM code

After Fukushima accident, the importance of accident management (AM) is widely recognized and it is required for us to quantify importance of various accident scenarios and important components to support selection of cost effective AM measures.

To identify the important scenarios, it is necessary to figure out uncertainty of accident sequence frequencies and uncertainty of component importance measures. To obtain realistic values, it is necessary to consider correlation between component failures, but the number of codes capable for it was limited. Since SECOM2-DQFM code is one of the few codes, the authors added a feature for uncertainty analysis to it and named the new version SECOM2-DQFM-U.

4.1 Modifications of equations for the uncertainty analysis capability

To add the new feature for uncertainty analysis, it was necessary to enhance equations for point estimate analysis, to allow uncertainty analysis. An example of the equations for point estimate analysis is shown as follows,

$$C_i = C_{mi} \times \exp\{(\beta_{Ri}^2 + \beta_{Ui}^2)^{1/2} \times X_i\} \qquad \text{Eq 1}$$

where C_i is a response for i-th component generated artificially, and expected to distribute lognormally. C_{mi} is the median of response for i-th component. β_{Ri} and β_{Ui} are standard deviations due to aleatory uncertainty and epistemic uncertainty, respectively. X_i is random sampling number following standard normal distribution. Eq 1 could be used to generate artificial capacity as well. SECOM2-DQFM-U code compares the artificial response and the artificial capacity, and judges the occurrence of failure of the component if response is greater than the capacity. Then the code counts up the number of the failure, and calculates failure probability by dividing the number of the failure by the number of total iteration for Monte-Carlo simulation.

In general, epistemic uncertainty should be estimated in uncertainty bounds of target measures (e.g. CDF etc.), then Eq 1 was modified and the following equation was developed,

$$C_i = C_{mi} \times \exp(\beta_{Ri} \times Y_i + \beta_{Ui} \times Z_i) \qquad \text{Eq 2}$$

where Y_i is a random sampling number following standard normal distribution, generated for Monte-Carlo iteration for calculating median fragility curve. It corresponds to X_i in Ex 1. Z_i is a random sampling number following standard normal distribution, generated for Monte-Carlo iteration used for uncertainty analysis. It expresses deviation from the median fragility.

Now the SECOM2-DQFM code provides uncertainty analysis capability for two importance measures (Fussell-Vesley(FV)) measure and the Risk Achievement Worth(RAW)) as well as the uncertainty analysis for accident sequence frequencies.

4.2 Decomposition of correlation coefficients

Uncertainty analysis considering correlations involves an issue that the analyst (the user of the code) has to provide his resolution. That is the decomposition of correlation coefficients. When correlation is considered in a point-estimate analysis, the DQFM method requires a matrix of correlation coefficients to generate a set of correlated random sampling numbers shown as X_i in Eq 1. For uncertainty analysis, X_i was decomposed into Y_i and Z_i in Eq 2. Then correlation coefficients must also be decomposed and given by users of the code. The definition of correlation coefficients is as follows,

$$\rho_{C_i,C_j} = \frac{\mathrm{Cov}(C_i, C_j)}{\beta_{C_i} \times \beta_{C_j}} \qquad \text{Eq 3}$$

where $\rho_{Ci,Cj}$ is a correlation coefficient between responses (or capacities) of i-th and j-th components. $\mathrm{Cov}(C_i,C_j)$ is covariance between responses (or capacities) of i-th and j-th components. β_{Ci} and β_{Cj} are standard deviations of responses (or capacities) of i-th and j-th components, respectively. In typical seismic PRA, C_i and C_j can be considered to be decomposed into epistemic element and aleatory element, as shown below.

$$\begin{aligned} C_i &= R_i \times U_i \\ C_j &= R_j \times U_j \end{aligned} \qquad \text{Eq 4}$$

Here, if we assume that epistemic elements and aleatory elements are completely independent, Eq 3 can be expanded to the following equation.

$$\rho_{C_i,C_j} = \frac{\beta_{R_i}\beta_{R_j}\rho_{R_i,R_j} + \beta_{U_i}\beta_{U_j}\rho_{U_i,U_j}}{\sqrt{\beta_{R_i}{}^2 + \beta_{U_i}{}^2} \times \sqrt{\beta_{Rj}{}^2 + \beta_{U_j}{}^2}} \qquad \text{Eq 5}$$

In Eq 5, $\rho_{Ci,Cj}$ could be obtained if correlation coefficient for aleatory element $\rho_{Ri,Rj}$ and for epistemic element $\rho_{Ui,Uj}$ are given, since β_R and β_U should have been already known in a seismic PRA.

If knowledge of responses or capacities are limited, β_U would be larger than β_R. For example, if the data is given that β_{Ui} and β_{Uj} are 0.5, β_{Ri} and β_{Rj} are 0.1, and $\rho_{Ci,Cj}$ is 0.75, then the range of $\rho_{Ui,Uj}$ is limited in 0.73 - 0.75 in Eq 5, since $\rho_{Ri,Rj}$ can't have the value more than 1.0 or less than 0.0. It means that composite $\rho_{Ci,Cj}$ is dominated by $\rho_{Ui,Uj}$ of epistemic element which has larger uncertainty.

The data set used in this study are in almost the same situation as above. In the following analysis, we applied the rules used in a seismic PRA[6] for NUREG-1150 for $\rho_{Ci,Cj}$, then it was assumed that $\rho_{Ri,Rj}$ are 0.0. The rules determine the correlation coefficients for responses of two components on the basis of similarities in their location in building and natural frequencies. This assumption gives a bounding estimation on potential effect of correlation of uncertainty in responses. However the value of $\rho_{Ri,Rj}$ is not expected to affect the results significantly if we can assume epistemic elements are larger than aleatory elements. In general, it is likely to have small β_R and large β_U. In such cases, Eq 5 and the above approach helps to decide correlation coefficients.

Based on the above equations, uncertainty involved in accident sequence frequencies can be quantified. In the following sections, results of uncertainty analysis are shown for cases with and without consideration of correlation of failure.

4.3 Results of uncertainty analysis without considering correlation

Uncertainty of conditional core damage probability (CCDP) without correlation is shown as follows.

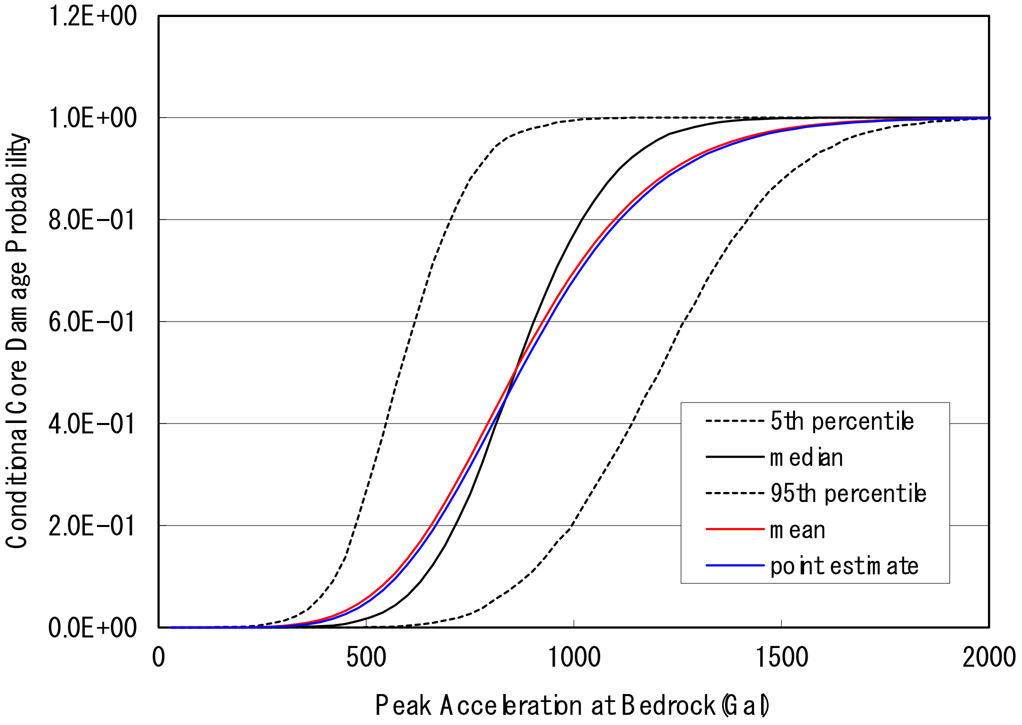

Fig 3 Uncertainty analysis result for conditional core damage probability

The mean curve of uncertainty analysis shows good agreement with the curve calculated in point estimate analysis, and the uncertainty bounds are quantified in the figure as well.

The seismic hazard to be multiplied by CCDP in the analysis is shown as follows.

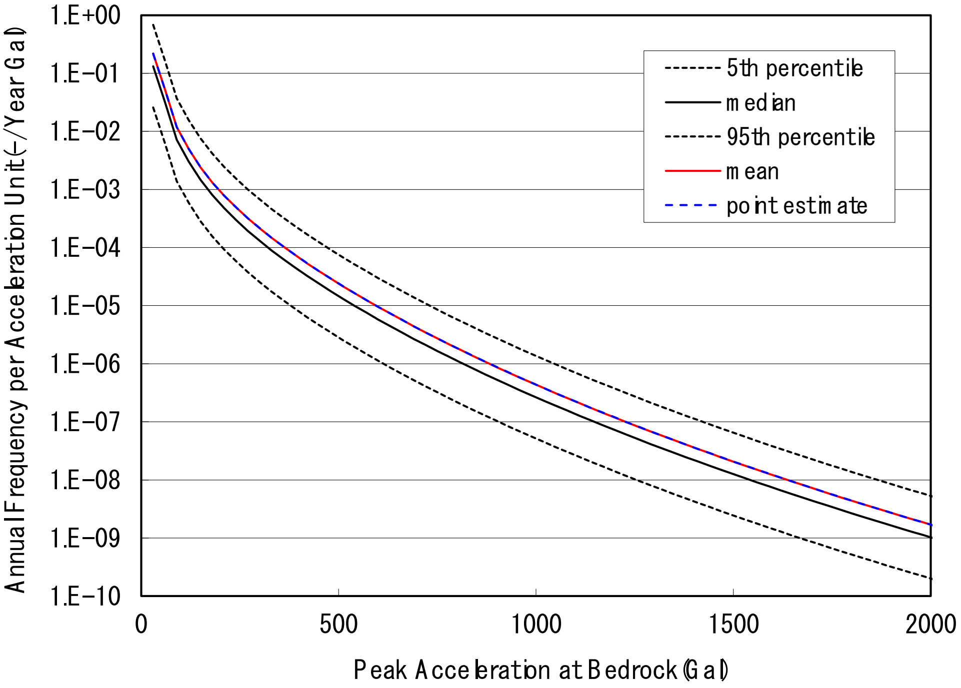

Fig 4 Uncertainty of seismic hazard

Total CDF is calculated from seismic hazard information and the conditional core damage probability (CCDP) at each seismic level. When the uncertainty of seismic hazard is considered in uncertainty analysis, the uncertainty bounds of total CDF increases, since the seismic hazard has also significant uncertainty as shown in Fig 4.

Tab 2 Uncertainty analysis result for total core damage frequency

	without considering uncertainty of seismic hazard	considering uncertainty of seismic hazard
5th percentile	1.9E-6	8.6E-7
median	1.4E-5	8.0E-6
mean	1.9E-5	2.4E-5
95th percentile	5.9E-5	8.5E-5
error factor	5.6	9.9

Using the event trees that define the accident sequences, the SECOM2-DQFM-U code calculates accident sequence frequencies, an example of which is shown in Tab 3.

Tab 3 Uncertainty analysis result of occurrence frequency of accident sequences

accidnet sequence	annual frequency (-/year)					
	point estimate	mean	median	5th percentile	95th percentile	error factor
RPV	1.3E-08	1.7E-08	0.0E+00	0.0E+00	2.0E-09	-
AW	1.5E-07	1.3E-07	5.3E-11	0.0E+00	2.7E-07	5187
AUW	9.7E-08	1.1E-07	3.4E-10	0.0E+00	2.8E-07	823
AUV	3.7E-08	2.5E-08	8.6E-11	0.0E+00	7.0E-08	817
AC	2.5E-08	4.1E-08	0.0E+00	0.0E+00	1.8E-08	-
AB	3.0E-07	3.3E-07	4.5E-10	0.0E+00	8.9E-07	1974
ABU	4.8E-07	4.2E-07	1.9E-08	8.1E-13	1.8E-06	92
ABC	2.0E-08	3.5E-08	4.0E-11	0.0E+00	5.2E-08	1284
S1W	2.3E-07	1.5E-07	2.5E-09	0.0E+00	4.5E-07	179
S1UW	1.3E-07	1.0E-07	3.4E-09	0.0E+00	4.0E-07	117
S1UV	4.7E-08	2.8E-08	7.2E-10	0.0E+00	1.1E-07	155
S1UX	5.7E-09	2.3E-09	2.3E-11	0.0E+00	9.9E-09	430
S1C	3.8E-08	3.5E-08	3.6E-12	0.0E+00	3.8E-08	10494
S1B	4.3E-07	3.9E-07	9.5E-09	0.0E+00	1.3E-06	133
S1BU	6.0E-07	5.2E-07	6.4E-08	1.4E-10	2.5E-06	39
S1BC	2.3E-08	2.1E-08	1.2E-10	0.0E+00	6.0E-08	500
S2W	7.2E-07	7.5E-07	4.6E-08	6.7E-11	3.0E-06	65
S2U1W	1.9E-07	2.3E-07	5.6E-09	0.0E+00	7.4E-07	133
S2UW	1.1E-07	1.2E-07	5.7E-09	9.5E-12	4.8E-07	84
S2UV	4.1E-08	5.9E-08	1.3E-09	0.0E+00	1.2E-07	95
S2UX	3.6E-09	2.8E-09	1.7E-10	0.0E+00	1.0E-08	61
S2C	9.1E-08	1.9E-07	3.8E-11	0.0E+00	1.1E-07	2950
S2B	1.1E-06	1.6E-06	8.6E-08	1.2E-10	4.9E-06	56
S2BU1	5.3E-07	4.5E-07	2.3E-08	0.0E+00	1.8E-06	77
S2BU	6.6E-07	6.4E-07	1.2E-07	1.3E-09	3.1E-06	26
S2BC	3.8E-08	4.0E-08	2.6E-10	0.0E+00	1.1E-07	443
TW	4.7E-06	5.1E-06	8.3E-07	1.9E-08	1.9E-05	23
TU1W	1.1E-06	9.9E-07	1.6E-07	2.8E-09	4.3E-06	27
TUW	3.8E-07	3.8E-07	3.6E-08	5.9E-10	1.5E-06	42
TUV	1.3E-07	1.4E-07	6.3E-09	4.4E-11	5.3E-07	85
TUX	2.9E-07	2.7E-07	6.9E-08	1.6E-09	1.3E-06	18
TC	7.5E-08	6.7E-08	4.6E-11	0.0E+00	9.9E-08	2135
TB	5.5E-06	5.9E-06	9.2E-07	1.4E-08	2.0E-05	22
TBU1	2.6E-06	2.4E-06	2.9E-07	5.8E-09	8.6E-06	29
TBU	1.9E-06	1.8E-06	4.3E-07	1.3E-08	7.1E-06	16
TBC	9.1E-08	9.1E-08	4.4E-10	0.0E+00	2.4E-07	534
total CDF	2.3E-05	2.3E-05	7.9E-06	8.6E-07	8.5E-05	10

The error factor (EF) of the total CDF was about 10. But the EFs of individual sequences are significantly larger than that of the total CDF, especially for the sequences of smaller frequency. The reason for this was explained as follows. In general, sequences with smaller frequencies have failures of more redundant systems than the others, then the uncertainty can be calculated to be large because uncertainties of several redundant systems are multiplied in those sequences.

Using the same seismic PRA model, importance measures can also be obtained as follows.

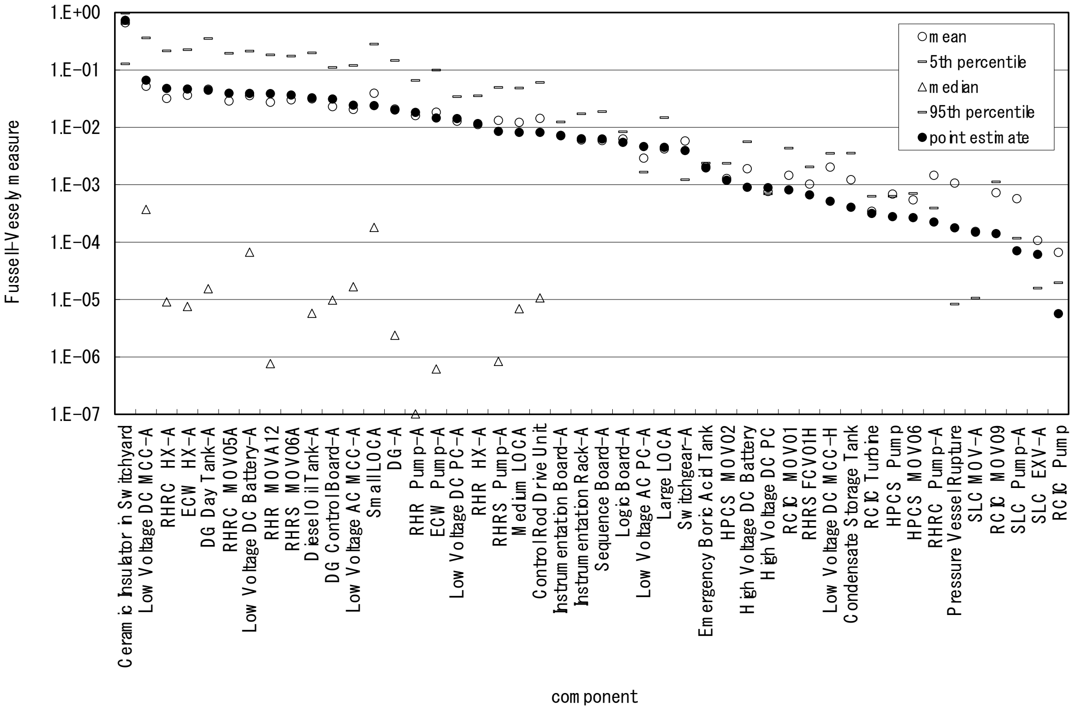

Fig 5 Uncertainty of Fussell-Vesely measure

The mean values showed good agreement with the point estimates. As for uncertainty bounds, the range of uncertainties in FV measures for almost all components are quite large. But the differences between mean values and 95th percentiles are much smaller than the uncertainty toward lower bounds. This may be interesting for PRA analysts.

4.4 Results of uncertainty analysis with considering correlation

Uncertainty of CDF calculated with consideration of correlation of failure is shown in Table 4.

Tab 4 Uncertainty analysis result for total core damage frequency considering correlation

β	the same as base case		reduced to half	
correlation	independent	considered	independent	considered
point estimate	2.3E-5	3.1E-5	6.9E-7	1.0E-6
5th percentile	8.6E-7	3.9E-7	5.0E-8	4.1E-8
median	7.2E-6	6.4E-6	2.9E-7	4.5E-7
mean	2.1E-5	3.3E-5	6.0E-7	1.0E-6
95th percentile	7.7E-5	1.6E-4	2.0E-6	2.9E-6
error factor	9.4	20.4	6.3	8.5

The results using the same data as the section 4.3 is shown in the left half of Tab 4. The EF considering correlation is 2 times larger than the EF without correlation. It implies that uncertainty could be underestimated if correlation is ignored (independence between component responses).

On the other hand, it is also analyzed using β of all component responses and capacities reduced to half, shown in the right half of Tab 4. In general, reducing uncertainty of component responses and capacities makes not only EF of total CDF decrease, but also the median and mean values of total CDF decrease. In this case, the difference between EFs for independent case and correlated case is decreased by reducing β of all component responses and capacities.

Without reducing β, importance measures were also quantified as shown in Fig 6.

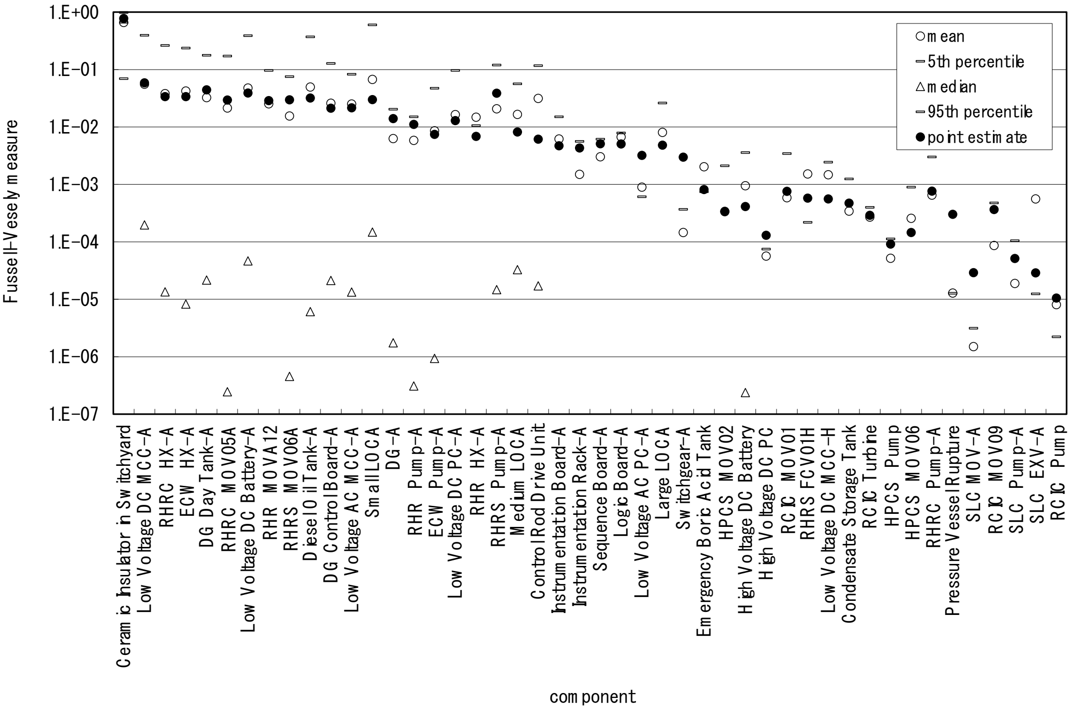

Fig 6 Uncertainty of Fussell-Vesely measure considering correlation

In Fig 6, the order of components from left to right is completely the same as that in Fig 5. Fig 6 shows that the values of importance measures were changed, and uncertainty of importance measures were also changed by considering correlation, relative to Fig 5. It implies that the importance of components and its uncertainty can be misunderstood if correlation is ignored. But the changes due to correlation are not so significant, that is, less than an order of magnitude for Fussell-Vesely measures.

5. Conclusions

The authors proposed how to consider correlation and how to set correlation coefficients in uncertainty analysis. Based on this proposal, uncertainty analysis methodology of accident sequence occurrence frequency and importance measures considering correlation is introduced into a PRA analysis code, and the effectiveness of the feature is confirmed by application to a model plant of a light water reactor.

6. References

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