DEVELOPMENT OF A COMPUTATIONAL FRAMEWORK OF UNCERTAINTY ANALYSIS FOR LEVEL 2 PSA TO CONSIDER BOTH ALEATORY AND EPISTEMIC UNCERTAINTIES

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ABSTRACT

Good understanding of uncertainties associated with the results of probabilistic safety assessment(PSA) is an essential prerequisite for effective use of PSA for regulation or management of nuclear power plants (NPPs). For the purpose of guiding an uncertainty analysis in a PSA at the Japan Atomic Energy Research Institute (JAERI), this paper proposes a computational framework of uncertainty analysis for level 2 PSA for internal events of NPPs based on the PSA methodology developed at JAERI. An important feature of this proposed approach is the explicit separation of aleatory and epistemic uncertainties, which is expected to contribute to clarification of definition of uncertainty and to avoiding potential overestimation of uncertainty caused by mixed treatment of these two types of uncertainties.

1. INTRODUCTION

In recent years, use of probabilistic safety assessment (PSA) of nuclear power plants(NPPs) for decision making in regulation and management is rapidly expanding in many countries. However results from PSAs include uncertainties originating from utilized models and data. It may be liable to become an indistinct assessment if it is performed without clarifying what sort of causes generate uncertainties. Considering this basic needs, the Japan Atomic Energy Research Institute (JAERI) started a program to develop a methodology for uncertainty analysis in PSAs for NPPs.

For guiding an uncertainty analysis of PSAs at JAERI, this paper proposes a computational framework of uncertainty analysis for level 2 PSAs for internal events of NPPs based on the PSA methodology developed at JAERI, placing emphasis on the calculation of a risk curve expressed by a exceedance frequency of source terms. An important feature of the proposed approach is the explicit separation of aleatory and epistemic uncertainties. Here epistemic uncertainty means subjective uncertainty due to the lack of knowledge which can be reduced by further studies while aleatory uncertainty means objective uncertainty known as randomness or variability of underlying stochastic system. These two types of uncertainties have not been separately treated in the practice of PSAs for NPPs except for PSAs for seismic events[1]. Separate treatment has been regarded as an area that needs further development[2] and is expected to contribute to clarification of definition of uncertainty and to avoiding potential overestimation of uncertainty in PSAs caused by mixed treatment of these two types of uncertainty.

The level 2 PSA procedures developed at JAERI and proposed treatment of uncertainties are described in sections 2 and 3, respectively, and some results of a pilot calculation and concluding remarks are given in sections 5 and 6.

2. LEVEL 2 PSA PROCEDURES DEVELOPED AT JAERI

2.1 Outline

JAERI has been continuing PSA study for the purpose of providing a set of procedures for assessing risks of

LWRs. The procedures of level 2 PSA are shown in Fig. 1 and briefly described below.

2.2 Accident Frequency Analysis

Accident frequency analysis provides the information of core damage sequences necessary to initiate an accident progression analysis. So called large event tree (ET) / small fault tree (FT) approach was adopted at JAERI.

Accident frequency analysis is performed by four steps: (i) initiating events are selected based on examination of possible disturbances to operation and consideration of success criteria for such disturbances, (ii) for each initiating event, accident sequences are delineated using systemic ETs, (iii) failure probabilities of safety systems are determined by FT analysis and used for quantification of the systemic ETs, and finally (iv) core damage sequences are redefined by the use of front-line system ETs which are smaller than the systemic ETs. Front-line system ETs are considered to be detailed enough for defining plant conditions for accident progression analysis by containment event trees (CETs) and severe accident codes. This approach is different from that of NUREG-1150[3] where core damage sequences were grouped into smaller number of "plant damage states" as input conditions for accident progression analyses.

2.3 Accident Progression Analysis

Accident progression analysis examines the potential for the containment failure. Scenarios of containment failure are delineated and quantified by a CET for each core damage sequence. Here the plant response has to be analyzed taking into account various physical phenomena and recovery actions with their interactions. For the purpose of efficiently constructing a CET, Watanabe et al.[4] proposed the accident progression stage event tree (APSET) method where the accident progressions are divided into several stages, for example, the pre-stage before core melt, the core melt stage, the stage just after reactor pressure vessel (RPV) failure, and the long term progression stage. In each stage, occurrence probabilities are evaluated for possible containment failure modes.

2.4 Source Term Analysis

The release and transport of fission products(FPs) from the reactor core to the environment is assessed along the accident progression for all containment failure scenarios identified by CETs for core damage sequences.

The source term analysis is performed mainly by using the severe accident analysis code system THALES/ART developed at JAERI. In this system THALES[5] simulate accident progression in the RPV and the containment while ART[6] simulates fission product transport using thermal-hydraulic conditions from THALES. These codes have been replaced by a fully integrated code THALES-2[7] which simulates thermal-hydraulics and FP transport with consideration of various interactions between events in the RPV and in the containment, between FP behavior and thermal-hydraulic conditions, and between physical phenomena and plant systems.

Use of detailed severe accident codes has merit and demerit as compared to the source term analysis in the NUREG-1150 where simple parametric model called XSOR[8] were used for easier conduct of uncertainty propagation analysis and accommodation to the use of expert judgment. The use of severe accident analysis codes directly for source term evaluation in PSAs has the merit of transparency of the models and higher accuracy which allows clearer consideration of dependency of source terms on accident sequences and plant design. Therefore the use of detailed code is consistent with the use of front-line system ETs for definition of accident conditions.

Since THALES or THALES-2 does not cover energetic events, namely steam explosion, direct containment heating(DCH) and hydrogen detonation, the source terms for energetic events are determined by using simplified models. For example, source terms for steam explosion are determined with an assumption that all radionuclides in the core debris and containment atmosphere would be released to the environment. Sush simple treatments for energetic events may be justified when likelihoods of such events are small.

2.5 Integration of Containment Failure Frequencies and Source Terms

The results from above steps are examined for qualitative or quantitative understanding of risk contributors. Among various types of figures and tables produced to help such examination, an important output from a level 2 PSA is a risk curve expressed by source terms. A risk curve in this paper is defined as a graph of exceedance frequency of release for a FP element as a function of release fraction (fraction of total mass of that element). This paper concentrates on the uncertainty of a risk curve.

3. PROPOSED APPROACH FOR UNCERTAINTY ANALYSIS

3.1 Outline

The development of uncertainty analysis method by the authors started with reviewing of the method used in NUREG-1150 which was considered to be the state of the art. The method proposed by the authors is intended to combine the merits of JAERI's level 2 PSA methodology and the works in NUREG-1150, namely the extensive collection of expert opinions, many of which seem to have general applicability. One should also note that generally applicable values have inevitable uncertainty due to plant-to-plant or sequence-to-sequence differences.

The scope of the present work is limited to uncertainty factors in the accident progression analysis and source term analysis. It does not include the accident frequency analysis (level 1 PSA) or environmental consequence analysis. The proposed method consists of the following tasks, descriptions of which are given in this section.

(1) identification of important uncertainty issues,
(2) determination of parameters to represent the important uncertainty issues and evaluation of their range of uncertainty, considering both aleatory and epistemic uncertainties, and
(3) uncertainty propagation calculation to determine the uncertainty in the risk curve.

3.2 Identification of Important Uncertainty Issues

(1) General discussion
First the analyst who performs the PSA has to review the models and data used for the PSA and identify sources of uncertainty that may have meaningful influence on PSA results. Then he estimates roughly the relative importance of the effect of each uncertainty source and selects a set of important uncertainty issues to be considered in the uncertainty propagation. In this process, the uncertainties in modeling and data as well as uncertainties due to incompleteness should be considered as far as possible. The effect of incompleteness is the most difficult item to treat but at least the analyst can review the models in existing PSAs or related studies to identify items that he has not been considered in his models. Comparison with other works will also help in recognizing modeling uncertainties. Having a peer review by independent experts may be another way of identifying uncertainty sources. Practical suggestions by Hickman et al.[2] such as making a list of modeling assumptions could be used.

(2) Uncertainty issues in accident progression analysis
Since accident progression analysis is made with CETs and the headings of CETs are selected as items that influence the accident progression, CET headings are reasonable candidates of uncertainty sources in accident progression. The authors compared the CET headings in JAERI's PSA and in NUREG-1150 and found that the containment failure modes considered at each accident progression stages were almost the same. Based on this comparison, the authors judged that headings of JAERI's CET can be used as candidates of uncertainty issues.

(3) Uncertainty issues in source term analysis
First candidates of uncertainty sources in source terms are models and data used in the severe accident codes. There are many information sources including the uncertainty analysis using the STCP[9] by Khatib-Rahbar et al.[10], code comparisons [11,12,13], sensitivity studies[14,15], reviews of experiences[16] as well as the expert opinions for NUREG-1150[17]. Considering the high cost of uncertainty analysis for large codes like that by Khatib-Rahbar[10] and the limitation of such analysis for consideration of modeling uncertainty (codes can not analyze phenomena that are not modeled), the authors are trying another approach, that is, the assigning of an uncertainty range for the calculated source terms as a whole (not for input or individual models in the code) by analyst's judgment based on available information sources such as the references indicated above. In this approach, the selected uncertainty sources are the source terms for each combination of accident sequence, accident progression stage and containment failure mode.

3.3 Determination of Probability Distribution Functions for Uncertainty Parameters

(1) Form of probability distribution function
As shown in Fig. 2 the branch probabilities of CETs and the source terms are uncertainty parameters in the proposed method. They are quantified as probability distribution functions by the analyst's judgment based on his experience and

available information such as the expert opinions in NUREG-1150.

For convenience of making judgment and computational handling, the probability distributions of parameters are assumed to have a form of modified lognormal distribution. Since lognormal distribution has been used to represent the uncertainties of component failure probabilities in level 1 PSAs, the use of the same form to CET branch probabilities and source terms (release fractions of FPs) is not a unique proposal. If a future application of this method indicates it is too restrictive, more general forms of distribution functions such as table of cumulative probability function used in NUREG-1150 can be incorporated in our computational framework discussed in the next section.

Furthermore the uncertainties are decomposed in analogy to expressions in seismic PSAs. In seismic PSAs[1], seismic load and strength of components are treated as random variables with lognormal distribution where uncertainty of each variable is separately treated as uncertainty due to randomness and uncertainty due to lack of knowledge as shown in the next equation. Only the latter was considered as true uncertainty to be used in unceratinty propagation calculations[2].

$$X = \overline{X}\, \varepsilon_R\, \varepsilon_U \qquad (3.3\text{-}1)$$

where X and $\overline{X}$ are an uncertainty parameter and its median, and ε_R and ε_U are random variables around a median value of unity and lognormally distributed with standard deviation of β_R and β_U, respectively. "R" and "U" mean "randomness" and "uncertainty", respectively, in the conventional notation of the seismic fragility corresponding to the aleatory and epistemic uncertainties.

Every uncertainty parameter is assumed to be lognormally distributed (with some modification to be discussed later) with its logarithmic standard deviation, β, and it is also assumed that the uncertainty represented by β can be separated into aleatory and epistemic uncertainties as the following:

$$\beta = \sqrt{\beta_R^2 + \beta_U^2}\ . \qquad (3.3\text{-}2)$$

(2) Use of modified lognormal distribution

Since branch probabilities of CETs and source terms (release fractions) have values between 0 and 1, it is more convenient to use some probability distribution function limited between 0 and 1 than to use lognormal distribution. Therefore, the authors adopted the use of lognormal distribution modified to have upper and lower limits.

Here we assume that each branch probability or source term has such a probability distribution that its function X defined by next equation follows a lognormal distribution.

$$X = \frac{Xv}{1 - Xv}\ . \qquad (3.3\text{-}3)$$

where Xv is our uncertainty parameter and X is a function of Xv. It is known that the distribution of Xv is very similar to lognormal distribution in a range not close to the limits.

In this manner, all uncertainty parameters can be set to have distributions limited between 0 and 1, maintaining convenient characteristics of lognormal distribution. In the following parts of this paper, "logarithmic standard deviation" means that of X, not that of our uncertainty parameter Xv (branch probability or source term).

(3) Simple approach for separation of uncertainties

In order to discuss possible approaches for uncertainty separation, we examined the issue of steam explosion as an example. The mechanism of this phenomenon is not sufficiently understood. Based on the expert opinions documented in reference[18], the issue was decomposed into sub-issues as shown in Fig. 3. Then we judged to which side these sub-issues are closer, aleatory or epistemic. The results are shown in Fig. 3. Here we judged that uncertainties of those sub-issues for which understanding of mechanism and development of models are in sufficient are epistemic while uncertainties of those for which mechanisms are known but there are uncertainties due to variability of accident conditions, material properties, etc. are aleatory. The uncertainty in accident conditions are epistemic if we really don't know what kind of accident conditions occur. The authors however suppose that accident conditions (thermal hydraulic conditions and plant design conditions) with their variabilities can be defined by available information and tools. By this sort of examinations, we hope that a rough classification of the uncertainty types would become possible.

Simple criteria would be useful for guiding engineering judgments by the analyst. Here we suppose that from information of expert judgment or other sources we can estimate a composite logarithmic standard deviation β (a standard deviation including both epistemic and aleatory components) for an uncertainty parameter. Then, in such cases, we assume that such logarithmic standard deviation can be divided into two components by a separation factor f as

$$\beta_R : \beta_U = f : (1 - f) \tag{3.3-4}$$

where β_R and β_U are logarithmic standard deviations of aleatory and epistemic uncertainties, respectively, and f is fraction of aleatory component. The factor f may be chosen from a discrete numbers such as [0, 0.25, 0.5, 0.75, 1] corresponding to analysts judgment of [none, smaller than epistemic, comparable, larger than epistemic, all].

3.4 Uncertainty Propagation Calculation

A computer code was developed to perform propagation of uncertainties in CET branch probabilities and source terms to the exceedance frequencies of source terms with use of a double-loop Monte Carlo simulation as shown in Fig. 4. In this figure, the outer loop is for a usual Monte Carlo iteration for uncertainty propagation. The inner loop was added to explicitly treat the aleatory uncertainty. Since aleatory uncertainty is considered to be really existing variabilities of parameters, the results from calculations iterated along the inner loop will be combined to draw a single exceedance frequency curve. The procedure in Fig. 4 consists of the following five steps which are described below.

(1) sampling of epistemic uncertainty parameters,
(2) sampling of aleatory uncertainty parameters,
(3) quantification of CETs and assignment of source terms to each containment failure scenario,
(4) production of an exceedance frequency curve for source terms by iteration of steps (2) and (3),
(5) production of median and 5 and 95 percentile curves of exceedance frequency of source terms by iteration of (1) to (4).

(1) Sampling of epistemic uncertainty parameters

In the outer loop, sampling of epistemic uncertainty parameters is made to determine median values for random variability (aleatory uncertainties) of the parameters. The assumption of lognormal distribution limited between 0 and 1 makes it easier to treat the complicated analysis. A random sampling from lognormal distribution with upper and lower limits can be made as follows.

First we generate a random variable P that has a uniform distribution in the range of [0,1]. Then we transform it to a lognormally distributed random variable, u, by solving the next equation for u.

$$P = \Phi(u) = \int_{-\infty}^{u} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{u'^2}{2}\right) du' \quad . \tag{3.4-1}$$

where $\Phi(u)$ is the cumulative distribution function for a normal random variable. Further, we transform u to a random variable of a lognormal distribution limited in the range of [0,1] using the following relationship.

$$u = \frac{\log\left(\frac{Xv_U}{1 - Xv_U}\right) - \log X_G}{\beta v_U} \tag{3.4-2}$$

where Xv_U is a variable that represents the variability of the uncertainty parameter due to epistemic uncertainty, X_G

is median of parameter Xv, and βv_U is logarithmic standard deviation of Xv corresponding to epistemic uncertainty. In this way, sampling of each uncertainty parameter is made for their epistemic uncertainties.

(2) Sampling of aleatory uncertainty parameters
Each iteration of inner loop produces an exceedance frequency curve for source terms. Here, sampling is made for aleatory uncertainty (random variability) assuming that variable Xv has a modified lognormal distribution around the median value Xv_U determined in step (1) with logarithmic standard deviation βv_R which corresponds to the aleatory part of uncertainty. Sampling for every Xv in the inner loop is performed in the similar manner as Xv_U in the outer loop using the following relationship.

$$u = \frac{\log\left(\frac{Xv_R}{1 - Xv_R}\right) - \log Xv_U}{\beta v_R}. \qquad (3.4\text{-}3)$$

(3) Quantification of CETs and assignment of source terms to each containment failure scenarios
At each iteration of the inner loop, frequencies of all paths of CETs(containment failure scenarios) and corresponding source terms are determined using variables sampled as shown in Fig. 2. Since CETs are large, this step produces numerous frequency vs. source term pairs. Then these pairs are sorted from larger source terms to smaller ones and used to get a frequency distribution function of source terms.

(4) Production of an exceedance frequency curve for source terms
Steps (2) and (3) are iterated in the inner loop to produce a number of frequency distribution functions. Theses frequency distributions are averaged to make a frequency distribution function that includes the effect of aleatory uncertainty. Integration of this distribution function produces an exceedance frequency curve for source term.

(5) Production of median and 5 and 95 percentiles of exceedance frequency curves for source terms
All steps are iterated to produce a number of exceedance frequency curves. Then at each level of source term magnitude, the values of exceedance frequencies are used to determine the median and 5 and 95 percentile points. Finally by connecting such points, median and 5 and 95 percentiles of exceedance frequency curves for source terms are produced.

4. Example

4.1 Results of the Level 2 PSA at JAERI Used for Pilot Calculation

A pilot calculation was performed as a starting point for uncertainty analysis of a level 2 PSA. In this calculation, point estimate values were all taken from a PSA conducted at JAERI for a generic BWR with a Mark-II containment, which is a bell-shaped steel containment with a suppression pool under the drywell floor. The relative contributions of core damage sequences, source terms calculated by the THALES/ART code system, and CET models and branch probabilities have been published as references [19], [15], [4], respectively.

51 accident sequences were identified by front-line system event trees and the analysis of these sequences by THALES/ART indicated that these sequences can be grouped by the similarity in timings of events such as the RPV failure and containment failure into five groups: (1) accident sequences caused by loss of decay heat removal systems (RHR) with success of high pressure core spray system (HPCS) or reactor core isolation cooling system (RCIC), (2) those caused by loss of RHR with success of low pressure core spray system (LPCS) or low pressure core injection system (LPCI), (3) those caused by loss of all injection systems, (4) those caused by loss of all AC power with core cooling available by RCIC, and (5) those caused by failure of reactor scram[15]. The frequencies of various containment failure scenarios were evaluated for the 51 accident sequences by a CET analysis.
The source terms for Xe, CsI, CsOH and Sr were calculated for the 51 accident sequences using THALES/ART with assumption of overpressure failure of the containment. These calculations indicated that the iodine release fraction for the sequences in the same group of above 5 groups had similar trends and were within the range of about one order of magnitude. It was also indicated that the source terms are strongly influenced by the containment failure locations, that is, in the drywell or the wetwell, because of the difference in the effect of pool scrubbing in the suppression pool. This

effect changed the source term by one to three orders of magnitude [15]. A sensitivity study using the THALES-2 code indicated that modeling differences between THALES/ART and THALES-2 may result in difference in source terms of about one order of magnitude [15].

4.2 Pilot Calculations by the Proposed Method of Uncertainty Analysis

A pilot calculation was performed using above results. In these calculations, the frequencies of core damage sequences were assumed to have no uncertainties. For easier interpretation of the results, two simplified cases of calculation were made: Case 1 assumed that branch probabilities of CETs had no uncertainty and only the uncertainties of source terms were considered and Case 2 considered uncertainties of both branch probabilities and source terms.

In these cases, composite logarithmic standard deviations (standard deviation including both aleatory and epistemic contributions) of branch probabilities of CETs and source terms were given uniform values as follows:

For branch probabilities, $\beta = 0.978$ (Equivalent to $\text{Error Factor} = 5 = e^{1.645\beta}$). (4.2-1)

For source terms, $\beta = 1.400$ (Equivalent to $\text{Error Factor} = 10$). (4.2-2)

Moreover, for examining the possible effect of separation, following relationships were assumed for the two cases:

(1) $\beta_U : \beta_R = 1.0 : 0.0$ (4.2-3)

(2) $\beta_U : \beta_R = 0.5 : 0.5.$ (4.2-4)

The results of two cases are shown in Figs. 5 and 6. These figures show the exceedance frequencies normalized by the total frequency of containment failure for iodine release fractions. Calculated uncertainty bounds in Case 2 are wider than that of Case 1 because more uncertainty sources were considered. The uncertainty bounds for condition (1) are larger than that for (2) indicating that difference in assumptions on the fraction of aleatory uncertainties may make considerable difference in risk curves. Although these are merely a sensitivity study with assumed uncertainty bounds, the authors feel that the assumed error factors factors for source terms are not unreasonably large and contribution of aleatory uncertainty of 50% may not be a too large estimate. These figures suggest that if such feelings are true for some cases, the proposed approach can reduce uncertainties in the risk curves.

5. CONCLUDING REMARKS

Procedures and a computational framework of uncertainty analysis for level 2 PSA for internal events of NPPs has been proposed for guiding uncertainty analysis based on the level 2 PSA methodology developed at JAERI. An important feature of this proposed approach is the explicit separation of aleatory and epistemic uncertainties, which is expected to contribute to clarification of definition of uncertainty and to avoiding potential overestimation of uncertainty caused by mixed treatment of these two types of uncertainty. Since epistemic uncertainty corresponds to our lack of knowledge and aleatory uncertainty to unavoidable random variability, separated treatment of the two uncertainties will contribute to clarifcation of the issues where our knowledge should be increased. Therefore, to complete the proposed procedures of uncertainty analysis and collection of necessary information will lead us to a better use of level 2 PSA.

The authors are planning to apply the proposed method to the level 2 PSA for a generic BWR based on experiences of severe accident research and analysis at JAERI and information from NUREG-1150 and other existing PSAs to obtain further insights on uncertainties in level 2 PSA of NPPs.

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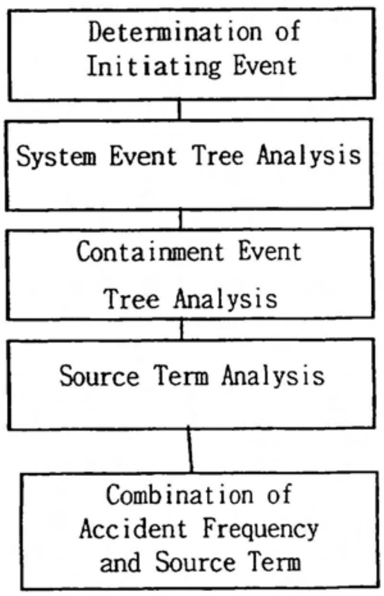

Figure 1 The level 2 PSA procedure developed at JAERI.

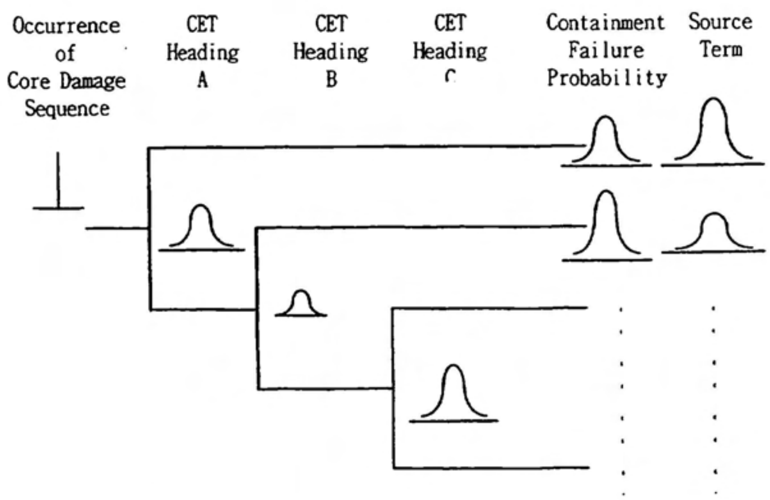

Figure 2 Parameters considered in the proposed uncertainty analysis procedure

Progression of steam explosion	Understanding of the phenomena	Type of uncertainty
core melt	data ambiguity due to dependence on sequences and availability of cooling functions	Aleatory
relocation	insufficient modeling due to our lack of knowledge	Epistemic
premixing	insufficient modeling due to our lack of knowledge	Epistemic
triggering	insufficient modeling due to our lack of knowledge	Epistemic
propagation	insufficient modeling due to our lack of knowledge	Epistemic
explosion energetics	insufficient modeling due to our lack of knowledge	Epistemic
damage consequence	randomness	Aleatory

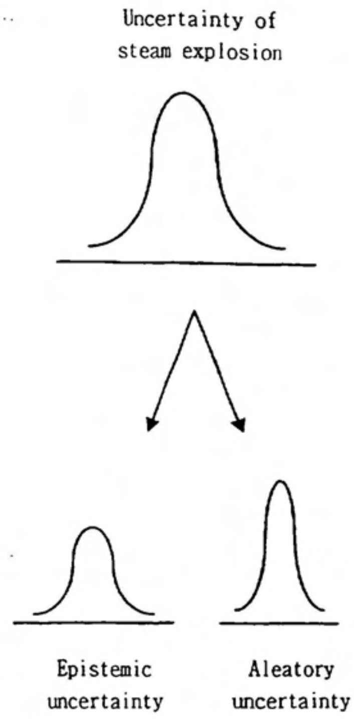

Figure 3 Example analysis : causes of uncertainties in steam explosion

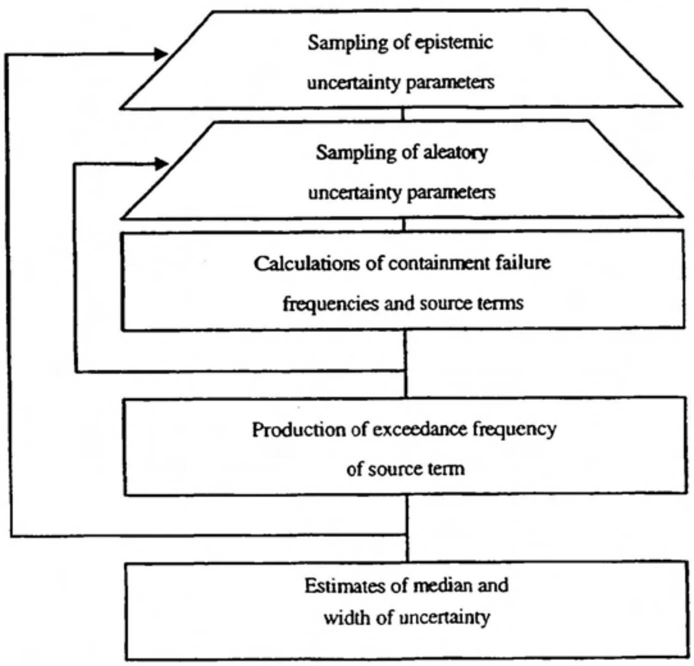

Figure 4 Calculation flow of uncertainty analysis

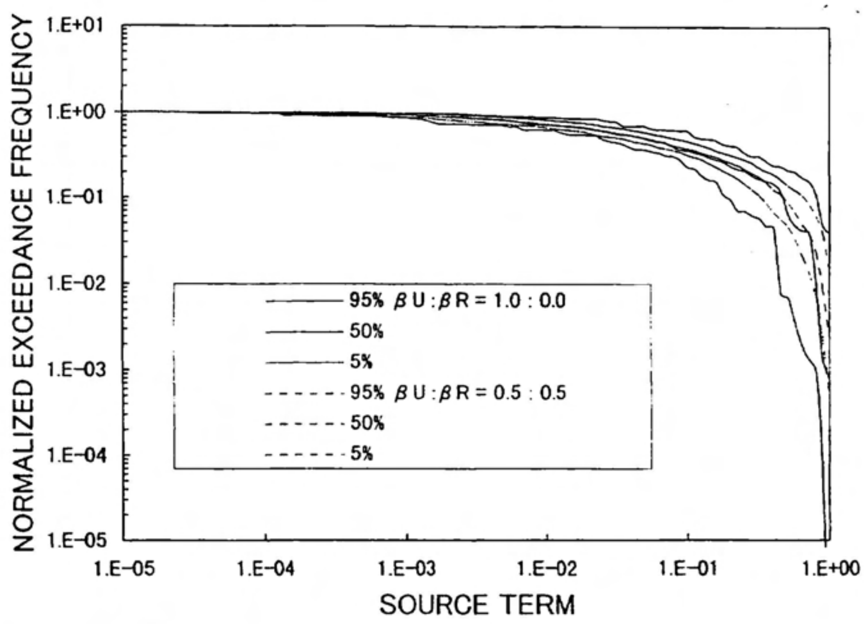

Figure 5 Exceedance frequency for source term
(Iodine release fractions obtained by considering only uncertainties of source terms)

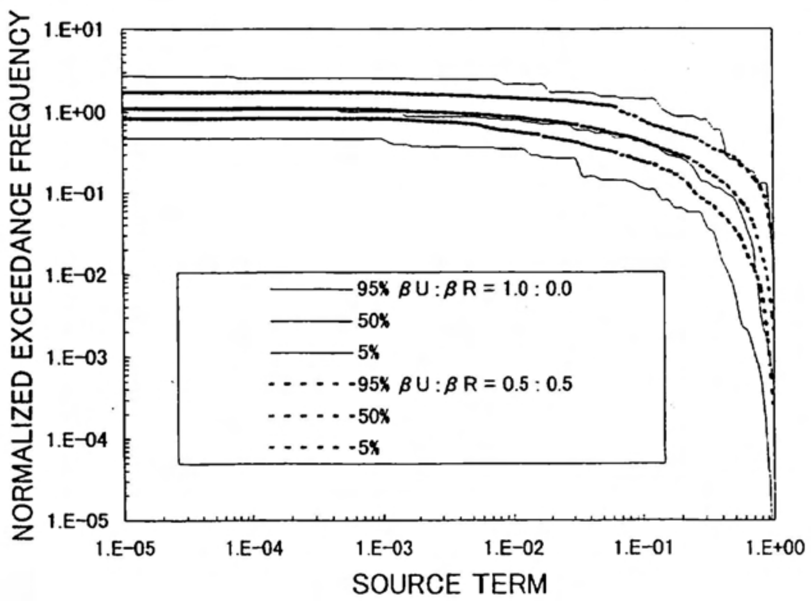

Figure 6 Exceedance frequency for source term
(Iodine release fractions obtained by considering both uncertainties of CET branch probabilities and source terms)