Uncertainty and Conservatism in Safety Evaluations Based on a BEPU Approach

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ABSTRACT

Atomic Energy Society of Japan has published “Standard Method for Safety Evaluation using Best Estimate Code Based on Uncertainty and Scaling Analyses with Statistical Approach” to be applied to accidents and AOOs in the safety evaluation of LWRs. In this method, hereafter named as the AESJ-SSE (Statistical Safety Evaluation) method, identification and quantification of uncertainties will be performed and then a combination of the best estimate code and the evaluation of uncertainty propagation will be performed. Uncertainties are categorized into bias and variability. In general, bias is related to our state-of-knowledge on uncertainty objects (modeling, scaling, input data, etc.) while variability reflects stochastic features involved in these objects. Considering many kinds of uncertainties in thermal-hydraulics models and experimental databases show variabilities that will be strongly influenced by our state of knowledge, it seems reasonable that these variabilities are also related to state-of-knowledge.

The design basis events (DBEs) that are employed for licensing analyses form a main part of the given or prior conservatism. The regulatory acceptance criterion is also regarded as the prior conservatism. In addition to these prior conservatisms, a certain amount of the posterior conservatism is added with maintaining intimate relationships with state-of-knowledge. In the AESJ-SSE method, this posterior conservatism can be incorporated into the safety evaluation in a combination of the following three ways, (1) broadening ranges of variability relevant to uncertainty objects, (2) employing more disadvantageous biases relevant to uncertainty objects and (3) adding an extra bias to the safety evaluation results.

Knowing implemented quantitative bases of uncertainties and conservatism, the AESJ-SSE method provides a useful ground for rational decision-making. In order to seek for “the best estimation” as well as reasonably setting the analytical margin, a degree of the posterior conservatism shall be lowered by constant efforts of enhancing our state-of-knowledge, i.e.

reducing uncertainties in inputs, improvement in modeling, enhancement of experimental database, etc. Pursuing this direction will lead to higher accountability of the analytical margin.

KEYWORDS

BEPU, safety analysis, uncertainty, posterior conservativeness, AESJ SSE standard

1. INTRODUCTION

The conventional licensing practice in Japan consists of using conservative boundary and initial conditions (BICs), assumptions and analytical codes. The safety analyses for licensing purpose are inherently deterministic. Therefore, conservative BICs and assumptions, such as a single failure, must be employed as the prior conservativeness in these analyses. On the other hand, use of conservative analytical codes is not regarded as an essential condition in the safety evaluation of nuclear power plants. When new operational conditions, such as a new fuel design or extended power uprating, are introduced, there arises questions such as “How large are influences on the safety margin?” or “How safe is safe enough?” The conventional conservative license analyses cannot necessarily answer these questions.

In the following discussions, it can be interpreted that causes of unquantifiable conservativeness employed in the conventional licensing analyses can be attributed to uncertainty objects included in the entire safety evaluation process (developing analytical codes, verification & validation (V&V), establishing inputs, etc.). Therefore, if we can give quantitative bases to these uncertainty objects, a significant part of conservativeness can be expressed by mathematical forms such as probability density functions. In other words, a comprehensive discussion from code developments to license evaluations is indispensable to improve a philosophy of conservatism.

As already recognized in several nuclear communities [1], uncertainties can be classified into two fundamental types. “the aleatory uncertainty” that results from the stochastic effect of “inherent randomness” or “unpredictable variability” and “the epistemic uncertainty” that results from the “imperfect knowledge” or “incomplete information” regarding values of parameters of the underlying model. Formally, the former type of uncertainties has nothing to do with our state-of-knowledge and remains as an unquantifiable component. This type of uncertainties can be normally expressed as variability. The latter type of uncertainties is quantifiable in relation with state-of-knowledge and can be reduced through enhancement of state of relevant knowledge. This type of uncertainties can be expressed as bias and also as variability. As a consequence, bias and variability are regarded as two major uncertainty components that shall be given quantitative bases in the AESJ-SSE method.

A combination of a best estimate code and a methodology of quantifying individual uncertainties and their propagation (BEPU=Best Estimate Plus Uncertainties) is indispensable for reflecting these uncertainties in the safety evaluation. In 2008, after three years of intensive discussions on evolution in the BEPU method in the nuclear industries, the standard committee of Atomic Energy Society of Japan (AESJ) has drawn up the standard [2] defining a framework of applying best estimate codes with uncertainty analyses with preserving the present Japanese deterministic license philosophy. This standard or the methodology is named the AESJ-SSE (statistical Safety Evaluation) method in this paper.

Applying this method, it is also expected that the latest knowledge would be timely reflected in confirming the nuclear power plant safety. If individual uncertainties pertaining to analytical conditions, analytical codes and computational models that would give significant effects to safety evaluation results can be adequately quantified, the safety evaluation method standardized here will contribute to discussions of more efficient safety research programs and nuclear power plant designs.

A framework of fourteen steps defined in the AESJ-SSE method is basically retained from that of the successful prior methodology of CSAU [3]. On the other hand, it needs to be noted that the original CSAU method that was developed for the large break LOCA analyses of Westinghouse 4-loop PWRs has been evolved toward a wider application. In a theoretical aspect, generalizations in the Phenomena Identification and Ranking Table (PIRT) method [4] and the scaling theory [5] need to be recognized as reinforcing applicability of CSAU. In a practicality aspect, international benchmarks on the BEPU method has been organized where different methods of different participants were compared their performance for mutual brush up. [6], [7] A treatment of user effects is one of main subjects found in these communities. Based on these experiences, NRC drew up the guideline for certifying best-estimate codes as RG1.203 that is generally known as EMDAP [8]. These progresses subsequent to the original CSAU were also reflected in the AESJ-SSE standard. Besides these proceeding works, a particular concept was proposed to relate a degree of quantification of uncertainties with the posterior conservativeness. With this concept, it is possible to break down major components of the analytical margin.

Most of uncertainty evaluations against state variables relating to a specific phenomenon seemed to have been performed under the premise that referred experimental results are dispersed without identification of uncertainties related to state-of-knowledge. These methodologies can be regarded as seeking a systematic approach to evaluate model uncertainties by ignoring the degree of freedom of experiments. The Code Accuracy Based Uncertainty Estimation (CABUE) [9] using experimental data covering separate effect tests (SETs) is based on the premise that there are sufficient well-scaled SETs for important phenomena or components. CIRCÉ [10] and DIPE [11] are other examples of the systematic approach. Although these approaches provide systematic ways to create PDFs according to both measurement data and code characteristics, they premise absence of measurement error, stochastic randomness of each uncertain input parameter due to its independence on other parameters and monotony of prediction deviation against measurement data. It should be emphasized, however, that a certain uncertainty due to a lack in state-of-knowledge naturally underlies in experimental data. If these uncertainties can be quantified with a systematic recognition of state-of-knowledge, they are no longer regarded as random and a more rational treatment of the conservativeness will be possible.

2. Basic Framework of AESJ-SSE Standard

Before starting a main part of this paper, let us introduce a basic structure of the AESJ-SSE standard. The standard is composed of a main body, four annexes and relevant commentary documents. Normative elements are described in the main body and Annexes A, B and C. Annex D describes sample cases of PWR-LOCA and BWR-AOOs. Relationships between the main body and annexes are illustrated in Fig. 1. The CSAU method was originally established for LOCA analysis of Westinghouse 4-loop PWR plants assuming a use of the best estimate code, TRAC/PF1 developed by USNRC. Basic procedures that are almost identical to those of CSAU are described in Annex A. In recent years, the original CSAU has been further reinforced and generalized from the viewpoint of the statistical method and the scaling theory and widely applied in the United States for licensing issues including not only LOCA but also AOOs. Because applied codes in these applications are developed by plant manufacturers or fuel vendors, USNRC published the regulatory guide regarding code development and assessment [8]. For covering both scopes in the AESJ-SSE standard, required conditions in development, V&V (Verification and Validation) and maintenance of the best estimate code are also described in Annex B. In Annex C, a generalized approach of establishing PIRT is described. Annex D exemplifies application of this standard for both PWRs and BWRs by describing each step in detail. As for the commentary documents, the six subjects as listed in Table 1 were included in the present version.

Table 1 List of Commentary documents in AESJ-SSE standard

No.	Subject Title
1	Preface: Purpose, Background, scope and structure of AESJ-SSE standard
2	Commentary of Annex A: Detailed procedures of AESJ-SSE method
3	Commentary of Annex B: Conditions and maintenance of best-estimate codes
4	Commentary of Annex C: Establishment of PIRT
5	Conservativeness to be included in AESJ-SSE method
6	Philosophy of confidence level of probability in AESJ-SSE method

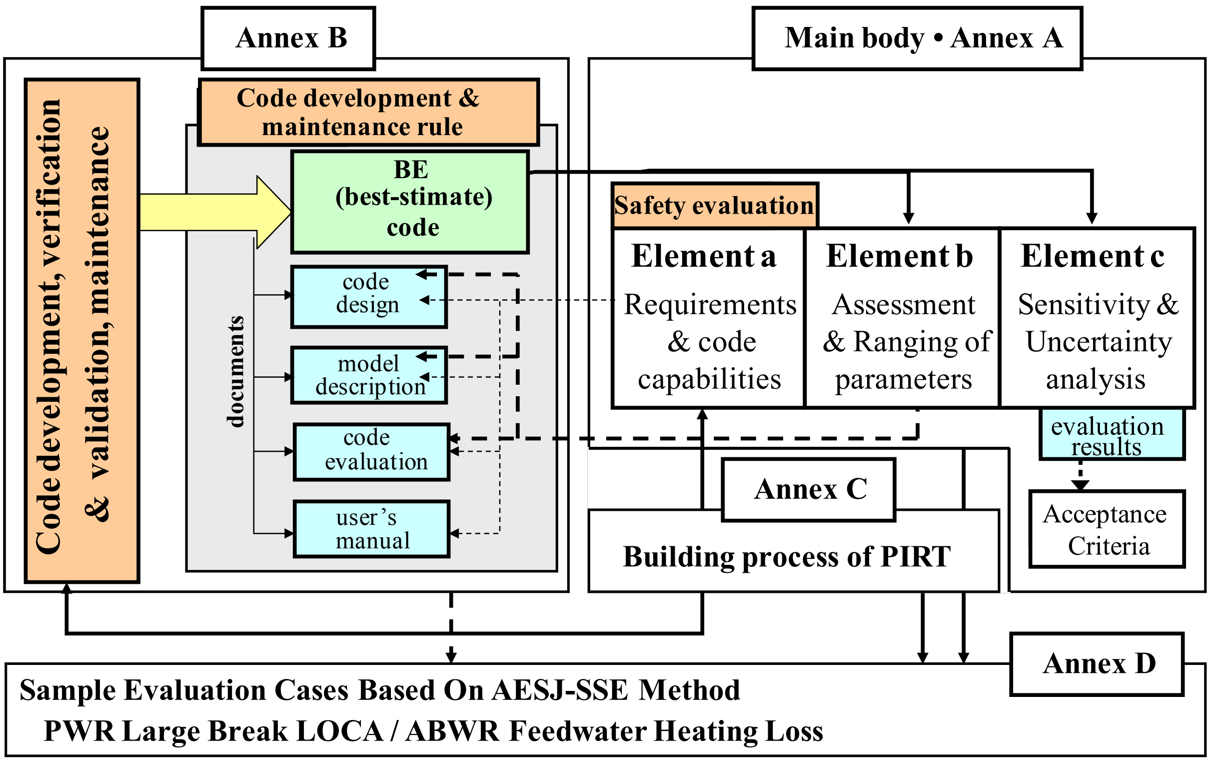

Fig. 1 Relationships between documents included in AESJ-SSE standard

3. CONCEPT OF SAFETY MARGIN AND CONFIDENCE LEVEL OF PROBABILITY IN BEPU SAFETY EVALUATION

3.1. Concept of safety margin

The IAEA has introduced a concept of the safety margin existing in the safety analysis of nuclear power plants (IAEA-TECDOC-1418) [12]. The TECDOC of IAEA gives an explanation that the substantial safety margin can be divided into four components; I - Safety margin (absolute term), Ⅱ - Licensing margin, Ⅲ - Analytical margin and Ⅳ - Operational margin. Fig. 2 shows this concept schematically for BWR AOOs. Definitions of each item reflecting BWR characteristics are debatable. However, this concept is very useful to clarify the focal point discussed in this paper. In the safety analysis of BWR AOOs, the operating limit (OLMCPR) is set in such a way that the licensing margin becomes zero. The TECDOC also states that the licensing margin can be zero when accuracy of the safety calculation is warranted and that the safety margin should be maintained under any postulated circumstances.

In the AESJ-SSE method, the acceptance criterion in the current licensing assessment will not be altered because the acceptance criterion depends on the safety limit with regardless of the safety analysis methodology. Furthermore, the operational margin is obviously out of the scope of the licensing. Target DBEs and scenarios that form the prior conservatism are given. Only the analytical margin will be influenced by statistical treatments implemented in the AESJ-SSE method. In other words, introducing the AESJ-SSE method leads to reconstruction of the analytical margin by replacing the conventional ambiguous conservatism with a synthesis of quantified uncertainties that leads to a more transparent definition of an appropriate degree of the conservatism.

Figures 3 and 4 show rough sketches how the analytical margin can be decomposed in the current licensing method and the AESJ-SSE method. In the current licensing method, as shown in Fig. 3, the analytical margin is expressed as a buildup of conservative inputs or models like building blocks. As a consequence, the calculation result becomes a discrete value for which neither the confidence level nor the coverage level can be specified. In the AESJ-SSE method, on the other hand, it is required that the validated best-estimate code is available for target DBEs and scenarios. As shown in Fig.4, uncertainties in relevant uncertainty objects (modeling, scaling, input data, etc.) are quantified as probability density functions (PDFs) in the validation process. The evaluated value is determined at the a priori specified confidence level and the coverage level by the statistical approach such as the One-Sided Upper Tolerance Limit (a parametric method) or the Wilks formula (a nonparametric method).

From the practical point of view, this uncertainty quantification cannot be performed without engineering judgments in order to compensate for inherent complexity of relevant physical phenomena, lack in information in models and inputs, experimental errors, etc. Baseline PDFs established based on limited knowledge will be exposed to examination in order to ensure conservatism required in the license safety evaluation. Through this discussion, the baseline PDFs will be modified into the final PDFs by disadvantageously biasing the mean values and broadening variances so that the final evaluation result becomes sufficiently conservative to compensate for the above-mentioned shortages. As shown in Fig.4, a difference between these two evaluation results is regarded as the posterior conservativeness in this paper. As will be described more in detail in Section 5, the posterior conservativeness will be dominated mainly by state-of-knowledge in computer codes, modeling, inputs and scaling effects.

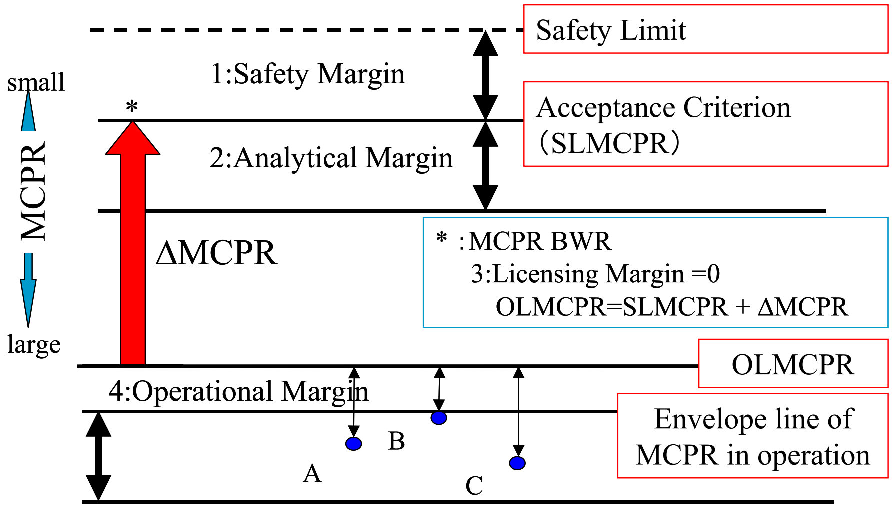

Fig. 2 Concept of safety margin in BWRs' AOOs

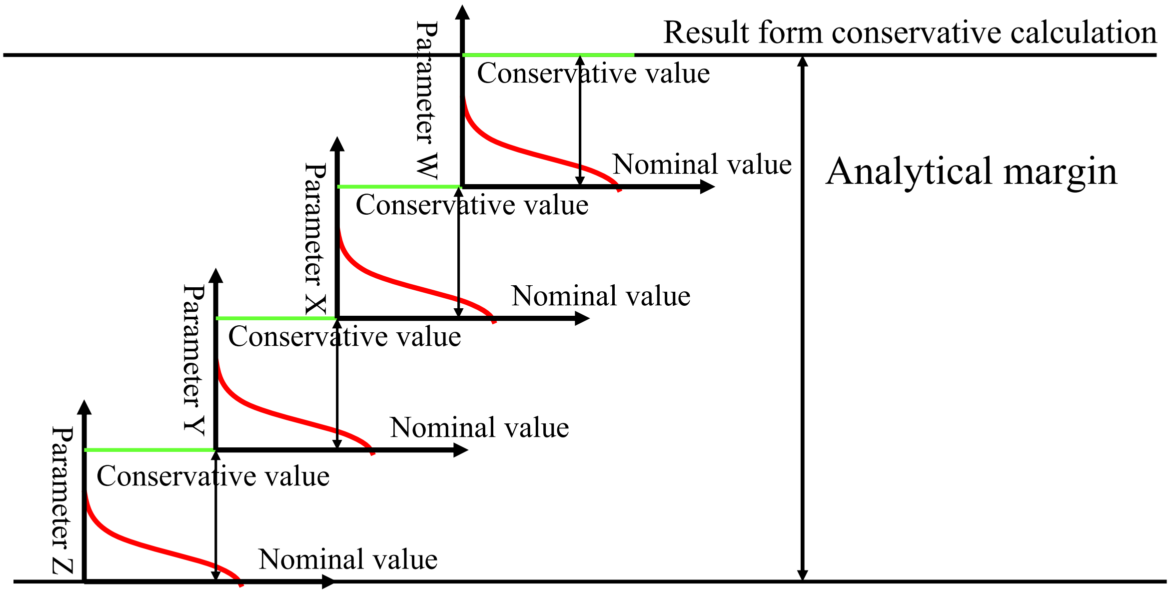

Fig. 3 Decomposition of analytical margin in current licensing analysis

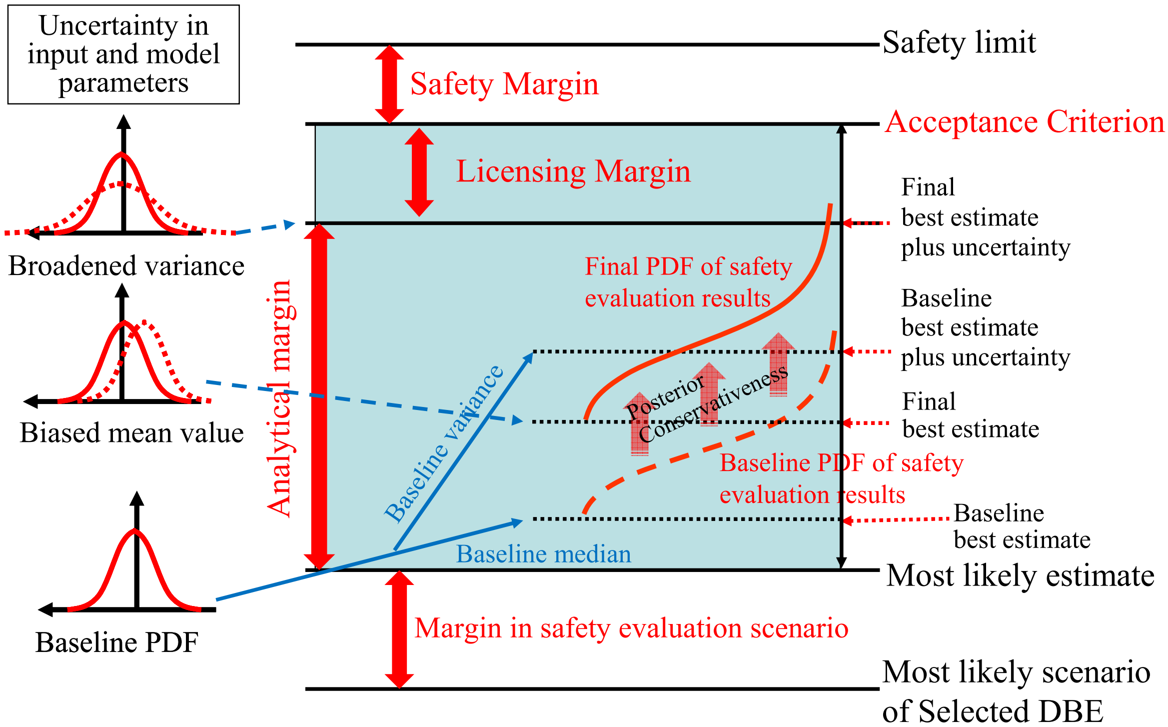

Fig. 4 Decomposition of analytical margin in AESJ-SSE method

3.2 Confidence level of probability applied to safety evaluation

In the statistical safety evaluation method, a hypothesis regarding the population (i.e. conformance to the acceptance criterion) will be judged based on a finite number of sample evaluation results. Quantitatively, this judgment is realized by assessing the two measures, how much coverage we can ensure (the cumulative probability) and to which extent the given sample represents the population (the confidence level). In the AESJ-SSE method, a combined measure of these two values has been named "the confidence level of probability (CLOP)". When the non-parametric method is applied, at least 59 samples are required for ensuring CLOP of 95%/95% based on the Wilks formula. An increase in either the cumulative probability or the confidence level leads to a requirement of a larger number of samples. The target CLOP needs to be set up prior to the statistical evaluation according to importance and characteristics of subjects under assessment along with technical environments of the safety evaluation, i.e. state-of-knowledge from experiments and actual plants, technologies in numerical modeling, computer software and hardware, instrumentations employed in experiments, etc. In other manufacturing industries such as assuring quality of mechanical and electric parts, the 95%/95% CLOP has been widely accepted as a reasonably attainable target value.

In 10CFR50.46 revised in 1988, it is required to demonstrate that there is a high level of probability that the criteria would not be exceeded in the safety evaluation. [13] "A high level of probability" for the best-estimate calculation of ECCS has been specified as 95% or more in RG.1.157. [14] In the original CSAU method (NUREG/CR-5249), the sample calculation results were given as the 95% coverage values based on the response surface method. While the 95%/95% CLOP was accepted in the past license application of CSAU in the US, the same level of probability is also employed in the BEPU methods developed in European countries and Korea. Looking back to the present Japanese safety evaluation guidelines of

LWRs, the statistical approach has been introduced in the core thermal design evaluation of PWR (the DNB criterion) with regarding the 95%/95% CLOP as ensuring a sufficiently low probability of DNB. In the fuel thermal-mechanical design method of BWR and PWR, the 95% coverage values given by the Monte Carlo method is compared with the acceptance criteria.

As for the target CLOP of the experimental data that form an important basis of the uncertainty evaluation, a recommended uncertainty level of both the random error uncertainty and the systematic error uncertainty is 95% in the ASME measurement uncertainty methodology. [15] Finally, in the safety evaluation of nuclear power plants, the design base events are categorized as the anticipated operational occurrences or accidents according to their frequencies. Those events that are regarded as sufficiently rare events are excluded from DBEs according to this point of views.

Based on the above-mentioned consensus in the safety evaluation of nuclear power plants, it is appropriate to define the 95%/95% CLOP as ensuring that the criteria would not be exceeded with a high level of probability.

4. PROCEDURES OF UNCERTAINTY COMBINATION IN AESJ-SSE METHOD

4.1 Description of procedures

Fig. 5 shows procedures in the AESJ-SSE method. Procedures mainly consist of three elements, that is, assessment of code applicability, ranging of parameters' uncertainty, and sensitivity and uncertainty analysis. Each element is composed of several steps. Assessment of code applicability element that consists of Step 1 through Step 6 prescribes specification of both event scenarios and NPP, selection of a best estimate code and procedures to establish a PIRT. The PIRT is used to identify important phenomena relating to transient scenarios of the target plant and to clarify and address the analytical design basis, which is conducted by engineering decision-making by the expert group. Ranging of parameters' uncertainty elements that consists of Step 7 through Step 10 prescribes establishment of an assessment matrix, definitions of NPP nodalization, definitions of code or model uncertainties, and determination of effects of scale. Uncertainty definition, that is performed on each important phenomena described in the PIRT, is conducted based on statistical analysis for the difference between code prediction and experimental data. Sensitivity and uncertainty analysis element that consists of Step 11 through Step 14 prescribes procedures to provide the total uncertainty in the safety variable evaluation by combining the individual uncertainties for models, input data and so on.

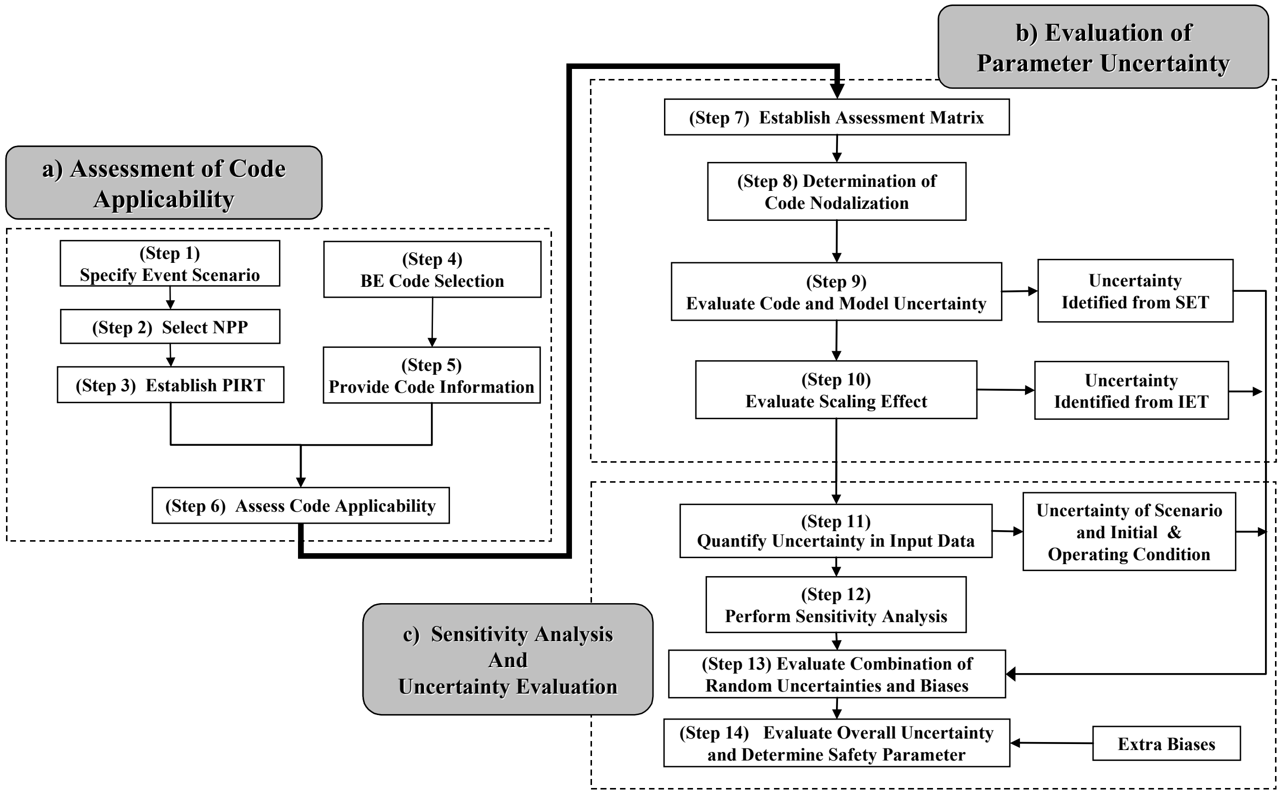

Fig. 5 Procedures in AESJ-SSE method

A combination of uncertainties is performed by using several optional statistical approaches, for instance, the parametric statistics and/or the order statistics applied to the results obtained from random sampling Monte Carlo calculations with or without the Latin Hypercube Sampling.

It is worth noting that uncertainties from three origins are evaluated and are combined. They are uncertainties from (1) comparisons with SETs in Step 9, (2) those with integrated effect tests (IETs) in Step 10 and (3) initial and operating conditions and scenarios in Step 11. Furthermore, an extra bias might be added to the total uncertainty considering other unquantifiable uncertainty sources in Step 14. As mentioned in INTRODUCTION, the standard defines uncertainties are composed of bias and variability. They are normally expressed as the mean value and the variance, respectively, of PDFs of relevant models and inputs.

4.2 Characterization of uncertainties

In accordance with state-of-knowledge of each model, there are three basic stances of dealing with uncertainties specified in the standard. They are a) to perform ranging of uncertainties of relevant models, b) to use models based on acknowledgement of their intrinsic conservatism and c) to recognize influences due to absence of the models required for the analyses on important phenomena.

In the standard, quantification of an uncertainty range shall be performed based on normal distributions, uniform distributions and arbitrary histograms according to properties of sample frequency distributions. For those cases where it is difficult to define appropriate PDFs or models were selected according to the a priori defined event scenario, however, the user may select either PDFs that are prone to yield conservative results or bounding conditions.

It is allowed, when certain models are used with acknowledgement of intrinsic conservatism, to use these models by documenting their individual conservativeness on the safety variable as biases. And it is also allowed, when conservatism has been confirmed for the code prediction on the safety variable, that the code may be used without modification. Otherwise, biases shall be quantified on the prediction of the safety variable.

Before formalizing quantification of the posterior conservativeness indicated in Fig.4, it is necessary to associate concepts of uncertainty ranging with state-of-knowledge. As already introduced in INTRODUCTION, a classification of the aleatory and the epistemic uncertainty is useful in this discussion. According to RG 1.174 [16], "*The epistemic uncertainty has been referred to as state-of-knowledge uncertainty.*" Further in the RG, the epistemic uncertainty is classified into three categories: *parameter uncertainty*, *model uncertainty* and *completeness uncertainty*. Therefore, it is straightforward that the posterior conservativeness is mainly dominated by the epistemic uncertainty.

One typical stance can be that the epistemic uncertainty shall be treated mostly as biases in the safety evaluation. In the standard, from the practical standpoint of plant system analyses, it is assumed that variability may consist of both aleatory and epistemic aspects because ranges of variability or variance can be altered depending on either enhancement or lack of relevant knowledge. For instance;

a) A mathematical model that describes a thermal-hydraulic phenomenon is generally multivariate with non-linear couplings and biases and/or differences in dependencies on each variable would be combined to form an overall variability of dependent variables.
b) Variabilities in measured experimental databases would be revised through improvements in experimental facilities, some changes in the range of experimental conditions, and/or provision of additional experimental databases.

As a consequence, it seems reasonable to treat these kinds of variabilities as the epistemic uncertainty. On the other hand, biases are employed from the standpoint of putting emphasis on the difference between code predictions and experimental data.

It seems that discrimination of the three categories of the epistemic uncertainty is not necessarily easy in actual safety evaluations. For instance, experimental data may include completeness uncertainties and individual model uncertainties derived based on these data may also be influenced by completeness uncertainty. Therefore, formal discrimination of these three categories is indispensable in order to define a clear out frame of the epistemic uncertainty. Dependencies among them can be incorporated into the safety evaluation by arbitrary rational methods as far as they will not induce non-conservative influences. Although a definition of detailed procedures is out of the scope of this standard, a basic concept can be introduced by the following example.

Assignment of PDFs is a crucial point that dominates plausibleness and a range of applicability of uncertainty quantifications. The normality test for frequency distributions of given samples is performed to infer whether or not the PDF of its underlying population can be treated as a normal distribution. Application of other non-parametric tests is possible and they ensure a wider range of applicability. If the normality hypothesis is accepted in terms of some indices such as the p-value from Anderson-Darling statistic, then the mean value and the standard deviation are evaluated as indices of the bias and the variability. Once PDFs were assigned, they are regarded as approximate mathematical expressions for physical uncertainty elements. Not only the aleatory uncertainty but also the epistemic uncertainty will be mixed in this process. Without any prior agreement on uncertainty treatments, it becomes difficult to separate the epistemic part from these resultant PDFs.

Practically, a comprehensive discussion of uncertainty causes is desirable from the viewpoint of separating the epistemic uncertainty. In particular, recognition of the afore-mentioned three categories and their interactions is essential in determining an amount of the posterior conservativeness shown in Fig.4. A certain degree of engineering judgment will be necessary in this discussion. Some uncertainties depend not only on fidelity and scalability of models but also on appropriateness of experiments, both of which are major elements of state-of-knowledge. In addition, the CLOP level given by these PDFs should be consistent with that required in the safety evaluations.

5. CONSERVATISM IN AESJ-SSE METHOD

5.1 Origin of biases and random uncertainties, and their propagation in procedures of BEPU safety analyses

In this section, a classification of uncertainties (biases and variabilities) to be quantified and obtainment of the posterior conservativeness to be required in the AESJ-SSE method will be summarized.

In evaluation models that are applied in conventional conservative safety evaluations, it is often difficult to quantify uncertainties included in component models and inputs and to evaluate their influences on evaluation results. As a consequence, evaluation procedures will be maneuvered so that a large amount of conservatism will be included in evaluation results without strict quantitative discussions. In the AESJ-SSE method, it is required to classify important uncertainties arisen in those uncertainty objects such as component models, computational models and scale-up capability of experimental results, etc. and quantify their influences on evaluation results. Through these treatments, it is possible to compare evaluation results with acceptance criteria with a high level of probability such as the 95%/95% CLOP.

Figure 6 depicts uncertainties generated in each evaluation step in the AESJ SSE method. The following five categories of variability and bias, UC1 to UC5, will be extracted.

a) Variabilities relating to computer codes and computational models. (UC1)
b) Variabilities relating to scaling effects. (UC2)
c) Variabilities relating to input data. (UC3)
d) Biases extracted in Steps 9, 10 and 11. (UC4)
e) Extra bias given based on the engineering judgment. (UC5)

The term, UC5, is the extra bias that arises from those uncertainties that cannot be treated as the foregoing four categories and may induce non-conservative evaluation results. Based on the engineering judgment, UC5 will be added under the following scenes:

f) Quantification of biases in Steps 9, 10 and 11 is difficult due to insufficient quality of experimental data.
g) It is difficult to prove conservative influences due to absence of important models (Step 9) on safety evaluation variables and even it is difficult to quantify relevant uncertainties.
h) It is necessary to include biases in safety evaluation variables when the approximation approach such as the response surface method is applied.
i) It is necessary to include enveloping conditions that cannot be treated by specific analytical conditions, such as establishing a sufficiently wide framework in the preliminary design stage.

In performing statistical safety evaluations based on a set of statistical input parameters, UC1, UC2 and UC3 are eventually treated as their variances while UC4 is treated as their mean values. UC5 is an additive term to evaluation results and is regarded as a part of the posterior conservativeness.

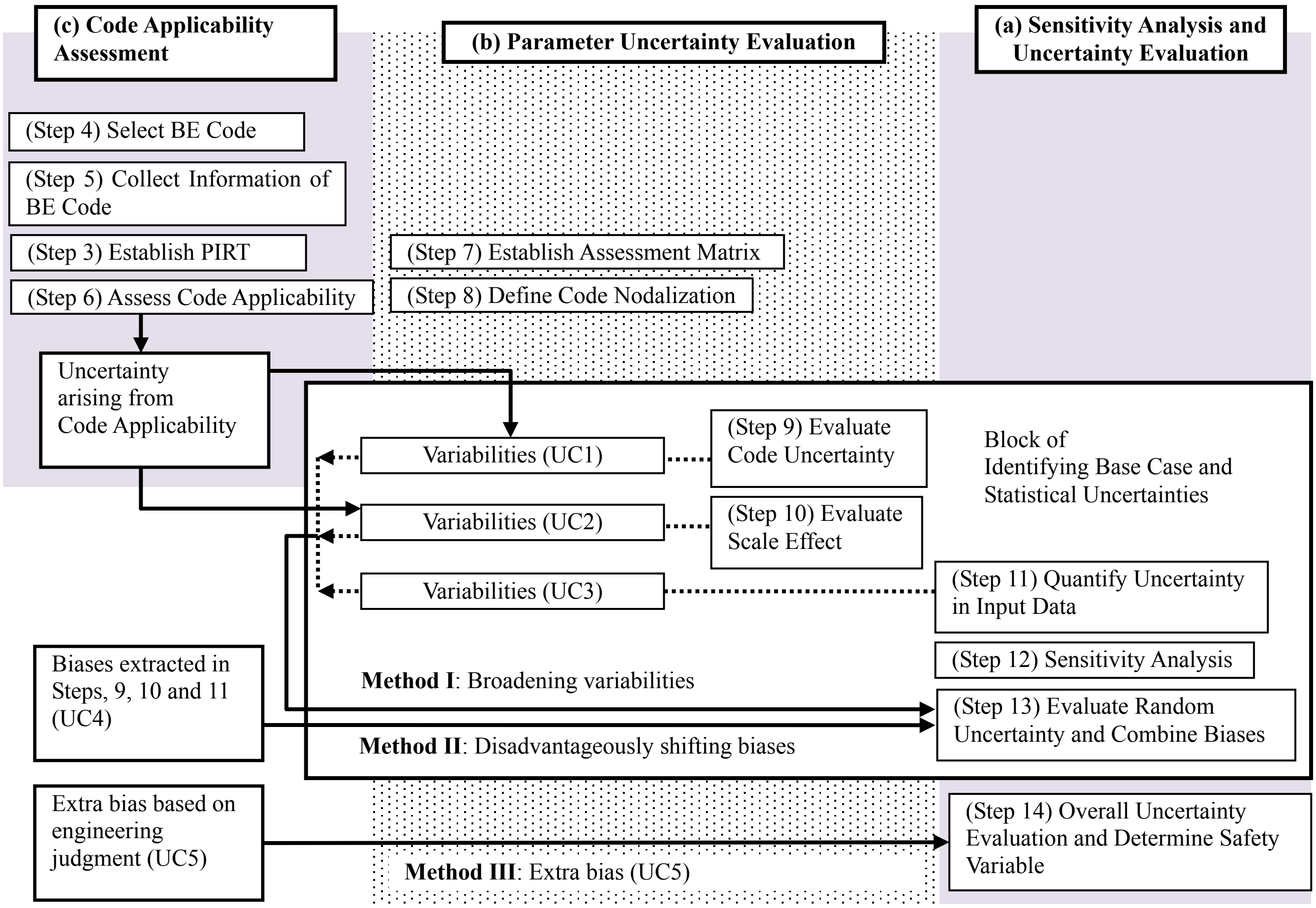

Fig. 6 Origins of uncertainties and their propagation paths in AESJ-SSE method

5.2 Three typical methods to realize posterior conservatism in accordance with evaluation of biases and variabilities

Having the above-mentioned classification of uncertainties in mind, the three basic concepts of realizing the posterior conservatism as depicted in Fig. 7 can be normally applied. In this figure, definitions of UC1 through UC5 are common with those of Fig.6.

a) Method I : Variabilities arising from modeling, scaling and input data, UC1, UC2 and UC3, are quantified in Step 9 through Step 11. According to specifications of these three steps, ranges of these components will be broadened. For example, variances of input data are increased. Generally, the resultant estimate tends to be broader and the 95% coverage value becomes more conservative.
b) Method Ⅱ: Biases to corresponding modeling, scaling and input data and biases to safety variables, UC4, are quantified in Step 9 through Step 11. According to specifications of these three steps, these biases are shifted disadvantageously that larger conservativeness will be obtained. During this process, it is possible to re-assess, or sometimes reduce, ranges of corresponding variabilities, UC1, UC2 and UC3.
c) Method Ⅲ: The extra bias, UC5, to evaluation results as already defined in Section 5.1 is quantified. UC5, is given so that larger conservativeness will be obtained.

In actual safety evaluations, these three methods can be combined. Easy application of Method Ⅲ may not be desirable when we cannot justify rationality of the extra bias. It is again emphasized that addition of the extra bias is exceptional and is performed only to make sure that we do not commit Type I error based on the engineering judgment. [17]

The extra bias is not based on the same philosophy as are other regular biases, UC4, which are based on examinations of experimental or numerical observations. The authors recognize a frank criticism that the extra bias may cause “the extra conservatism” and that it is not consistent with a rationalizing approach that is sought in the BEPU method. However, flexibility in the expert (engineering) judgment is important in enhancing practicality of the AESJ-SSE method to be applied in the safety evaluation of nuclear power plants.

The prior conservativeness such as a basic enveloping premise as DBEs is ensured in establishing event scenarios (boundary and initial conditions, system availabilities, operators’ actions, etc.). Consideration of these two types of conservativeness along with the high CLOP value forms the total conservatism of the AESJ-SSE method.

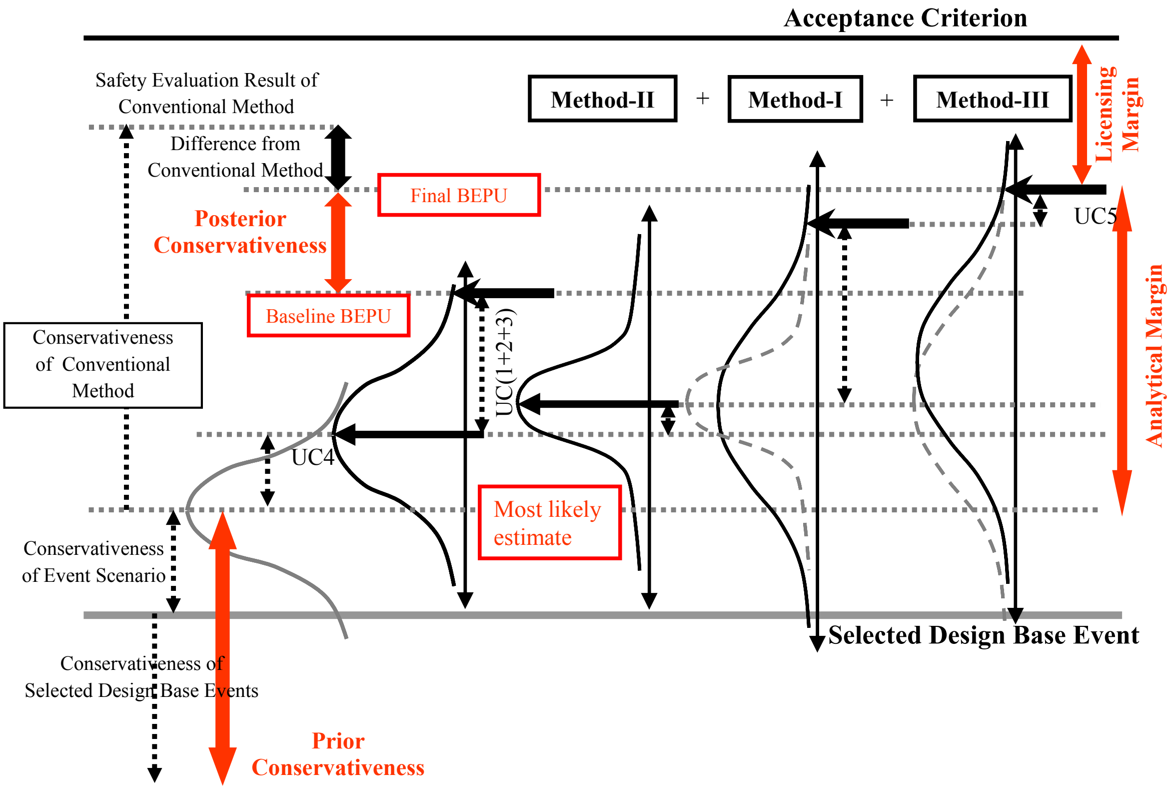

Fig.7 Three basic procedures of obtaining posterior conservativeness

5.3 Actual examples of conservativeness

In Table 2, examples of classifying uncertainties in actual plant analyses are shown for a large break LOCA in PWRs and anticipated operational occurrences in BWRs. Particularly, UC5 is not normally considered in BWR AOOs while it is considered in PWR LOCA. The posterior conservativeness can be included in these uncertainty components. Major differences of these two cases arise from biases due to computational modeling relating to constitutive equations, UC4, and variabilities and biases due to scaling effects, UC2 and UC4. While bounding assumptions are implemented in important models in PWR LOCA analyses, a non-biased modeling philosophy is generally sought for in BWR AOO analyses. As for uncertainties due to scaling effects, they are quantified based on SETs and IETs for PWR LOCA analyses. In case of BWR AOO analyses, it is often possible to perform full-scale IETs for identifying those physical phenomena having important influences on safety variables. When experiments for representative transient scenarios are performed in actual plants, there is a small need of utilizing IETs for quantifying scaling effects. These differences of two sample cases cannot be attributed to differences in plant types but to differences between accidents and AOOs in availability of full-scale experimental data.

Table 2. Classification of uncertainties and their relation with posterior conservatism for PWR-LOCA and BWR-AOO

		Large Break LOCA in PWR		AOO in BWR	
		Uncertainties Expressed by PDFs (Objectives in Methods I and II)	Biases Determined based on Bounding Conditions, etc. (Objectives in Method II)	Uncertainties Expressed by PDFs (Objectives in Methods I and II)	Biases Determined based on Bounding Conditions, etc. (Objectives in Method II)
Models	BE Code or Component Models	(UC1, UC4) Quantified based on PIRT and Validations (OST, SET)	(UC4) Bypass Time of ECCS Steam Binding Effects Core Three Dimensional Flow	(UC1, UC4) Quantified based on PIRT and Validations (OST, SET)	(UC4) Quantified based on Validations (SET, IET) N/A
	Scale Effects	(UC2, UC4) Quantified based on Validations (SET, IET)	(UC4) Quantified based on Validations (SET, IET)	(UC2, UC4) Quantified based on Validations (SET, IET, and Plant Tests)	(UC4) Quantified based on Validations (SET, IET)
Boundary and Initial Conditions		(UC3, UC4) Core Power, etc.	(UC4) Plugging Ration in S/G Linear Heat Generation Rate in Low Power Region of Core	(UC3, UC4) Core Power	(UC4) Core Thermal-hydraulic Conditions Injection Cold Water Temperature
Extra Bias based on Engineering Judgment (Objectives of Method III)		(UC5) When the response surface method is applied in combination with TRAC/PF1, an extra bias can be included with taking into account of those effects resulting from hot channel, Forslund-Rohsenow correlation, entrainment, ECC bypass, nitrogen, etc.		(UC5) There is no extra bias.	
Prior conservativeness in -License Requirements -Event Scenarios		Location of Break Point Onset Signal of ECCS Response Systems except for Power Supply and ECCS Conservative Assumptions of System Failures Operators' Action		Malfunction of Turbine Bypass Valves Malfunction of Control Systems Loss of Off-Site Power Supply Conservative Assumption of Instrumentations and Safety-Guard Systems	

6. SUMMARY AND CONCLUSIONS

1) In the AESJ-SSE method, the analytical margin was reconstructed by replacing the conventional ambiguous conservatism with a synthesis of quantified uncertainties that leads to a more transparent definition of an appropriate degree of conservatism.
2) In the analytical margin, a certain amount of the posterior conservatism is added with recognizing intimate relationships with state-of-knowledge. This posterior conservatism can be incorporated into the safety evaluation in a combination of the following three ways, (1) by broadening uncertainty ranges of variability relevant to uncertainty objects, (2) by employing more disadvantageous biases relevant to uncertainty objects and (3) by adding an extra bias to the safety evaluation results.
3) Examples of classifying uncertainties in actual plant analyses are shown for a large break LOCA in PWRs and anticipated operational occurrences in BWRs.
4) An amount of the posterior conservatism, being related to state of relevant engineering knowledge, is determined through quantification of the epistemic uncertainties and can be decreased in accordance with enhancements of state-of-knowledge in modeling, inputs and experimental technologies.

In the AESJ-SSE method, a concept of relating the epistemic uncertainties with the posterior conservativeness was given. As the original CSAU does, this standard specifies a basis framework or a road map to realize the BEPU method, but with a clearer concept of the conservatism. Therefore, there are a range of options in applying this standard in actual safety issues. One thing that should be noted is that the highest quality of the “best-estimate” code and a highest degree of state-of-knowledge are not essential conditions as far as they conform to each requirement specified in the standard. However, incompleteness in these aspects is quantified as a form of the posterior conservativeness. Based on this concept, efforts in improving the “best-estimate” code and enhancing state-of-knowledge will be compensated by reducing the posterior conservativeness.

ACKNOWLEDGMENTS

The Authors would like to show their gratitude to the members of the Subcommittee on the Statistical Safety Evaluation Methods of AESJ. Many of important ideas described in this paper were created in discussions with them.

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