Risk-informed Safety Margin Characterization for A Large Break Loss-of-coolant Accident of Nuclear Power Plants and Associated Peak Cladding Temperature Margin Evolution

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Abstract

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The evaluation of methodology for large break loss of coolant accident (LBLOCA) licensing analysis involves two kinds of methodologies, namely deterministic methodology and risk-informed methodology. In the deterministic methodologies required for design-basis LBLOCA analysis, only epistemic or calculation uncertainty is addressed by either the conservative appendix K approach or the BEPU approach. Calculation uncertainty generally consists of physical model uncertainty and plant status uncertainty. In the risk-informed methodology, not only the epistemic uncertainty but also the aleatory are addressed by conducting a peak cladding temperature (PCT) load spectrum of LBLOCA.

According to the existing 10 CFR50.46, LBLOCA is one of the most essential design-basis accidents (DBA) and a deterministic methodology shall be applied to perform LBLOCA analysis based on a so-called surrogate sequence. Without considering how low this sequence occurrence probability is, this surrogate sequence satisfies all the required licensing

assumptions. However, in the to-be-issued 10 CFR 50.46a, the LBLOCA will be categorized as accidents beyond design basis and the peak cladding temperature margin shall be evaluated in a risk-informed manner. According to the risk-informed safety margin characterization methodology (RISMC), a process has been suggested to evaluate the risk-informed PCT margin. Following the RISMC methodology, a load spectrum of peak cladding temperature for LBLOCA has been generated for the Taiwan's Maanshan Nuclear Power plant and 14 probabilistic significant sequences have been identified. It was observed in the load spectrum that the conditional PCT generally ascends with the descending sequence occurrence probability. With the load spectrum covering both aleatory and epistemic uncertainties, the risk-informed PCT margin can be evaluated by either expecting value estimation method or sequence probability coverage method. It was found that by comparing with the traditional deterministic methodology, the PCT margin evaluated by the RISMC methodology can be enlarged by 38.3-42.6 K. Besides, to have a cumulated occurrence probability over 99% in the load spectrum, the occurrence probability of the sequence referred is about $5.07*10^{-3}$, whereas for the traditional surrogate or licensing sequence generally applied in the deterministic methodology, the occurrence probability is only about $5.46*10^{-5}$.

Finally, observed from the evolution of LBLOCA methodologies, the safety margin of a LBLOCA can be released from traditional Appendix K methodology by (i) relaxing plant

bounding state assumption (DRHM), (ii) performing realistic LOCA analysis with statistical consideration of both model uncertainties and plant status uncertainties (BEPU), and (iii) relaxing licensing sequence assumption and evaluating the peak cladding temperature margin in a proper risk-informed manner (RISMC).

Key words: PCT margin, Deterministic, Best-estimate, Uncertainties, Risk-informed, Licensing sequence, Load spectrum

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Nomenclature

ABBREVIATIONS

BELOCA	The Best-Estimate LOCA
BEPU	Best-estimate plus uncertainty quantification methodology
CCPs	Centrifugal charging pumps
CCW	Component cooling water
CDF	Core Melt Frequency
CHF	Critical heat flux
CSAU	Code, scaling, applicability ad uncertainty
CPCT	Conditional peak cladding temperature
CSS	Containment spray system
DBA	Design-basis accidents
DRHM	Deterministic-realistic hybrid methodology
ECCS	Emergence Core Cooling System
FSAR	Final Safety Analysis Report
HHSI	High Head Safety Injection
LBLOCA	Large Break Loss of Coolant Accident
LHSR	Low-head Safety Recirculation
LOCA	Loss of Coolant Accident
LHSI	Low Head Safety Injection
PCT	Peak Cladding Temperature
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PIRT	Phenomena Identification Ranking Table
PSA	Probabilistic Safety Assessment
PWR	Pressurized water reactor
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RISMC	Risk-informed Safety Margin Characterization
RPS	Reactor Protection System
RWST	Refueling-Water Storage Tank
SBLOCA	Small Break Loss of Coolant Accident
SOP	Sequence Occurrence Probability
SP	Sequence Probability

SYMBOLS

β	Confidence level
γ	Tolerance limit
N	Required number of samples
P	Number of output variables
μ_p	Population mean
σ_p	Population standard deviation
μ_s	Sample mean
σ_s	Sample standard deviation
$\sigma_s^2(n-1)$	σ_s^2 under (n-1) degree of freedom
t_α (n-1)	Student t variable at the (1-α) confidence level under (n-1) degree of freedom
$\chi^2_{1-\alpha}(n-1)$	χ^2 variable at the (1-α) confidence level under (n-1) degree of freedom
$PCT_{95/95}$	The PCT statistical upper bounding value determined by the parametric approach
PCT_{order}	The PCT statistical upper bounding value estimated by the non-parametric order statistic method

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Chapter 1. Preface

For general design basis accidents (DBA), such as Small Break Loss of Coolant Accident (SBLOCA) and Large Break Loss of Coolant Accident (LBLOCA), the traditional deterministic safety analysis methodologies are always applied to analyze events based on a so called surrogate or licensing sequence, without considering how low this sequence occurrence probability is. In the traditional deterministic licensing safety analysis for DBA events, epistemic or calculation uncertainty which involves both model uncertainty and plant status uncertainty, also needs to be considered bases on the chosen surrogate sequence. According to the 10 CFR50.46 (USNRC, 1988), two kinds of deterministic methodologies are accepted for design-basis LBLOCA licensing analysis, namely conservative Appendix K methodology (USNRC, 1974) and best-estimate plus uncertainty quantification (BEPU) methodology (Boyack, 1989). Before 1988, only the conservative Appendix K methodology was allowed to perform the LBLOCA licensing analysis. Whereas, in the revised 10 CFR 50.46, BEPU methodology has been allowed and regulatory guide 1.157 (USNRC, 1989) clearly states how to quantify associated calculation uncertainty. Although BEPU methodology is legally allowed to replace the conservative Appendix K methodology, it is still a revised deterministic methodology based on a predetermined licensing sequence. In the current advanced commercial BEPU licensing safety analysis methodologies (Westinghouse, 2005) (Martin, R.P., 2005) (Framatome ANP, 2001), only epistemic uncertainty is considered which involves both best-estimate mechanistic models and realistic plan status parameters.

Regarding the deterministic LBLOCA methodologies, the peak cladding temperature (PCT) margin quantified by the traditional appendix K methodology with conservative appendix K models and bounding plant parameters can be enlarged by 41.5 K (Chou, 2014) with the deterministic-realistic hybrid methodology (DRHM), in which conservative Appendix K models and realistic plant parameters are utilized. It was noted that the PCT margin released by realistic plant parameters can be about 1/4-1/5 of the margin generated by a full-scoped BEPU methodology with both best-estimate models and realistic plant parameters.

However, according to the to-be-issued 10 CFR 50.46a (USNRC, 2010a), “alternative acceptance criteria for emergency core cooling systems for light water nuclear power reactors,” any Loss of Coolant Accident (LOCA) with a break size greater than the transition break size (USNRC, 2010b) can be considered as an accident beyond the design basis. As stated in paragraph (e) (3) of the to-be-issued10 CFR 50.46a, calculations for LBLOCA may take credit for the availability of offsite power and do not require the assumption of a single failure. Moreover, realistic initial conditions and the availability of non-safety-related equipment may be assumed if supported by plant-specific data or analysis. As also stated in the to-be-issued 10 CFR 50.46a, any applicant, permit holder, or licensee or other entity who wishes to make changes enabled by this new rule, to the facility, facility design, or procedures or to the technical specifications shall perform a risk-informed safety margin evaluation. As required, when evaluating the risk-informed safety margin, the uncertainties considered should include phenomenology, modeling, plant construction, plant operation, etc. (USNRC, 2010c). Therefore, the risk-informed safety margin refers to a view of the margin based on a broader perspective than the safety margin determined by traditional deterministic LOCA methodologies. According to the proposed 10 CFR 50.46a, statements about the margin should have meaning not only with respect to a design-basis event sequence, but more generally with reference to a group of success sequences, as shown in Figure 1-1.

In the to-be-issued 10 CFR 50.46a, the LBLOCA will be categorized as accidents beyond design basis and the PCT margin shall be evaluated in a risk-informed manner. In a risk-informed methodology, a probabilistic load spectrum of PCT needs to be conducted, as shown in Figure 1-2, to evaluate the risk-informed PCT margin. With the load spectrum covering both aleatory and epistemic uncertainties, the contribution of the PCT margin from all success sequences can be considered to be either weighted by the sequence occurrence probability, or evaluated by the sequence probability coverage (Liang, 2016).

In this work, according to the risk-informed safety margin characterization (RISMC) methodology, a process has been suggested to evaluate the risk-informed PCT margin. Following the RISMC methodology, a load spectrum of PCT for LBLOCA has been generated for the Taiwan's Maanshan Nuclear Power plant and 14 probabilistic significant sequences have been identified. It was observed in the load spectrum that the conditional PCT generally ascends with the descending sequence occurrence probability. It was also found that by comparing with the traditional deterministic methodology, the PCT margin evaluated by the RISMC methodology can be greater by 38-43 K. Besides, to have a cumulated occurrence probability over 99% in the load spectrum, the occurrence probability of the sequence referred is about $5.07*10^{-3}$, whereas for the traditional surrogate or licensing sequence generally applied in the deterministic methodology, the occurrence probability is only about $5.46*10^{-5}$. Finally, the evaluation of methodologies, from conservative Appendix K, best-estimate plus uncertainty quantification to risk-informed safety margin characterization, for a

LBLOCA licensing analysis will be addressed and discussed, and the PCT margin enlarged by different methodologies will be compared.

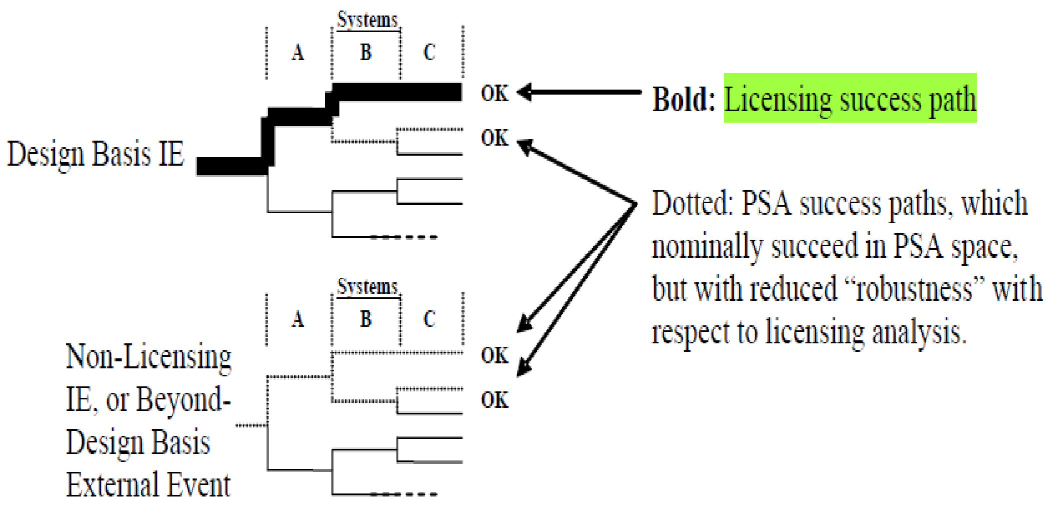

Figure 1-1. Deterministic Approach versus Risk-informed Approach (IAEA, 2008)

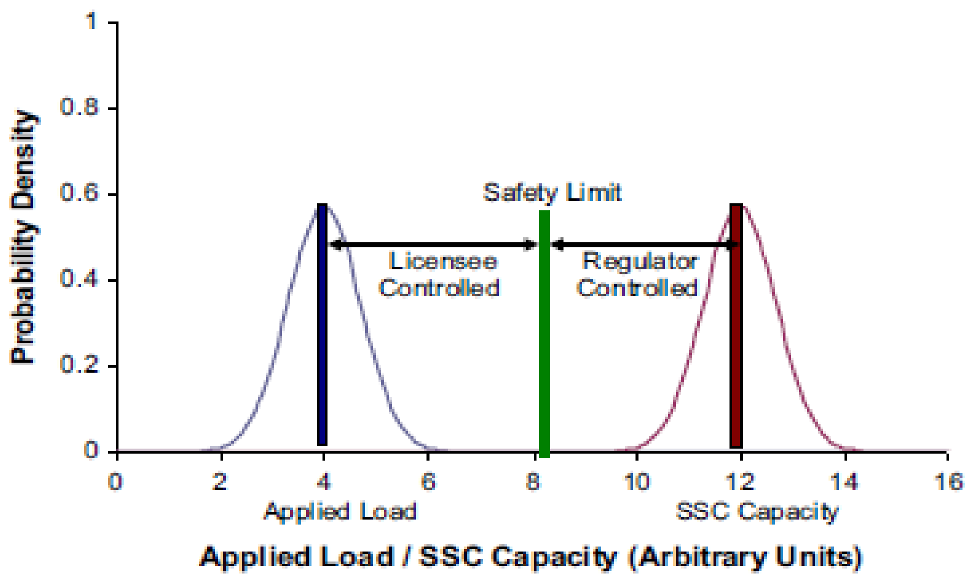

Figure 1-2. Load Spectrum (Hess, 2009)

Chapter 2. Traditional Methodologies for Safety Analysis

Traditionally, there are two kinds of methodologies involved for reactor safety analysis, namely deterministic methodologies and probabilistic methodology. Currently, deterministic methodology is applied to perform licensing analysis of design basis accidents listed in Chapter 15 of Final Safety Analysis Report (FSAR) of nuclear power plants. While probabilistic methodology is applied to quantify failure rate of nuclear system, such as core damage frequency (CDF) or large early release frequency (LERF), with event tree and fault tree analysis techniques. In this chapter, the traditional deterministic licensing safety analysis for LBLOCA and Traditional Probabilistic Safety Assessment (PSA) analysis will be introduced separately in the following sections.

2.1 Deterministic licensing safety analysis for LBLOCA

Regarding the deterministic methodology, evaluation of safety of a DBA can only be performed based on a surrogate sequence to satisfy all the licensing assumption requirements, such as single failure criteria, no credit taken for non-safety systems and loss of off-site power, etc. Although the occurrence probability of such a licensing sequence can be very low, it does satisfy all the required licensing assumptions for a DBA safety analysis. And the design safety margin can only be defined by the difference between safety limit and the calculated figure of merit based on proper deterministic licensing methodology.

In the traditional deterministic licensing safety analysis for DBA events, only epistemic or calculation uncertainty which involves both model uncertainty and plant status uncertainty, needs to be considered based on the chosen surrogate sequence. According to the 10 CFR50.46 (USNRC, 1988), two kinds of deterministic methodologies are accepted for design-basis LBLOCA licensing analysis, namely conservative Appendix K methodology (USNRC, 1974) and best-estimate plus uncertainty quantification (BEPU) methodology (Boyack, 1989). Before 1988, only the conservative Appendix K methodology was allowed to perform the LBLOCA licensing analysis. Whereas, in the revised 10 CFR 50.46, BEPU methodology has been allowed and regulatory guide 1.157 (USNRC, 1989) clearly states how to quantify associated calculation uncertainty. The historical prospective of LBLOCA regulation is stated in Table 2-1.

Although the BEPU methodology is legally allowed to replace the conservative Appendix K methodology, it is still a revised deterministic methodology based on a predetermined licensing sequence. In the current advanced commercial BEPU licensing safety analysis methodologies (Westinghouse, 2005) (Martin, R.P., 2005) (Framatome ANP, 2001), only epistemic uncertainty is considered which involves both best-estimate mechanistic models and realistic plan status parameters.

The LOCA analytical results with licensing methodologies of either deterministic or risk-informed approaches shall all satisfy the acceptance criteria for emergency core cooling systems for light water nuclear reactors. Those associated acceptance criteria involve；

(1) Peak cladding temperature

The calculated maximum fuel element cladding temperature shall not exceed 2200 °F.

(2) Maximum cladding oxidation

The calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation. As used in this subparagraph total oxidation means the total thickness of cladding metal that would be locally converted to oxide if all the oxygen absorbed by and reacted with the cladding locally were converted to stoichiometric zirconium dioxide. If cladding rupture is calculated to occur, the inside surfaces of the cladding shall be included in the oxidation, beginning at the calculated time of rupture. Cladding thickness before oxidation means the radial distance from inside to outside the cladding, after any calculated rupture or swelling has occurred but before significant oxidation.

(3) Maximum hydrogen generation

The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the fuel, excluding the cladding surrounding the plenum volume, were to react.

(4) Coolable geometry

Calculated changes in core geometry shall be such that the core remains amenable to cooling.

(5) Long-term cooling

After any calculated successful initial operation of the Emergence Core Cooling System (ECCS), the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

It should be noted that the acceptance criteria of ECCS performance evaluation include PCT, oxidation limit and hydrogen generation. Each criterion needs to be justified separately. In this dissertation, we are focusing on risk-informed PCT margin characterization to demonstrate the RISMC methodology. The characterization of other safety parameter in a risk-informed manner can go through the same process suggested in our work.

2.1.1 Traditional Appendix K methodology

Historically the initial licensing procedures that governed analysis were established in 1974 when the USNRC published rules for LOCA analysis in 10 CFR 50.46 and Appendix K. Analysis following these rules is known as a (very) conservative approach. In the traditional Appendix K methodology, not only all the conservative physical models required by the Appendix K of 10 CFR 50 shall be adopted, but also the conservative plant parameters need to be applied to define a plant bounding status for LBLOCA licensing analysis. According to the Appendix K of 10 CFR 50, there are totally about 30 individual requirements and those conservative requirements can be divided into four groups；

(1) Source of heat during LOCA

Associated consideration includes (a) initial operating power, (b) power distribution, (c) initial stored energy in fuel, (d) fission heat, (e) decay of actinides, (f) fission product decay, (g) water metal reaction, (h) reactor internal heat transfer, and (i) Pressurized water reactor (PWR) primary-to-secondary heat transfer.

(2) Swelling and rupture of cladding and fuel rod thermal parameters

Each evaluation model shall include a provision for predicting cladding swelling and rupture from consideration of the axial temperature distribution of the cladding and from the difference in pressure between the inside and outside of the cladding, both as functions of time. The degree of swelling and rupture shall be taken into account in calculations of gap conductance, cladding oxidation and embrittlement, and hydrogen generation.

(3) Blowdown hydraulics and heat transfer

Associated consideration includes (a) break spectrum analysis, (b) discharge model, (c) end of blowdown, (d) nodding near break and the ECCS injection points, (e) frictional losses in pipes and other components, (f) conservation of momentum equation, (g) pump model, (h) hot channel cross flow, inlet enthalpy, and core flow smoothing, (i) critical heat flux, (j) nucleate boiling heat transfer lockout during blowdown, (k) post-CHF heat transfer correlations, and

(l) transition boiling heat transfer lockout during blowdown.

(4) Post blowdown hydraulics and heat transfer

Associated consideration includes (a) single failure criterion, (b) containment back pressure, (c) calculation of reflood rate for PWRs, (d) steam interaction with ECC water in PWRs, and (e) refill and refold heat transfer for PWRs.

2.1.2 Best-estimate plus uncertainty quantification methodology (BEPU)

As stated in the current 10 CFR 50.46, realistic LOCA analysis is accepted. However, the uncertainties in the analysis method and input must be identified and assessed so that the uncertainty in the calculated results can be estimated. This calculational uncertainty must be accounted for, so that, when the calculated cooing performance is compared to the acceptance criteria, there is a high level of probability that the acceptance criteria would not be exceeded.

Generally, there three kinds of uncertainty were contributed to the calculational uncertainty, namely code uncertainty, plant status uncertainty and representation uncertainty. The original sources of code uncertainty generally involve conservation equations, closure and constitutive equations, scaling effects, special process and component models and numerical methods. As for origins of the plant status uncertainty, operational uncertainty, measurement uncertainty and fabrication uncertainty are generally involved. Regarding the representation uncertainty, it is originated from different nodding scheme. However, nodding criteria would be fixed when quantifying associated model uncertainty by simulation of appropriate separate-effect experiments or integral-effect experiments. In traditional Appendix K methodology, above three kinds of uncertainties all are conservatively treated by applying conservative Appendix K models, bounding state assumptions and nodding sensitivity studies.

To quantify the calculational uncertainty of a realistic LOCA analysis, a CSAU (code, scaling, applicability ad uncertainty) methodology (Boyack et al., 1989) was suggested and endorsed by the U.S. NRC. 14 steps defined in the CSAU methodology were strictly followed to properly quantify calculational uncertainty, and they are shown in Figure 2-1. Fourteen steps are grouped into three elements；

(I) Element one； requirements and capabilities

Scenario modeling requirements are identified and compared against code capabilities to determine the code’s applicability to the particular scenario and to identify potential limitations. The applicability of a code to the analysis of a transient in Nuclear power plant (NPP) is determined by comparison of the scenario and plant-dictated requirements with the simulation capabilities of the code. This element consists of 6 steps. Six steps include (1) specify scenario, (2) select NPP, (3) identify and rank phenomena, (4) select frozen code, (5) provide complete code documentation, and (6) determine code applicability.

(II) Element two； assessment and ranging of parameters

Code capabilities to calculate processes important to the scenario are assessed against experimental data and to specify ranges of parameters needed for sensitivity studies. The determination of a code's uncertainty must be based on a sufficient data set. Assessment studies are particularly important for the minimum data base will necessarily include both separate and integral effects tests. To develop the assessment matrix, the Phenomena Identification Ranking Table (PIRT) is reviewed and experiments selected that best address the important phenomena and component. This element consists of 4 steps. Four steps involve (7) establish assessment matrix, (8) define nodalization for NPP calculation, (9) determine code and experiment accuracy, and (10) determine effect of scale.

(III) Element three； sensitivity and uncertainty analysis

The effect of individual contributors to total uncertainty is obtained and the propagation of uncertainty through the transient is properly determined. The ultimate objective of the CSAU process is to provide a simple, singular statement of uncertainty with the primary safety criteria used as the basis for determining the acceptability of a specific reactor design. This element consists of 4 steps. Four steps involve (11) determine effect of reactor input parameters and state, (12) perform NPP sensitivity calculations, (13) combine biases and uncertainties, and (14) total uncertainty to calculate specific scenario in a specific NPP.

Typical PCT responses of different trials from LBLOCA BEPU analysis were shown in Figure 2-2, and a general process of BEPU analysis can be depicted in Figure 2-3.

2.1.3 Deterministic-realistic hybrid methodology (DRHM)

Considering uncertainties in a best-estimate LOCA analysis, generally there are two kinds of uncertainties required to be identified and quantified, namely model uncertainties and plant status uncertainties, as depicted in Figure 2-3. Particularly, it will take huge effort to systematically quantify individual model uncertainty for a best-estimate LOCA code, such as RELAP5-3D (Jonson, 1989), TRAC (Liles, 1981), CATHARE (Bestion, 1990), et al. As recommended by the U.S. NRC, the CSAU methodology was endorsed by USNRC to quantify the calculation uncertainty in the

PCT evaluation. As stated in the CSAU methodology, there are three major elements involving 14 steps to quantify LBLOCA calculation uncertainty. These three elements are (1) requirements and capabilities, (2) assessment and ranging of parameters, and (3) sensitivity and uncertainty analysis.

Instead of applying a full-range The Best-Estimate LOCA (BELOCA) methodology to cover both model and plant status uncertainties, a deterministic-realistic hybrid methodology (DRHM) (Liang, 2011) was developed to support the LOCA licensing analysis with RELAP5-3D/K. In the DRHM methodology, Appendix K deterministic evaluation models are still adopted to ensure model conservatism, while BEPU methodology is applied to quantify the effect of plant status uncertainty on PCT calculation.

In the DRHM methodology, to statistically consider the plant status uncertainties six sequential steps are included, which are (1) ranking of plant status parameters, (2) ranging of plant status uncertainties, (3) development of a run matrix by random sampling, (4) using the conservative E.M. model to perform the LOCA analysis of each trial, (5) statistical analysis of the calculated figure of merit (PCTs), and (6) determining licensing value of PCT. The DRHM procedure is presented in Figure 2-4. Each step is elaborated as follows；

(1) Ranking of Plant Status Parameters

Essential plant parameters should be identified and ranked to limit the scope of uncertainty analysis. Three kinds of elements contribute to the uncertainty of a particular plant status parameter, namely measurement uncertainty, fabrication uncertainty and normal operational range. Typical PWR essential plant status parameters are listed in Table 2-2. The RCS flow and containment pressure are conservatively set as the thermal design flow and atmospheric pressure respectively. Therefore, they are not included in Table 2-2.

(2) Ranging of Plant Status Uncertainties

To define the uncertainty of a plant parameter, not only the uncertainty range but also the distribution function should be specified. The major plant status parameters generally define the system initial conditions, core initial conditions, ECCS initial conditions, boundary conditions and system settings. The uncertainty ranges of major plant parameters listed in Table 2-2 are directly cited from Westinghouse BELOCA analysis for Taiwan's Maanshan PWR (Taiwan Power Company, 2013).

(3) Development of a Run Matrix by Random Sampling

Once the major system parameters have been identified and ranged, random sampling of each parameter needs to be performed to generate a run matrix. In each trial, each plant parameter listed in Table 2-2 will be randomly selected within its' uncertainty range. Therefore, the uncertainty of each parameter can be randomly combined in each trial. Typical parameter samplings of Tavg, P, FQ and FΔH are presented in Figure 2-5. The run matrix should consist of trials of either 59 sets, 93 sets or 124 sets according to the order statistic method (David and Nagaraja, 1980).

(4) Using the Conservative E.M. Model to Perform LOCA Analysis of Each Trial

The conservative plant E.M. model should be applied to analyze each trial to calculate the associated PCT. RELAP5-3D/K, an Appendix K version of the RELAP5-3D, was adopted to build a plant specific model.

(5) Statistical Analysis of the Calculated Figure of Merit (PCTs)

Once the PCT of each trial is calculated, both non-parametric (David, 1980) and parametric (Devore, 2004) statistical approaches can be applied to determine the statistical upper tolerance limit. The non-parametric approach can conservatively estimate of value of $PCT_{95/95}$, while parametric approach can directly calculate the $PCT_{95/95}$

(i) Non-parametric approach,

In this approach, it is not necessary to identify the distribution of PCT outcomes. If only one outcome is cited from each trail, the Wilk's formula (David, 1980) can be applied to calculate the estimator of the 95/95 upper tolerance limit.

$$\beta = 1 - \gamma^{N} \tag{2-1}$$

where β is the confidence level, γ is the tolerance limit and N is the required number of samples. According to the Wilk's formula, the 95/95 value can be conservatively estimated by the greatest PCT value from 59 trials, the 2nd highest PCT value from 93 trials, or the 3rd highest PCT value from 124 trials. That is；

$$Y_{95/95} \approx Y_{1st}(59) \text{ or } Y_{95/95} \approx Y_{2nd}(93) \text{ or } Y_{95/95} \approx Y_{3rd}(124) \tag{2-2}$$

If more than one outcome needs to be cited from each trial, Guba's formula (Guba, 2003) can be used；

$$\boldsymbol{\beta = \sum_{j=0}^{N-P} \frac{N!}{(N-J)!J!} \gamma^{j} (1-\gamma)^{N-j}} \tag{2-3}$$

where N is the sample size and P is the number of output variables. If the output variable is only one, then the Guba's formula will be reduced to Wilk's formula.

(ii) Parametric approach

In this approach, the distribution of outcome needs to be identified by using fitting test, such as goodness-of-fitting test. If a certain distribution can be identified, such as normal distribution or uniform distribution, the population mean (μ_p) and population standard deviation (σ_p) can be projected by the sample mean (μ_s) and the sample standard deviation (σ_s) under a certain confidence level, such as 95%. If a normal distribution can be assumed by the goodness-of-fitting test, then

$$\mathbf{P}\left\{-\mathbf{t}_{\boldsymbol{\alpha}}(\mathbf{n}-\mathbf{1}) \leq \left[{(\boldsymbol{\mu}_{\mathbf{s}}-\boldsymbol{\mu}_{\mathbf{p}})}\Big/{(\boldsymbol{\sigma}_{\mathbf{s}}/\sqrt{\mathbf{n}})}\right]\right\} = \mathbf{1}-\boldsymbol{\alpha} \tag{2-4}$$

and

$$\mathbf{P}\left\{\boldsymbol{\chi}^{\mathbf{2}}_{\mathbf{1}-\boldsymbol{\alpha}}(\mathbf{n}-\mathbf{1}) \leq \left[{\boldsymbol{\sigma}^{\mathbf{2}}_{\mathbf{s}}(\mathbf{n}-\mathbf{1})}\Big/{\boldsymbol{\sigma}^{\mathbf{2}}_{\mathbf{p}}}\right]\right\} = \mathbf{1}-\boldsymbol{\alpha} \tag{2-5}$$

are all satisfied as 1-α confidence level. Therefore, μ_p and σ_p under the 1-α confidence level can be expressed as；

$$\boldsymbol{\mu}_{\mathbf{p},\mathbf{1}-\boldsymbol{\alpha}} \leq \left[\boldsymbol{\mu}_{\mathbf{s}} + \mathbf{t}_{\boldsymbol{\alpha}}(\mathbf{n}-\mathbf{1}) * \boldsymbol{\sigma}_{\mathbf{s}}/\sqrt{\mathbf{n}}\right] \tag{2-6}$$

$$\boldsymbol{\sigma}^{\mathbf{2}}_{\mathbf{p},\mathbf{1}-\boldsymbol{\alpha}} \leq \frac{\boldsymbol{\sigma}^{\mathbf{2}}_{\mathbf{s}}(\mathbf{n}-\mathbf{1})}{\mathbf{x}^{\mathbf{2}}_{\mathbf{1}-\boldsymbol{\alpha}}(\mathbf{n}-\mathbf{1})} \tag{2-7}$$

where $t_\alpha(n-1)$ is the student t variable at the (1-α) confidence level under (n-1) degree of freedom, and $\chi^2_{1-\alpha}(n-1)$ is χ^2 variable at the (1-α) confidence level under (n-1) degree of freedom. Once μ_p and σ_p can be projected at the 95% confidence level ($\mu_{p,95\%}$, $\sigma_{p,95\%}$), the 95/95 coverage can be directly expressed as；

$$Y_{95/95} = \mu_{p,95\%} + 1.645\,\sigma_{p,95\%} \tag{2-8}$$

(6) Determining the Licensing Value of PCT

If both parametric and nonparametric approaches can be applied to calculate the 95/95 upper tolerance limit, then the maximum value of these two calculations will be defined as the licensing value of PCT. That is；

$$PCT_{Licensing} = \max(PCT_{95/95}, PCT_{order}) \tag{2-9}$$

where $PCT_{95/95}$ is the PCT statistical upper bounding value determined by the parametric approach, and PCT_{order} is the PCT statistical upper bounding value estimated by the non-parametric order statistic method.

2.2 Probabilistic Safety Assessment (PSA) analysis.

General speaking, all uncertainties can be categorized into epistemic uncertainty and aleatory uncertainty. Epistemic uncertainty results from the "imperfect knowledge" regarding values of parameters of the underlying computational model, whereas aleatory uncertainty results from the effect of "inherent randomness" or "stochastic variability". Aleatory uncertainty represents the nondeterministic and unpredictable random nature of the performance of the system and its components. In the current advanced deterministic BEPU licensing safety analysis methodologies (Westinghouse, 2005) (Martin, R.P., 2005) (Framatome ANP, 2001), only epistemic uncertainty is considered which involves both best-estimate mechanistic models and realistic plan status parameters. On the contrary to a surrogate sequence generally applied in traditional deterministic methodologies, to dealing with the aleatory uncertainty, a group of sequences should be identified for a particular initiating event with Probabilistic Safety Assessment (PSA) skill (Henley and Kumamoto, 1981) to account systems or components failure by random probability. In a sense, the aleatory uncertainty causing system and/or component radon failure is systematically considered in PSA event tree and fault tree analysis techniques.

2.2.1 Risk assessment method

PSA models developed for nuclear power plants can provide insights into the contributors to plant safety and a vehicle for marking future decisions on a variety of issues affecting operation and safety. In order to make the PSA to be useful in this way, it is essential that the methods used to develop the plant model and obtain the quantitative results be clearly understood, reproducible, and adaptable. A summary of the methods for the PSA analysis is provided below.

The traditional PSA model is an attempt to describe in logical way the many events that can occur in a nuclear plant following a requirement to shut the reactor down. There is therefore the requirement to evaluate how the equipment and operators perform in order to prevent core melt over the widest possible range of component failure and success. By means of data derived from plant operating experience of nuclear plants, it is possible to estimate the frequency with which these events will occur.

The risk assessment is performed in three stages；

I. Development of plant system and operations model

II. Quantification of core melt sequences

III. Interpretation of results

This process is iterated, in whole and in part, to the extent necessary to ensure that the final results constitute the most accurate model of the plant and reflect a thorough understanding of the most significant aspects of system design and operation. When the quantification phase of analysis is complete, it is necessary to identify the highest core melt frequency and determine what assumptions have been made during the analysis. Most of the methods used in the study are described in detail in the PRA Procedures Guide (USNRC, 1983).

The breakdown of the three phases of the analysis into the various tasks and subtasks is shown in figure 2-6. The three tasks in the first phase are definition of the initiating event leading to reactor trip；establishment of the success criteria for the various system called upon following reactor trip；and delineation of the sequences of events that result from the successes of failures of these systems or from failures on the part of the operator, and that lead to core melt. The model for the latter task is the event tree. Once the various combinations of system failures and successes for a given sequence of events are defined, the frequency of each sequence is then determined from the data on component failure and other failures modeled. This quantification is performed using the appropriate software (such as WinNURPRA 3.0). Finally, the dominant sequences are examined in detail and range of importance, sensitivity, and uncertainly analyses are performed in order to identity the important contributor to core melt.

Initiating events are divided into two types："internal," or those cause either by the failure of component or by personnel action during testing or maintenance；and "external," those arising outside the direct confines of the system and whose occurrence not only leads to reactor trip but also affects the performance of mitigating systems. The analysis thereof involves constructing the various plant models and performing the quantification for the internal events, and then repeating the process for the external events. It can be seen from figure 2-6 that substantial supporting analysis is required. This is described below.

Success Criteria

In order to determine the performance required of system or group of systems, it is first necessary to define "success." It has been defined as keeping the fuel temperature below 1477.6 K and over the long term keeping the containment pressure below its evaluated failure pressure.

It is convenient to consider requirement for success in term of one or more of the following basic functions；

1. Reactivity control.
2. Reactor coolant system boundary overpressure control.
3. Reactor coolant inventory control.
4. Long-term containment heat removal.

Each of the system in the plant, both safety and non-safety grade, is assessed for its capability to perform one or more of the above functions. Finally, the minimal group of systems that can perform the necessary functions to maintain core cooling for each group of initiating event can be defined.

Event Trees

The next step is the analysis is to develop the sequences of events that lead to core melt following the initiating event. The model used to present this information is the event tree shown in figure 2-6. Each tree is developed horizontally by a series of heading. The first heading on the left identifies the initiating event and succeeding ones the various stages in the accident sequence. The latter include those system responses and operator actions specified in the development of the success criteria. There is often a branching of the tree at each point in the sequence that is, below each heading. The upper branch signifies an affirmative answer and lower branch a negative answer to question implicit in the heading. Thus, for a heading like "Bleed and Feed", the upper branch represent the success thereof and the lower branch failure. No branching under a heading means that the system or operator response is irrelevant to the core damage state. The resulting event tree identifies the various paths to core melt as well as the many success paths.

Each of the heading in this tree represents one of the key system identified in the success criteria, or a combination of two or more systems. Each of these systems depends on other systems, hence a failure logical model must be constructed to show the combination of failures that can lead to functional failure. This model is known as function-level fault tree. Such trees can be quite complicated when all functional dependencies, include operator error, are included.

System Modeling (Fault Tree)

As insufficient data exist for determining the probability of failure of each system directly, it is necessary to model the system in a logical way, breaking it down to individual components for which failure data are available or can be estimated. The basic model used in this study as in all other PSA is the fault tree.

The systems for which fault tree models are required are defined in the development of the success criteria and event trees. The list includes the support systems such as instrumentation and control, electric power, cooling, and air. For each system a tree has been developed to the level of individual component failures, either failure to operate failure by being in the wrong position, unavailability due to testing or maintenance, or failure on the part of the operator. The interface between a system such as high-head safety injection system and the electric power, cooling, and instrumentation and combined with that for the front-line system. In the case of instrumentation and electric power, the various trains and subsystem have been modeled to the level of individual relays, sensors, and breakers to ensure that commonalities between systems are now lost.

Human factors

System and functional failure may result from the operator's failure to perform certain functions of his performance of the on correct function. Therefore, operator actions are included in the event and fault trees for internally and externally initiated events. In this analysis, therefore, two types of failure have been clearly identified；

1. Human error occurring prior to the accident.
2. Human error of failure to perform a function in response to an accident.

The first group can be broken down into actions that leave a system in a failed state, such as leaving valves in the wrong position following maintenance, and actions that cause a rector to trip. Moreover, the second group can be broken down into three sets of actions； failing to take the correct action, taking the incorrect actions by stopping an already successful system, or failure to take the appropriate recovery action following a system failure.

2.2.2 Traditional Large LOCA event (AEC, 1987)

The PSA LBLOCA sequence analysis is focusing on the quantification of CDF contributed by an initiating event of LBLOCA. Therefore, the traditional analysis of PSA LBLOCA sequences will include long-term system responses and operator action. While as for the PSA LBLOCA analysis for the risk-informed LOCA PCT safety margin characterization, only short-term LBLOCA phases (blowdown, refill and reflood) will be involved and operator action will not allow.

The sequence of events following a large break LOCA can be divided into four phases； blowdown, refill, reflood, and long-term cooling. Appendix B1 (AEC, 1987) illustrates the sequence of events and timing for each of the phases and provides data on long-term containment response. After the safety inject signal (less 1 sec), two high-head pumps and two Residual Heat Removal (RHR) pumps should automatically start. For the success criteria, to prevent damage to the fuel, two accumulators and the at least one low-head RHR pump must inject water to reflood the core Reactor Coolant System (RCS). The High Head Safety Injection (HHSI) system cannot inject sufficient water to reflood the core fast enough and at least one low-head pumps. The steam blowdown raises the containment pressure high enough to actuate the containment spray system (CSS) (about 20 sec).

The Refueling-water Storage tank (RWST) decrease rapidly as injection continues with full flow from two centrifugal charging pumps (CCPs), two RHR pumps, and two containment spray pumps, all of which take suction from the RWST in the injection phase. When the RWST low-low level alarm occurs, the operator must change over to recirculation. The low-low level signal automatically opens the engineered-safety-feature recirculation sump to RHR pump suction valves both on train A and train B, and the operators are required to close the RWST to the RHR pump and CCP suction valves. It is no essential for the operator to close the RWST suction valves immediately, as the pressure in the containment and thus at the pump suction is well above atmospheric pressure and because of this, water is not being sucked from the RWST. The two high-head pumps and the two containment spray pumps keep on drawing water from RWST. As there is no automatic opening of the containment spray sump valves, the operator has to manually open these valves and close the RWST spray system suction valves before the RWST in empty. According to analysis, the low-low level is reach in 24 min, and the time from that level to empty is 14 min.

A large break in one of the cold legs can have an impact on the ability to cool the core in the long term；an extended period of boiling in the core may lead to the precipitation of sufficient boron to block flow through the core, thereby producing a loss of cooling and, ultimately, core damage. This can occur because most of the flow into the cold legs does enter the core but drains through the broken leg. To counteract the precipitation of boron, it is necessary to change over to hot-leg recirculation, thereby producing reverse flow through the core sometime before 24 hours have passed. The exact timing is not critical, and clear instructions concerning the changeover are given in the procedures.

Another impact of the large cold-leg break is a sharp reduction in the direct transfer of decay heat to the circulation sump water that bypasses the core. Most of this water is released into the containment as stem, thus accelerating the increase in containment pressure.

Although the spry system is not essential for preventing containment overpressure in a large LOCA, its operation is critical to the required initiation of long -term containment heat removal is response to a cold-leg break. In the long term, decay heat is removed from the containment by means of either RHR heat exchange of fan cooler. Both of them rely on cooling by component cooling water (CCW). Failure of the CSS reduces the transfer of heat to the sump water and hence the RHR heat exchanger is less effective；thus, only the fan cooler is capable or removing heat from the containment. According to calculations, the containment pressure reaches 120 psig in 21 hours if neither the CSS nor the fan cooler is actuated. Assuming the CSS actuates and runs, containment pressure does not reach 120 psig until about 28 hours into the event. Containment spray system performance is a very important consideration in the development of source terms.

Figure 2-7 shows the event tree for a large LOCA. Note that the reactor protection system (RPS) is not required for successful mitigation, as the rapid depressurization and steam voiding render the reactor subcritical. The success criteria for each of the functions are summarized below.

Heading I：Injection of two effective accumulators

The accumulators are designed to injection when RCS pressure drops to 600 psig.

For a double-ended-rupture LOCA, this occurs about 11 sec after the break and accumulators empty about 45 sec. For a large LOCA, two effective accumulators are required to inject. Injection flow into the ruptured loop is not considered to be effective. Although failure of accumulator injection may not lead to core meltdown if low-head pump injections, it dose cause some fuel damage and thus is considered a core melt sequence in LBLOCA. The success criterion is as follows：

Two of two effective accumulators inject into the undamaged loops.

Heading J：Low-head safety injection

For successful injection, one of two RHR pumps must inject water with in 1 min. In the standby mode, the pumps are aligned to take suction from the RWST. No credit is taken for manual initiation of the pumps because of the short time available for such action. Since RWST above the low-low level, in the event of the largest break and full injection flow, the low-low level alarm occurs after approximately 24 min. However, in the case of the minimal injection flow (with one RHR pump and no containment spray pumps), it occurs at 110 min. Thus, the time used for determining the pump-running failure probability is based on the latter running time.

The success criterion is as follows：

One of two RHR pumps automatically starts and injects water into one unruptured leg of the RCS for 2 hours.

Heading H：Low-head safety recirculation

When the RWST low-low level alarm setpoint is reached, the RHR sump suction valves automatically open. As the containment pressure is much higher than that of the RWST (i.e., atmospheric pressure) the sump water is circulated through the RCS. The high-head pumps and containment spray pumps continue to take suction from RWST. At the low-low level alarm setpoint, 14300 gal remain in the RWST and, therefore, to avoid failure of the high-head pumps and possible ingress of air into the recirculation system when the containment pressure drops to around atmospheric pressure, the operator is required to isolate the RHR and containment spray pump suctions from the RWST before it is empty. The timing for this action is 14 min. However, since containment pressure is higher than atmospheric pressure for a very long time, isolation of the RWST from RHR is not required for successful low-head safety recirculation.

The success criterion for low-head safety recirculation is as follows：

One train of RHR sump suction valves automatically open on an RWST low-low level signal. One RHR pump operates for 24 hours in the low-head recirculation mode, taking suction from the containment sump and discharging to one unruptured cold leg of the RCS.

Heading F：Containment spray system recirculation

The CSS is not required to operate to prevent core melt. It is included in the event tree, however, because in the event of a large cold-leg break it significantly affects to the timing of cations prior to containment failure. After such a break, the decay heat is essentially transferred directly to the containment and not both the sump water and the containment, for the reasons cited earlier. If the containment spray is available, then the containment atmosphere and sump water remain in equilibrium and the pressure rise is more gradual, allowing a much longer time in witch to initiate long-term heat removal. More important, following successful containment spray recirculation, either the RHR heat exchanger or fan coolers can remove heat from the containment； with the CSS inoperative, the fan coolers are the only effective heat removal system. The success criterion for containment spray is as follow：

The operator performs changeover to recirculation in 14 min after the RWST reaches the low-low level. One containment spray train operates in the recirculation mode for 24 hours, taking suction from the containment sump and discharging through one header.

Heading G：Long-term containment heat removal

Containment heat removal can be accomplished by either of two system： the RHR system or the containment fan coolers. In each case one train or unit is adequate to prevent containment overpressure. The two sequences in the event tree following successful changeover to low-head safety recirculation (LHSR) are success and failure of containment spray. For the latter case, the RHR heat exchanger is considered to be ineffective. If both the fan coolers and the CSS fail to operate, changeover to hot-leg recirculation earlier (less than 20 hours into the event) can prevent early containment failure, and decay heat can be removed by the RHR heat exchanger. As these sequence do not make a significant contribution to the overall core melt frequency, this level of detail has not been modeled. The success criteria for this function are as follow：

For successful containment spray operation：

One train of the RHR heat exchanger system or one unit of the containment fan coolers is initiated within 28 hours following the successful establishment of recirculation.

For unsuccessful containment spray operation：

One unit of the containment fan coolers is initiated within 21 hours and operates for 24 hours.

Heading H_H：Low-head hot-leg recirculation

To avoid channel blockage due to boron precipitation, the operator is required to transfer from cold-leg recirculation to hot-leg recirculation within 24 hours into the event. Failure of the changeover results in core damage, bit core meltdown is unlikely. In the fault tree for this top event, only the operator actions and the performance of the associated valves are modeled. Failure of the RHR pump to run for 24 hours is considered in the modeling of low-head (cold-leg) recirculation, hence not in this function. The succeed criterion for changeover to hot-leg recirculation is as follow：

The operator performs the necessary to change over to hot-leg recirculation before core channel blockage occurs. According to the procedure, he takes this action approximately 24 hours into the event.

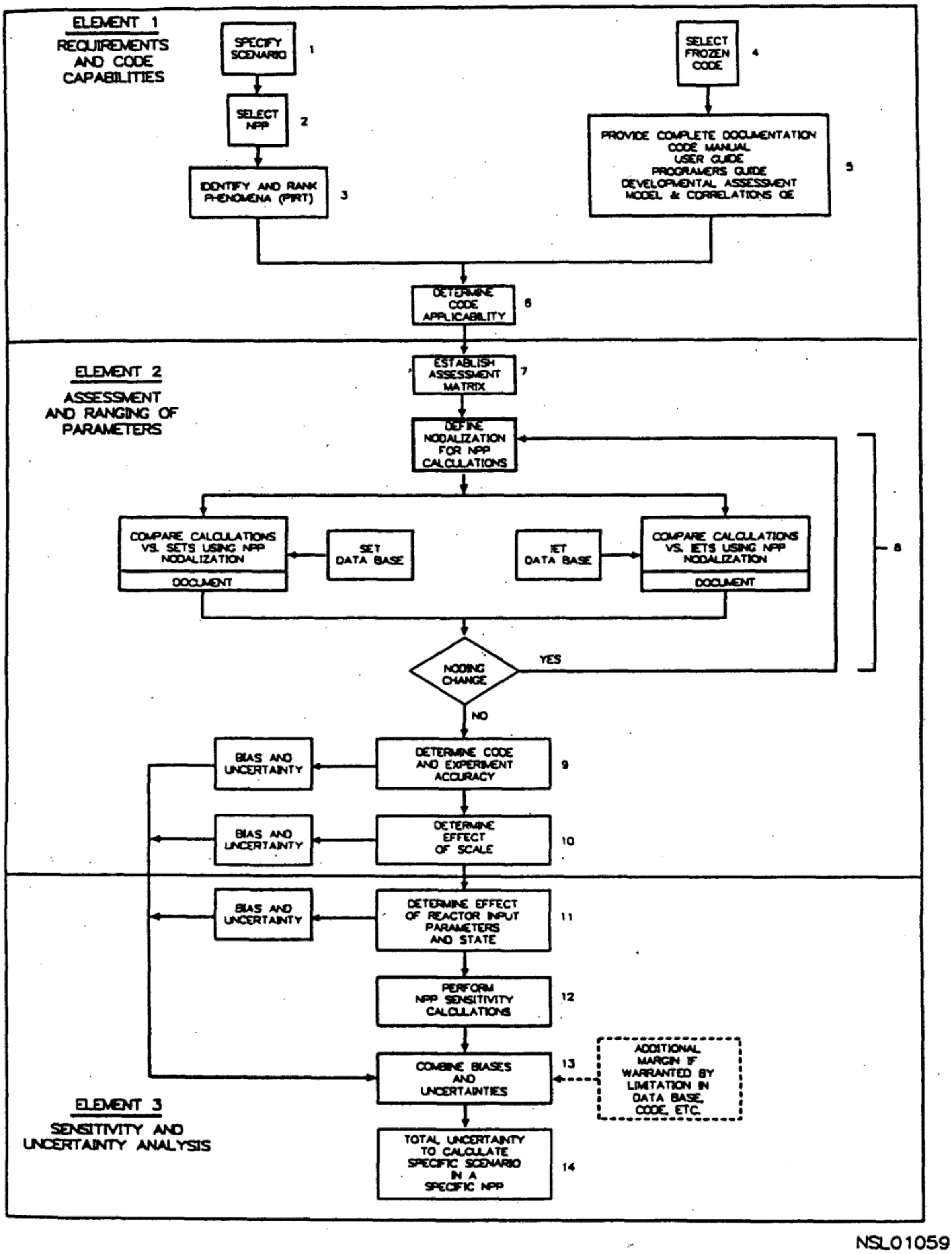

Figure 2-1. 14 Steps of CSAU Methodology (Boyack et al., 1989)

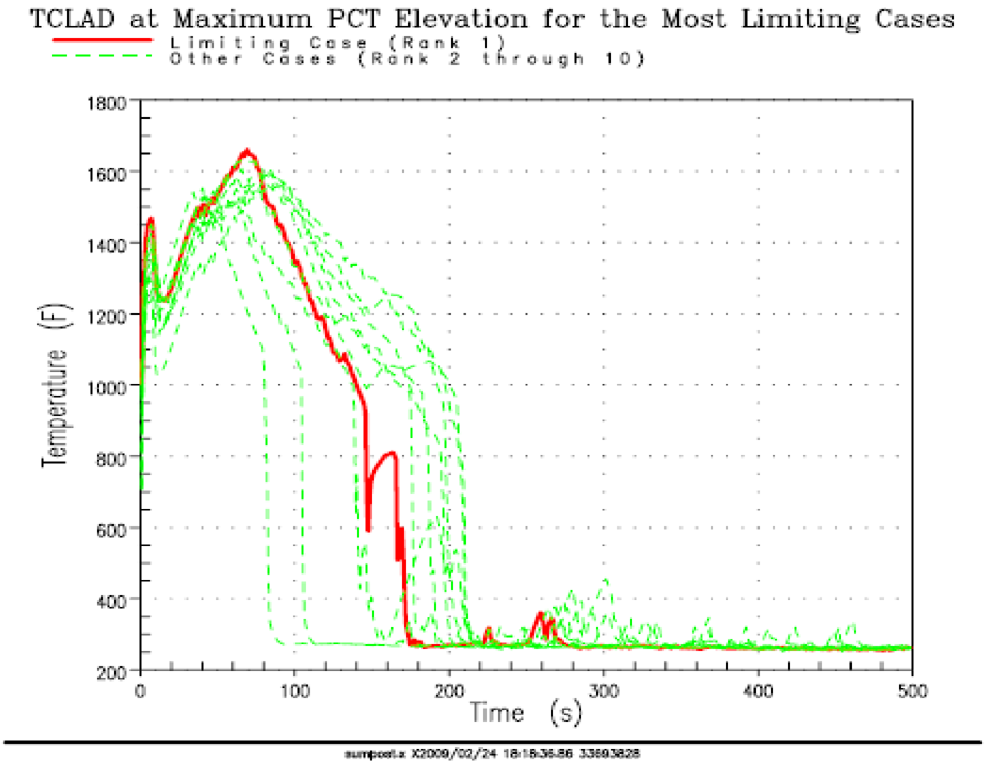

Figure 2-2. PCTs of Different Trials from Westinghouse BEPU LBLOCA Analysis (Westinghouse, 2005)

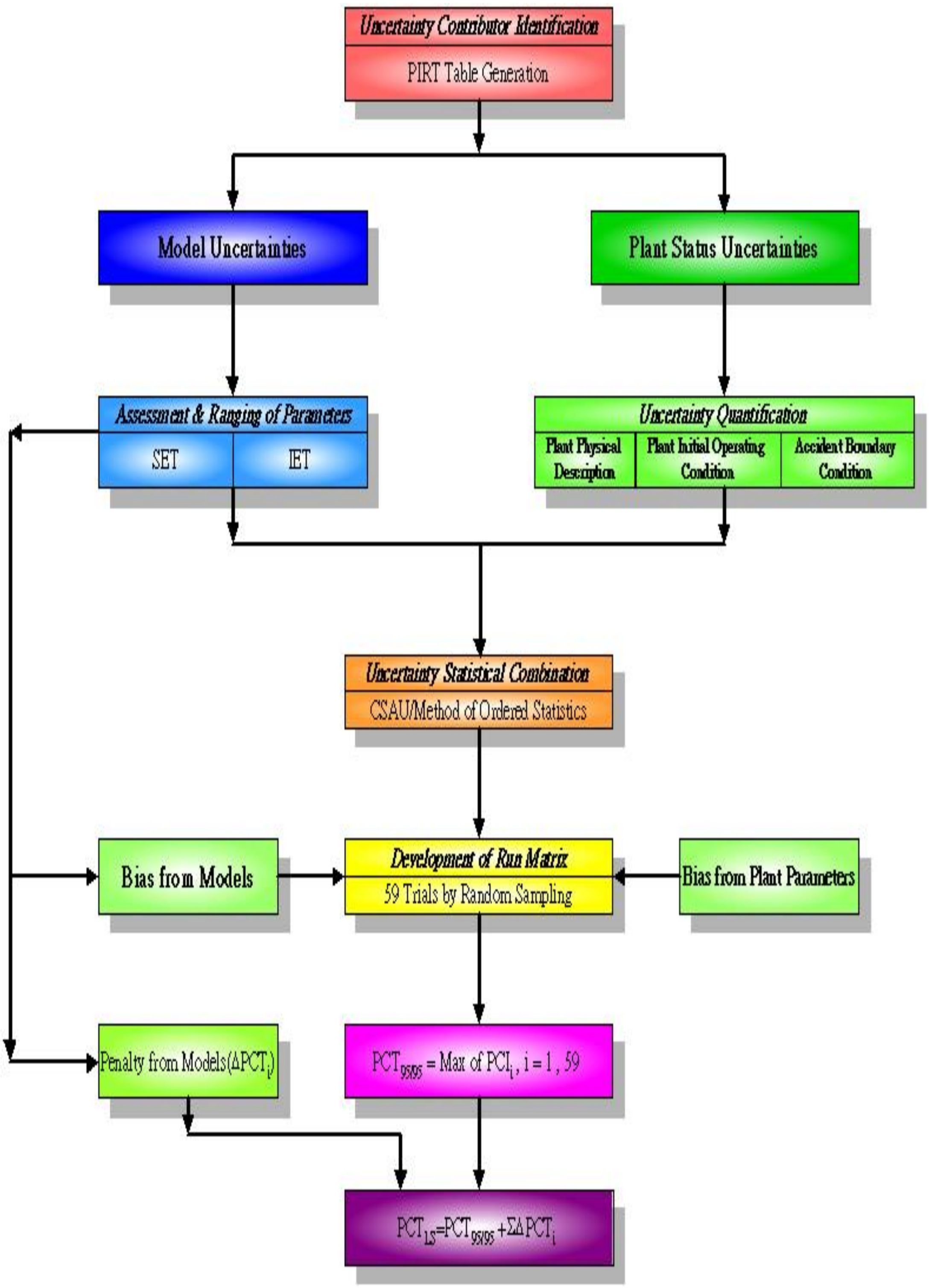

Figure 2-3. General Process for BEPU Analysis

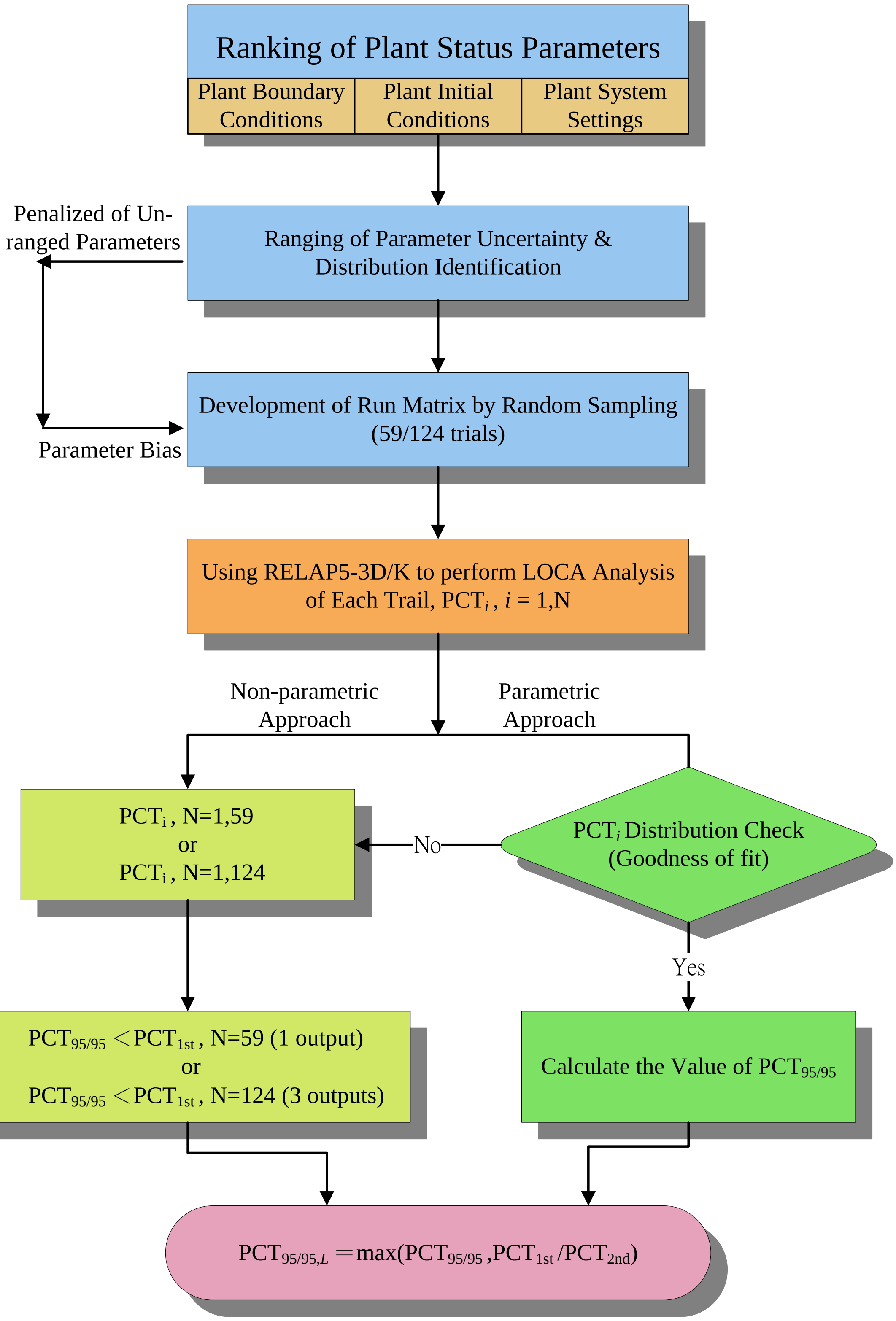

Figure 2-4. Procedures of DRHM

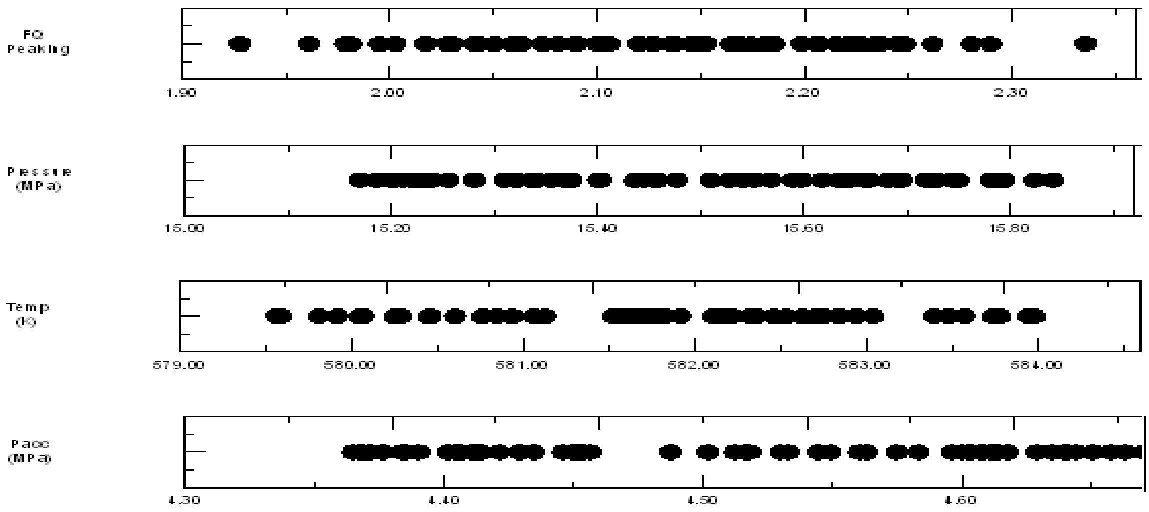

Figure 2-5. Typical Parameter Samplings

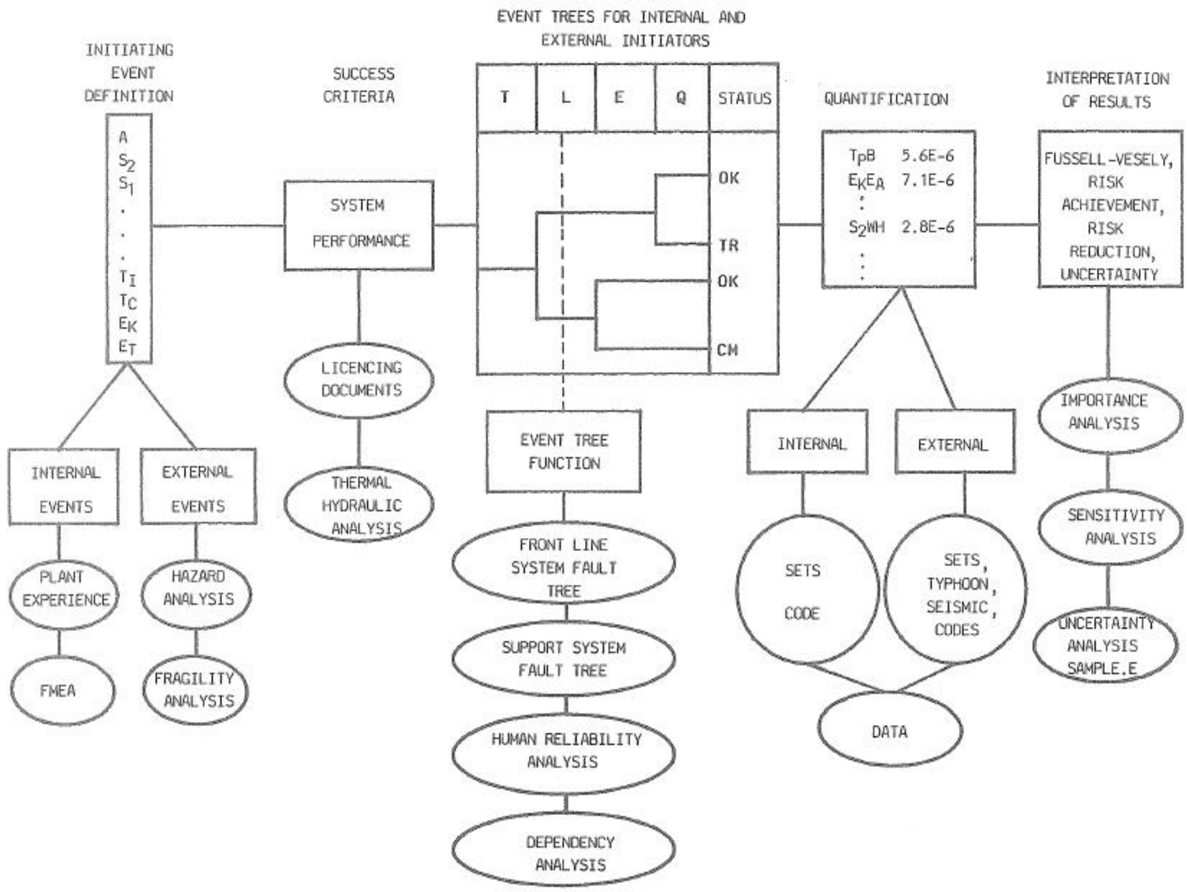

Figure 2-6. Analysis flow for determining core melt frequency (AEC, 1987)

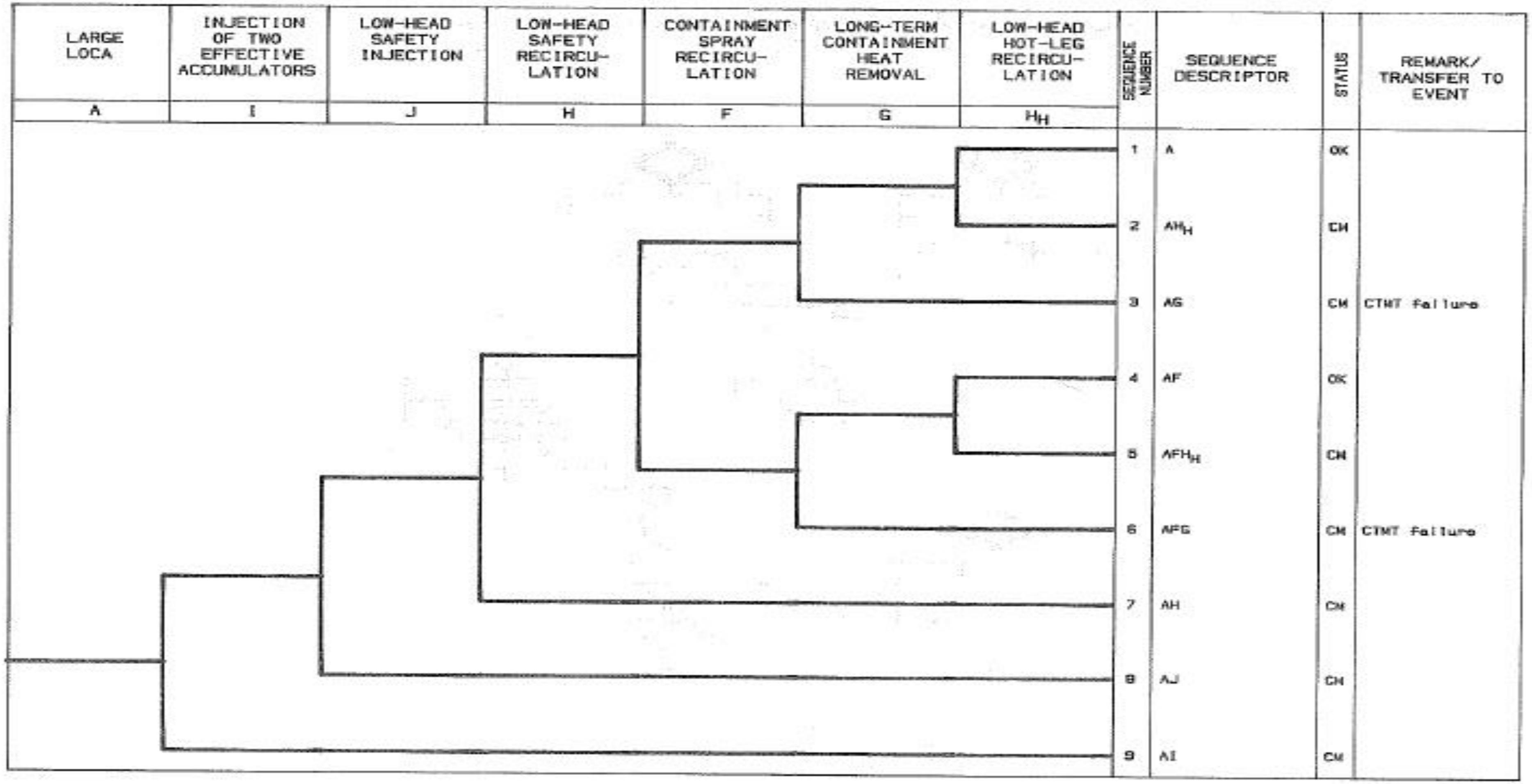

Figure 2-7. Event tree for a large LOCA (AEC, 1987)

Table 2-1 Historical Prospective of LBLOCA Regulation

Years	Events
Prior to 1966	LBLOCA not considered for ECCS design
1966 - 1969	Atomic energy Commission concerned about LBLOCA, and accumulators added to plant design.
1971	Interim acceptance criteria, LBLOCA become design basis accident.
1974	Final acceptance criteria, 10 CFR 50.46 and Appendix K requirements defines evaluation model of 1974.
1988	10 CFR 50.46 revised to allow best-estimate calculations.
1996	First best estimate LBLOCA evaluation model approved for Westinghouse (CSAU)
2003	Best estimate LBLOCA evaluation model approved for AREVA (order statistics)
2003	Revised best estimate LBLOCA evaluation model approved for Westinghouse (order statistics)

Table 2-2. Uncertainties of the Major Plant Parameters of Typical PWRs

Parameter	Distribution	Min	Max
Core thermal power	Uniform	101.38%	102%*
Initial average fluid temperature (T_{avg}),K	Uniform	579.71	584.15*
Pressurizer pressure (P_{RCS}), kpa	Uniform	15168.47	15857.94*
Accumulator liquid volume (V_{ACC}), m^3	Uniform	27.89*	28.74
Accumulator pressure (P_{ACC}), kpa	Uniform	4357.49*	4688.44
Accumulator temperature (T_{ACC}), K	Uniform	310.93	338.71*
Safety injection temperature (T_{SI}),	Uniform	282.59	322.04*
Peak heat flux hot channel factor (F_Q)	Uniform (2.137±0.137) & normal (σ=2.6%)	2.000-4σ	2.274+4σ (2.42*)
Peak hot rod enthalpy rise hot channel factor ($F_{\triangle H}$)	Normal (mean=1.65, σ=2.43%)	Mean-4σ	Mean+4σ (1.72*)
Off-site power	Random	Loop*	Non-loop

Chapter 3. Fundamentals of RISMC Methodology

A traditional deterministic safety analysis methodology is generally applied to analyze DBA based on a surrogate or licensing sequence, without considering how low this sequence occurrence probability is. Although the occurrence probability of such licensing sequence generally is lower, it does satisfy all required conservative assumptions for DBA licensing analysis, such as single-failure criteria, loss of off-site power, et al. In traditional licensing safety analysis, other than the chosen surrogate sequence, calculation uncertainty also needs to be considered, which involves both model uncertainty and plant status uncertainty. By proper consideration of these two uncertainties (IAEA, 2008), calculation uncertainty can be well quantified. In general, these two types of uncertainties can be categorized as epistemic uncertainty. Traditionally, only conservative Appendix K methodology is allowed to perform LBLOCA licensing analysis. Whereas, in the revised 10 CFR 50.46 (USNRC, 1988), best estimate plus uncertainty (BEPU) has been allowed and regulatory guide 1.157 (USNRC, 1989) clearly states how to quantify associated calculation uncertainty. Although BEPU methodology (Boyack, et al., 1989) is legally allowed to replace conservative Appendix K methodology (USNRC, 1974), it is still a revised deterministic methodology based on a predetermined licensing sequence.

In general, all uncertainties can be categorized into epistemic uncertainty and aleatory uncertainty. Epistemic uncertainty results from the “imperfect knowledge” regarding values of parameters of the underlying computational model, whereas aleatory uncertainty results from the effect of “inherent randomness” or “stochastic variability”. Aleatory uncertainty represents the nondeterministic and unpredictable random nature of the performance of the system and its components. In the current advanced BEPU licensing safety analysis methodologies (Westinghouse, 2005) (Martin, R.P., 2005) (Framatome ANP, 2001), only epistemic uncertainty is considered which involves both best-estimate mechanistic models and realistic plan status parameters. On the contrary to a surrogate sequence generally applied in traditional deterministic methodologies, to dealing with the aleatory uncertainty, a group of sequences should be identified for a particular initiating event with Probabilistic Safety Assessment (PSA) skill (Henley and Kumamoto, 1981) to account systems or components failure by random probability. In a sense, the aleatory uncertainty causing system and/or component radon failure is systematically considered in PSA event tree and fault tree analysis techniques.

As stated in the to-be-issued 10 CFR 50.46a, any applicant, permit holder, or licensee or other entity who wishes to make changes enabled by this new rule considering the LBLOCA as a beyond DBA accident, to the facility, facility design, or procedures or to the technical specifications shall perform a risk-informed evaluation. According to the 10 CFR 50.46a, the risk-informed assessment process must include methods for evaluating compliance with the risk criteria, defense-in-depth criteria, safety margin criteria, and performance measurement criteria. As required, when evaluating the risk-informed safety margin, uncertainties considered should include phenomenology, modeling, plant construction, plant operation, etc. (USNRC, 2010c). The risk-informed safety margin therefore refers to a view of margin based on a broader perspective compared to the safety margin determined by traditional deterministic LOCA methodologies. Therefore, according to the proposed 10 CFR 50.46a, statements about margin now need to have meaning not only with respect to a design-basis event sequence, but more generally with reference to a non design-basis sequence, or even group of sequences； a success path or a family of success paths. The newly developed risk-informed safety margin characteristic (RISMC) methodology (Hess, 2009) (Smith, et al., 2012) (Kang, et al., 2013) (Sherry, et al., 2013) can be applied to calculate the risk-informed safety margin for LBLOCA to satisfy the to-be-issued 10 CFR 50.46a.

The RISMC methodology is a systematic approach to consider both aleatory and epistemic uncertainties. To replace the surrogate-based decision making, the main scope of the RISMC methodology is to generate a probabilistic load spectrum as shown in Figure 1-2, and quantify the safety margin in a proper risk-informed manner. To construct a risk-spaced load spectrum, a set of probabilistically significant scenarios (PSS) generated by PSA event tree analysis will be identified and the associated consequence will be analyzed with BEPU techniques.

The risk-informed safety margin characterization (RISMC) pathway provides a view of safety margin based on probabilistically significant sequences, which is no longer just based on one surrogate or licensing sequence. RISMC claims to reflect both stochastic uncertainty and epistemic uncertainty on all probabilistically significant sequences. It also suggests that next generation analysis capability should identify two distinct activities； one includes the generation, characterization, and quantification of scenarios； The other is the analysis of a phenomenology of probabilistically-significant event (R.W. Youngblood, 2010). Therefore, the associated methodology should have the capability to complete the integrative analysis of both probabilistically significant scenarios (PSSs) and phenomenology. The concept of RISMC methodology can be depicted in Figure 3-1. The RISMC methodology intends to combine both PSA (Kumamoto and Henley, 1996) and BEPU (Boyack et al., 1989) analysis to consider both the aleatory and epistemic uncertainties and to help create more optimized basis for decision makings in nuclear power plants (NNPs).

The RISMC methodology systematically combines both probabilistic and mechanistic approaches to estimate the safety margin. The probability analysis is represented by the stochastic risk analysis with PSA techniques involving both event tree and fault tree analysis, whereas mechanistic analysis is represented by the physical calculation with evaluation models satisfying requirements set forth in the to-be-issued 10 CFR 50.46a. Evaluation models can be either conservative Appendix K model or realistic models with uncertainty quantification. With the combination of both probabilistic and mechanistic analyses, both aleatory uncertainty and epistemic uncertainty can be well quantitatively addressed, and a risk-informed peak cladding temperature (PCT) margin of LBLOCA can be evaluated.

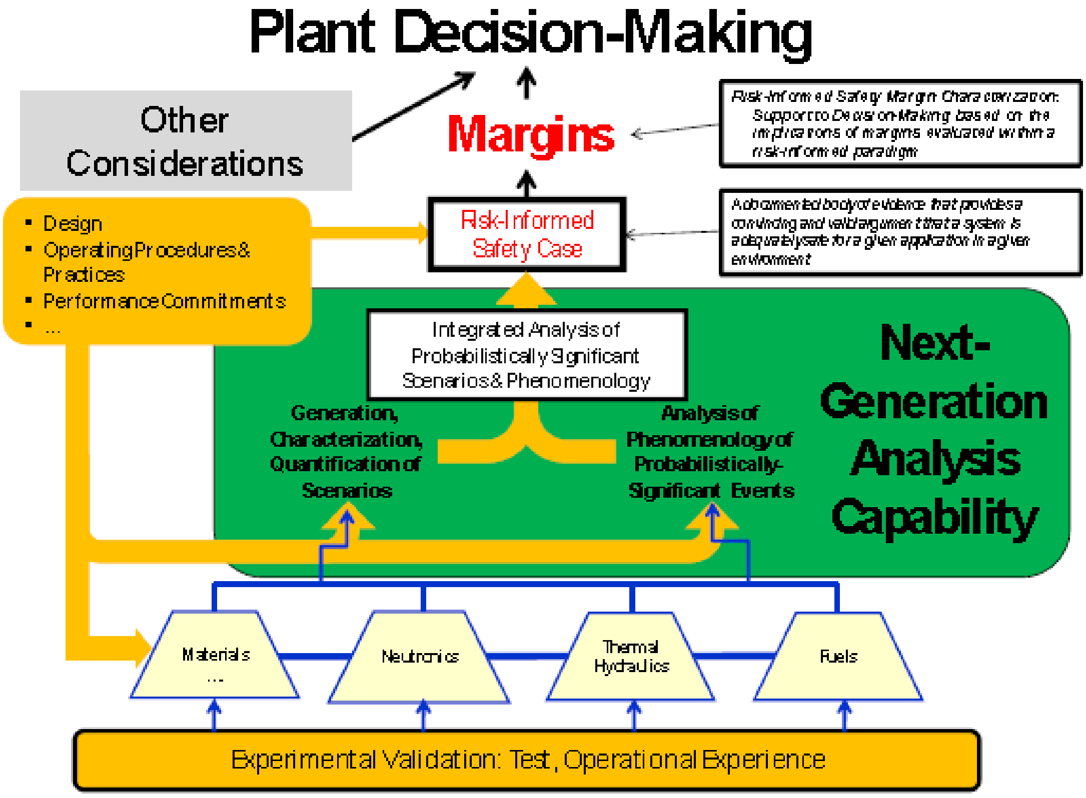

Figure 3-1. Pathway of RISMC Methodology (R.W. Youngblood, 2010)

Chapter 4. Analysis of a Large Break Loss of Coolant Accident and PCT Margin Evaluation with the RISMC Methodology

To perform risk-informed LBLOCA analysis with the RISMC methodology, a load spectrum of LBLOCA will be generated and both aleatory and epistemic uncertainties will be quantified. In the risk-spaced load spectrum, the sequence occurrence probability (SOP) of each probabilistically significant sequence will be quantified and associated conditional PCT will be evaluated. The following process was recommended to calculate the licensing PCT of a LBLOCA to satisfy the risk-informed safety margin evaluation requirement stated in the to-be-issued 10 CFR 50.46a.

(1) Identification of the LBLOCA Sequences

With the probabilistic safety assessment techniques (Kumamoto & Henley, 1996), possible scenarios or sequences of LBLOCA will be identified.

(2) Quantification of LBLOCA sequence occurrence probabilities

To address the aleatory uncertainty, the occurrence probability of each sequence (sequence occurrence probability, SOP) will be quantified by both event tree and fault tree analysis. As a result, those probabilistically significant sequences can be identified.

(3) Calculation of the nominal PCT for LBLOCA sequences

As required by the to-be-issued 10 CFR 50.46a, a proper evaluation model which meets the requirement of traditional LBLOCA licensing calculation shall be applied to perform LBLOCA analysis with nominal settings of both models and plant parameters to calculate the nominal conditional peak cladding temperature ($CPCT_{\mu}$) for each probabilistically significant LBLOCA sequence.

(4) Conducting a preliminary load spectrum of LBLOCA

By having the $CPCT_{\mu}$ of each probabilistically significant scenario or sequence and associated sequence probability, a preliminary load spectrum of LBLOCA can be conducted；

(5) Quantification of calculation uncertainty of the preliminary load spectrum

In principle, the $CPCT_{95/95}$ of each probabilistically significant sequence needs to be calculated to quantify the PCT calculation uncertainty of each sequence. However, there might be too many cases to be calculated. To reduce the load of calculation, a practical assumption can be made. That is the calculational uncertainty evaluated base on the traditional licensing sequence can be applied to other probabilistically significant sequences. Therefore, to account for the epistemic or calculation uncertainty of CPCT resulting from physical models and plant status for the preliminary load spectrum, the $CPCT_{95/95}$ will be calculated with proper methodologies (Westinghouse, 2005) (Liang, et al., 2011) (Ludmann, M., 1999) based upon the traditional surrogate or licensing sequence, and then quantify the difference between the $CPCT_{95/95}$ and the nominal $CPCT_{\mu}$ calculated in step (3) on this surrogate sequence；

$$\Delta PCT_{un,ss} = CPCT_{95/95,ss} - CPCT_{\mu,ss} \tag{4-1}$$

It should be noted that the assumption of using the calculation uncertainty evaluated on the traditional licensing sequence to represent the general calculation uncertainty needs to be further verified. A reasonable conservatism of the surrogate calculation uncertainty needs be demonstrated. Otherwise, $CPCT_{95/95}$ of each probabilistically significant sequence needs to be quantified individually.

(6) Conducting the final load spectrum for LBLOCA

With the calculation uncertainty evaluated on the surrogate sequence ($\Delta PCT_{un,ss}$), the preliminary load spectrum of LBLOCA will be shifted, as shown in Figure 4-1, to reflect the calculation uncertainty, instead of calculating the $CPCT_{95/95}$ for each sequence. Therefore, the final CPCT for sequence "i" will be；

$$CPCT_{\mu+\Delta,i} = CPCT_{\mu,i} + \Delta PCT_{un,ss} \tag{4-2}$$

and the PCT margin of sequence “i” can then be calculated as；

$$\Delta PCT_{SM,i} = PCT_{SL} - CPCT_{\mu+\Delta,i} \tag{4-3}$$

Where PCT_{SL} is the safety limit required by the regulation and generally is 1477.5K (2200.0°F).

(7) The Risk-informed PCT Safety Margin Characterization

The risk-informed PCT safety margin (ΔPCT_{RI}) can be calculated by two different methods； the first one is the expecting value estimation method and the second one is the sequence probability coverage method. In the first method, the risk-informed safety margin can be mathematically defined as (Gavrilas, M., et al., 2007)；

$$\Delta PCT_{RI} = \frac{\sum_i \Delta PCT_{SM,i} * SP_i}{\sum_i SP_i} \tag{4-4}$$

Note that when $\Delta PCT_{SM,i}$ of any sequence “i” is less than 0.0, it will be set as 0.0 to reflect the fact that the risk-informed safety margin of PCT can only be contributed by those sequence with positive $\Delta PCT_{SM,i}$. Moreover, note that the summation of total sequence probability is equal to unity.

Alternatively, in the second sequence probability coverage method, the risk-informed peak cladding temperature ($PCT_{RI}^{99\%}$) will be defined by a particular sequence with a cumulated occurrence probability greater than 99%. Therefore, the $PCT_{RI}^{99\%}$ of the second method can be defined by the final $CPCT_{\mu+\Delta}$ of sequence K；

$$PCT_{\mathrm{RI}}^{99\%} = CPCT_{\mu+\Delta,k} \tag{4-5}$$

where the sequence “K” is determined by the summation of all the sequence probabilities (ΣSP_{1-k}) from the sequence with the lowest $CPCT_{\mu+\Delta, i}$ by ascending order until the ΣSP_{1-k} is greater than 99%.

$$\Sigma SP_{1-k} = \sum_{i=1}^{k} SP_i \geq 99\% \text{ , with } CPCT_{\mu+\Delta,i} \leq CPCT_{\mu+\Delta,k} \tag{4-6}$$

Therefore, by the second sequence probability coverage method, the risk-informed safety PCT margin will be；

$$\Delta PCT_{RI} = PCT_{SL} - PCT_{RI}^{99\%} \tag{4-7}$$

The above seven major steps were summarized in Figure 4-2 for illustration. In the following chapter, the Taiwan’s Maanshan PWR plant (Westinghouse, 1987) was referred to demonstrate how to evaluate the risk-informed PCT safety margin for LBLOCAs.

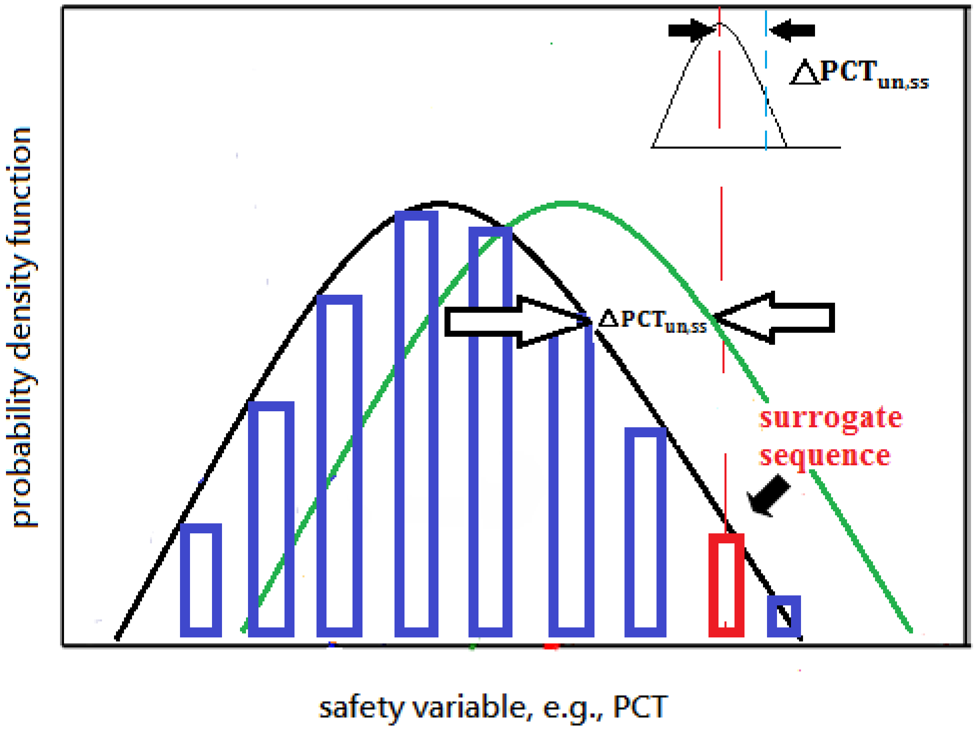

Figure 4-1. Shifted Load Spectrum to Reflect Calculation Uncertainty

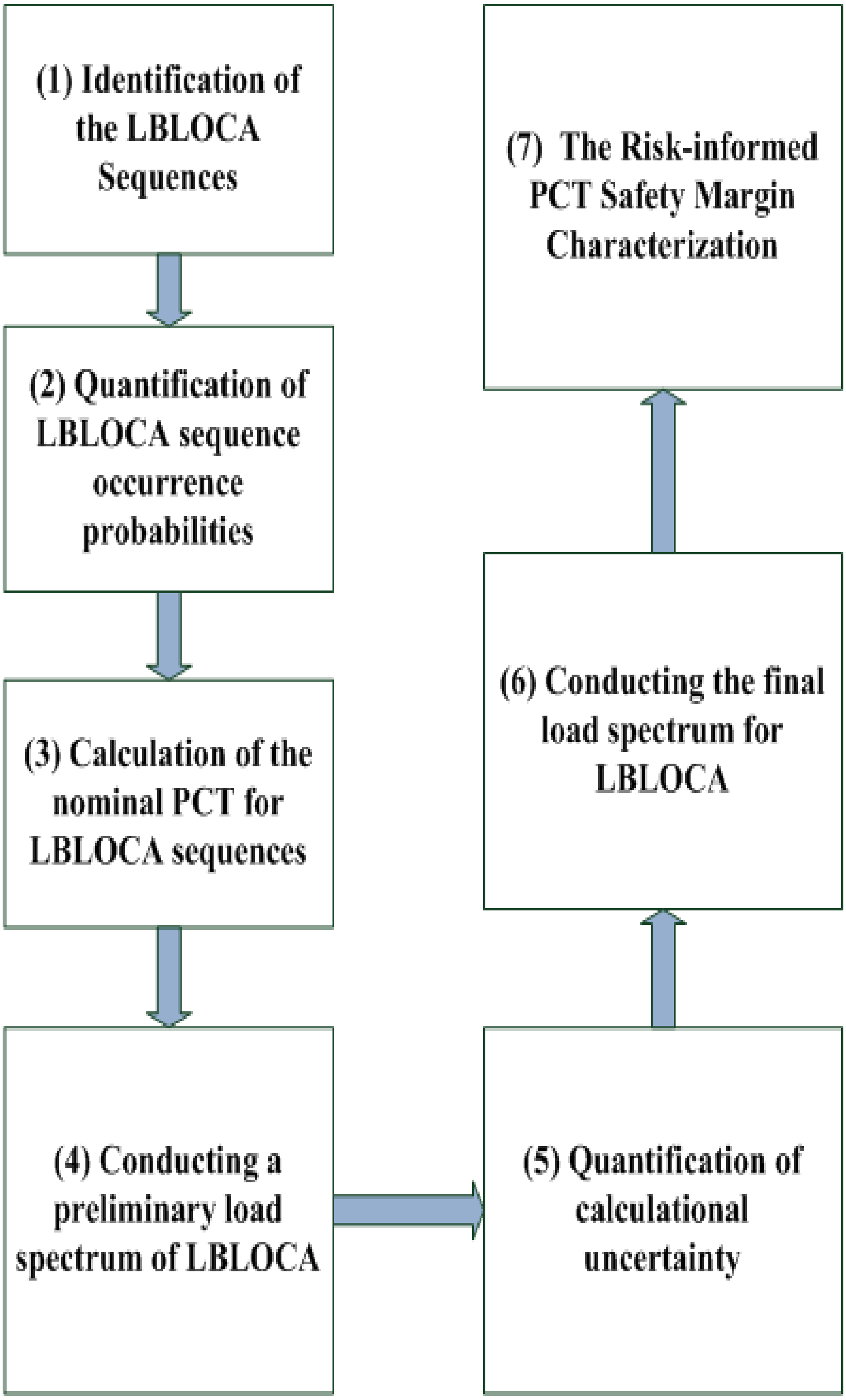

Figure 4-2. Process for Risk-informed PCT Safety Margin Evaluation

Chapter 5. Application of the RISMC Methodology to Evaluate the Risk-informed PCT Margin of Taiwan's Maanshan PWR Plant

5.1 LBLOCA sequence identification and occurrence probability quantification

According to the to-be-issued 10 CFR 50.46a, LBLOCA will be considered as beyond design basis accidents and traditional deterministic licensing sequence can be relaxed. Therefore, to address the effect of system and component random failure caused by aleatory uncertainty, with probability and risk assessment techniques all possible LBLOCA sequences will be identified and the occurrence probability of each sequence (sequence probability, SP) can be quantified. In the short term LBLOCA PCT analysis, possible sequences were configured by the random combination of the individual safety injection system available.

Considering Taiwan's Maanshan nuclear plant, a traditional 3-loop Westinghouse PWR, Emergence Core Cooling System (ECCS) includes high head injection system, low head injection system and accumulators for medium head injection. All above safety systems satisfy the single failure criteria and redundancy criteria. To address the aleatory uncertainty, the occurrence probability of each sequence (sequence probability, SP) will be quantified by both event tree and fault tree analysis and consequently, probabilistic significant sequences can be identified.

In this thesis, the modified PSA model is mainly divided into two parts；

I. Identify heading of Events

II. Modify fault tree models

The traditional analysis of PSA LBLOCA sequences will include long-term system responses and operator action. While as for the PSA LBLOCA analysis for the risk-informed LOCA PCT safety margin characterization, only short-term LBLOCA phases (blowdown, refill and reflood) will be involved and operator action will not allow. In traditional PSA model, the event tree is not a time-dependent model and each top heading (function) is not necessarily in temporal sequence in the event analysis. Therefore, in order to address the effect of system and component random failure caused by aleatory uncertainty with PSA analysis, we should consider the timing of thermal hydraulic calculation in LBLOCA and then identify heading of event tree. And also consider the impact for fault model, filtering the factors are caused by the long-term effect in LBLOCA, like Human factor, etc. , and then modify fault tree model.

I. Identify heading of Events

In section 2.2.2, the procedure of traditional probabilistic safety assessment for LBLOCA analysis was stated. In order to combine with RISMC methodology, there are two main subjects need to be revised. Frist of all, according the traditional PSA definition, the success criteria of PSA model is based on calculating the dominant core melt sequences in LBLOCA event and the total Core Melt Frequency (CDF). Compare with the purpose of RISMC methodology, to quantify all kind system failure combination sequences should be the first priority in LBLOCA analysis. Thus, the interaction of ECC system and the definition of the event tree will no longer be dominated by the core melt sequence. Secondly, considering the results and simulation timing of thermal hydraulic calculation in LBLOCA, the peak cladding temperature (highest temperature in case) appears within 10 minutes.

Therefore, we need to modify the traditional PSA model based on above subjects in RISMC methodology with focus on the short term PCT evaluation. In traditional LBLOCA event tree (Figure 2-7), heading H, heading F, heading G, and heading H_H will be removed. And then new headings will be added to consider the interaction of ECCS in LBLOCA.

Figure 5-1 shows the new event tree for a large LOCA PSA analysis, and each of the heading (functions) definition is summarized as following：

Heading LOCA：Initiating event for LBLOCA

Heading LOP：Loss of offsite power

Heading H0-：Two of centrifugal charging pumps can start and inject coolant to RCS

Heading H1-：One of centrifugal charging pumps can start and inject coolant to RCS

Heading AC0-：All of accumulators inject into loops

Heading AC1-：Two of accumulators inject into loops

Heading AC2-：One of accumulators inject into loops

Heading AC3-：One of accumulators inject into the undamaged loops

Heading L0-：All of RHR pumps automatically start and inject water into RCS.

Heading L1-：One of RHR pumps automatically starts and injects water into RCS.

II. Modify fault tree model

The required system fault tree models are defined in the development of new event tree. Following the above suggestions for modification of PSA model, each system fault (function level) tree will be modified to filter the factors related to the long-term effect and interaction of each system in LBLOCA, like Human factor, success criteria of switching pump and long-term containment heat removal, etc.

The calculation of the fault tree model will perform the most dominant factors in the result. The final result also can be selected to represent the combination of the most dominant factors. In this study, we choose to present 15 important factor combinations cut sets to check the correctness of the fault tree model. Each result of system fault tree model is shown in Figure 5-2, Figure 5-3, and Figure 5-4.

Finally, after modifying the traditional PSA model, in the new headings of the event tree analysis, all possible system random failure combinations are considered and consequently 108 different event sequences are degenerated. With appropriate fault tree analysis, the occurrence probability of each sequence can be well quantified. The possible system combination of each sequence is shown in the LBLOCA event tree plot (Figure 5-5) and occurrence probabilities of the top fourteen probabilistic significant LBLOCA sequences are summarized in Table 5-1.

5.2 Preliminary load spectrum of LBLOCA

As indicated in section 5.1, fourteen probabilistic significant sequences of LBLOCA of Taiwan's Maanshan nuclear power plant have been identified, as listed in Table 5-1. The total occurrence probability of those fourteen probabilistic significant sequences is more than 99.99% coverage. To generate a load spectrum for the LBLOCA while considering both aleatory and epistemic uncertainties, a two-step approach was adopted as elaborated in Chapter 4. The first step is to generate a preliminary load spectrum by using RELAP5-3D/K (Liang, K.S., et al., 2002a) (Liang, K.S., et al., 2002b) to calculate the nominal conditional PCT ($CPCT_{\mu}$) for each sequence, and the second step is to account for the epistemic or calculation uncertainty of the preliminary load spectrum by using the deterministic-realistic hybrid methodology (DRHM) (Liang, K.S., 2011). In the DRHM methodology, conservative Appendix K models were adopted to cover model uncertainty, whereas realistic plant status parameters were used with statistical uncertainty analysis.

To calculate the $CPCT_{\mu}$ of those probabilistic significant sequences in the first step, all the plant status parameters are set as their nominal values, and a conservative plant model for Maanshan LBLOCA analysis (Taiwan Power Company, 2013) is applied, as shown in Figure 5-6. The $CPCT_{\mu}$ of the top fourteen probabilistic significant LBLOCA sequences were calculated and the associated responses are shown in Figure 5-7. Moreover, the resulted $CPCT_{\mu}$ of each probabilistic significant sequence are also summarized in Table 5-1 and a plot of $CPCT_{\mu}$ versus associated sequence probability is shown in Figure 5-8 to represent the preliminary LBLOCA load spectrum of the Maanshan nuclear power plant. It can be observed from the preliminary load spectrum that the $CPCT_{\mu}$ generally ascends with the descending sequence occurrence probability.

5.3 Final load spectrum with calculational uncertainty quantification

As stated in section 5-2, a preliminary load spectrum was generated by the quantification of each sequence occurrence probability and associated conditional nominal PCT ($CPCT_{\mu}$). Regarding the feature of the preliminary load spectrum, only the aleatory uncertainty was considered, which dictates the configuration of system and/or component random failure and associated sequence occurrence probability. In this section, the epistemic or calculational uncertainty will be evaluated to modify the preliminary load spectrum.

5.3.1 Calculational uncertainty evaluation base on the deterministic licensing sequence

To account for the calculation uncertainty in the second step with DRHM methodology, since conservative Appendix evaluation model (RELAP5-3D/K) is applied, the remaining calculation uncertainty will be the plant status uncertainties. The effect of the plant status uncertainty on PCT calculation was evaluated on the basis of the traditional licensing sequence (sequence LOCAS74 in Table 5-1).

Referring to a typical PWR best estimate LBLOCA licensing analysis (Framatome ANP, 2001), important plant parameters were identified and summarized in Table 5-2 with uncertainty ranges. According to the DRHM methodology, at least 59 trials were required to be randomly generated to quantify the effect of plant status uncertainty. It should be noted that break size is not assigned as an uncertainty contributor in Table 5-2. In BEPU LOCA methodology, whether the break size is assigned as an uncertainty contributor, depends on the methodology itself. In this research, since our focus is the study and application of risk-informed safety margin characterization (RISMC) methodology, we simply exclude the break size as a major uncertainty contributor by assuming bounding 200% break size. Typical parameter samplings are shown in Figure 2-5 for illustration and the detailed 59 trials are listed in Table 5-3. The PCT responses of 59 trials are also shown in Figure 5-9 and the PCT of each trial are summarized in Table 5-4. Besides, the scattering plot of PCT of each trial is also shown in Figure 5-10. By the Wilk's formula (David and Nagaraja, 1980), the PCT of 95% percentile and 95% confidence level can be estimated by the highest PCT amount those 59 trials, which is 1367.5 K. With the nominal PCT value of 1289.46 K ($CPCT_{\mu,ss}$) and $PCT_{95/95}$ value of 1367.5 K($CPCT_{95/95,ss}$) evaluated on the licensing sequence, the calculation uncertainty according to Equation (4-1) caused by plant status uncertainty can be quantified as；

$$\Delta PCT_{un,ss} = CPCT_{95/95,ss} - CPCT_{\mu,ss} \tag{5-1}$$

$$=78.0 \text{ K}$$

Accordingly, the preliminary load spectrum can be shifted by 78.0 K to reflect the calculation uncertainty

$$CPCT_{\mu+\Delta,i} = CPCT_{\mu,i} + 78.0\,K \tag{5-2}$$

The final $CPCT_{\mu+\Delta}$ of those fourteen probabilistic significant sequences with calculation uncertainty evaluated solely based on the licensing sequence are listed in the 4th column in Table 5-1.

5.3.2 Evaluation of the surrogate based calculational uncertainty

As stated in section 5.3.1, the calculational uncertainty of the LBLOCA load spectrum is evaluated base on the sequence 74 named as the surrogate or licensing sequence. In this section to evaluate surrogate based assumption, the calculational uncertainties of probabilistically significant sequences of top three will also evaluated, which involve sequence 1, sequence 55 and sequence 56. The major differences of those 4 sequences were summarized in Table 5-5. It should be noted that the accumulated sequence occurrence probability of the top 3 sequences is more than 99.3%.

To evaluate the calculation al uncertainty of each dominant sequence, 59 trials generated by random sampling for sequence 74 still can be applied on those major plant status parameters listed in Table 5-2. Those plant parameters determined by random sampling were summarized in Tables 5-3. It should be noted that since the differences between sequences are purely availability of systems, therefore the associated sequences 1, 55, 56 and 74 can share the common 59 trials of plant status parameters. That is, when analyzing any particular trial for each sequence, the associated system availability will be different according to the target sequence to be analyzed. The resultant 59 PCTs of sequences 1, 55 and 56 are listed in Table 5-6, 5-7 and 5-8, respectively, and the associated data scattering of 59 PCTs of each sequence are plotted in Figures 5-11, 5-12 and 5-13. Moreover, the 59 PCT plots for each sequence are also shown in Figures 5-14, 5-15 and 5-16, respectively.

According to the Wilk's formula (David and Nagaraja, 1980), the PCT of 95% percentile and 95% confidence level can be estimated by the highest PCT amount those 59 trials. Therefore, the $PCT_{95/95}$ of sequences 1, 55 and 56 can be estimated as 1322.22 K, 1328.14 and 1329.22 K, respectively. Along with the nominal PCT of each sequence listed Table 5-1, the calculation uncertainty of sequences 1, 55 and 56 can be defined as；

$$\Delta PCT_{un,s1} = CPCT_{95/95,s1} - CPCT_{\mu,s1}$$

$$= 1322.22K - 1224.36K = 97.89K \tag{5-3}$$

$$\Delta PCT_{un,s55} = CPCT_{95/95,s55} - CPCT_{\mu,s55}$$

$$= 1328.14K - 1229.52K = 98.62K \tag{5-4}$$

$$\Delta PCT_{un,s56} = CPCT_{95/95,s56} - CPCT_{\mu,s56}$$

$$= 1329.22K - 1245.12K = 84.1K \tag{5-5}$$

As compared with the calculational uncertainty (78.0 K, equation 5-1) evaluated on the licensing sequence, sequence 74, it can be observed that evaluation of the calculational uncertainty of the load spectrum solely based on the licensing sequence is not a conservation assumption. The calculational uncertainties of sequences 1, 55, 56 and 74 are summarized in Table 5-9 for comparison.

5.4 Risk-informed PCT margin evaluation

Since the calculational uncertainty evaluated on the licensing sequence is not conservation enough, the associated calculation uncertainties of probabilistically significant sequences of top three, namely sequences 1, 55 and 56, will be revised, and the final load spectrum for LBLOCA is indicated in the last column of Table 5-1. It is worth to note that the accumulated sequence occurrence probability of the top 3 sequences is more than 99.3%. The risk-informed PCT safety margin (ΔPCT_{RI}) can be calculated by two different methods； the first one is the expecting value estimation method (equation 4-4) and the second one is the sequence probability coverage method (equation 4-5). By using the first expecting value estimation method and data listed in Table 5-1, the risk-informed safety margin can be mathematically calculated according to Equation (4-4) as follows；

$$\Delta PCT_{RI} = \sum_{i} \Delta PCT_{MR,i} * SP_{i} \tag{5-6}$$

$$= 152.72 \text{ K}$$

As for the second sequence probability coverage method, it was found that the summation of the first 3 sequence (LOCAS01, LOCAS55 and LOCAS56) probabilities is 99.3%. Therefore, the third sequence with a value of 1329.22 K will be applied to define the risk-informed $PCT_{RI}^{99\%}$, and the risk-informed safety margin will be as follows

$$\Delta PCT_{RI} = PCT_{SL} - PCT_{\mathrm{RI}}^{99\%} \tag{5-7}$$

$$= 148.38 \text{ K}$$

Comparing the risk-informed safety margins evaluated by above two methods, it can be found that the ΔPCT_{RI} calculated by the sequence probability coverage method is reasonably conservative by 4.34 K. Because the occurrence probability was dominated by the first three sequences, it was expected that the risk-informed PCT safety margin evaluated by either the expecting value estimation method or the sequence probability coverage method should not have a significant difference.

It was observed in the Table 5-1 that in the second sequence probability coverage method, the third sequence (LOCAS56) was applied to define the risk-informed safety margin ($\Delta PCT_{RI}^{99\%}$) and its' associated occurrence probability is $5.07*10^{-3}$, while the occurrence probability of the traditional licensing sequence (LOCAS74) applied in the classical deterministic methodology is only $5.46*10^{-5}$. In the traditional licensing sequence (LOCAS74) only one train of high head and low head injection are available respectively to satisfy single failure criteria. While in sequence referred in the evaluation of risk-informed PCT safety margin (LOCAS56) to cover 99% cumulated occurrence probability, there are two trains of low head injection and one train of high head injection available instead. The detailed differences of the first three sequences and the traditional surrogate sequence are summarized in Table 5-5.

It was also noted that according to the deterministic methodology, the licensing PCT can only be evaluated by the traditional surrogate sequence (LOCAS74) and the correspondent value is 1367.5K as indicated in Table 5-1. Consequently, the traditional deterministic safety margin is only 110.1K (1477.6 K -1367.5 K) by applying the DRHM methodology. Therefore, the PCT safety margin of LBLOCA evaluated by the RISMC methodology can be greater by 38.3 K-42.6 K than the margin evaluated by the DRHM deterministic methodology. It was also worth to note that by relaxing the bounding state assumption for traditional Appendix k methodology, the DRHM methodology can enlarge PCT margin by 1385.2-1367.5=17.7K, where 1385.2 K is the PCT evaluated by traditional Appendix K methodology with bounding state assumption, and 1367.5K is the $CPCT_{95/95}$ evaluated on the licensing sequence 74 with DRHM methodology. The evolution of PCT margin by different methodologies, traditional Appendix k methodology, DRHM methodology and RISMC methodology, can be depicted in Figure 5-17. It can be found that by relaxing the bounding state assumption in the DRHM methodology, the PCT margin can be enlarged by 17.7 K, while by relaxing the deterministic assumption in the RISMC methodology, the PCT margin can be further enlarged by 42.6-38.8K.

Table 5-1. Summary of the Top 14 Probabilistic Significant LBLOCA Sequences

Sequence	Occurrence Probability	$CPCT_{\mu}$, (K)	$CPCT_{\mu+\Delta}$, (K) sequence 74 based	$CPCT_{\mu+\Delta}$, (K) /revised
LOCAS01	4.946E-01	1224.36	1302.36	1302.36/1322.22
LOCAS55	4.935E-01	1229.52	1307.52	1307.52/1328.14
LOCAS56	5.067E-03	1245.12	1323.12	1323.12/1329.22
LOCAS91	4.522E-05	1263.21	1341.21	1341.21
LOCAS73	1.252E-03	1264.37	1342.37	1342.37
LOCAS02	5.087E-03	1276.48	1354.48	1354.48
LOCAS58	1.322E-05	1278.05	1356.05	1356.05
LOCAS19	1.070E-04	1287.59	1365.59	1365.59
LOCAS37	4.522E-05	1289.01	1367.01	1367.01
LOCAS74	5.460E-05	1289.46	1367.5	**1367.50**
LOCAS20	5.692E-05	1293.70	1371.7	1371.7
LOCAS04	1.322E-05	1331.42	1409.42	1409.42
LOCAS07	2.644E-05	1429.63	1507.63	1507.63
LOCAS61	2.644E-05	1499.76	1577.76	1577.76

Table 5-2. Uncertainties of Major Plant Parameters of Typical PWRs

Parameters	Distribution	Min	Max
Core thermal power	Uniform	101.38%	102%
Initial average fluid temperature (T_{avg}),K	Uniform	579.71	584.15
Pressurizer pressure (P_{RCS}), kpa	Uniform	15168.47	15857.94
Accumulator liquid volume (V_{ACC}), m^3	Uniform	27.89	28.74
Accumulator pressure (P_{ACC}), kpa	Uniform	4357.49	4688.44
Accumulator temperature (T_{ACC}), K	Uniform	310.93	338.71
Safety injection temperature (T_{SI}),	Uniform	282.59	322.04
Peak heat flux hot channel factor (F_Q)	Uniform (2.137±0.137) & normal (σ=2.6%)	2.000-4σ	2.274+4σ
Peak hot rod enthalpy rise hot channel factor ($F_{\triangle H}$)	Normal (mean=1.65, σ=2.43%)	Mean-4σ	Mean+4σ
Axial power distribution (P_{BOT})	Uniform	0.22	0.44
Axial power distribution (P_{MID})	Uniform	0.31	0.43
Off-site power	Random	Loop	Non-loop

Table 5-3 Sampling result of major plant parameters (1/3)

No.	Power	Tavg(ºF)	Prcs(psi)	Vacc(ft³)	Pacc(psi)	Tacc(ºF)	Tsi(ºF)	F_Q	$F_{\Delta H}$	P_{BOT}	P_{MID}	Break type	Break area (ft²)
1	1.0169	587.5963	2206.22	1005.103	646.3588	129.5097	95.7862	2.0305	1.6957	0.3747	0.339	DECLG	8.2492
2	1.0156	586.1147	2290.332	993.3706	638.4155	134.6662	57.8399	2.1493	1.5828	0.229	0.3806	DECLG	8.2492
3	1.0175	591.3862	2261.072	1013.874	640.1612	112.8883	115.8528	2.1274	1.6432	0.2279	0.3263	DECLG	8.2492
4	1.0168	589.447	2257.851	995.4742	669.0733	132.6744	112.3858	2.3355	1.6436	0.265	0.4175	DECLG	8.2492
5	1.015	590.7064	2227.102	992.5059	674.5105	145.348	71.9687	2.2334	1.6925	0.3406	0.3931	DECLG	8.2492
6	1.0192	587.3371	2220.506	995.1147	634.7178	146.1245	108.9548	2.2359	1.6727	0.2633	0.4246	DECLG	8.2492
7	1.0164	587.6268	2290.656	1003.16	638.8373	147.4176	56.1347	2.0504	1.7034	0.3955	0.3496	DECLG	8.2492
8	1.0192	585.4027	2274.324	1014.229	673.112	144.8398	62.8427	2.0999	1.606	0.2225	0.3703	DECLG	8.2492
9	1.0151	584.4391	2240.032	991.2057	643.1967	115.7607	70.7815	2.0889	1.6712	0.4388	0.3679	DECLG	8.2492
10	1.0175	591.7589	2238.774	998.754	640.0405	122.3518	105.1037	2.2207	1.6994	0.412	0.323	DECLG	8.2492
11	1.014	586.5056	2224.703	1002.732	666.6141	119.131	85.6064	2.1204	1.6843	0.3297	0.3735	DECLG	8.2492
12	1.0142	589.7196	2289.574	993.1257	667.1876	106.3211	94.7764	2.2482	1.6848	0.4024	0.3728	DECLG	8.2492
13	1.0139	588.7747	2279.692	1013.897	645.6597	135.5572	74.9353	2.2895	1.6294	0.273	0.324	DECLG	8.2492
14	1.0185	584.2499	2229.885	1005.16	646.0137	132.8664	68.3119	2.0903	1.6418	0.3772	0.3576	DECLG	8.2492
15	1.0155	589.885	2207.576	1007.576	655.2908	130.8868	111.0251	2.2618	1.6163	0.258	0.3353	DECLG	8.2492
16	1.0161	587.803	2210.246	1011.739	675.5284	100.0901	106.6688	2.2052	1.6308	0.3813	0.3737	DECLG	8.2492
17	1.0197	589.6965	2241.536	1006.425	659.8234	109.2442	65.1874	2.0174	1.6599	0.2306	0.3596	DECLG	8.2492
18	1.0184	585.0372	2233.636	996.8651	633.0546	107.7832	98.7053	2.0811	1.6497	0.2389	0.3751	DECLG	8.2492
19	1.0184	591.3947	2252.093	1003.213	673.5952	143.2371	97.1074	2.0591	1.7463	0.2782	0.3668	DECLG	8.2492
20	1.016	588.587	2262.247	988.418	667.5772	106.2253	108.9691	2.2448	1.6905	0.37	0.3688	DECLG	8.2492

Table 5-3 Sampling result of major plant parameters (2/3)

No.	Power	Tavg(ºF)	Prcs(psi)	Vacc(ft^3)	Pacc(psi)	Tacc(ºF)	Tsi(ºF)	F_Q	$F_{\Delta H}$	P_{BOT}	P_{MID}	Break type	Break area (ft^2)
21	1.0183	588.4564	2290.7654	1008.3694	672.1804	123.1078	71.9039	2.1354	1.6858	0.3628	0.4194	DECLG	8.2492
22	1.015	591.3896	2207.562	987.3439	633.6742	113.5246	67.4812	2.2071	1.6112	0.2469	0.4262	DECLG	8.2492
23	1.0168	584.7204	2267.5422	1011.8876	645.3787	128.711	82.8093	2.0737	1.7012	0.4375	0.3714	DECLG	8.2492
24	1.0139	589.6973	2212.5981	1002.5597	669.1973	130.3917	117.103	2.1853	1.6086	0.3663	0.4165	DECLG	8.2492
25	1.0192	590.8565	2209.2212	1010.7917	644.8517	138.5184	71.0606	2.2244	1.6476	0.2579	0.3239	DECLG	8.2492
26	1.0166	585.4194	2297.5518	1013.2338	657.0225	127.8988	64.4309	2.3747	1.6745	0.2242	0.3737	DECLG	8.2492
27	1.0192	589.3237	2279.9758	1007.8224	639.7548	136.8406	56.1315	2.041	1.6494	0.3247	0.3729	DECLG	8.2492
28	1.0198	588.4827	2222.1021	1012.0129	667.72	118.5146	98.9042	2.1197	1.6605	0.2831	0.3815	DECLG	8.2492
29	1.0176	585.1127	2276.2366	1004.2615	661.4443	114.1959	70.6952	2.1523	1.6779	0.3063	0.3664	DECLG	8.2492
30	1.0162	584.2513	2249.4958	1011.1449	654.4634	139.1606	88.6397	2.0613	1.6324	0.3073	0.4289	DECLG	8.2492
31	1.0163	587.8657	2280.741	993.1591	657.4806	146.2103	96.3524	1.928	1.5721	0.3177	0.3911	DECLG	8.2492
32	1.0186	591.3221	2202.5002	1013.0596	638.3533	102.8953	57.5436	2.1742	1.6754	0.4285	0.3763	DECLG	8.2492
33	1.0172	586.5009	2268.5908	997.931	664.7537	113.6851	101.3691	2.1802	1.6622	0.2768	0.4123	DECLG	8.2492
34	1.0142	588.8104	2253.8679	1013.4982	652.9421	105.9717	91.6721	2.2068	1.6385	0.2856	0.3974	DECLG	8.2492
35	1.0144	588.3864	2269.0745	996.4833	655.0034	121.7309	57.6253	1.9784	1.6054	0.2549	0.3401	DECLG	8.2492
36	1.0147	587.6184	2284.2449	1010.6799	635.8043	108.6544	107.9216	1.9951	1.7061	0.4164	0.3539	DECLG	8.2492
37	1.0182	589.1495	2275.6848	1012.7617	639.1672	107.3295	65.4206	2.1047	1.6708	0.2781	0.3762	DECLG	8.2492
38	1.0155	583.8067	2255.6101	986.692	641.2699	128.3677	111.7968	2.1454	1.6523	0.3769	0.3597	DECLG	8.2492
39	1.0172	591.6923	2271.1099	986.7904	677.4421	117.6094	69.8319	2.1644	1.6842	0.2856	0.428	DECLG	8.2492
40	1.0145	591.0203	2229.0779	1007.8519	636.0159	144.7528	84.1107	2.1266	1.6961	0.3264	0.3263	DECLG	8.2492

Table 5-3 Sampling result of major plant parameters (3/3)

No.	Power	Tavg(ºF)	Prcs(psi)	Vacc(ft^3)	Pacc(psi)	Tacc(ºF)	Tsi(ºF)	F_Q	$F_{\Delta H}$	P_{BOT}	P_{MID}	Break type	Break area (ft^2)
41	1.0153	587.5408	2295.0288	1005.1652	668.2175	128.045	93.0676	2.1375	1.6182	0.4311	0.3805	DECLG	8.2492
42	1.0182	585.0449	2207.8301	989.7984	672.8804	111.7549	80.4071	2.0634	1.6529	0.3149	0.3343	DECLG	8.2492
43	1.015	589.5508	2283.4583	1012.7112	636.7563	138.367	96.7894	2.2453	1.6551	0.4086	0.3632	DECLG	8.2492
44	1.015	585.9604	2254.1921	1004.2035	678.7186	129.8304	49.352	2.1466	1.6259	0.2587	0.3935	DECLG	8.2492
45	1.0167	583.8482	2274.4849	988.8352	668.3654	120.5071	103.9573	2.1832	1.6737	0.3691	0.3371	DECLG	8.2492
46	1.0167	590.0641	2204.9866	1005.6825	634.0316	127.5935	103.8502	2.2273	1.6428	0.3391	0.3164	DECLG	8.2492
47	1.0182	584.6722	2271.6912	987.3613	661.8533	128.8962	94.6552	2.0276	1.6937	0.4152	0.3649	DECLG	8.2492
48	1.0141	587.726	2265.1018	994.8865	668.8404	133.6242	65.3268	2.0425	1.6207	0.2977	0.3463	DECLG	8.2492
49	1.0196	587.5303	2224.9912	1014.5881	663.5226	141.7063	86.3679	2.2155	1.6071	0.3471	0.4048	DECLG	8.2492
50	1.0156	587.6816	2208.2803	992.1831	669.7471	116.2731	75.9711	1.9611	1.637	0.3006	0.3804	DECLG	8.2492
51	1.0189	589.0216	2216.2361	997.7368	676.334	123.1817	67.5152	2.2805	1.615	0.3384	0.3749	DECLG	8.2492
52	1.015	588.0416	2288.8535	1005.5166	659.1129	134.4682	113.2772	2.1687	1.6588	0.269	0.333	DECLG	8.2492
53	1.018	585.6785	2234.0076	1003.4197	671.3772	106.8327	89.4246	2.1986	1.6194	0.3165	0.3984	DECLG	8.2492
54	1.0144	587.4326	2244.6465	994.8892	645.8608	122.4561	78.5097	2.0028	1.6355	0.2971	0.3495	DECLG	8.2492
55	1.0193	587.8782	2281.2744	992.9033	650.85	123.9796	53.9661	2.1058	1.5899	0.2228	0.3718	DECLG	8.2492
56	1.0181	586.6215	2204.4404	993.2461	678.3618	130.678	75.7681	2.237	1.6574	0.3221	0.357	DECLG	8.2492
57	1.0162	588.4556	2241.9468	1013.7851	640.233	109.9856	63.5129	1.9813	1.6654	0.3561	0.333	DECLG	8.2492
58	1.0159	588.8334	2224.1868	987.2167	633.4017	115.0645	58.2151	1.9279	1.6716	0.3527	0.4049	DECLG	8.2492
59	1.0185	586.2753	2200.1514	995.7124	642.4063	121.7193	82.3877	2.3987	1.6593	0.3207	0.3131	DECLG	8.2492

Table 5-4 59 PCT(K) of Sequence 74

1023.821	1203.56	1241.282	1276.127	1299.377
1064.06	1204.493	1244.877	1282.166	1302.127
1092.049	1208.071	1253.749	1282.399	1303.438
1100.049	1211.382	1257.827	1283.854	1303.682
1113.899	1212.071	1265.604	1286.427	1307.588
1153.482	1213.677	1266.799	1287.382	1313.493
1158.627	1227.438	1267.238	1287.938	1319.771
1160.688	1227.471	1268.327	1291.049	1330.071
1162.371	1232.027	1273.716	1292.204	1337.827
1178.777	1236.154	1273.882	1292.232	1341.66
1187.404	1239.66	1275.532	1298.077	1367.499
1189.482	1241.104	1275.627	1299.066	

Table 5-5 Summary of Target Sequence Difference

Sequence ID	Sequence probability	Loss of off-site power	High Head Injection	ACC Injection	Low Pressure Injection
LOCAS01	4.946E-01	no	2 trains	3	2 trains
LOCAS55	4.935E-01	yes	2 trains	3	2 trains
LOCAS56	5.067E-03	yes	1 trains	3	2 train
LOCAS74	5.460E-05	yes	1 train	3	1 train

Table 5-6 59 PCT(k) of Sequence 1

1047.85	1160.888	1196.827	1229.566	1270.743
1106.97	1164.216	1201.682	1236.638	1272.81
1114.25	1167.621	1206.843	1238.038	1273.01
1125.1	1171.06	1206.954	1238.749	1273.582
1131.15	1182.632	1210.632	1242.277	1278.254
1133.68	1184.066	1213.16	1250.577	1281.704
1134.41	1184.466	1214.299	1252.999	1293.393
1143.88	1185.921	1215.432	1255.91	1296.499
1149.17	1192.193	1223.521	1256.527	1305.116
1151.1	1193.138	1223.754	1262.127	1313.66
1152.42	1193.56	1224.954	1266.782	1322.238
1156.48	1195.943	1229.116	1267.06	

Table 5-7 59 PCT(k) of Sequence 55

1018.91	1160.516	1212.143	1237.91	1282.36
1051.888	1166.016	1220.732	1239.599	1290.199
1066.238	1166.749	1220.799	1243.36	1294.138
1076.56	1170.138	1221.849	1248.482	1295.754
1082.532	1175.36	1226.393	1252.304	1299.01
1104.182	1178.827	1228.466	1256.16	1306.321
1106.543	1189.393	1229.254	1256.743	1306.349
1113.06	1190.966	1231.627	1265.254	1309.332
1146.538	1195.049	1232.899	1265.443	1309.543
1152.521	1195.188	1233.727	1277.521	1317.504
1159.093	1209.054	1235.243	1278.521	1328.154
1160.288	1211.821	1235.477	1280.554	

Table 5-8 59 PCT(k) of Sequence 56

1018.91	1152.027	1193.36	1214.916	1259.316
1038.46	1159.049	1193.466	1218.793	1259.538
1051.888	1164.904	1194.96	1223.221	1259.582
1069.982	1165.249	1198.338	1225.277	1260.027
1077.016	1165.382	1199.188	1225.877	1262.171
1082.532	1166.016	1199.577	1226.332	1276.793
1085.038	1171.56	1201.299	1230.46	1284.916
1127.421	1177.571	1203.993	1232.582	1286.304
1137.416	1182.627	1207.677	1236.16	1305.582
1140.471	1182.738	1211.327	1237.743	1325.121
1140.938	1187.593	1211.838	1247.654	1329.227
1149.821	1188.732	1212.282	1252.143	

Table 5-9 Comparison of Calculational Uncertainty of Each Sequence

Sequence	PCT_{μ}	$PCT_{95/95}$	ΔPCT
1	1224.4	1322.22	97.89
55	1229.5	1328.14	98.62
56	1245.1	1329.22	84.10
74	1289.5	1367.50	78.0

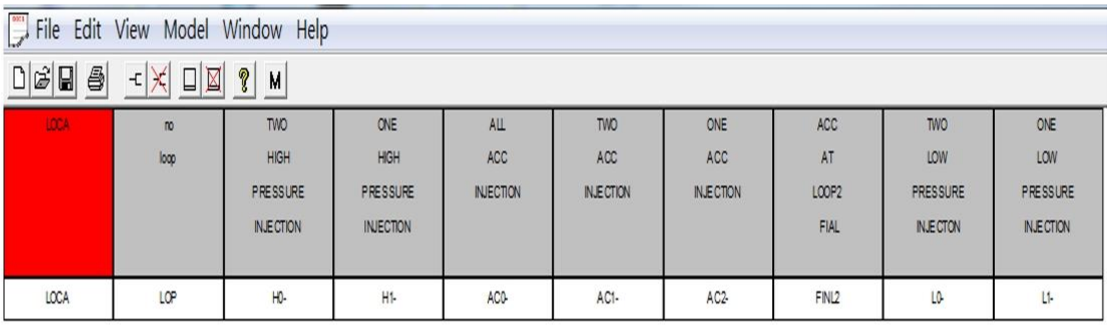

Figure 5-1 Heading of LBLOCA event tree

```
=============================================================================
WinNUPRA 3.0 Production (SR-3)File: H10.FTP              Licensed to: TAIPOWER
=============================================================================

          Minimum Cut Set Solution for fault tree H10, FT Rev. # = 3

       WIN NURELMCS Solution, Performed: Tuesday, February 03, 2015  12:53

       Cut Set Equation produced is  : H10.EQN
       ______________________________________________________________________
       HIGH HEAD SAFETY INJECTION (HHSI) FAULT TREE (S/T PK)
       ______________________________________________________________________
       Top event: GH100112
       Top event unavailability (r.ev. appr)=   4.795E-003
       Cutoff value used                    =    1.00E-010
       Number of Boolean Indicated Cut Sets =            0
       Number of MCS in equation file       =          729
       MINIMAL CUT SETS SORTED BY UNAVAILABILITY
       ______________________________________________________________________
         1.   4.657E-003 FRAC-RCSLP1CLLOC FRAC-RCSLP2CLLOC FRAC-RCSLP3CLLOC
         2.   6.660E-005 MVDBG-LV-1CCF12
         3.   1.849E-005 TRYA-HHSI-S      TRYB-HHSI-S
         4.   1.220E-005 BAD-SEA-WATER1
         5.   9.718E-006 MVDA-BH-HV-20    TRYB-HHSI-S
         6.   7.660E-006 PMAEF-P103CCF1-4
         7.   5.108E-006 MVDA-BG-LV-115B  MVDB-BG-LV-115D
         8.   2.958E-006 SCFA-BH-HV-20    TRYB-HHSI-S
         9.   1.555E-006 MVDB-BG-LV-115D  SCFA-BG-LV-115B
        10.   1.555E-006 MVDA-BG-LV-115B  SCFB-BG-LV-115D
        11.   1.190E-006 PMEBG-P091CCF123
        12.   1.000E-006 TRZA-EG-CCWA     TRZB-EG-CCWB
        13.   1.000E-006 TRYB-EG-CCWB     TRZA-EG-CCWA
        14.   1.000E-006 TRYA-EG-CCWA     TRZB-EG-CCWB
        15.   1.000E-006 TRYA-EG-CCWA     TRYB-EG-CCWB
```

Figure 5-2 Fault tree result for High Head Safety Injection (HHSI)

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================================================================================
WinNUPRA 3.0 Production (SR-3)File: L10.FTP              Licensed to: TAIPOWER
================================================================================

     Minimum Cut Set Solution for fault tree L10, FT Rev. # = 3

   WIN NURELMCS Solution, Performed: Tuesday, February 03, 2015  12:53

   Cut Set Equation produced is  : L10.EQN
   ____________________________________________________________________________
   圖C-16. FLT FOR LHSI
   ____________________________________________________________________________
   Top event: GL100112
   Top event unavailability (r.ev. appr)=   4.771E-003
   Cutoff value used                    =    1.00E-010
   Number of Boolean Indicated Cut Sets =            0
   Number of MCS in equation file       =          961
   MINIMAL CUT SETS SORTED BY UNAVAILABILITY
   ____________________________________________________________________________
    1.  4.657E-003 FRAC-RCSLP1CLLOC FRAC-RCSLP2CLLOC FRAC-RCSLP3CLLOC
    2.  5.100E-005 PMABC-P024CCF12
    3.  1.220E-005 BAD-SEA-WATER1
    4.  9.790E-006 PMEBC-P024CCF12
    5.  7.660E-006 PMAEF-P103CCF1-4
    6.  2.372E-006 PMAA-BC-P024     PMAB-BC-P025
    7.  1.694E-006 PMAB-BC-P025     XVOA-BC-V001
    8.  1.694E-006 PMAA-BC-P024     XVOB-BC-V002
    9.  1.346E-006 PMAB-BC-P025     PMEA-BC-P024
   10.  1.346E-006 PMAA-BC-P024     PMEB-BC-P025
   11.  1.210E-006 XVOA-BC-V001     XVOB-BC-V002
   12.  1.060E-006 PMAB-BC-P025     SCFA-BC-P024
   13.  1.060E-006 PMAA-BC-P024     SCFB-BC-P025
   14.  1.056E-006 TRYA-RHR-A       TRZB-RHR-B
   15.  1.000E-006 TRZA-EG-CCWA     TRZB-EG-CCWB
```

Figure 5-3 Fault tree result for Low Head Safety Injection (LHSI)

```
================================================================================
WinNUPRA 3.0 Production (SR-3)File: AC(1).FTP            Licensed to: TAIPOWER
================================================================================

     Minimum Cut Set Solution for fault tree AC(1), FT Rev. # = 3

   WIN NURELMCS Solution, Performed: Tuesday, February 03, 2015  12:53

   Cut Set Equation produced is  : AC(1).EQN
   ____________________________________________________________________________
   圖C-15. FLT FOR ACCO
   ____________________________________________________________________________
   Top event: GA010112
   Top event unavailability (r.ev. appr)=   2.144E-009
   Cutoff value used                    =    1.00E-015
   Number of Boolean Indicated Cut Sets =           27
   Number of MCS in equation file       =           27
   MINIMAL CUT SETS SORTED BY UNAVAILABILITY
   ____________________________________________________________________________
    1.  1.690E-010 CVDA-BH-V073     CVDB-BH-V071
    2.  1.690E-010 CVDA-BH-V070     CVDB-BH-V074
    3.  1.690E-010 CVDA-BH-V073     CVDC-BH-V075
    4.  1.690E-010 CVDB-BH-V071     CVDC-BH-V075
    5.  1.690E-010 CVDA-BH-V073     CVDC-BH-V072
    6.  1.690E-010 CVDA-BH-V070     CVDC-BH-V075
    7.  1.690E-010 CVDA-BH-V070     CVDC-BH-V072
    8.  1.690E-010 CVDB-BH-V071     CVDC-BH-V072
    9.  1.690E-010 CVDA-BH-V070     CVDB-BH-V071
   10.  1.690E-010 CVDA-BH-V073     CVDB-BH-V074
   11.  1.690E-010 CVDB-BH-V074     CVDC-BH-V075
   12.  1.690E-010 CVDB-BH-V074     CVDC-BH-V072
   13.  9.568E-012 CVDA-BH-V073     TKRB-BH-T006
   14.  9.568E-012 CVDC-BH-V075     TKRB-BH-T006
   15.  9.568E-012 CVDA-BH-V070     TKRC-BH-T007
```

Figure 5-4 Fault tree result for accumulator system

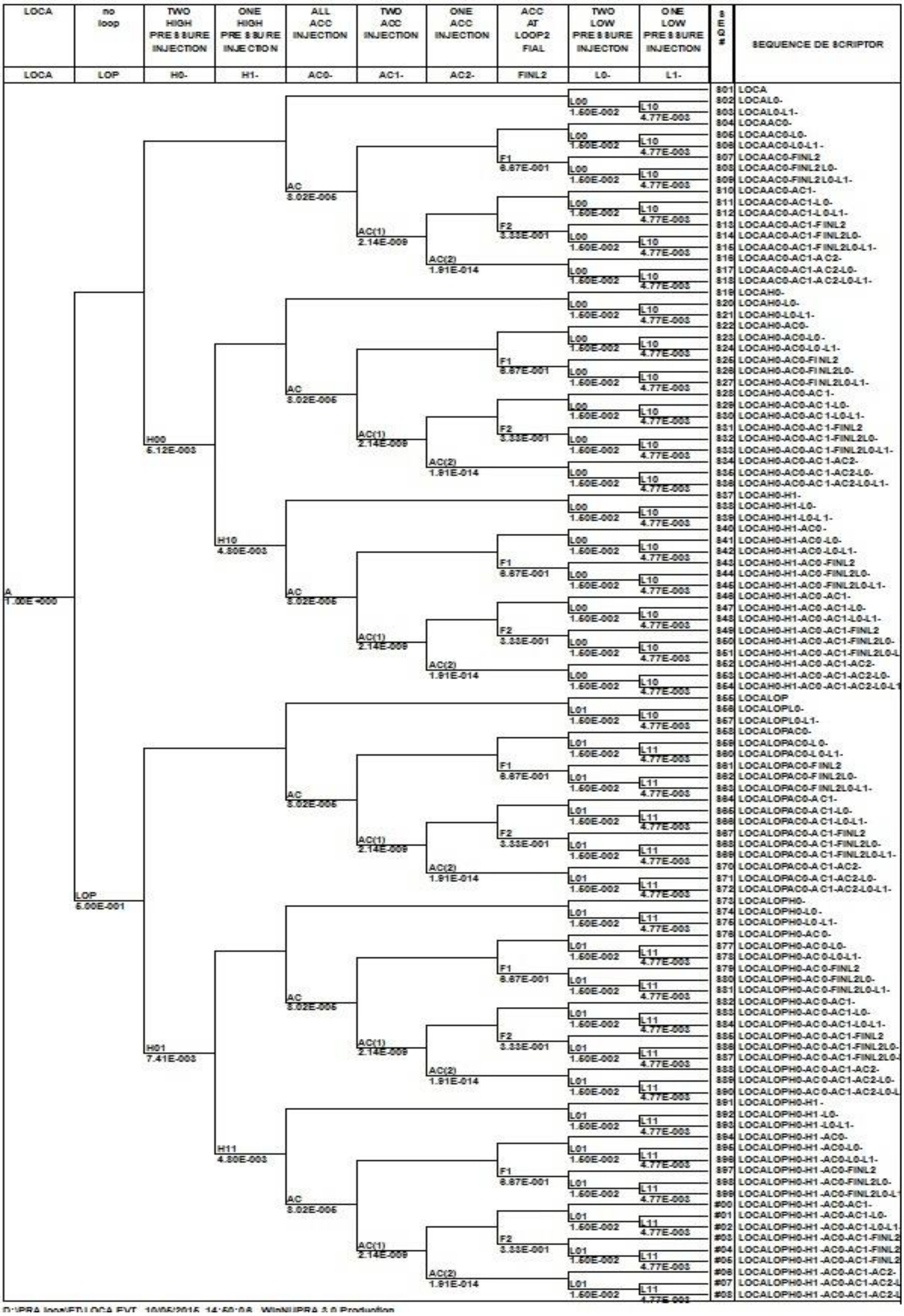

Figure 5-5 Sequence Identification and Quantification for LBLOCA

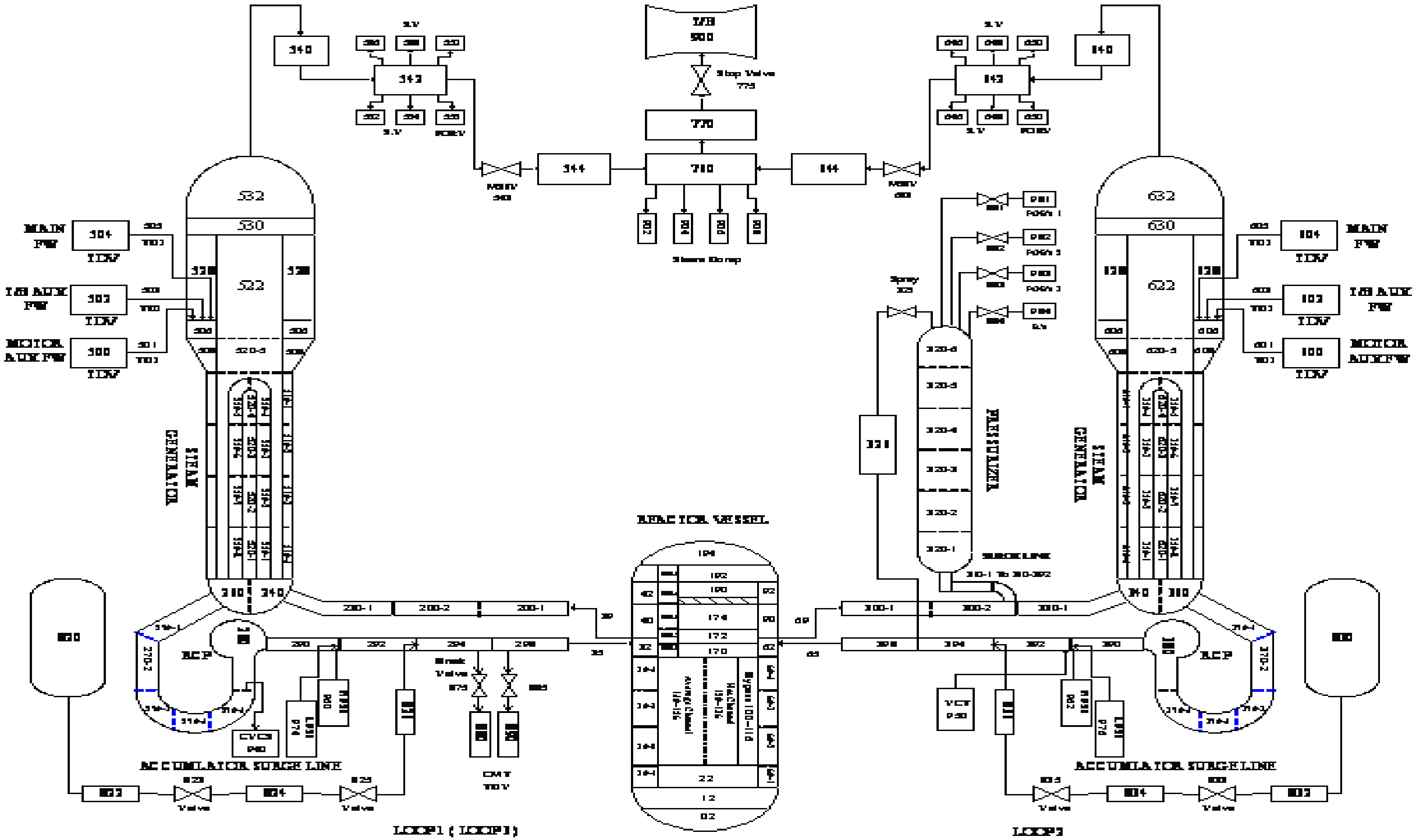

Figure 5-6 RELAP5 Nodding Diagram for Maanshan PWR LBLOCA Analysis

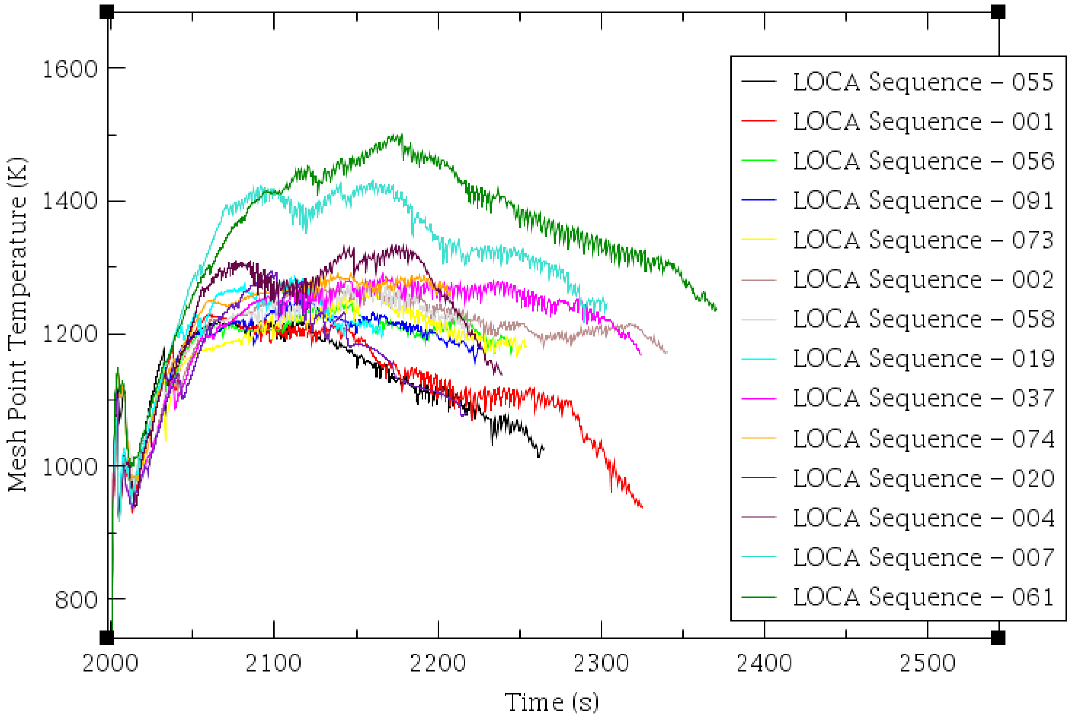

Figure 5-7 Responses for the Probabilistic Significant LBOCA Events

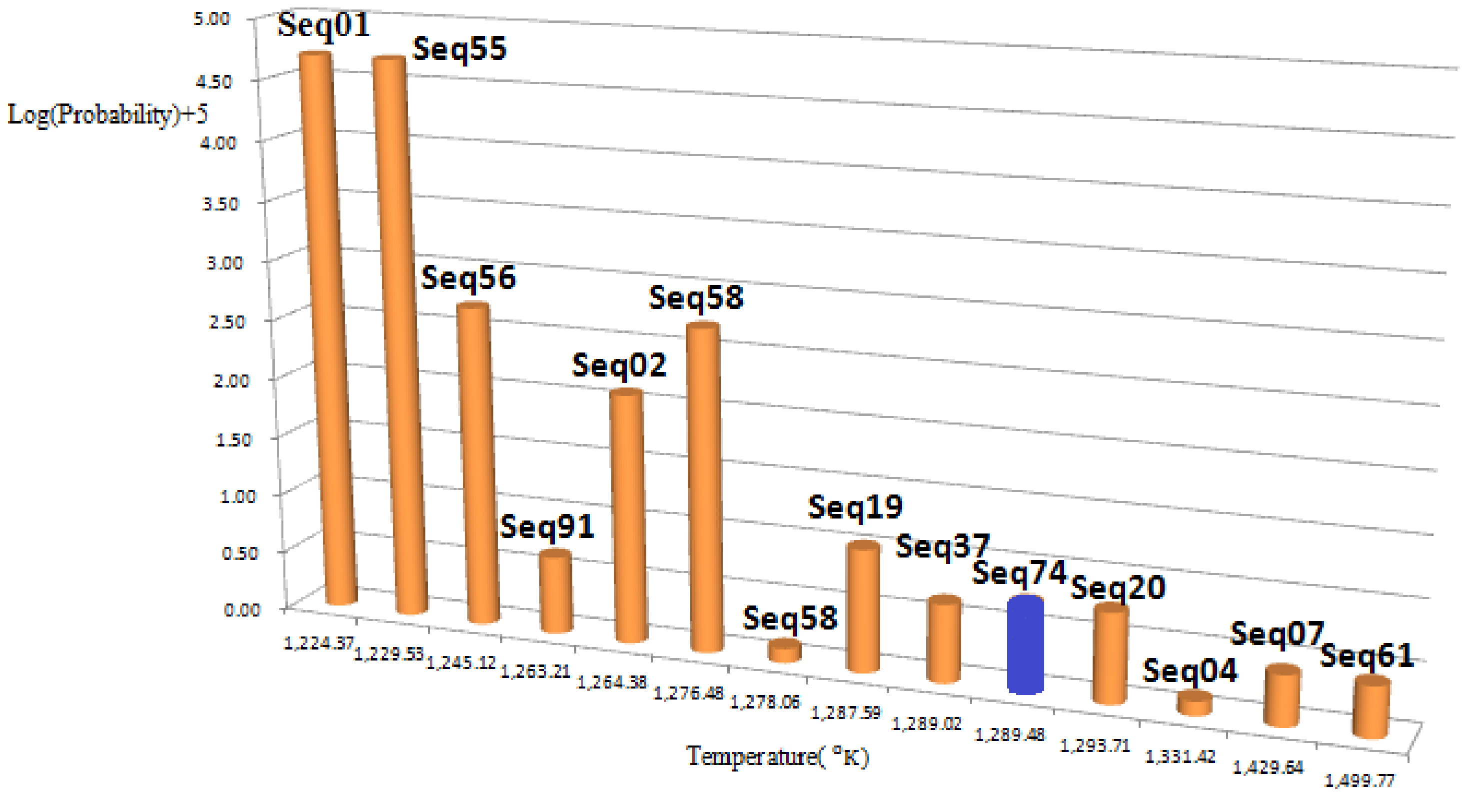

Figure 5-8 Preliminary Load Spectrum for Maanshan PWR LBLOCA

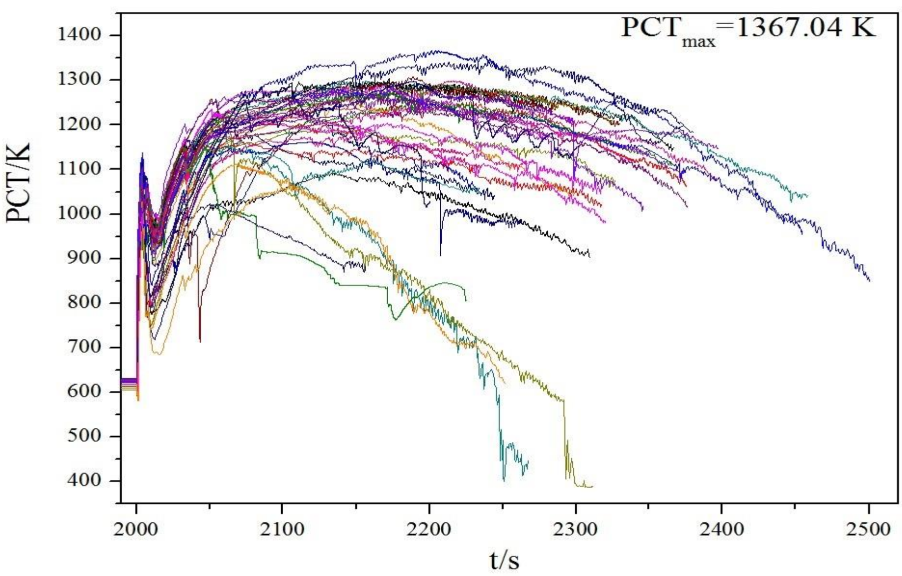

Figure 5-9 59 PCT Plots of Sequence-74

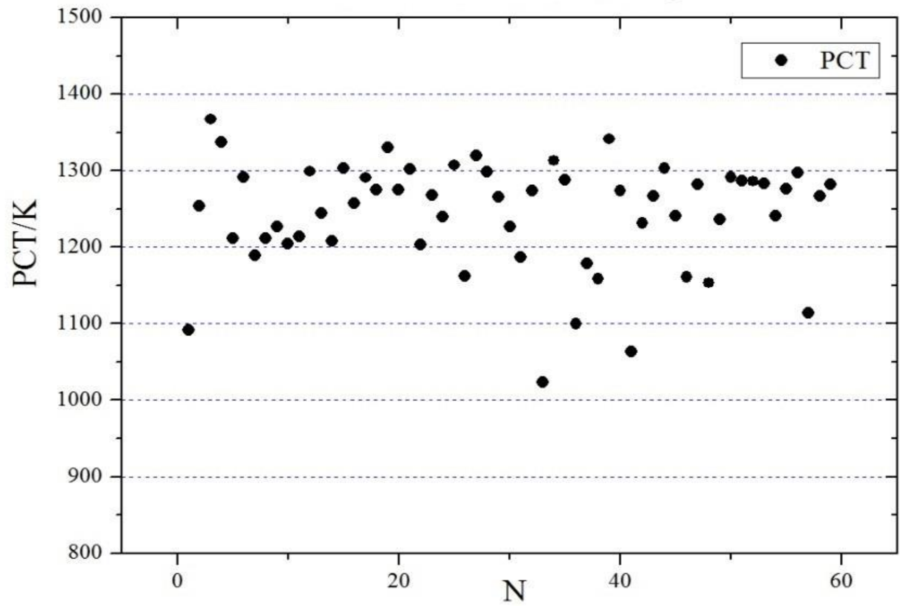

Figure 5-10 PCT scattering Plot of Sequence-74

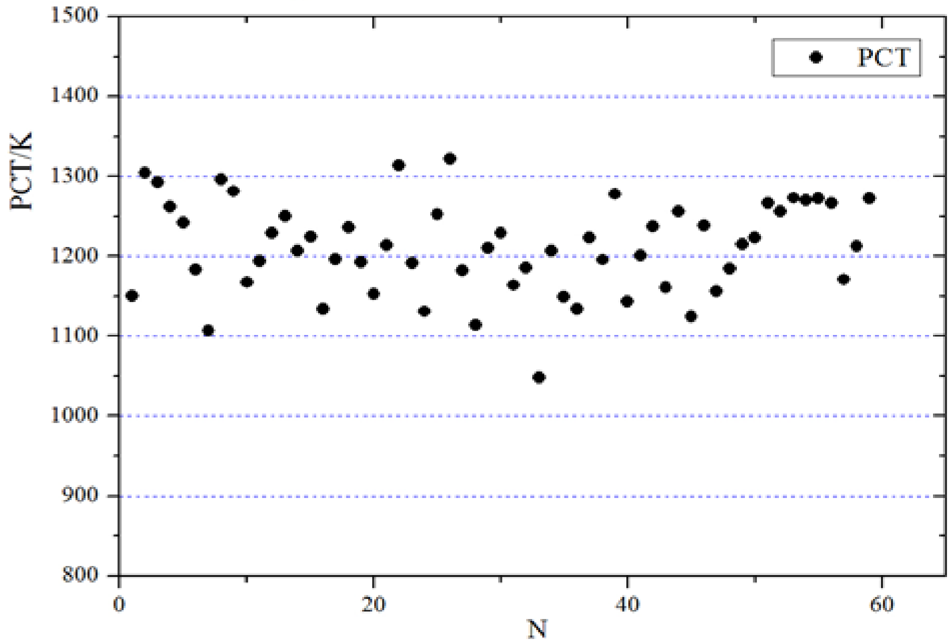

Figure 5-11 PCT scattering Plot of Sequence-1

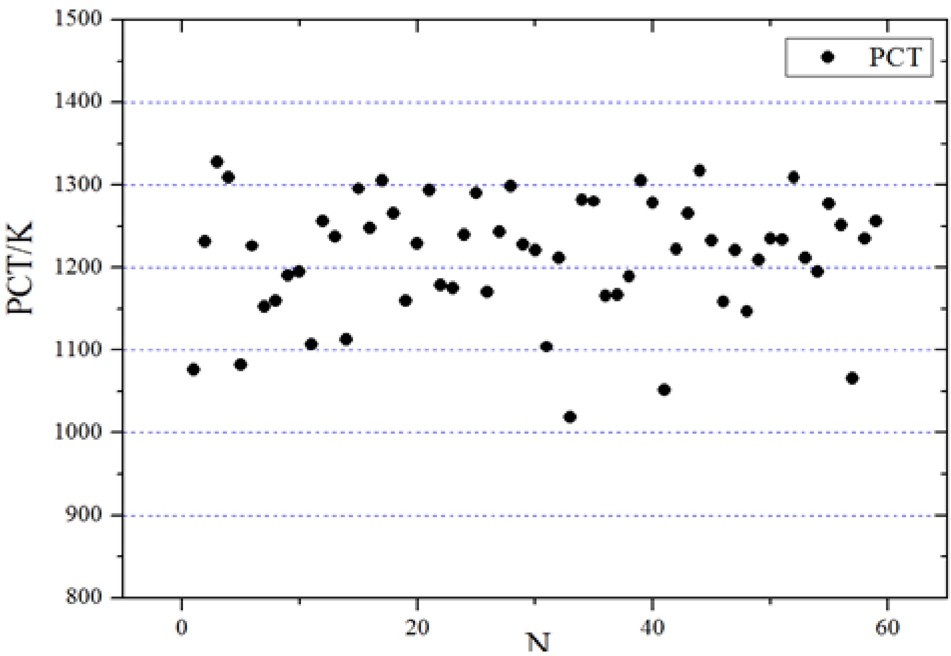

Figure 5-12 PCT scattering Plot of Sequence-55

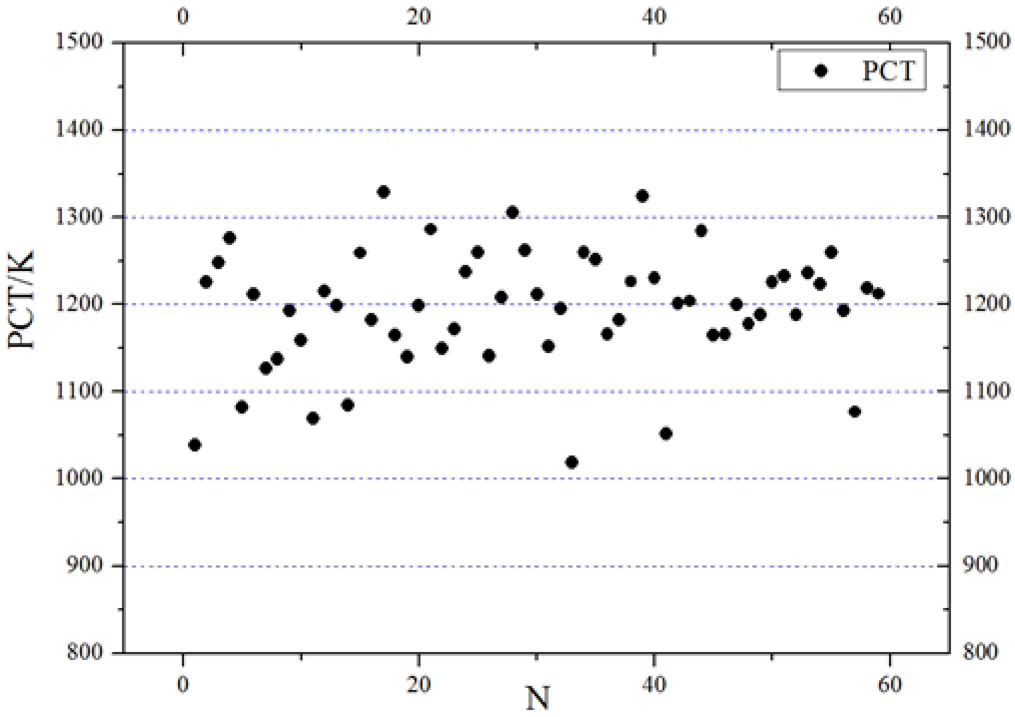

Figure 5-13 PCT scattering Plot of Sequence-56

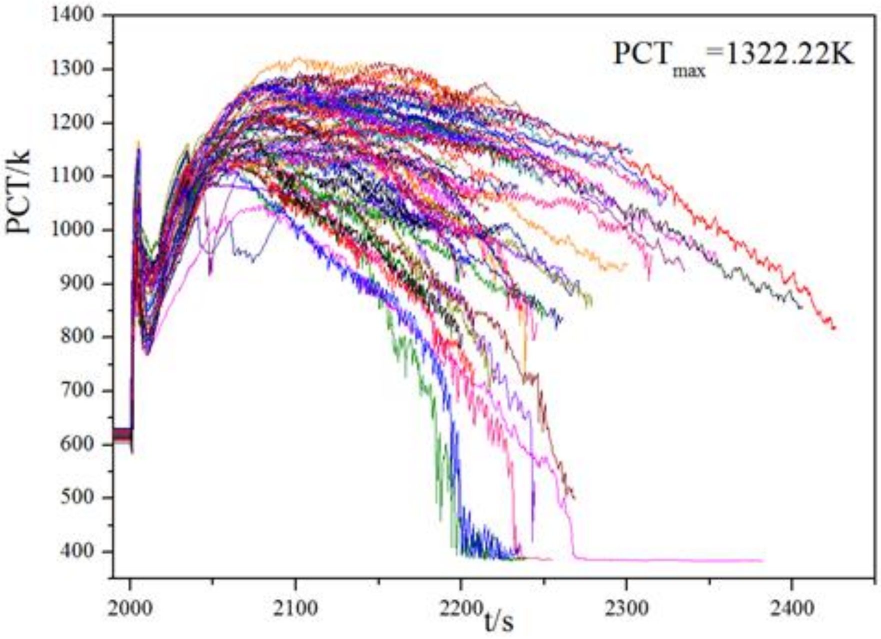

Figure 5-14 59 PCT Plots of Sequence-1

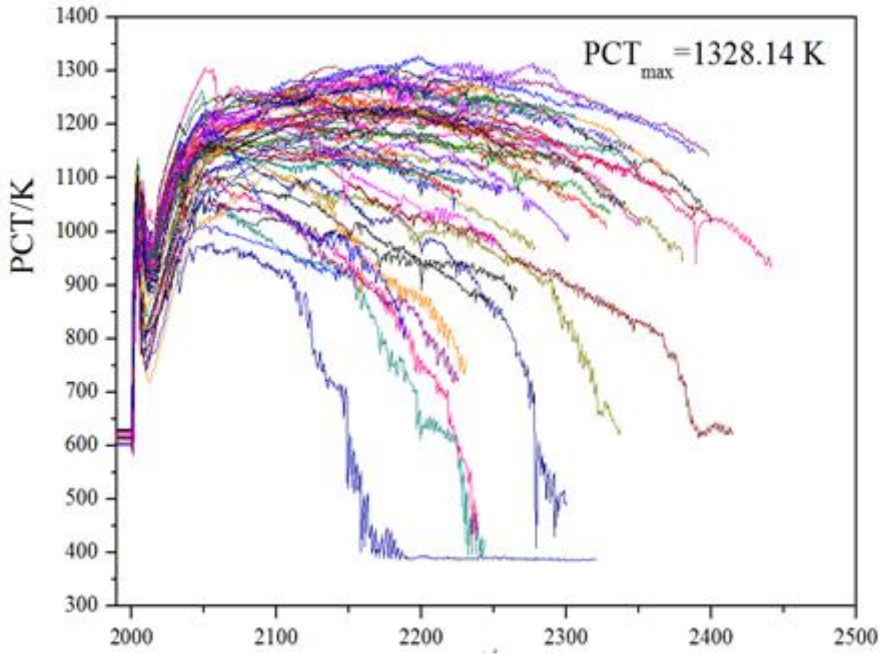

Figure 5-15 59 PCT Plots of Sequence-55

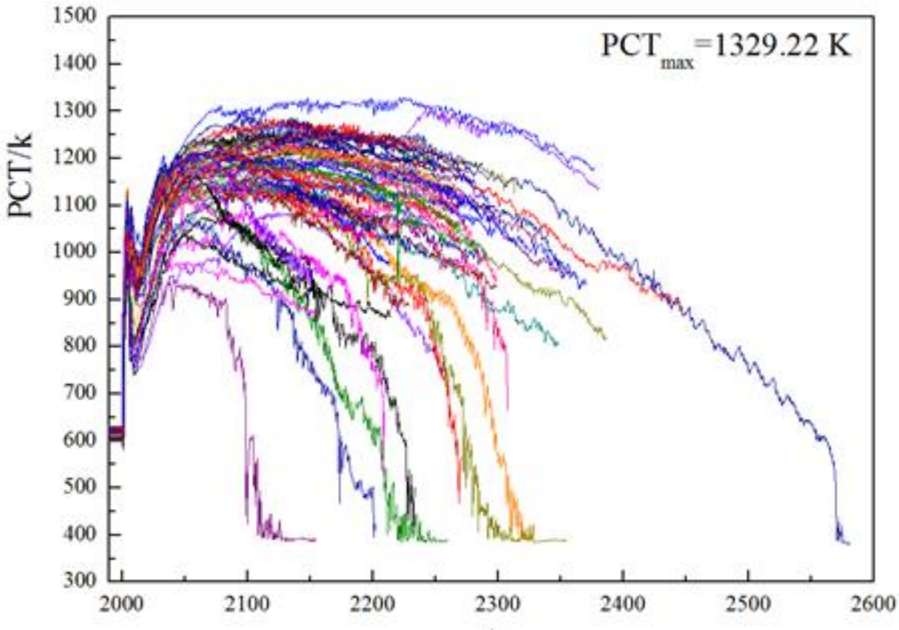

Figure 5-16 59 PCT Plots of Sequence-56

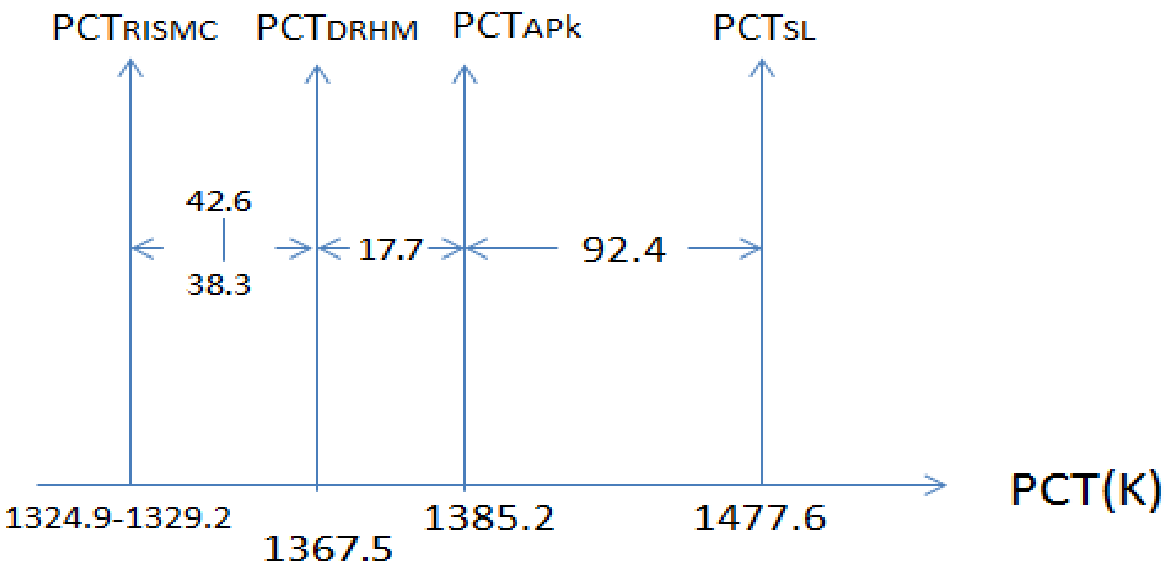

Figure 5-17 Evolution of PCT Margin

Chapter 6. Evolution of Licensing Methodology for the Large Break Loss of Coolant Accident Analysis and Associated PCT Margin Quantification

In this chapter, the evolution from a deterministic methodology to a risk-informed methodology for LBLOCA analysis was elaborated, and the PCT margin quantified by associated methodologies was compered. Among the deterministic methodologies, the traditional Appendix K methodology and the deterministic-realistic hybrid methodology (DRHM) (Liang, 2011) were involved in this paper；DRHM methodology is a BEPU methodology of partial scope. In the traditional Appendix K methodology, both conservative appendix K models and conservative plant status parameters would be applied. While in the DRHM methodology, physical models required by Appendix K were still adopted to ensure model conservatism, whereas realistic plant status parameters were used with statistical uncertainty analysis. As for the risk-informed methodology, the newly developed risk-informed safety margin characteristic (RISMC) methodology (Hess, 2009) (Smith, 2012) (Sherry, 2013) was applied with a proper E.M. model to generate a probabilistic load spectrum and to calculate the risk-informed PCT margin for LBLOCA to satisfy the to-be-issued 10 CFR 50.46a. To make the PCT margin comparison meaningful enough, the E.M. model applied for above methodologies all utilized RELAP5-3D/K (Liang, 2002a, 2002b), an Appendix K version of RELAP5-3D (Jonson, 1998). To calculate the PCT of a LBLOCA with RELAP5-3D/K, three distinguished phases are involved, namely blowdown, refill and reflood, and during each phase associated Appendix K requirements are all satisfied.

6.1 Deterministic Methodology

According to the existing 10 CFR 50.46, the LBLOCA can only be analyzed by deterministic licensing methodologies with E.M. models based on a surrogate sequence which satisfies all the required licensing assumptions. The associated procedure that guides the development of the E.M. models for transient and accident analyses provided by USNRC was thoroughly stated in Regulatory Guide 1.203 (USNRC, 2005). In the design-basis LBLOCA licensing analysis, the revised 10 CFR 50.46 in 1988 indicates that two kinds of E.M. models are accepted, namely conservative E.M. models developed in conformance with the required and acceptable features of Appendix K of 10 CFR 50, and realistic E.M. models with uncertainty quantification. As stated in the revised 10 CFR 50.46, an alternative ECCS performance, based on best estimate method, may be used to provide more realistic estimates of plant safety margins, provided the licensee quantifies the uncertainty of the estimates and includes the uncertainty when comparing the calculated results with prescribed acceptance limits. It was well recognized that a realistic LOCA analysis with uncertainty quantification can generate a greater safety margin than the traditional conservative LOCA analysis using Appendix K evaluation models.

Traditional Appendix K methodology calculation

To perform a traditional Appendix K LBLOCA licensing analysis, a system code of the Appendix K version shall be applied and bounding plant parameters shall be assumed. To demonstrate a traditional appendix K LBLOCA analysis, Taiwan's Maanshan nuclear power plant, which is a Westinghouse three-loop PWR plant, was analyzed with an Appendix K version of RELAP5-3D (RELAP5-3D/K). Besides, bounding plant parameters were also assumed and summarized in Table 2-2 marked by "*". Other than those assumed bounding plant parameters, to maximize the steam binding effect constant atmospheric containment pressure was also conservatively assumed. A typical cladding temperature response is shown in Figure 6-1. It can be seen that the resultant licensing PCT is 1385.2 K (Taiwan Power Company, 2013) with an associated PCT margin of 92.4 K. Generally, the PCT margin evaluated by the traditional Appendix K methodology should be much less than that analyzed by the BEPU methodology, as shown in Figure 6-2.

Best-estimate plus uncertainty quantification methodology (BEPU) calculation

Generally, the PCT margin evaluated by the BEPU methodology should be much greater than that analyzed by the traditional Appendix K methodology, as shown in Figure 6-2. Comparing the new licensing PCT (1179.25 K) (Westinghouse, 2009) of the Taiwan Maanshan plant evaluated by the Westinghouse full-ranged ASTRUM best-estimate LBLOCA methodology with the WCOBRA/TRAC code (Westinghouse, 2005), and the previous licensing PCT (1383.8 K) (Westinghouse, 1987) evaluated by the Westinghouse Appendix K methodology with BASH code (Westinghouse, 1981), it can be observed that margin released from the traditional appendix K approach versus the full-ranged BELOCA methodology can be 204.6 K.

Deterministic-realistic hybrid methodology (DRHM) calculation

To perform the Maanshan LBLOCA licensing analysis with DRHM methodology using RELAP5-3D/K, 59 trails are generated by random sampling of the major plant parameters listed in Table 2-2. The resultant PCT of each trial is shown in Figure 5-9. It was noted that the greatest PCT among 59 sets is 1367.5 K. Regarding the parametric approach, it was found that normal distribution was rejected by the goodness-of-fitting test. Therefore, the $PCT_{95/95}$ can only be estimated by order statistic method；

$$PCT_{95/95} \approx PCT_{order} = Max\left[PCT_i, i = 1,59\right] = 1367.5\,K \tag{6-1}$$

and the associated PCT margin is 110.1 K (1477.6-1367.5 K). Comparing with the PCT margin (92.4K=1477.6-1385.2) evaluated by the traditional Appendix K bounding state approach, it can be observed that only by relaxing bounding plant parameter settings, extra margin can be generated by 17.7 K (110.1-92.4 K) as shown in Figure 6-3, which is about 1/10 of the margin released by a full-scoped BEPU methodology covering the uncertainties of both physical model and plant status.

6.2 Risk-informed methodology

Regarding the risk-informed methodology for beyond design-basis LBLOCA analysis, two kinds of uncertainties need to be addressed, namely epistemic uncertainty and aleatory uncertainty. Epistemic uncertainty results from the “imperfect knowledge” regarding values of parameters of the underlying computational model, whereas aleatory uncertainty results from the effect of “inherent randomness” or “stochastic variability”. Aleatory uncertainty represents the nondeterministic and unpredictable random nature of the performance of the system and its components. Epistemic uncertainty generally can be refereed as calculation uncertainty. In the current advanced BEPU licensing safety analysis methodologies (Westinghouse, 2005) (Martin, R.P.,

2005) (Framatome ANP, 2001), only epistemic uncertainty is considered on a particular surrogate sequence which satisfies all the required licensing assumptions. To deal with the aleatory uncertainty, a group of sequences should be identified for a particular initiating event with PSA skill to take into account systems or components failure by random probability.

The RISMC methodology is a systematic approach that considers both aleatory and epistemic uncertainties. To replace the surrogate-based decision making, the main scope of the RISMC methodology is to generate a probabilistic load spectrum as shown in Figure 1-2, and to quantify the safety margin in a proper risk-informed manner. The RISMC methodology can systematically combine both probabilistic and mechanistic approaches to estimate the safety margin. The probability analysis is represented by the stochastic risk analysis with PSA techniques involving both event tree and fault tree analysis, whereas mechanistic analysis is represented by the physical calculation with evaluation models satisfying the requirements set forth in the to-be-issued 10 CFR 50.46. Evaluation models can either be a conservative Appendix K model or a realistic model with uncertainty quantification. With the combination of probabilistic and mechanistic analyses, both aleatory uncertainty and epistemic uncertainty can be well quantitatively addressed, and a risk-informed PCT margin of LBLOCA can be evaluated.

The following process was recommended (Liang, 2016) to calculate the licensing PCT of a LBLOCA to satisfy the risk-informed safety margin evaluation requirement stated in the to-be-issued 10 CFR 50.46a. The associated seven steps are shown in Figure 8 and elaborated as follows；

(1) Identification of the LBLOCA sequences；

(2) Quantification of LBLOCA sequence occurrence probabilities；

(3) Calculation of the nominal PCT for LBLOCA sequences；

(4) Conducting a preliminary load spectrum of LBLOCA；

(5) Quantification of the calculation uncertainty of the preliminary load spectrum；

(6) Conducting the final load spectrum for LBLOCA； and

(7) The Risk-informed PCT Safety Margin Characterization.

Detailed elaboration of each step was stated in Chapter 4 and the application of the RISMC methodology to evaluate the risk-informed PCT of LBLOCA of the Maanshan plant was presented in Chapter 5. The final load spectrum for LBLOCA of the Maanshan plant is indicated in the last column of Table 5-1.

The risk-informed PCT safety margin (ΔPCT_{RI}) can be calculated by two different methods； the first one is the expecting value estimation method (equation 4-4) and the second one is the sequence probability coverage method (equation 4-5). By using the first expecting value estimation method and data listed in Table 5-1, the risk-informed safety margin can be mathematically calculated according to Equation (4-4) as follows；

$$\Delta PCT_{RI} = \sum_i \Delta PCT_{MR,i} * SP_i \tag{6-2}$$

$$= 152.72 \text{ K}$$

As for the second sequence probability coverage method, it was found that the summation of the first 3 sequence (LOCAS01, LOCAS55 and LOCAS56) probabilities is 99.3%. Therefore, the third sequence with a value of 1329.22 K will be applied to define the risk-informed $PCT_{RI}^{99\%}$, and the risk-informed safety margin will be as follows

$$\Delta PCT_{RI} = PCT_{SL} - PCT_{RI}^{99\%} \tag{6-3}$$

$$= 148.38 \text{ K}$$

Comparing the risk-informed safety margins evaluated by above two methods, it can be found that the ΔPCT_{RI} calculated by the sequence probability coverage method is reasonably conservative by 4.34 K. It was also noted that according to the deterministic methodology, the licensing PCT can only be evaluated by the traditional surrogate sequence (LOCAS74) and the correspondent value is 1367.5K as indicated in Table 5-

1. Consequently, the traditional deterministic safety margin is only 110.1K (1477.6 K-1367.5 K) by applying the DRHM methodology. Therefore, the PCT safety margin of LBLOCA evaluated by the RISMC methodology can be greater by 38.3 K-42.6 K than the margin evaluated by the DRHM deterministic methodology.

6.3 PCT margin evolution

As indicated in this chapter, PCT margins of LBLOCA can only be evaluated either by deterministic methodologies or risk-informed methodology. Regarding the deterministic methodologies, only epistemic uncertainty was considered, which majorly involves model uncertainty and plant status uncertainty. While for the risk-informed methodology, both the epistemic and aleatory uncertainties are all properly considered. In the traditional Appendix K deterministic methodology, both model uncertainty and plant status uncertainty are all conservatively treated. While for the DRHM deterministic methodology, although the conservative Appendix K models were still applied, realistic plant status parameters were adopted with statistical uncertainty quantification. As for the BEPU deterministic methodology, full scoped realistic LBLOCA analysis can be performed with statistical treatment of both model uncertainties and plant status uncertainties. Treatments of uncertainties by above methodologies are summarized in Table 6-1 for comparison. It is generally truly that the more conservative the methodology is the smaller margin can be generated. It is expected that amount those deterministic methodologies, the greatest margin can be generated by a full-scoped BEPU methodology, while smallest margin can be available when applying a traditional Appendix K methodology, with DRHM's margin lying in between. Furthermore, when applying a same evaluation model to perform LBLOCA analysis, the margin evaluated by the risk-informed methodology is expected to be greater than the margin generated from deterministic methodologies.

As indicated in this chapter, PCT margins of LBLOCA were evaluated by different methodologies with RELAP5-3D/K for Taiwan's Maanshan nuclear power plant. Regarding the deterministic methodologies, the PCT margin shall be evaluated based on the licensing sequence, and demonstrated methodologies include the traditional Appendix K methodology and the DRHM methodology. For the traditional Appendix K methodology, the conservative Appendix K code (RELAP5-3D/K) was adopted and conservative plant parameters were assumed to define a plant bounding status. The PCT margin evaluated by the traditional Appendix K methodology was 92.4 K, as shown in Figure 5-17. As for the DRHM methodology, it is a BEPU methodology of partial scope. In the DRHM methodology, physical models required by Appendix K were still adopted to ensure model conservatism, whereas realistic plant status parameters were used with statistical uncertainty analysis. The PCT margin evaluated by the DRHM methodology for the Maanshan plant is 110.1K (1477.6-1367.5K). An additional 17.1K (110.1K-92.4K) margin can be released only by relaxing the plant bounding state assumption with realistic plant parameters. As demonstrated by the Westinghouse in the LBLOCA licensing analysis of Taiwan's Maanshan plant, a full-scoped BEPU methodology with best-estimate models and realistic plant parameters can release PCT margin by about 204.6 K from traditional Appendix K approach (Westinghouse,2009) (Westinghouse,1987).

According to the current licensing rules, LBLOCA can only be evaluated by deterministic methodologies, unless the LBLOCA can be re-categorized as a beyond DBA event by the to-be-issued 10 CFR50.46a. For the non-design-basis LBLOCA, the risk-informed methodology can be applied to account the contribution of the PCT margin from all success LBLOCA sequences. As indicated by the risk-informed PCT evaluation in chapter 4, 14 probabilistic dominant sequences and associated occurrence probabilities have been identified and quantified. Consequently, the resultant risk-informed PCT margin can be 148.4-152.7 K by using RELAP5-3D/K. It then can be noted that the additional PCT margin of 38.3-42.6 K can be released from the deterministic DRHM methodology by relaxing the licensing sequence assumptions.

In summary, the PCT margin of LBLOCA evaluated by a traditional appendix K methodology (ΔPCT_{APK}) can be further enlarged by 17.7K when applying the DRHM methodology to relax the assumption of bounding plant status by realistic plant parameters and statistical analysis. While when applying a full-scoped BEPU methodology covering both best-estimate models and realistic plant parameters with statistical uncertainty analysis, the ΔPCT_{APK} can be enlarged by 204.6 K. Furthermore, when applying RISMC to relax the licensing sequence assumption and perform the risk-informed LBLOCA analysis, the PCT margin evaluated by deterministic DRHM methodology can be further enlarged by 38.3-42.6 K. The PCT margin evolution from different methodologies is summarized in Table 6-2.

Table 6-1. Summary of Uncertainty Treatment for Different Methodologies

		Epistemic uncertainty		Aleatory uncertainty
		Models	Plant status	
Deterministic methodology	Appendix K	conservative treatment	conservative treatment	Not included
	DRHM	conservative treatment	Statistical treatment	Not included
	BEPU	Statistical treatment	Statistical treatment	Not included
Risk-informed methodology		Properly treated		Properly treated

Table 6-2. PCT Margin Evolution from the Traditional Appendix K Methodology

	Relaxation of bounding plant status(DRHM)	Realistic physical models and plant parameters (BEPU)	Relaxation of licensing sequence assumption (RISMC)
ΔPCT_{MR} Enlarged	17.7 K	204.6 K	56.0-60.3 K

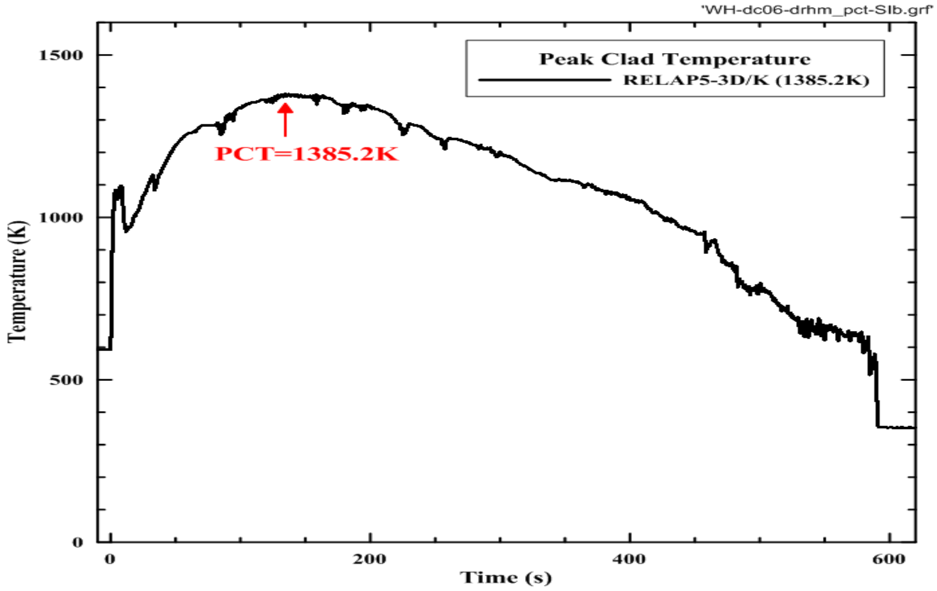

Figure 6-1. PCT Calculated by the Traditional Appendix K Methodology (Taiwan Power Company, 2013)

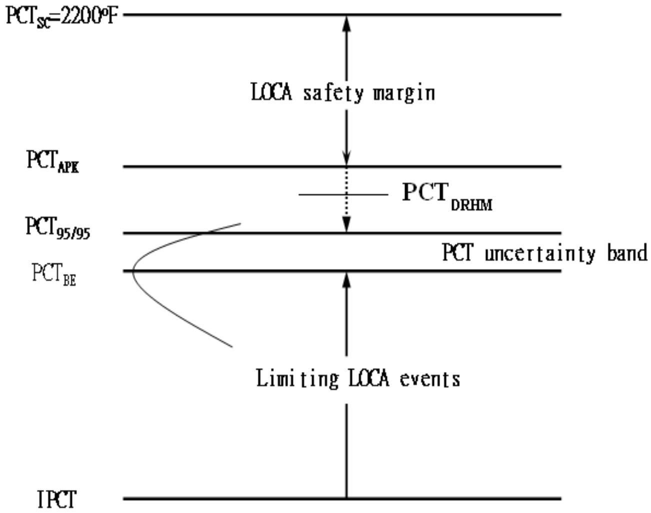

Figure 6-2. PCT Margin Evaluated by Appendix K and BEPU Deterministic Approaches

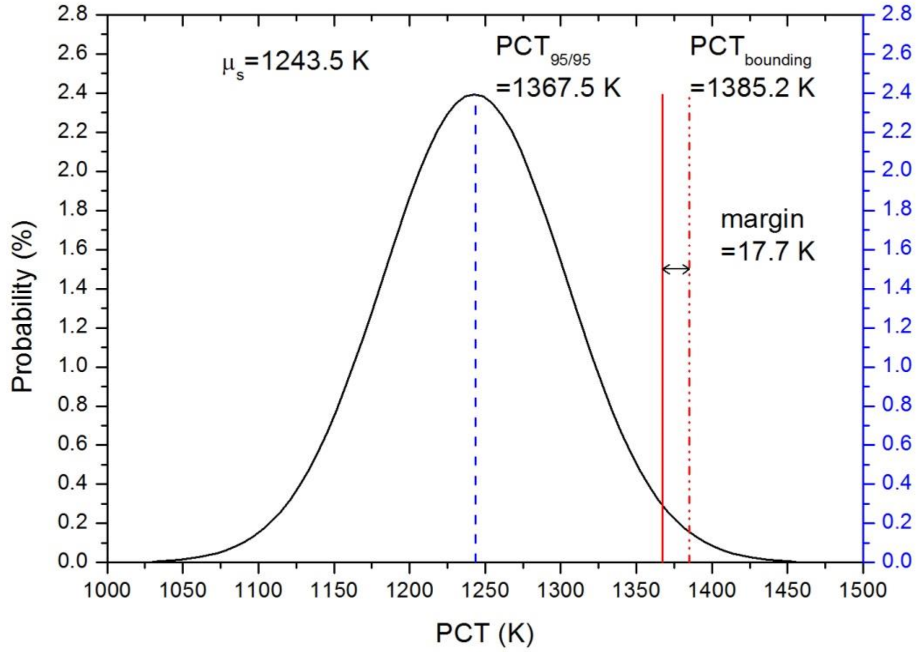

Figure 6-3. Comparison of PCTs from both DRHM and Appendix K Bounding State Analysis for Maanshan Plant

Chapter 7. Conclusions

According to the existing 10 CFR 50.46, both SBLOCA and LBLOCA are categorized as essential design basis accidents, and only deterministic methodologies can be applied to quantify the PCT safety margin based on a surrogate sequence, which satisfies all the required licensing assumptions. However, in the to-be-issued 10 CR 50.46a the LBLOCA can be regarded as a beyond design-basis accident, and the PCT margin shall be evaluated with a risk-informed methodology. To evaluate the risk-informed LBLOCA PCT margin, not only the traditional licensing sequence, but also the contributions of all other success LBLOCA sequences are considered in a proper risk-informed manner. Regarding the features of deterministic and risk-informed LBLOCA licensing methodologies and the associated PCT margin quantification, the following statements can be concluded；

(1) In the deterministic methodologies required for design-basis LBLOCA analysis, only epistemic or calculation uncertainty is addressed by either the conservative appendix K approach or the BEPU approach. Calculation uncertainty generally consists of physical model uncertainty and plant status uncertainty；

(2) In the risk-informed methodology, not only the epistemic uncertainty but also the aleatory are addressed by conducting a PCT load spectrum of LBLOCA. The PCT load spectrum showed that the conditional PCT generally ascends with the

descending sequence occurrence probability；

(3) all possible LBLOCA sequences have been conducted by applying traditional PSA technology, 14 probabilistic dominant sequences have been identified and associated occurrence probabilities also have been quantified；

(4) a load spectrum for LBLOCA has been conducted by calculating conditional PCT of each probabilistic significant sequence with proper LOCA evaluation models. Generally, the conditional PCT ascends with the descending sequence occurrence probability. In this load spectrum both aleatory and epistemic uncertainties have been considered；

(5) with the load spectrum, the risk-informed PCT can be evaluated by either the expecting value estimation method or the sequence probability coverage method；

(6) In the risk-informed methodology, to have a cumulated occurrence probability over 99% in the load spectrum, the third sequence by the order of ascending PCT was referred and the associated sequence occurrence probability is $5.07*10^{-3}$. While in the deterministic methodology, the occurrence probability of the traditional surrogate or licensing sequence is only $5.46*10^{-5}$；

(7) Regarding the deterministic LBLOCA methodologies, the PCT margin quantified by the traditional Appendix K bounding state methodology with RELAP5-3D/K code can be enlarged by 17.7 K using the DRHM methodology, in which realistic plant parameters and statistical uncertainty analysis are utilized. It was noted that the PCT margin released from bounding state assumption is about 1/10 of the margin released by a full-scoped BEPU methodology；

(8) By relaxing the licensing sequence assumption, an additional LBLOCA PCT margin of 38.3-42.6 K can be released from the deterministic DRHM approach by applying the risk-informed safety margin characterization (RISMC) methodology to consider the contribution of PCT margin from all success LBLOCA sequences；

(9) It is expected that amount deterministic methodologies, the greatest margin can be generated by a full-scoped BEPU methodology, while smallest margin can be available when applying a traditional Appendix K methodology, with DRHM's margin lying in between；

(10) When applying a same evaluation model to perform LBLOCA analysis, the margin evaluated by the risk-informed methodology is expected to be greater than the margin generated from deterministic methodologies；

(11) Finally, the safety margin of LBLOCA can be released from traditional Appendix K methodology by (i) relaxing plant bounding state assumption (DRHM methodology), (ii) performing realistic LOCA analysis with statistical consideration of both model uncertainties and plant status uncertainties (BEPU methodology), and (iii) relaxing licensing sequence assumption and evaluating the PCT margin in a proper risk-informed manner (RISMC methodology).

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