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

Thesis submitted in accordance with the
requirements of the University of Liverpool for
the degree of Master of Philosophy by

Ting-Huai Liang

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Abstract

The University of Liverpool

Master of Philosophy

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Ting-Huai Liang

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 $5.07 \times 10^{-3}$, whereas for the traditional surrogate or licensing sequence generally applied in the deterministic methodology, the occurrence probability is only about $5.46 \times 10^{-5}$.

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

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>BELOCA</td>
<td>The Best-Estimate LOCA</td>
</tr>
<tr>
<td>BEPU</td>
<td>Best-estimate plus uncertainty quantification methodology</td>
</tr>
<tr>
<td>CCPs</td>
<td>Centrifugal charging pumps</td>
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<tr>
<td>CCW</td>
<td>Component cooling water</td>
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<tr>
<td>CDF</td>
<td>Core Melt Frequency</td>
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<tr>
<td>CHF</td>
<td>Critical heat flux</td>
</tr>
<tr>
<td>CSAU</td>
<td>Code, scaling, applicability ad uncertainty</td>
</tr>
<tr>
<td>CPCT</td>
<td>Conditional peak cladding temperature</td>
</tr>
<tr>
<td>CSS</td>
<td>Containment spray system</td>
</tr>
<tr>
<td>DBA</td>
<td>Design-basis accidents</td>
</tr>
<tr>
<td>DRHM</td>
<td>Deterministic-realistic hybrid methodology</td>
</tr>
<tr>
<td>ECCS</td>
<td>Emergence Core Cooling System</td>
</tr>
<tr>
<td>FSAR</td>
<td>Final Safety Analysis Report</td>
</tr>
<tr>
<td>HHSI</td>
<td>High Head Safety Injection</td>
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<tr>
<td>LBLOCA</td>
<td>Large Break Loss of Coolant Accident</td>
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<tr>
<td>LHSR</td>
<td>Low-head Safety Recirculation</td>
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<tr>
<td>LOCA</td>
<td>Loss of Coolant Accident</td>
</tr>
<tr>
<td>LHSI</td>
<td>Low Head Safety Injection</td>
</tr>
<tr>
<td>PCT</td>
<td>Peak Cladding Temperature</td>
</tr>
<tr>
<td>NPP</td>
<td>Nuclear power plant</td>
</tr>
<tr>
<td>NRC</td>
<td>U.S. Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>PIRT</td>
<td>Phenomena Identification Ranking Table</td>
</tr>
<tr>
<td>PSA</td>
<td>Probabilistic Safety Assessment</td>
</tr>
<tr>
<td>PWR</td>
<td>Pressurized water reactor</td>
</tr>
<tr>
<td>RCS</td>
<td>Reactor Coolant System</td>
</tr>
<tr>
<td>RHR</td>
<td>Residual Heat Removal</td>
</tr>
<tr>
<td>RISMC</td>
<td>Risk-informed Safety Margin Characterization</td>
</tr>
<tr>
<td>RPS</td>
<td>Reactor Protection System</td>
</tr>
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<td>RWST</td>
<td>Refueling-Water Storage Tank</td>
</tr>
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<td>SBLOCA</td>
<td>Small Break Loss of Coolant Accident</td>
</tr>
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<td>SOP</td>
<td>Sequence Occurrence Probability</td>
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<tr>
<td>SP</td>
<td>Sequence Probability</td>
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<tr>
<td>SYMBOL</td>
<td>DESCRIPTION</td>
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<tr>
<td>---------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Confidence level</td>
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<tr>
<td>$\gamma$</td>
<td>Tolerance limit</td>
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<tr>
<td>$N$</td>
<td>Required number of samples</td>
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<td>Number of output variables</td>
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<tr>
<td>$\sigma_s$</td>
<td>Sample standard deviation</td>
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<td>$\sigma_s^2$ under (n-1) degree of freedom</td>
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</tr>
<tr>
<td>$\chi^2(n-1)$</td>
<td>$\chi^2$ variable at the (1-$\alpha$) confidence level under (n-1) degree of freedom</td>
</tr>
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<td>The PCT statistical upper bounding value determined by the parametric approach</td>
</tr>
<tr>
<td>PCT$_{order}$</td>
<td>The PCT statistical upper bounding value estimated by the non-parametric order statistic method</td>
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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 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. 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-issued 10 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 plant 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 cooling 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.

\[ \beta = 1 - \gamma^N \]  

(2-1)

where \( \beta \) is the confidence level, \( \gamma \) 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:

\[ Y_{95/95} \approx Y_{1st}^{(59)} \quad \text{or} \quad Y_{95/95} \approx Y_{2nd}^{(93)} \quad \text{or} \quad Y_{95/95} \approx Y_{3rd}^{(124)} \]  

(2-2)

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

\[ \beta = \sum_{j=0}^{N-P} \frac{N!}{(N-j)!} \gamma^j (1-\gamma)^{N-j} \]  

(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 (\( \mu_p \)) and population standard deviation (\( \sigma_p \)) can be projected by the sample mean (\( \mu_s \)) and the sample standard deviation (\( \sigma_s \)) under a certain confidence level, such as 95%. If a normal
distribution can be assumed by the goodness-of-fitting test, then

$$P \left\{ -t_\alpha(n-1) \leq \left[ \frac{(\mu_s - \mu_p)}{(\sigma_s/\sqrt{n})} \right] \right\} = 1 - \alpha \quad (2-4)$$

and

$$P \left\{ \chi^2_{1-\alpha}(n-1) \leq \left[ \frac{\sigma_p^2(n-1)}{\sigma_p^2} \right] \right\} = 1 - \alpha \quad (2-5)$$

are all satisfied as 1-\( \alpha \) confidence level. Therefore, \( \mu_p \) and \( \sigma_p \) under the 1-\( \alpha \) confidence level can be expressed as:

$$\mu_{p,1-\alpha} \leq \left[ \mu_s + t_\alpha(n-1) \times \sigma_s/\sqrt{n} \right] \quad (2-6)$$

$$\sigma_{p,1-\alpha}^2 \leq \left[ \frac{\sigma_p^2(n-1)}{\chi^2_{1-\alpha}(n-1)} \right] \quad (2-7)$$

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

$$Y_{95/95} = \mu_{p,95\%} + 1.645 \times \sigma_{p,95\%} \quad (2-8)$$

(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:

$$PCT_{Licens} = \max( PCT_{95/95}, PCT_{order} ) \quad (2-9)$$
where PCT$_{95/95}$ is the PCT statistical upper bounding value determined by the parametric approach, and PCT$_{\text{order}}$ 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 plant 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 making 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.

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 of 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 H₃ : 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, but 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

<table>
<thead>
<tr>
<th>Years</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to 1966</td>
<td>LBLOCA not considered for ECCS design</td>
</tr>
<tr>
<td>1966 - 1969</td>
<td>Atomic energy Commission concerned about LBLOCA, and accumulators added to plant design.</td>
</tr>
<tr>
<td>1971</td>
<td>Interim acceptance criteria, LBLOCA become design basis accident.</td>
</tr>
<tr>
<td>1974</td>
<td>Final acceptance criteria, 10 CFR 50.46 and Appendix K requirements defines evaluation model of 1974.</td>
</tr>
<tr>
<td>1988</td>
<td>10 CFR 50.46 revised to allow best-estimate calculations.</td>
</tr>
<tr>
<td>1996</td>
<td>First best estimate LBLOCA evaluation model approved for Westinghouse (CSAU)</td>
</tr>
<tr>
<td>2003</td>
<td>Best estimate LBLOCA evaluation model approved for AREVA (order statistics)</td>
</tr>
<tr>
<td>2003</td>
<td>Revised best estimate LBLOCA evaluation model approved for Westinghouse (order statistics)</td>
</tr>
<tr>
<td>Parameter</td>
<td>Distribution</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Core thermal power</td>
<td>Uniform</td>
</tr>
<tr>
<td>Initial average fluid temperature ($T_{avg}$), K</td>
<td>Uniform</td>
</tr>
<tr>
<td>Pressurizer pressure (P_{RCS}), kpa</td>
<td>Uniform</td>
</tr>
<tr>
<td>Accumulator liquid volume ($V_{ACC}$), m$^3$</td>
<td>Uniform</td>
</tr>
<tr>
<td>Accumulator pressure (P_{ACC}), kpa</td>
<td>Uniform</td>
</tr>
<tr>
<td>Accumulator temperature ($T_{ACC}$), K</td>
<td>Uniform</td>
</tr>
<tr>
<td>Safety injection temperature ($T_{SI}$),</td>
<td>Uniform</td>
</tr>
<tr>
<td>Peak heat flux hot channel factor ($F_Q$)</td>
<td>Uniform (2.137±0.137) &amp; normal (σ=2.6%)</td>
</tr>
<tr>
<td>Peak hot rod enthalpy rise hot channel factor ($F_{△H}$)</td>
<td>Normal (mean=1.65, σ=2.43%)</td>
</tr>
<tr>
<td>Off-site power</td>
<td>Random</td>
</tr>
</tbody>
</table>
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)
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\textsubscript{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\textsubscript{95/95} and the nominal CPCT\textsubscript{μ} calculated in step (3) on this surrogate sequence:

\[ \Delta PCT_{un, ss} = CPCT_{95/95, ss} - CPCT_{μ, ss} \]  \hspace{1cm} (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\textsubscript{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\textsubscript{95/95} for each sequence. Therefore, the final CPCT for sequence “i” will be:

\[ CPCT_{μ + Δ, i} = CPCT_{μ, i} + Δ PCT_{un, ss} \]  \hspace{1cm} (4-2)
and the PCT margin of sequence “i” can then be calculated as:

$$\Delta \text{PCT}_{SM,i} = \text{PCT}_{SL} - \text{CPCT}_{\mu + \Delta,i}$$ (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 (\(\Delta \text{PCT}_{RI}\)) 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):

$$\Delta \text{PCT}_{RI} = \frac{\sum \Delta \text{PCT}_{SM,i} * SP_i}{\sum SP_i}$$ (4-4)

Note that when \(\Delta \text{PCT}_{SM,i}\) 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 \(\Delta \text{PCT}_{SM,i}\). 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 (\(\text{PCT}_{RI}^{99\%}\)) 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 $K$:

$$PCT_{RI}^{99\%} = CPCT_{\mu+\Delta,k}$$

(4-5)

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

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

(4-6)

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

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

(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

(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 calculational uncertainty

(6) Conducting the final load spectrum for LBLOCA

(7) The Risk-informed PCT Safety Margin Characterization
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 H0 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) 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_μ 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_μ of the top fourteen probabilistic significant LBLOCA sequences were calculated and the associated responses are shown in Figure 5-7. Moreover, the resulted CPCT_μ of each probabilistic significant sequence are also summarized in Table 5-1 and a plot of CPCT_μ 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_μ 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 (CPCT₀). 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:

\[ \Delta PCT_{un,ss} = CPCT_{95/95,ss} - CPCT_{\mu,ss} \]  

\[ = 78.0 \, K \]  

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

\[ CPCT_{\mu+\Delta,ss} = CPCT_{\mu,ss} + 78.0 \, K \]  

\[ (5-2) \]
The final CPCT_{μ+Δ} 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\textsubscript{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:

\[ \Delta PCT\textsubscript{un,s1} = CPCT\textsubscript{95/95,s1} - CPCT\textsubscript{u,s1} \]
\[ = 1322.22 K - 1224.36 K = 97.89 K \quad (5-3) \]

\[ \Delta PCT\textsubscript{un,s55} = CPCT\textsubscript{95/95,s55} - CPCT\textsubscript{u,s55} \]
\[ = 1328.14 K - 1229.52 K = 98.62 K \quad (5-4) \]

\[ \Delta PCT\textsubscript{un,s56} = CPCT\textsubscript{95/95,s56} - CPCT\textsubscript{u,s56} \]
\[ = 1329.22 K - 1245.12 K = 84.1 K \quad (5-5) \]

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:

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\[ \Delta PCT_{RI} = \sum_i \Delta PCT_{MR_i} \times SP_i \]  \hspace{1cm} (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

\[ \Delta PCT_{RI} = PCT_{SL} - PCT_{RI}^{99\%} \]  \hspace{1cm} (5-7)

\[ = 148.38 \text{ K} \]

Comparing the risk-informed safety margins evaluated by above two methods, it can be found that the \( \Delta PCT_{RI} \) 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 \( 5.07 \times 10^{-3} \), while the
occurrence probability of the traditional licensing sequence (LOCAS74) applied in the classical deterministic methodology is only $5.46 \times 10^{-5}$. 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 1367.5 K as indicated in Table 5-1. Consequently, the traditional deterministic safety margin is only 110.1 K (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 K - 1367.5 K = 17.7 K, 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.
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<th>Sequence</th>
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<th>CPCT&lt;sub&gt;μ+Δμ&lt;/sub&gt;, (K)</th>
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Table 5-2. Uncertainties of Major Plant Parameters of Typical PWRs

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<td>Core thermal power</td>
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<td>102%</td>
</tr>
<tr>
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Table 5-3 Sampling result of major plant parameters (1/3)

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

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Table 5-5 Summary of Target Sequence Difference

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### Table 5-9 Comparison of Calculational Uncertainty of Each Sequence

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Figure 5-1 Heading of LBLOCA event tree

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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: H10.0

HIGH HEAD SAFETY INJECTION (HHSI) FAULT TREE (S/T PK)

Top event: H10.0112
Top event unavailability (rev. appr.) = 4.795E-003
Cutoff value used = 1.000E-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-RCSLPICLLOC FRAC-RCSLP2CLLOC FRAC-RCSLP3CLLOC
2. 6.660E-005 MDDB-GV-LV-1CCP12
3. 1.849E-005 TRYA-HHS1-S TRYB-HHS1-S
4. 1.220E-005 BAP-SHA-WATER1
5. 9.718E-006 MVDA-BH-HV-20 TRYB-HHS1-S
6. 7.660E-006 PMEBP-P091CCF1-4
7. 5.108E-006 MVDA-BG-LV-115B MDDB-BG-LV-115D
8. 2.958E-006 SCFA-BH-HV-20 TRYB-HHS1-S
11. 1.190E-006 PMEBP-P091CCF123
12. 1.006E-006 TRZA-BG-CCWA TRZB-BG-CCWB
13. 1.000E-006 TRYB-BG-CCWA TRYB-BG-CCWB
14. 1.000E-006 TRYB-BG-CCWA TRYB-BG-CCWB
15. 1.000E-006 TRYB-BG-CCWA TRYB-BG-CCWB

Figure 5-2 Fault tree result for High Head Safety Injection (HHSI)
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Figure 5-4 Fault tree result for accumulator system
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Figure 5-10 PCT scattering Plot of Sequence-74
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Figure 5-12 PCT scattering Plot of Sequence-55
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Figure 5-15 59 PCT Plots of Sequence-55
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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 compared. 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 :
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


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 ($\Delta PCT_{RI}$) 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:

\[ \Delta PCT_{RI} = \sum \Delta PCT_{MR,i} \times SP_i \]  

\[ = 152.72 \text{ K} \]

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

\[ \Delta PCT_{RI} = PCT_{SI} - PCT_{RI}^{99\%} \]  

\[ = 148.38 \text{ K} \]

Comparing the risk-informed safety margins evaluated by above two methods, it can be found that the \( \Delta PCT_{RI} \) 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 110.1 K (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 17.7 K 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

<table>
<thead>
<tr>
<th>Deterministic methodology</th>
<th>Epistemic uncertainty</th>
<th>Aleatory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Models</td>
<td>Plant status</td>
</tr>
<tr>
<td>Deterministic methodology</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Appendix K</td>
<td>conservative treatment</td>
<td>conservative treatment</td>
</tr>
<tr>
<td>DRHM</td>
<td>conservative treatment</td>
<td>Statistical treatment</td>
</tr>
<tr>
<td>BEPU</td>
<td>Statistical treatment</td>
<td>Statistical treatment</td>
</tr>
<tr>
<td>Risk-informed methodology</td>
<td>Properly treated</td>
<td>Properly treated</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Relaxation of bounding plant status (DRHM)</th>
<th>Realistic physical models and plant parameters (BEPU)</th>
<th>Relaxation of licensing sequence assumption (RISMC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔPCT_{MR} Enlarged</td>
<td>17.7 K</td>
<td>204.6 K</td>
</tr>
</tbody>
</table>
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 $5.07 \times 10^{-3}$. While in the deterministic methodology, the occurrence probability of the traditional surrogate or licensing sequence is only $5.46 \times 10^{-5}$;
(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 among 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).
References


Liang, K.S., et al., 2011. Development and Application of a Deterministic-Realistic Hybrid Methodology for LOCA Licensing Analysis. Nuclear Engineering and


Ludmann, M., Sauvage J.Y., 1999. LBLOCA Analysis Using the Deterministic Realistic Methodology – Application to the 3-Loop Plant. In; 7th International Conference on Nuclear Engineering (ICONE-7413), April 19-23, Tokyo, Japan.


Youngblood, R.W., et al., 2010. Risk-Informed Safety Margin Characterization


U.S. Nuclear Regulatory Commission, 2010c. Risk-Informed Changes to Loss-of-
Coolant Accident Technical Requirements (10 CFR 50.46a), SECY-10-0161.


**Westinghouse Company, 2009.** Best-Estimate Analysis of the Large-Break Loss-of-Coolant Accident for Maanshan Unit 1 and 2 Nuclear Power Plant Using the ASTRUM Methodology. WCAP-17054.