Risk-Informed Analysis of the Large Break Loss of Coolant Accident and PCT Margin Evaluation with the RISMC Methodology

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Abstract

For general design basis accidents, such as SBLOCA and 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 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. 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. 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 greater by 44-62 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 $5.46*10^{-5}$.

Key Words: Risk-Informed, LBLOCA Sequences, PCT margin, Deterministic, Probabilistic, RISMC Methodology

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1. **Introduction**

A traditional deterministic safety analysis methodology is generally applied to analyze design basis accidents (DBA) based on a so called 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 do 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, 2003), 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 allow 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 PSA skill (Henley and Kumamoto, 1981) to take into account systems or components failure by random probability.

In the current 10 CFR 50.46, both SBLOCA and LBLOCA are considered as design basis accidents, and only deterministic methodologies based on a conservative surrogate or licensing sequence are granted for LOCA licensing safety analysis. However, as stated in 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 LOCAs with break size greater than the transition break size (USNRC, 2010b) can be considered as accidents beyond the design basis. It was also stated in the paragraph (e) (3) of 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. Besides, Realistic initial conditions and availability of safety-related and 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 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 spectra as shown in Figure 1, and quantify the safety margin in a proper risk-informed manner. 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.

2. Process to Evaluate the Risk-Informed PCT Margin with RISMC Methodology

To perform risk-informed LBLOCA analysis with the RISMC methodology, a load spectrum of LBLOCA will be generated and both aleatory and epistemic uncertainties will be quantified. 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 probability, SP) will be quantified by both event tree and fault tree analysis and consequently, probabilistic 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 probabilistic significant LBLOCA sequence.

(4) Conducting a preliminary load spectrum of LBLOCA

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

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

To account for the epistemic or calculation uncertainty of CPCT resulting from physical models and plant status for the preliminary load spectrum, the CPCT at 95% coverage and 95% confidence level (CPCT$_{95/95}$) will be calculated with proper methodology (Westinghouse, 2005) (Liang, et al., 2011) (Ludmann, M., 1999) on the traditional surrogate or licensing sequence, and quantify the difference between the CPCT$_{95/95}$ and the nominal CPCT$_{\mu}$ calculated in step (3) on the surrogate sequence:Δ

$$\Delta PCT_{un,ss} = CPCT_{95/95,ss} - CPCT_{\mu} \qquad (1)$$

$_{,ss}$

(6) Conducting the final load spectrum for LBLOCA

With the calculation uncertainty (ΔPCT$_{un,ss}$) evaluated on the surrogate sequence, the preliminary load spectrum of LBLOCA will be shifted, as shown in Figure 2, to reflect the calculation uncertainty, instead of calculating the $CPCT_{95/95}$ for each sequence. Therefore, the final CPCT for sequence “i” will be:

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

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

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

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

(7) The Risk-informed PCT Safety Margin Characterization

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

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

Note that when $\Delta PCT_{SM,i}$ of any sequence “i” is less than 0.0, it will be set as shown in Figure 2, to reflect the calculation uncertainty, instead of calculating 0.0 to reflect the fact that the risk-informed safety margin of PCT can only be

contributed by those sequence with positive $\Delta PCT_{SM,i}$. Moreover, note that the summation of total sequence probability is equal to unity.

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

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

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

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

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

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

The above seven major steps were summarized in Figure 3 for illustration. In the following sections, the Taiwan's Maanshan PWR plant (Westinghouse, 1987) was referred to demonstrate how to evaluate the risk-informed PCT safety margin for LBLOCAs.

3. LBLOCA sequences identification and 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. Therefore, in the headings of the event tree analysis, all possible system 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 4) and occurrence probabilities of the top fourteen probabilistic significant LBLOCA sequences are summarized in Table 1.

4. Probabilistic Load Spectrum of LBLOCA

As indicated in section 3, fourteen probabilistic significant sequences of LBLOCA of Taiwan’s Maanshan nuclear power plant have been identified, as listed in Table 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 section 2. The first step is to generate a preliminary load spectrum by using RELAP5-3D/K (Liang, K.S., et al., 2002a) (Liang, K.S., et al., 2002b) to calculate the nominal conditional PCT ($CPCT_\mu$) for each sequence, and the second step is to account for the epistemic or calculation uncertainty of the preliminary load spectrum by using the DRHM methodology (Liang, K.S., 2011). In the DRHM methodology, conservative Appendix K models were adopted to cover model uncertainty, whereas realistic plant status parameters were used with statistical uncertainty analysis.

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

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 1). Referring to a typical PWR best estimate LBLOCA licensing analysis (Westinghouse, 2009), important plant parameters were identified and summarized in Table 2 with uncertainty ranges. According to the DRHM methodology, at least 59 trials were randomly generated to quantify the effect of plant status uncertainty. Typical parameter samplings are shown in Figure 8 for illustration and the PCT responses of 59 trials are also shown in Figure 9. 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 1337.76 K. With the nominal PCT value of 1289.46 K ($CPCT_{\mu,ss}$) and 95/95 PCT value of 1337.76 K($CPCT_{95/95,ss}$) evaluated on the licensing sequence, the calculation uncertainty according to Equation (1) caused by plant status uncertainty can be quantified as:

$$\Delta PCT_{un,ss} = CPCT_{95/95,ss} - CPCT_{\mu,ss} \tag{8}$$

$$=48.3\ \mathrm{K}$$

Accordingly, the preliminary load spectrum will be shifted by 48.3 K

$$CPCT_{\mu+\Delta,i} = CPCT_{\mu,i} + 48.3K \tag{9}$$

to reflect the calculation uncertainty. The final $CPCT_{\mu+\Delta}$ of those fourteen probabilistic significant sequences with calculation uncertainty are listed in the last column in Table 1.

5 Risk-Informed PCT Safety Margin Characterization

With the final load spectrum for LBLOCA as indicated in the last column of Table 1, the risk-informed PCT safety margin (ΔPCT_{RI}) can be calculated by two different methods; the first one is the expecting value estimation method and the second one is the sequence probability coverage method. By using the first expecting value estimation method and data listed in Table 1, the risk-informed safety margin can be mathematically calculated according to Equation (4) as follows:

$$\Delta PCT_{RI} = \sum_{i} \Delta PCT_{MR,i} *SP_{i} \tag{10}$$

$$= 202.1\ \mathrm{K}\Sigma$$

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 1293.42 K will be applied to define the risk-informed $PCT_{RI}^{99\%}$, and the risk-informed safety margin will be as follows

$$\Delta PCT_{RI} = PCT_{LS} - PCT_{\mathrm{RI}}^{99\%} \tag{11}$$

$$= 184.2\ \mathrm{K}$$

5 Risk-Informed PCT Safety Margin Characterization

Comparing the risk-informed safety margins evaluated by above two methods, it can be found that the ΔPCT_{RI} calculated by the sequence probability coverage method is reasonably conservative by 17.92 K. Because the occurrence probability was dominated by the first five 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 1 that in the second sequence probability coverage method, the third sequence (LOCAS56) was applied to define the risk-informed safety margin ($\Delta PCT_{RI}^{99\%}$) and its' associated occurrence probability is $5.07*10^{-3}$, while the occurrence probability of the traditional licensing sequence (LOCAS74) applied in the classical deterministic methodology is only $5.46*10^{-5}$. In the traditional licensing sequence (LOCAS74) only one train of high head and low head injection are available respectively to satisfy single failure criteria. While in sequence referred in the evaluation of risk-informed PCT safety margin (LOCAS56) to cover 99% cumulated occurrence probability, there are two trains of high head injection and one train of low head injection available instead. The detailed differences of the first three sequences and the traditional surrogate sequence are summarized in Table 3.

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 1337.76 K as indicated in Table 1. Consequently, the traditional deterministic safety margin is only 139.74 K by applying the DRHM methodology. Therefore, the PCT safety margin of LBLOCA evaluated by the RISMC methodology can be greater by 44.4-62.4 K than the margin evaluated by the DRHM deterministic methodology.

6 Conclusions

According to the to-be-issued 10 CFR 50.46a, the LBLOCA will be categorized as accidents beyond design basis. Therefore, the risk-informed safety margin characterization (RISMC) methodology has been applied to evaluate the PCT margin in a risk-informed manner for LBLOCA of Taiwan’s Maanshan PWR plant. By following the proposed process to evaluate risk-informed PCT margin, it can be concluded that:

(1) 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;

(2) 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;

(3) with the load spectrum, the risk-informed PCT can be evaluated by either the expecting value estimation method or the sequence probability coverage method. The risk-informed PCT safety margin was evaluated ranging from 184.2-202.1 K;

(4) By comparing with the DRHM deterministic methodology, the PCT margin evaluated by the RISMC methodology can be greater by 44.4-62.4 K by using the same LBLOCA evaluation model(RELAP5-3D/K); and

(5) In the RISMC methodology, to have a cumulated occurrence probability over 99% in the load spectrum, the occurrence probability of the sequence referred in the sequence probability coverage method is $5.07*10^{-3}$. While in the deterministic methodology, the occurrence probability of the traditional surrogate or licensing sequence is only $5.46*10^{-5}$. The traditional licensing sequence can only have one train of safety injection system to satisfy single failure criteria, while in sequence referred to evaluate the risk-informed PCT safety margin, there are two trains of high head injection and one train of low head injection are available instead.

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

Sequence	Occurrence Probability	$CPCT_{\mu}$, (K)	$CPCT_{\mu+\Delta}$, (K)
LOCAS01	4.946E-01	1224.36	1272.66
LOCAS55	4.935E-01	1229.52	1277.82
LOCAS56	5.067E-03	1245.12	1293.42
LOCAS91	4.522E-05	1263.21	1311.51
LOCAS73	1.252E-03	1264.37	1312.67
LOCAS02	5.087E-03	1276.48	1324.78
LOCAS58	1.322E-05	1278.05	1326.35
LOCAS19	1.070E-04	1287.59	1335.89
LOCAS37	4.522E-05	1289.01	1337.31
LOCAS74	5.460E-05	1289.46	1337.76
LOCAS20	5.692E-05	1293.70	1342.00
LOCAS04	1.322E-05	1331.42	1379.72
LOCAS07	2.644E-05	1429.63	1477.93
LOCAS61	2.644E-05	1499.76	1548.06

Table 2. Uncertainties of Major Plant Parameters of Typical PWRs

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

Table 2. Uncertainties of Major Plant Parameters of Typical PWRs

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

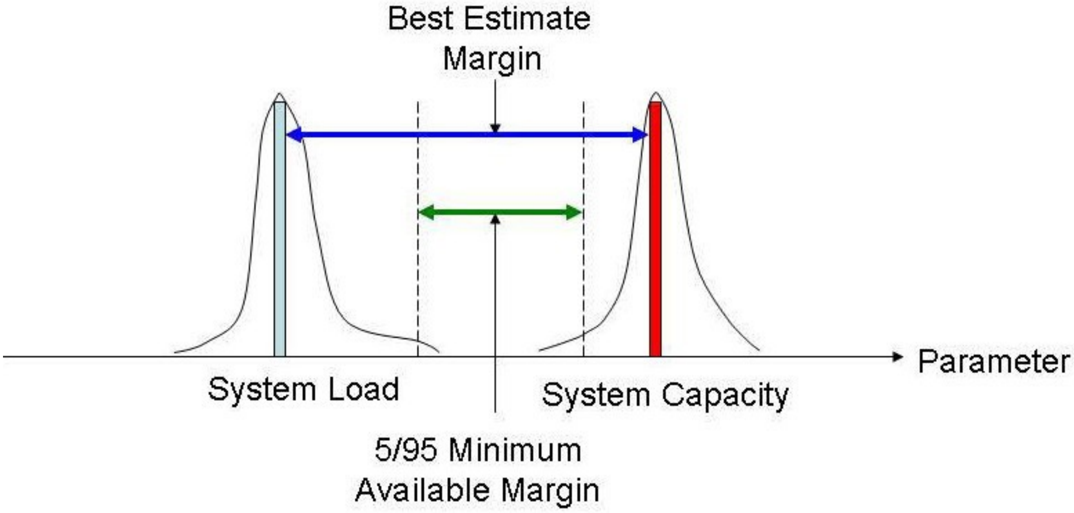

Figure 1. Load Spectrum (Hess, 2009)

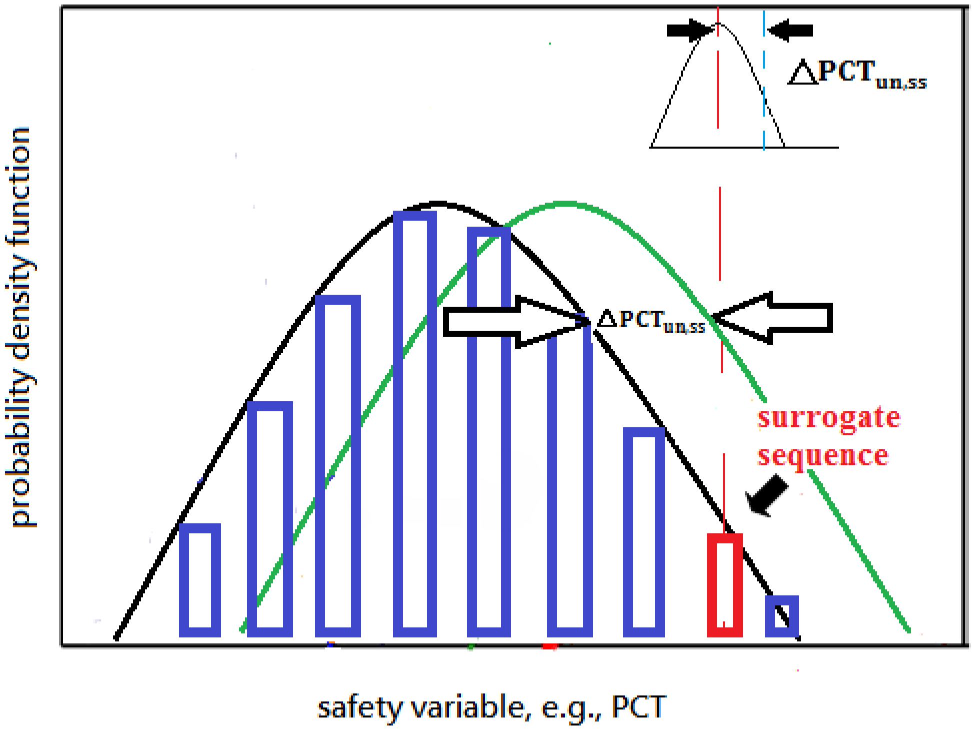

Figure 2. Shifted Load Spectrum to Reflect Calculation Uncertainty

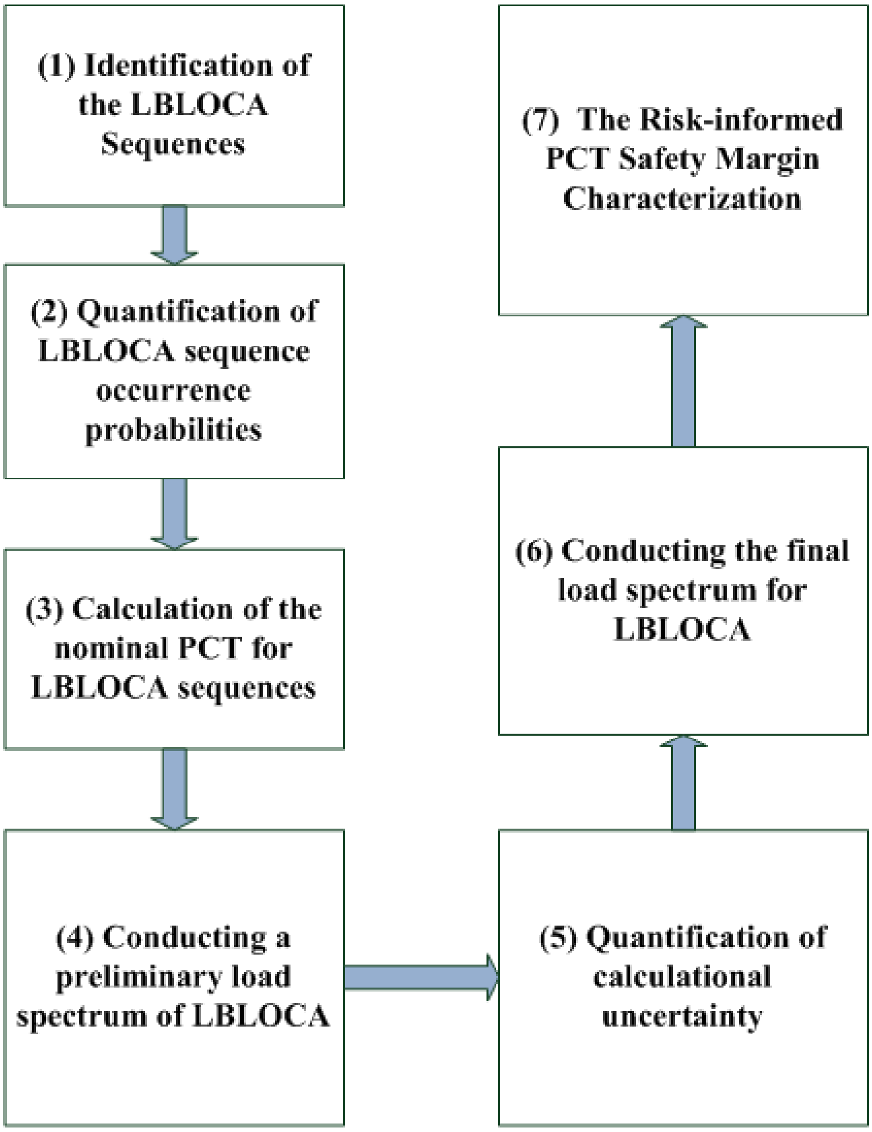

Figure 3. Process for Risk-informed PCT Safety Margin Evaluation

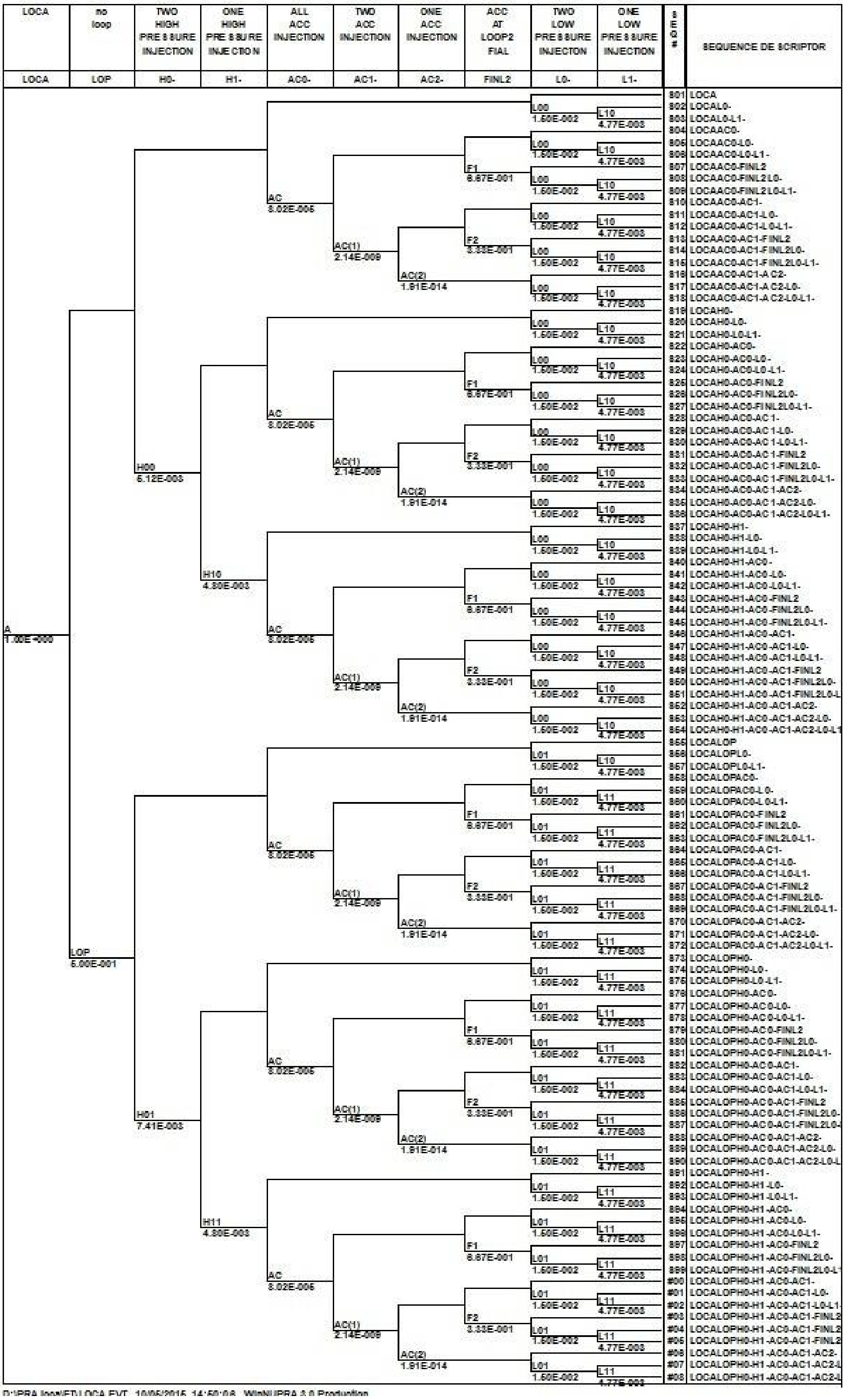

Figure 4. Sequence Identification and Quantification for LBLOCA

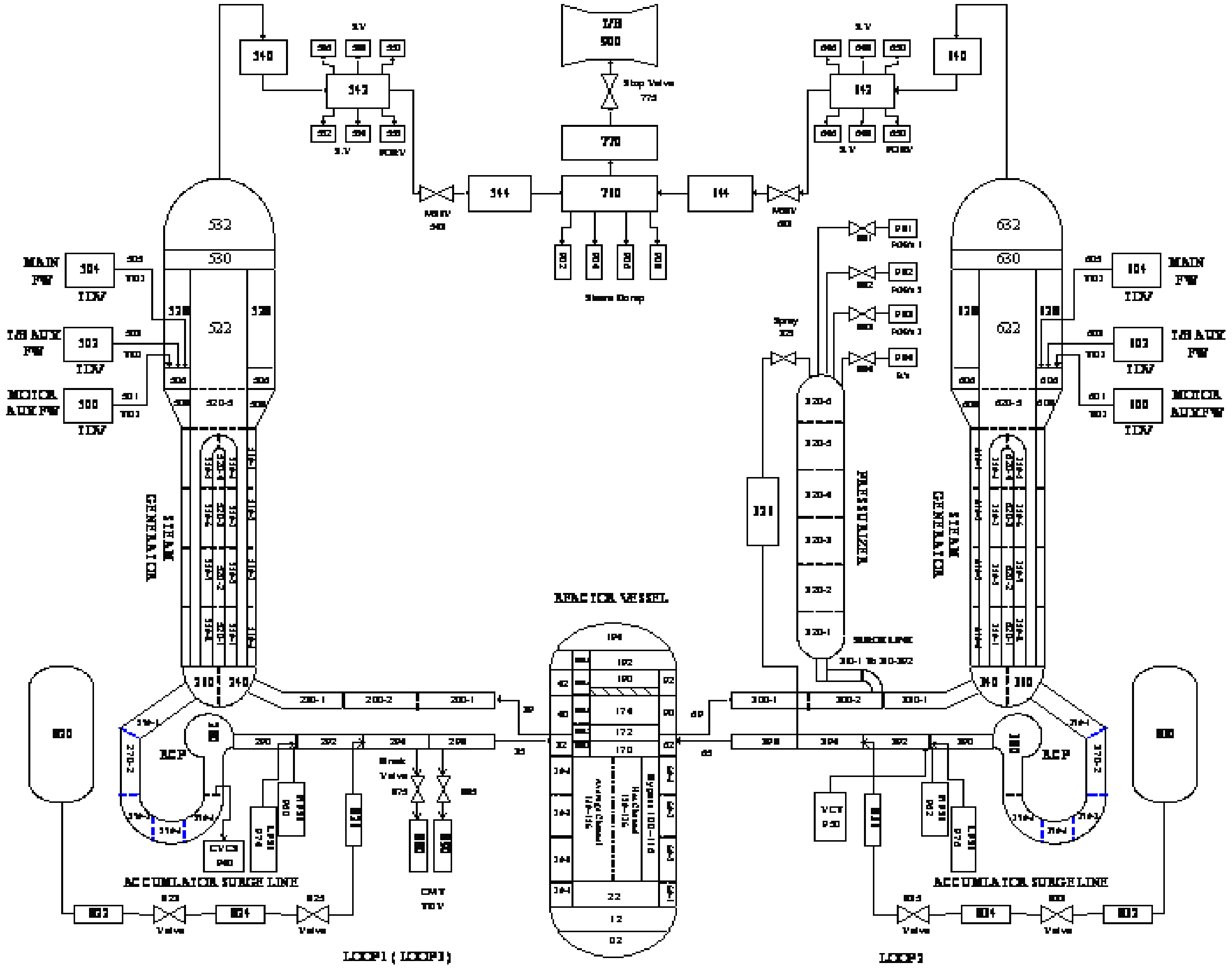

Figure 5. RELAP5 Nodding Diagram for Maanshan PWR LBLOCA Analysis

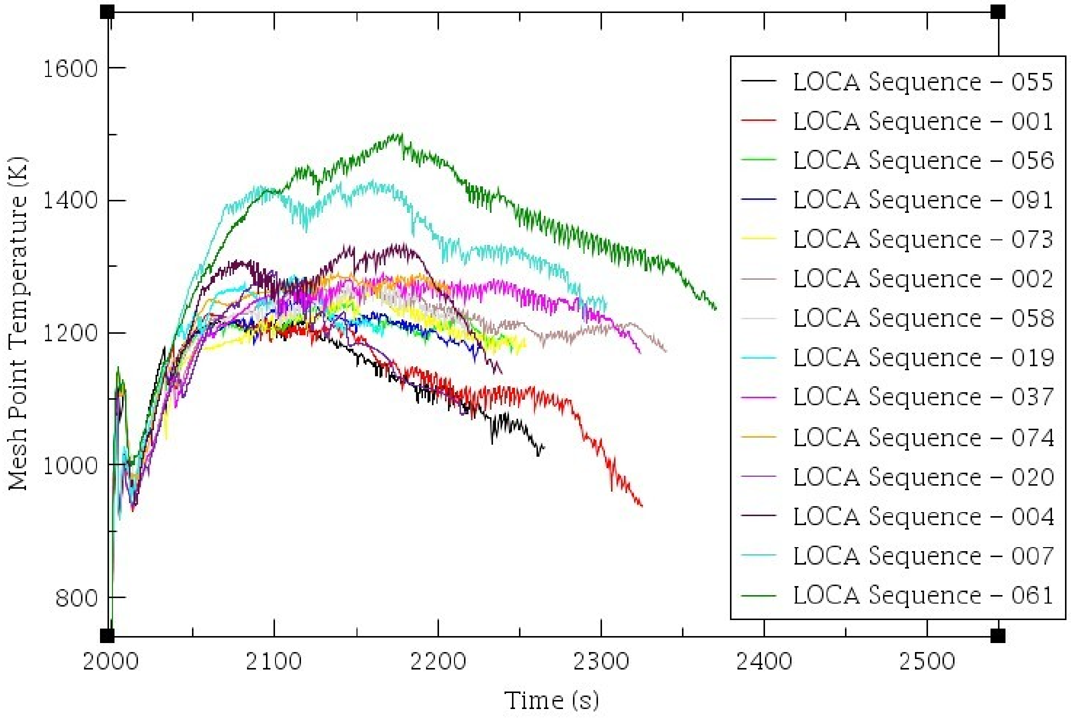

Figure 6. CPCT Responses for the Probabilistic Significant LBOCA Events

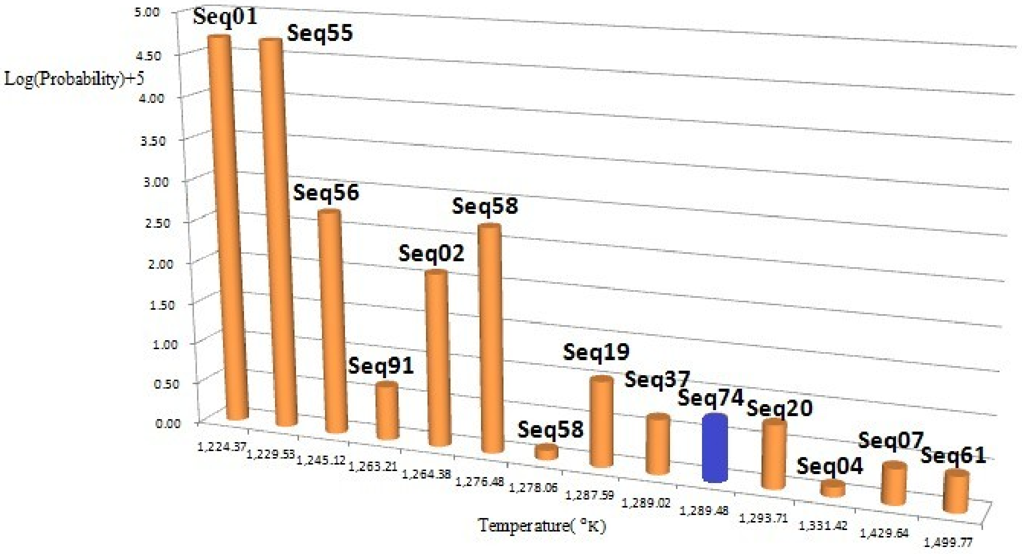

Figure 7. Preliminary Load Spectrum for Maanshan PWR LBLOCA

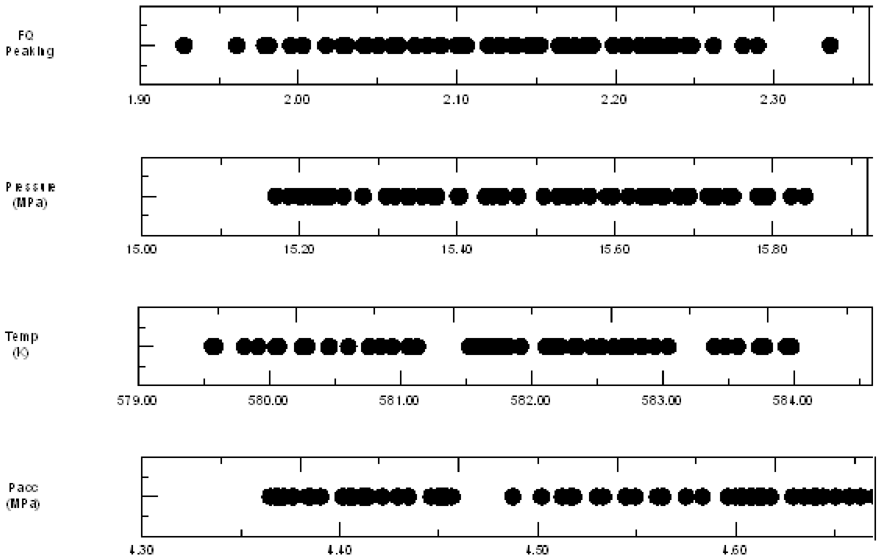

Figure 8. Typical Parameter Samplings

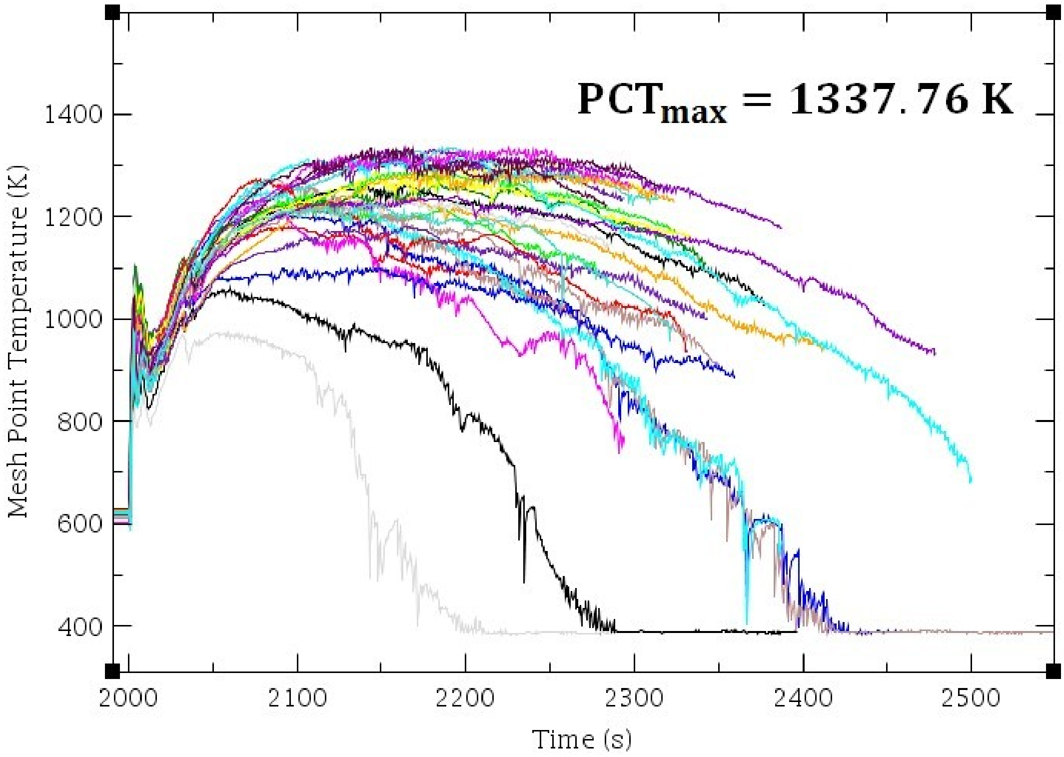

Figure 9. Calculated PCT of 59 Trials