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Development of an Appendix K Version of RELAP5-3D and Associated Deterministic-Realistic Hybrid Methodology for LOCA Licensing Analysis

Thomas K. S. Liang
Shanghai Jiao Tong University
China

1. Introduction

The Loss of Coolant Accident (LOCA) is one of the most important design basis accidents (DBA). In light water reactors, particularly the pressurized water reactor (PWR), the severity of a LOCA will limit how high the reactor power can operate. In the regulatory analysis (USNRC, 1987), it was estimated that if the peak cladding temperature (PCT) during a LOCA decreases by 100°F, it would be possible to raise the plant power by 10%. The revision of 10 CFR50.46 in 1988 stated that two kinds of LOCA licensing approaches can be accepted, namely the realistic and Appendix K methodologies. The realistic licensing technique describes the behavior of the reactor system during a LOCA with best estimate (BE) codes. However, the uncertainties of BELOCA analysis must be identified and assessed so that the uncertainties in the calculated results can be estimated to a high confidence level. Alternatively, the Appendix K approach will guarantee the conservatism of the calculation results, instead of answering the analytical uncertainty. It is widely believed that the realistic approach can more precisely calculate the sequences of a LOCA accident, and therefore provides a greater margin for the PCT evaluation. The associated margin can be more than 200K (Westinghouse, 2009). However, the development of a realistic LOCA methodology is long and costly, and the safety authority is highly demanding in their approach to evaluate uncertainties. Instead, implementation of evaluation models required by Appendix K of 10 CFR 50 (USNRC, 1988) upon an advanced thermal–hydraulic platform, such as RELAP5-3D (RELAP5-3D Code development Team, 1998), TRAC (Liles et al., 1981), CATHARE (Bestion, 1990) et al., also can gain significant margin in the PCT calculation. For instance, the PCT of Taiwan's Maanshan Nuclear Power Plant calculated by the latest Westinghouse Appendix K Evaluation Model BASH (Westinghouse, 1987) is 445°F (2170°F→1725°F) lower than that of 1981´s calculation (Taipower Company, 1982).

To develop a new Appendix K LOCA licensing tool using the most advanced version of RELAP5, namely RELAP5-3D, the compliance of the advanced RELAP5-3D code with Appendix K of 10 CFR 50 has been evaluated, and it was found that there are nine areas where code assessment and/or further modifications were required to satisfy the requirements set forth in Appendix K of 10 CFR 50. All of the ten areas have been evaluated

and the RELAP5-3D has been successfully modified to fulfill the associated requirements. It was also demonstrated that all the phases of both LBLOCA and SBLOCA can be covered in RELAP5-3D/K.

To quantify uncertainty in BELOCA analysis, generally there are two categories of uncertainties required to be identified and quantified, which involve model uncertainties and plant status uncertainties. Particularly, it will take huge effort to systematically quantify individual model uncertainty of a best estimate LOCA code. Instead of applying a full ranged BELOCA methodology to cover both model and plant status uncertainties, a deterministic-realistic hybrid methodology (DRHM) was also developed to support LOCA licensing analysis with RELAP5-3D/K. Regarding the DRHM methodology, Appendix K deterministic evaluation models are adopted to ensure model conservatism, while CSAU methodology (Boyack, B., et al., 1989) is applied to quantify the effect of plant status uncertainty on PCT calculation. Generally, DRHM methodology can generate about 80-100K (Liang, et al., 2011) margin on PCT as compared to traditional Appendix K bounding state LOCA analysis.

2. Development and assessment of RELAP5-3D/K

To develop an Appendix K version of RELAP5-3D, the best-estimate version of RELAP5-3D was modified and assessed (Liang et al., 2002) to fulfill requirements set forth in Appendix K of 10CFR50. Nine build-in models in RELAP5-3D need to be modified and assessed (Schultz et al., 1999), which include (1) Metal-Water Reaction Rate; (2) Discharge Model; (3) ECC Bypass Model; (4) Critical Heat Flux During Blowdown; (5) Post–CHF Heat Transfer During Blowdown; (6) Prevention from Returning to Nucleate Boiling and Transition Boiling Heat Transfer Prior to Reflood; (7) Core Flow Distribution During Blowdown; (8) Reflood rate for PWR; and (9) Refill and Reflood Heat Transfer for PWRs. Separate-effects experiments were applied to assess specific code models and ensure that each modification can function properly. The separate effects assessment cases for each modification are summarized in Table 1.

No.	Case	Phenomenon/Model	Applicable Appendix K Section
1	Cathcart oxidation data	Metal-water reaction	I.A.5
2	Marviken Test 22	Critical flow	I.C.1.a b
3	ORNL THTF Tests 3.07.9B 3.07.9N, 3.07.9W	Critical heat flux	I.C.4
4	ORNL THTF Tests 3.07.9B 3.07.9N, 3.07.9W	Film boiling	I.C.5
5	ORNL THTF Test 3.03.6AR	Transition Boiling	I.C.5
6	UPTF Test 6	End of bypass	I.C.1.c
7	EPRI flow blockage Run4 and Run 8	Core blockage and cross flow	I.C.7.a
8	FLECHT-SEASET Tests 31504, 31203, and 33338	Refill and Reflood rates	I.D.3
9	FLECHT-SEASET Tests 31504, 31203, and 33338	Refilled and Reflood heat transfer	I.D.5

Table 1. Matrix of Separate-effect assessments

2.1 Code modification and Separate-effect assessments
2.1.1 Metal-water reaction rate
Since melting of fuel cladding is not the applicable domain, the parabolic rate low from the Baker-Just model (Baker et al., 1962) would be applied to calculate the fuel oxidation from zirconium-water reaction. Once the oxidation thickness has been evaluated, the associated amount of reaction heat added to the cladding and hydrogen generation also would be calculated. The Cathcart data (Cathcart, 1977) was used to assess the implementation of the Baker-Just models into RELAP5-3D. Cathcart measured the isothermal reaction rates of Zircaloy-4 tubes in steam at elevated temperatures. After the specified oxidation time, the tube was removed and the oxide thickness was measured using standard metallographic techniques. Typical assessment calculation is shown in Figure 1. It can be seen that at a higher bath temperature (1500°C), the conservatism of the Baker-Just model is very clear.
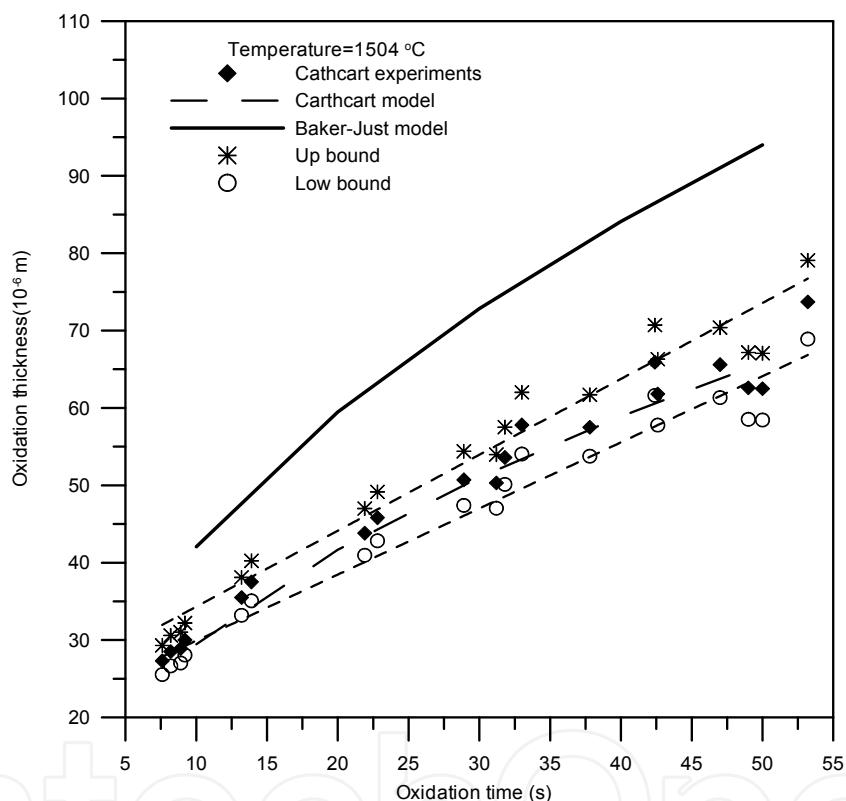

Fig. 1. Oxidation thickness of zirconium 4 (temperature 1504°C)

2.1.2 Discharge model
The Moody model (Moody, 1965) for the calculation of two phase choked flow and the Henry Fauske model (Fauske et al., 1971)for the single phase liquid choked flow were added to RELAP5-3D to make a break flow evaluation model. Regarding applying the Moody model, the stagnation conditions (p_o, h_o) need to be derived from the cell center immediately upstream of the exit plane. The stagnation enthalpy can be calculated from the cell center properties as:

$$h_0 = (h_f + \frac{v_f^2}{2})(1-x) + (h_g + \frac{v_g^2}{2})x \tag{1}$$

where the local enthalpies, fluid velocities and flow quality are evaluated at the equilibrium condition at the cell center. By assuming an isentropic process, the stagnation pressure can then be obtained from the local entropy defined by the cell center properties and the stagnation enthalpy through steam table iteration:

$$P_o = P_o\big(h_o, s(h, P)\big) \tag{2}$$

Data from Marviken Test 22 (Erickson et al., 1977) was used to assess the implementation of the Moody model. Marviken Test 22 was a full-scale critical flow test. The break was connected to the bottom of a large pressure vessel. The pressure vessel, which was originally part of the Marviken Nuclear Power Station in Sweden, was 5.2 meters in diameter and 24.6 meters tall. The vessel initially contained regions of subcooled liquid, saturated liquid and a steam dome. The assessment calculations against measured break flow are shown in Figure 2. The conservatism of the Moody model in two-phase choked flow was demonstrated.
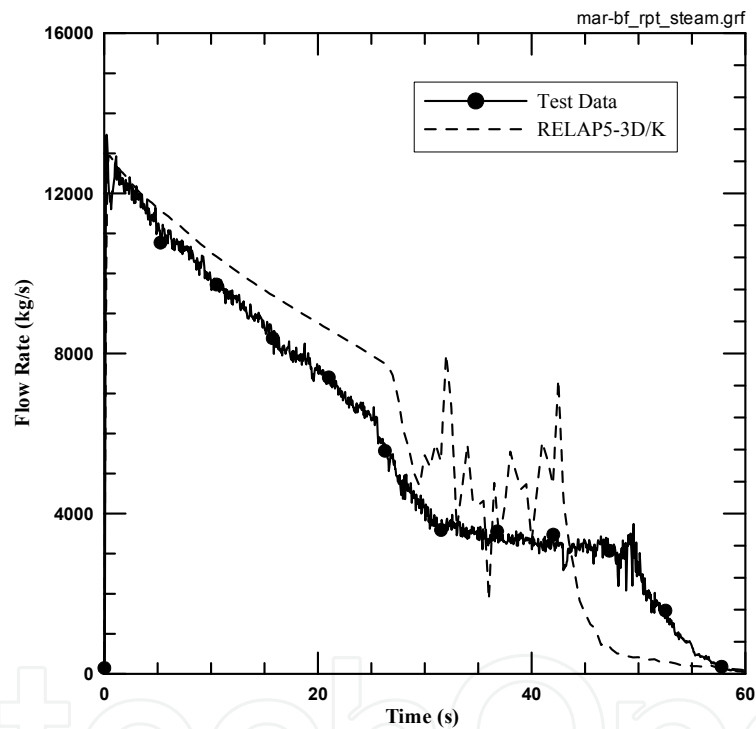

Fig. 2. Comparison of measured and calculated break flow

2.1.3 ECC bypass model

During the ECC bypass period, the emergency coolant would be held in the upper downcomer region. Those ECC water would accumulate in the inlet lines, and then leave RCS through the break without taking decay heat from the reactor core, until the vapor flow from the core can no longer sustain the water in the downcomer. The downcomer flooding model derived from the UPTF full-scale test (Siemens, 1988) was applied to determine when the ECC water could penetrate the downcomer through the RELAP5-3D regular CCFL input process. The UPTF downcomer flooding model is:

$$j_g^{*1/2} + 2.193 j_f^{*1/2} = 0.6208 \tag{3}$$

According to the requirement, before the end of the bypass period all the injected ECC water needs to be removed from the system. To fulfill the ECC subtraction requirement, a set of time dependent junction and volume (TMDPJUN, TMDPVOL) would be connected to the cold leg of the broken loop close to the downcomer. Equal amount of injected ECC water will be forced to be on-line removed from the reactor system by this artificial set of TMDPJUN and TMDPVOL before the end of ECC bypass. The boron transport calculation of RELAP5-3D can indicate when the end of ECC bypass takes place. This boron model will trace the transport of the borated ECC water. Once the borated ECC water penetrates the downcomer and reaches the lower plenum, a signal of the end of ECC bypass will be generated and the ECC subtraction scheme via the TMDPJUN and TMDPVOL will be automatically terminated. The comparison of actual injected ECC water in the LOFT L2-5 (Davis, 1998) and the one calculated by the Appendix K model is shown in Figure 3.
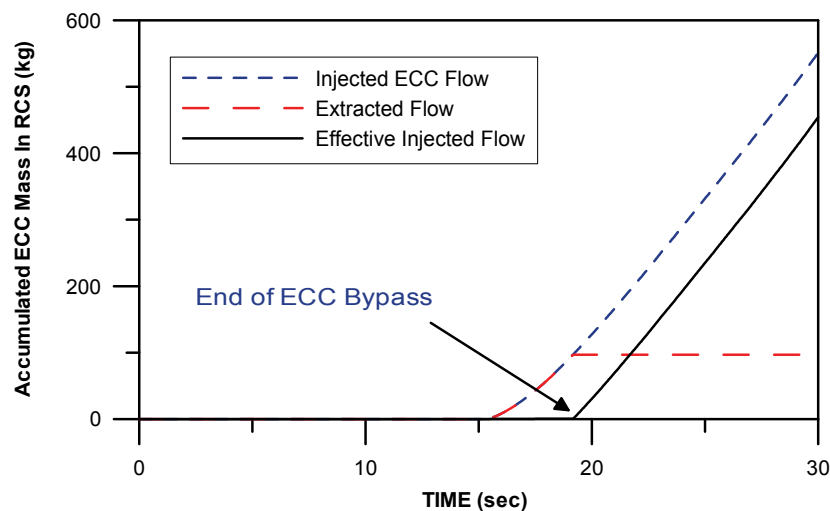

Fig. 3. Comparison of measured and calculated ECC water

2.1.4 Critical heat flux during blowdown

The set of three Appendix K CHF correlations used in RELAP4/MOD7 (Behling et al., 1981) would be adopted, which includes B&W-2, Barnett and Hughes (modified Barnett) correlations, to cover the pressure range of interest. For the high-pressure range (P>10.34 MPa), B&W-2 was applied; for the medium pressure range (8.96 MPa>P>6.89MPa), Barnett correlation was applied; for the low-pressure range (P < 5 MPa), the modified Branett was adopted. For pressures between ranges, interpolation by pressure was applied to calculate the correspond CHF:

$$q_{CHF} = \frac{(P_H - P)q_{CHF_L} + (P - P_L)q_{CHF_H}}{P_H - P_L} \tag{4}$$

where index H and L represent the high and low ends of the interpolation range. Rod bundle heat transfer tests (Yoder et al., 1982) performed in the Thermal-Hydraulic Test Facility (THTF) at Oak Ridge National Laboratory (ORNL) were used to assess the CHF model and film boiling heat transfer. These tests were performed using an 8 ×8 fuel bundle. The rod geometry was representative of 17 ×17 fuel bundles, and the full-length bundle was electrically heated and had uniform axial and radial profiles. Three tests were used for

assessment the CHF calculation, which include tests 3.07.9B, 3.07.9N and 3.07.9W. The range of conditions during this test was representative of those expected during a large break LOCA. A typical comparison of the location first experiencing CHF is shown in Figure 4. It can be seen that the CHF location predicted by the EM models was conservatively lower.
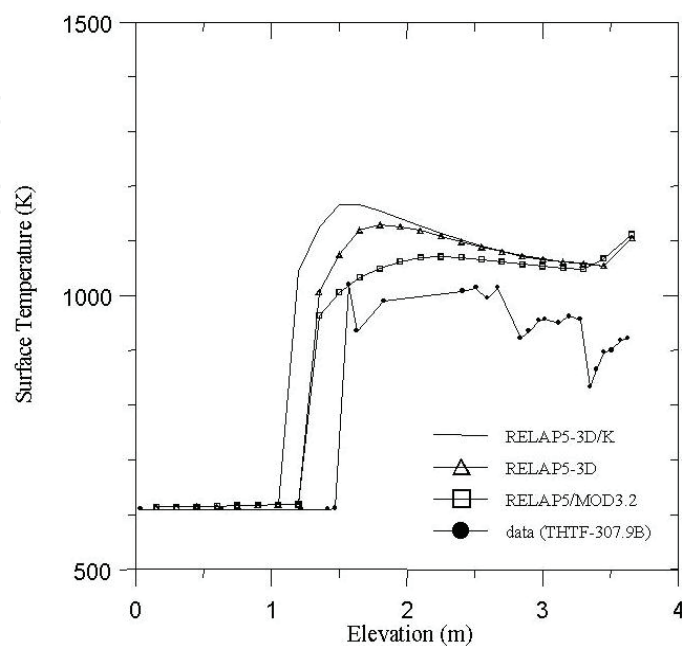

Fig. 4. Comparison of measured and calculated surface temperatures for THTF-307.9B test

2.1.5 Post-CHF heat transfer during blowdown

Two correlations suggested by Appendix K of 10 CFR 50 were adopted to calculate film boiling and transition boiling heat transfer. For the stable film boiling, Groeneveld 5.7 was applied, while the McDonough-Milich-King correlation was used for transition boiling heat transfer. Once CHF has occurred, the greater heat flux would be applied which were calculated by either the film boiling or transition boiling correlations. As stated in Appendix K, the Groeneveld correlation shall not be used in the region near its low-pressure singularity. As suggested by INEEL (Schultz et al., 1999), for high flow ($j_g^{*1/2} + j_f^{*1/2} > 1.36$ for up flow, $j_g^{*1/2} + j_f^{*1/2} > 3.5$ for downflow) if pressure is less than 1.38 MPa, the modified Dittus-Boelter correlation can be used to replace the Groeneveld correlation. If the core flow is not high, the modified Bromley correlation by Hsu with convection can be used to correct the low-pressure singularity. Typical assessments against THTF tests for film boiling heat transfer of the EM model are shown in Figure 5. As for the assessment of transition boiling heat transfer, THTF transition test with power ramping (THTF-303.6AR) was adopted. A typical comparison is shown in Figure 6.

2.1.6 Prevention from returning to nucleate boiling and transition boiling

As required by Appendix K, during the blowdown phase once CHF occurs, transition boiling and nucleate boiling heat transfer shall not be reapplied for the remainder of the LOCA blowdown, unless the reflood phase of the transition has been entered. Assessment of the artificial prevention algorithm is shown in Figure 7. This figure depicts the mode

Development of an Appendix K Version of RELAP5-3D and
Associated Deterministic-Realistic Hybrid Methodology for LOCA Licensing Analysis

49

change with and without the prevention algorithm. It can be seen that nucleate boiling heat transfer was successfully prevented by the algorithm which modifies the existing heat transfer logic.
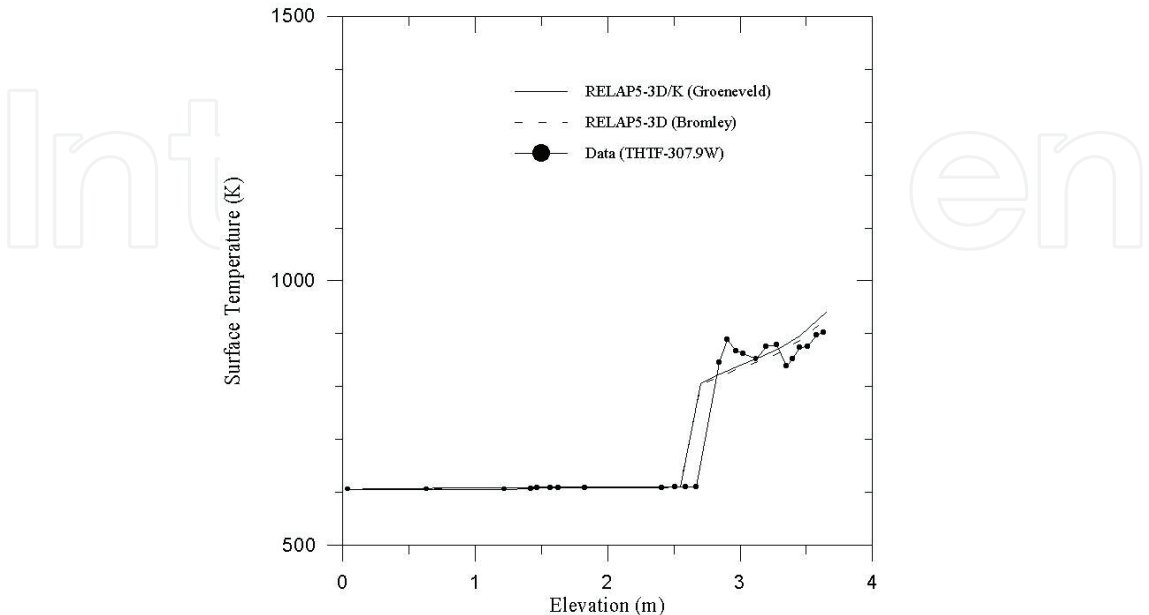

Fig. 5. Comparison of measured and calculated temperature changes for film boiling assessment
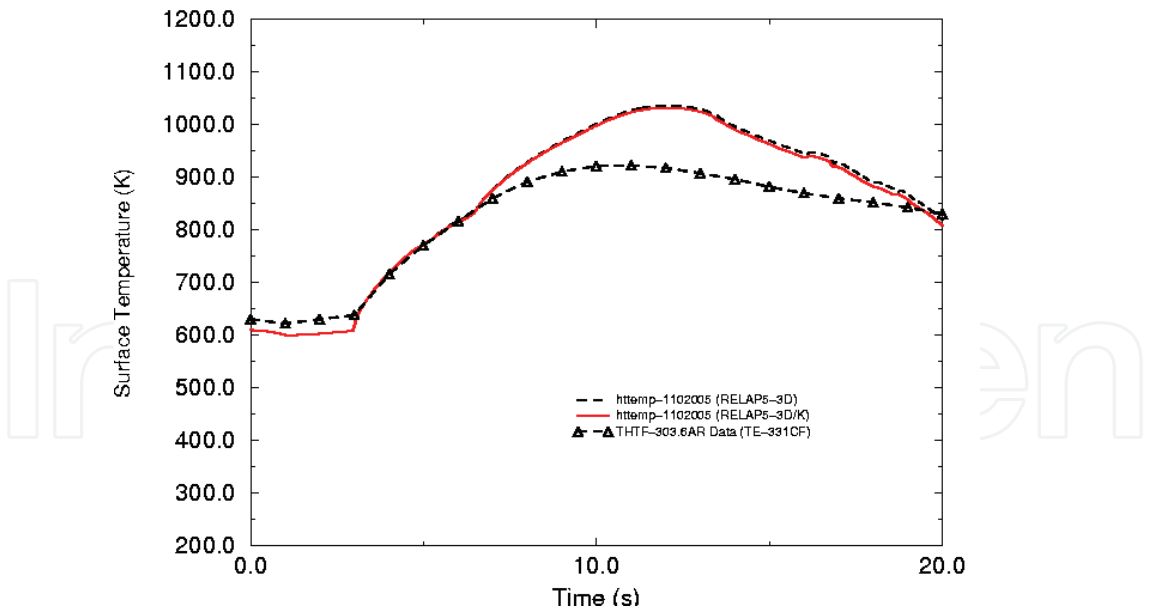

Fig. 6. Comparison of measured and for transition boiling assessment

2.1.7 Core flow distribution during blowdown

To fulfill the requirement of taking into account cross flow between regions and any flow blockage calculated to occur during blowdown as a result of cladding swelling or rupture, the feature of the cross flow junction of the RELAP5-3D would be applied. In cross flow

junctions, the transverse momentum convection terms are neglected. Therefore, there is no transport of x-direction momentum due to the flow in the transverse direction. To assess the calculation of core flow distribution under flow partial blockage, two EPRI flow blockage tests (Tapucu et al., 1984) were adopted in which single-phase liquid and two-phase air/water were used for a range of blockages and flow conditions. The comparisons of the calculated channel pressure distribution for the unblocked channel of the two-phase test against measurements is shown in Figure 8.
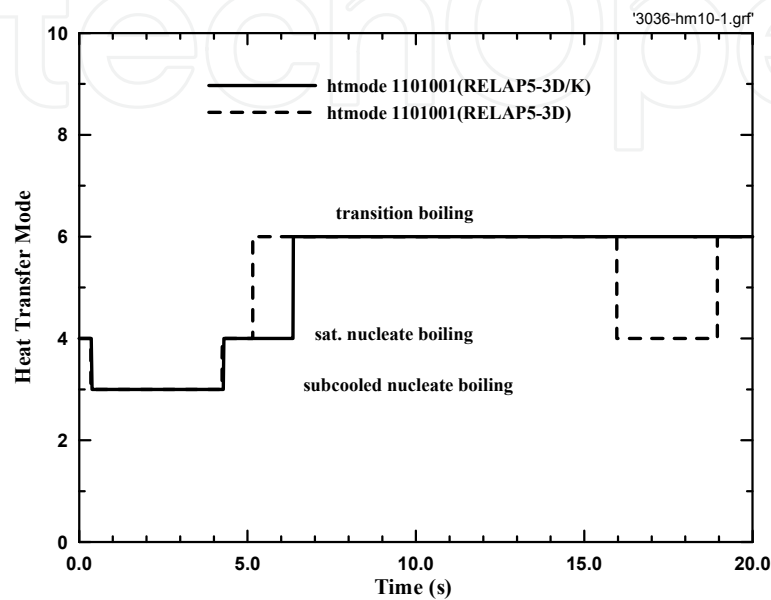
Fig. 7. Heat transfer mode calculated by the modified RELAP5-3D with & w/o nucleate boiling lock-out
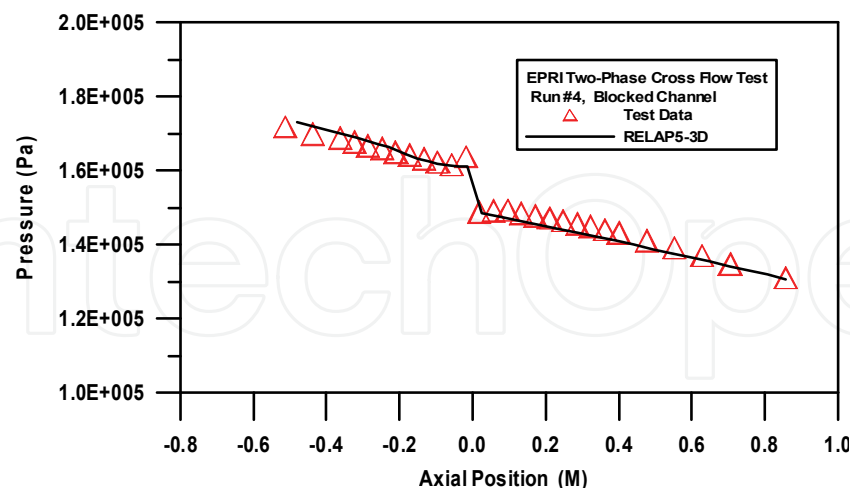
Fig. 8. Comparison of measured and calculated pressure distributions of the blocked channel

2.1.8 Reflood rate for PWRs

According to Appendix K of 10 CFR 50, the calculated carryover fraction and mass in bundle needs to be verified against applicable experimental data. In the existing PSI reflood

model (Analytis, 1996) of RELAP5-3D, the modified Bestion correlation was used for interfacial drag in vertical bubbly-slug flow at pressures below 10 bars to replace the EPRI correlation. Above 20 bars the EPRI correlation was used. Between 10 and 20 bars the interfacial drag was interpolated. To assess the performance of the PSI model in the best estimate version of the RELAP5-3D, five FLECHT-SEASET tests (31504, 31203, 31302, 31805 and 33338) (Loftus et al., 1980) were adopted. For the first four forced reflood tests, the flooding rates ranged from 0.81 inch/s to 3.01 inch/s. As for the last gravity-driven reflood test, the flooding rate was up to 11.8 inch/s during the accumulator injection period. Typical assessments were shown in Figures 9 and 10. Through the assessments against five reflood tests, it was found that the PSI model could predict the flooding rate reasonable well but with enough conservatism.
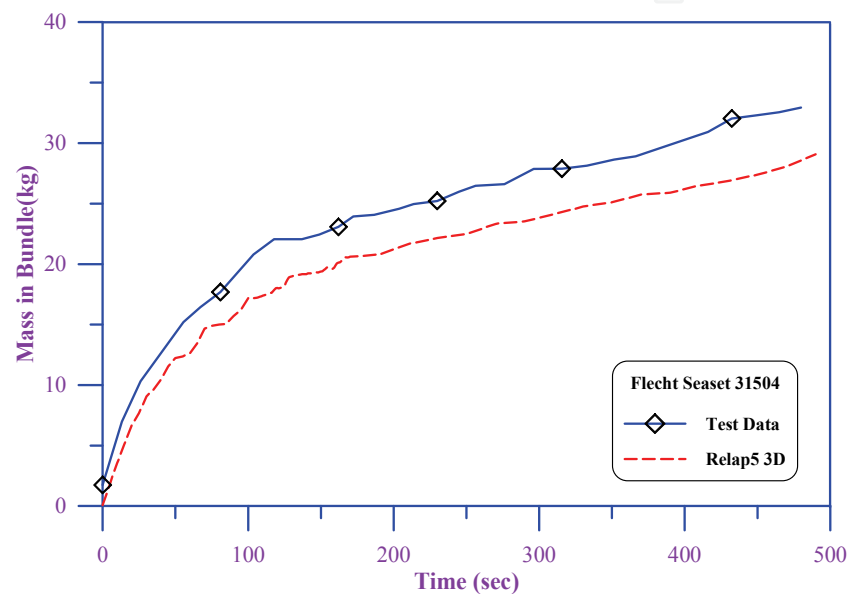

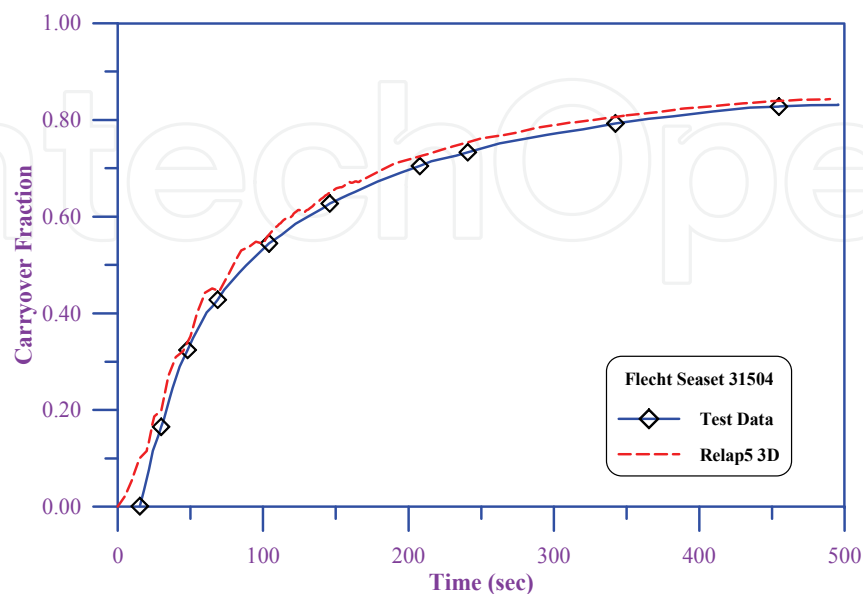Fig. 9. Comparison of measured and calculated carryover fractions

Fig. 10. Comparison of measured and calculated bundle masses

2.1.9 Refill and reflood heat transfer for PWRs

During reflood phase, the RELAP5-3D PSI model was adopted to fulfill the Appendix K requirement for a flooding rate greater than 1 inch/sec with necessary modifications. In the PSI model, a modified Weisman correlation calculating the heat transfer to liquid and a modified Dittus-Boelter correlation calculating the heat transfer to vapor replace the Chen transition boiling correlation. As for film boiling, heat transfer to liquid uses the maximum of a film coefficient contributed by the modified Bromley correlation, and a Forslund-Rohsenow coefficient. In addition, radiation to droplets is added to the final film-boiling coefficient to liquid. The heat transfer to vapor for film boiling is the same as the one for transition boiling, which was calculated by the modified Dittus-Boelter. As required by the Appendix K of 10 CFR 50, when the flooding rate is less than 1 inch/s, only steam cooling in the PSI model was allowed. Assessment calculations were performed to against the five FLECHT SEASET tests discussed above. To bind the peak cladding temperature (PCT) span on each measured fuel rods at the same elevation, the calculated heat transfer coefficient calculated by the original PSI model was reduced by a factor of 0.6 for the flooding rate greater than 1 inch/sec to ensure reasonable conservatism. Typical comparison of the PCTs is shown in Figures 11. While the comparison of heat transfer coefficients is shown in Figures 12.
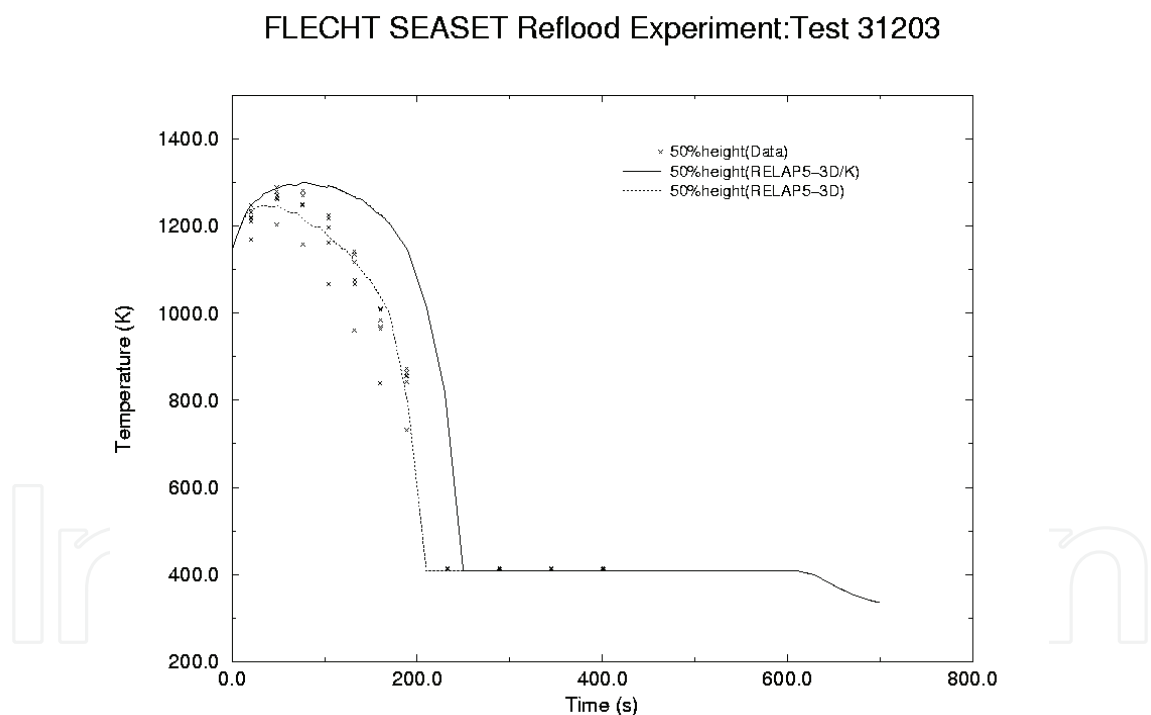

Fig. 11. Comparison of measured and calculated peak cladding temperatures

2.2 RELAP5-3D/K integral-effect assessments

To verify the overall conservatism of the newly developed Appendix K version of RELAP5-3D, 11 sets of integral LOCA experimental data covering SBLOCA and LBLOCA for both PWR and BWR, were applied, as listed in Table 2 and Table 3 for both PWR and BWR respectively. In this paper, only integral assessments LOFT LBLOCA experiment L2-5 (Anklam et al., 1982) and SBLOCA S-LH-1 (Grush et al., 1981) were summarized.
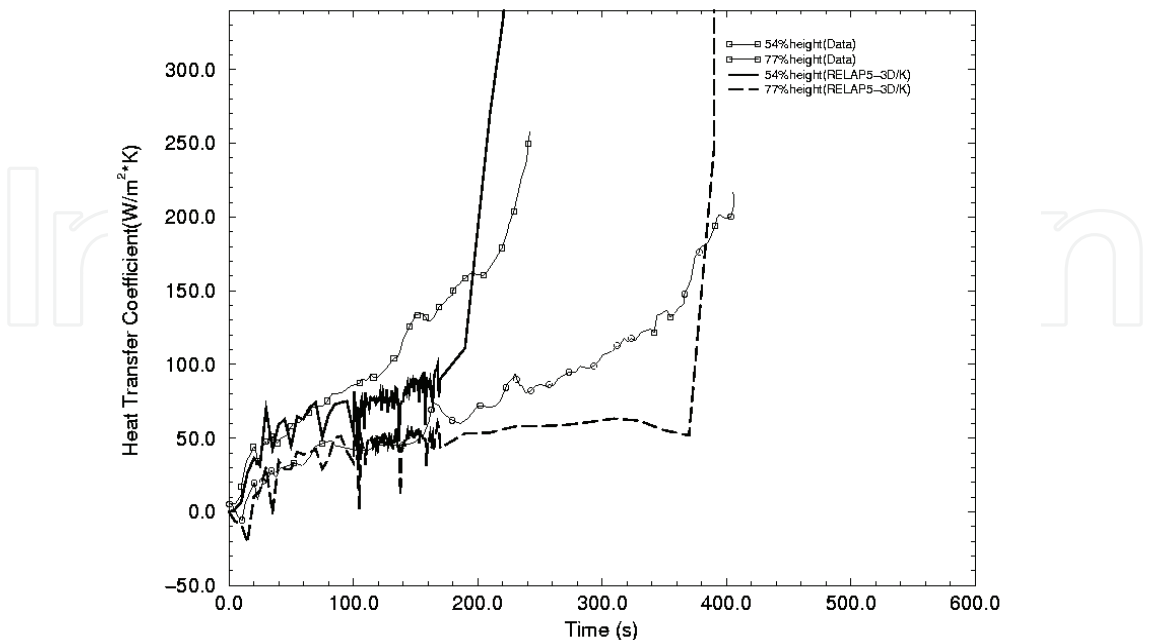
FLECHT SEASET Reflood Experiment:Test 31203

Fig. 12. Comparisons of measured and calculated heat transfer coefficients

Cases	L2-3	L2-5	Lp-Lb-1	S-06-3	L3-7	S-LH-1	IIST
Break Size	200%	200%	200%	200%	0.1%	5%	2%
Break Location	Cold Leg	Cold Leg	Cold Leg	Cold Leg	Cold Leg	Cold Leg	Cold Leg
Notes	RCP Running	RCP Tripped	Higher Power	RCP Running	Without Core Heatup	With Core Heatup	With Core Heatup

Table 2. Matrix of PWR LOCA integral effect assessments

Cases	TLTA 6425	FIST 6DBA1B	FIST 6LB1A	FIST 6SB2C
Break Size	200%	200%	100%	2%
Break Location	Recir. Line Break	Recir. Line Break	LPCI Line Break	Recir. Line Break
Notes			ADS Actuation	HPCS Unavailable

Table 3. Matrix of BWR LOCA integral effect assessments

2.2.1 LBLOCA assessment

In the assessment of LOFT L2-5, important parameters including break flow, downcomer water level and hot spot heat transfer coefficient calculated from both evaluation model (EM) and best estimate (BE) model were shown in Figures 13, 14 and 15 respectively. It can be seen that results from EM model are relatively conservative. The comparison of peak cladding temperature (PCT) against measurement was shown in Figure 16. The calculated PCT from EM model clearly bounds not only the BE PCT but also all the measurement scatterings. The conservative PCT calculated by RELAP5-3D/K against LBLOCA experiments

from both LOFT and Semi-scale was summarized in Table 4 and the conservative trend is shown in Figure 17. It can be seen that RELAP5-3D/K can conservatively predict PCT by 60-260 K.
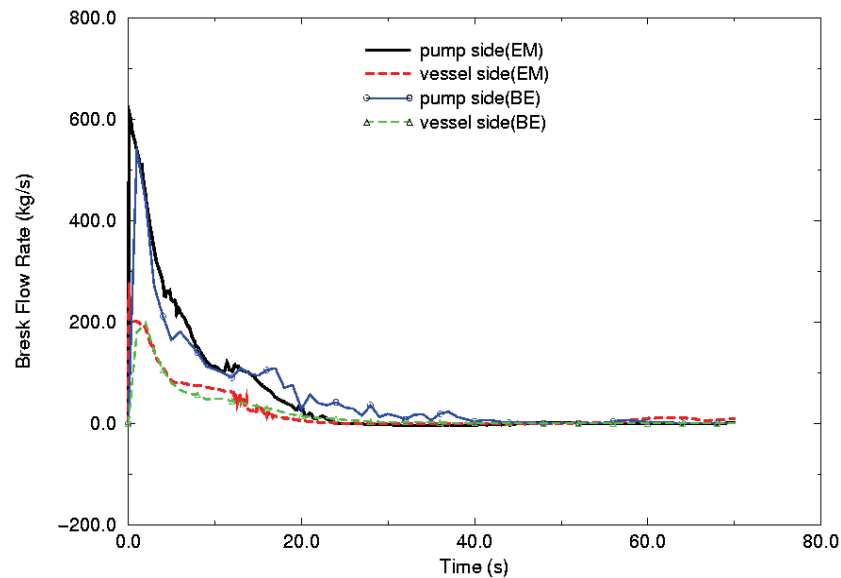

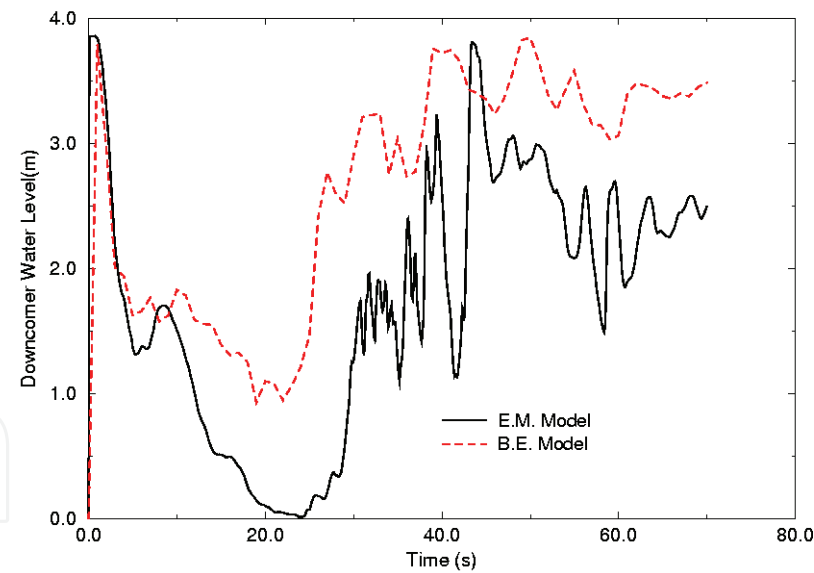Fig. 13. Comparison of break flow of LOFT LBLOCA L2-5

Fig. 14. Comparison of downcomer water level of LOFT LBLOCA L2-5

2.2.2 SBLOCA assessment

SBLOCA experiment Semi-Scale S-LH-1 is a typical 5% cold break. Most important SBLOCA phenomena were involved in S-LH-1 experiment, which includes early core uncover caused by the core level depression, loop seal clearance and later core heat up caused by core boiled off. The calculated break flow, core water level and PCT against S-LH-1 (5% SBLOCA) were shown in Figures 18, 19 and 20 respectively. The conservatism of RELAP5-3D/K in SBLOCA analysis generally can be observed.
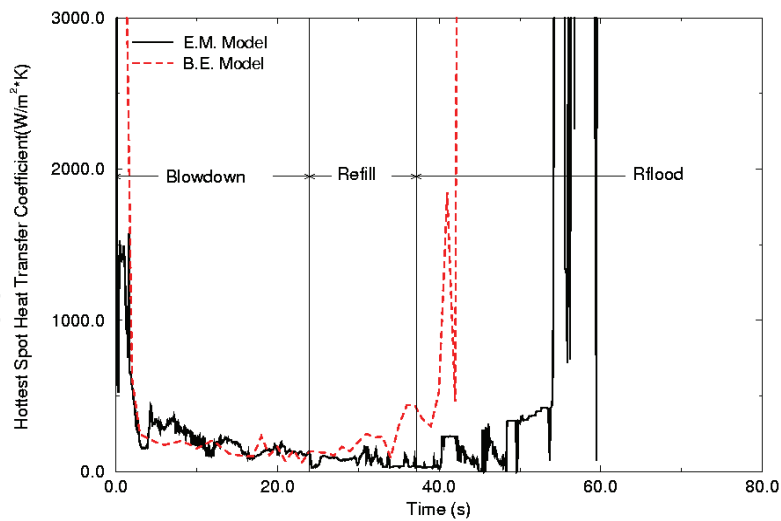
Fig. 15. Comparison of core heat transfer coefficient of LOFT LBLOCA L2-5
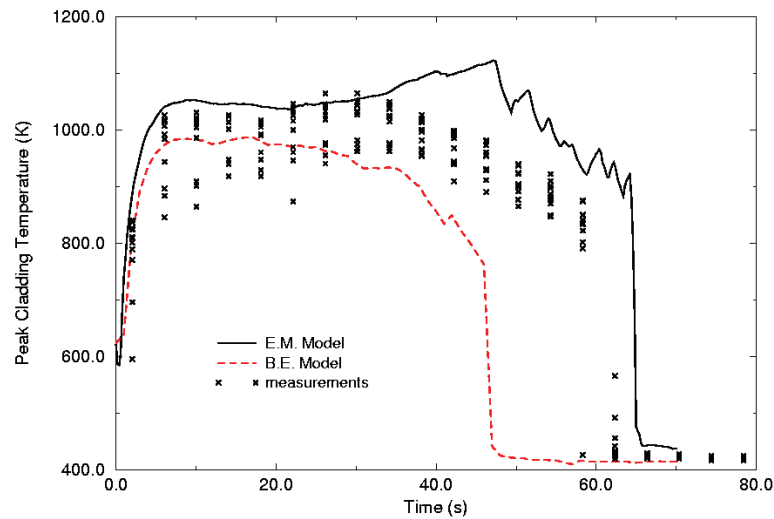
Fig. 16. Comparison of peak cladding temperature of LOFT LBLOCA L2-5
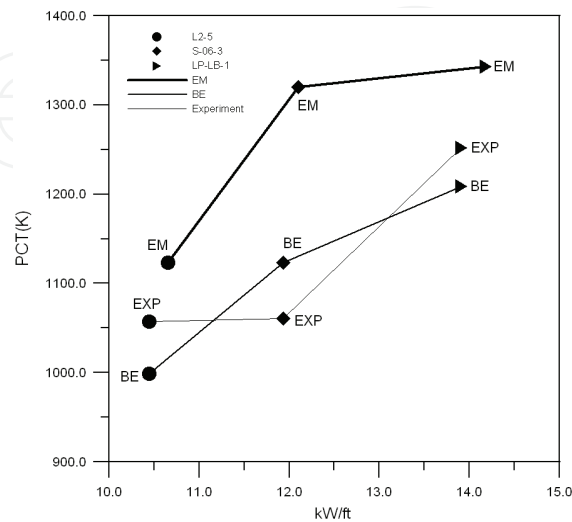
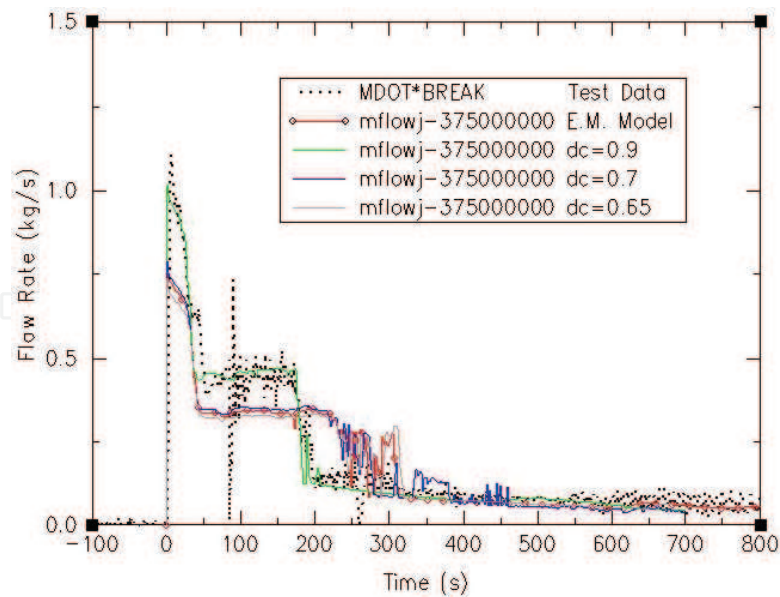Fig. 17. Conservative trend of PCT calculated by RELAP5-3D/K

Fig. 18. Comparison of breaks flow of semiscale SBLOCA S-LH-1

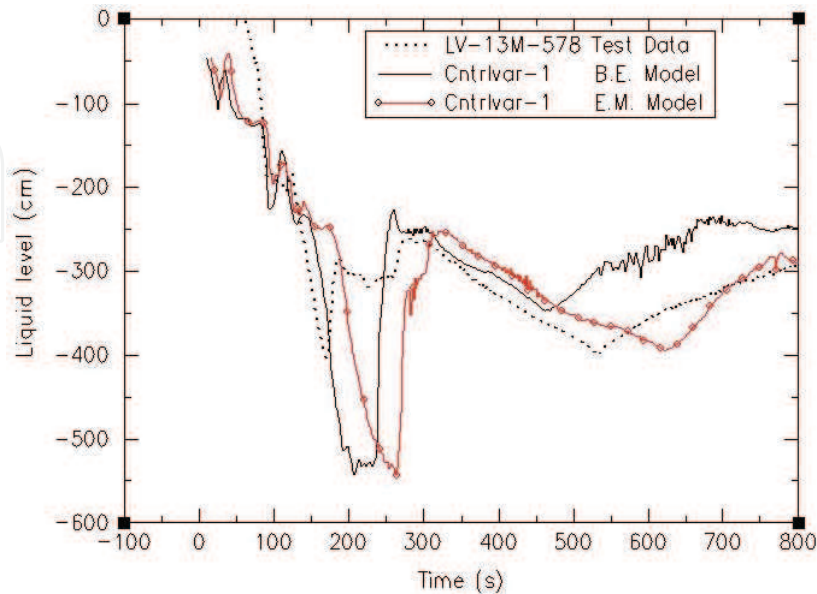| Cases	Measured PCTs (°K)	PCTs by BE Model (°K)	PCTs by EM Model (°K)	PCT (°K) (PCT$_{EM}$-PCT$_{exp}$)
L2-5	1057.2	998.6	1123.1	65.9
L2-3	898.3	938.1	1094.6	196.3
LP-LB-1	1252.4	1290.5	1343.4	91.0
S-06-3	1061.2	1123.7	1320.5(1271.2*)	259.3(210.0*)
TLTA6425	608.9	599.7	745.0	136.1
FIST 6DBA1B	646.9	691.3	714.9	68.0

Table 4. Summary of LBLOCA assessments

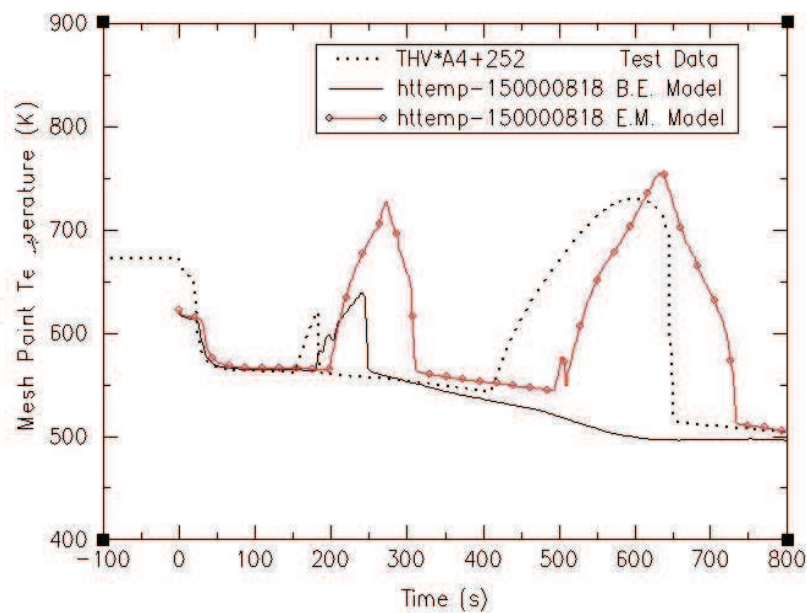Fig. 19. Comparison of core water level of semiscale SBLOCA S-LH-1

Fig. 20. Comparison of peak cladding temperature of semiscale SBLOCA S-LH-1

3. Deterministic-realistic hybrid methodology for LOCA licensing analysis

Instead of applying a full ranged BELOCA methodology to cover both model and plant status uncertainties, a deterministic-realistic hybrid methodology (DRHM) was developed to support LOCA licensing analysis with RELAP5-3D/K. In the DRHM methodology, Appendix K evaluation models are still adopted to ensure conservatism of physical model, while CSAU methodology is applied to quantify the effect of plant status uncertainty on PCT calculation. To ensure the model conservatism, not only physical model should satisfy requirements set forth in the Appendix K of 10 CFR 50, sensitivity studies also need to be performed to ensure a conservative plant modeling.
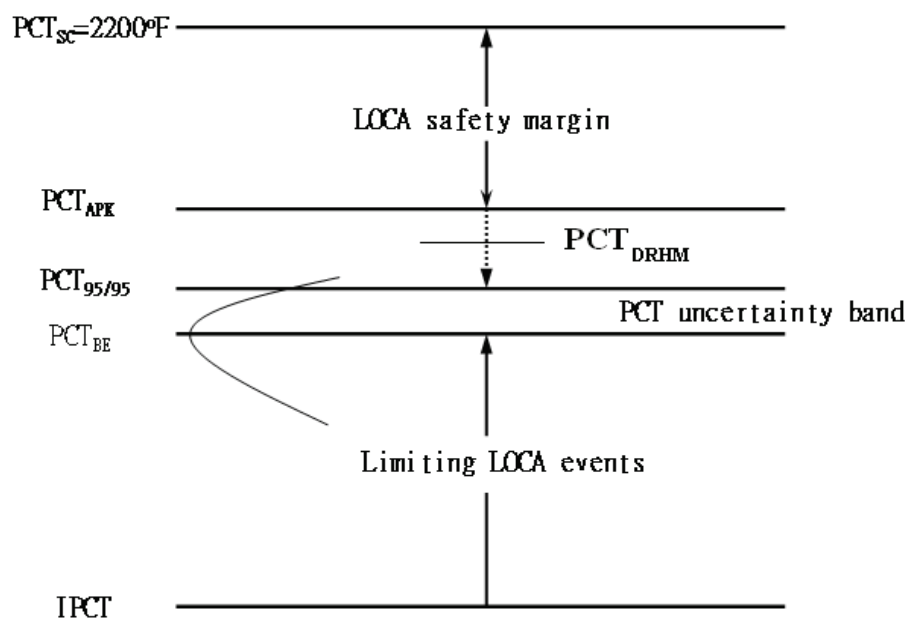

Fig. 21. PCT safety margins calculated by BE and appendix K LOCA methodologies

To statistically consider the plant status uncertainties, which involve uncertainties of plant initial condition, accident boundary condition and plant system settings, the NRC endorsed CSAU methodology is applied. Three major elements are involved in the CSAU methodology, which are (I) requirements and capabilities, (II) assessment and ranging of parameters and (III) sensitivity and uncertainty analysis. Since Appendix K conservative models will be adopted to cover physical model uncertainties, model assessments stated in element II are not related. Instead, ranking and ranging of plant status uncertainty would be the major focus. The resulting PCT by using DRHM method theoretically can be lower than the PCT_{APK} but higher than the $PCT_{95/95}$ (PCT calculated by BELOCA methodology) as illustrated in Figure 21.

In DRHM methodology, 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 conservative E.M. model to perform LOCA analysis of each trial, (5) statistical analysis of calculated figure of merit (PCTs) and (6) determine licensing value of PCT. The procedure of DRHM is shown in Figure 22 and each step will be elaborated as following:

Item Number	Uncertainty Attributes Plant Parameters
1	Break Type
2	Break Area
3	Core Average Linear Heat Rate
4	Initial Average Fluid Temperature
5	Pressurizer Pressure
6	Accumulator Liquid Volume
7	Accumulator Pressure
8	Accumulator Temperature
9	Safety Injection Temperature
10	Peak Heat Flux Hot Channel Factor (FQ)
11	Peak Hot Rod Enthalpy Rise Hot Channel Factor (FDH)
12	Axial Power Distribution (PBOT)
13	Axial Power Distribution (PMID)
14	Off-Site Power
15	ECCS Capacity

Table 5. Major plant status parameters

(1) Ranking of plant status parameters

Plant parameters which will affect LOCA analysis can be generally divided into three groups, namely plant initial conditions, accident boundary conditions and plant system settings. Essential plant parameters need to be identified and ranked to limit the scope of uncertainty analysis. Typical PWR important plant status parameters are listed in Table 5. Major plant status parameters generally involve system initial conditions, core initial conditions, ECCS initial conditions, boundary conditions and system settings.

(2) Ranging of plant status uncertainties

To define the uncertainty of a plant parameter, not only the uncertainty range needs to be quantified, but also the distribution function needs to be specified. Three different kinds of
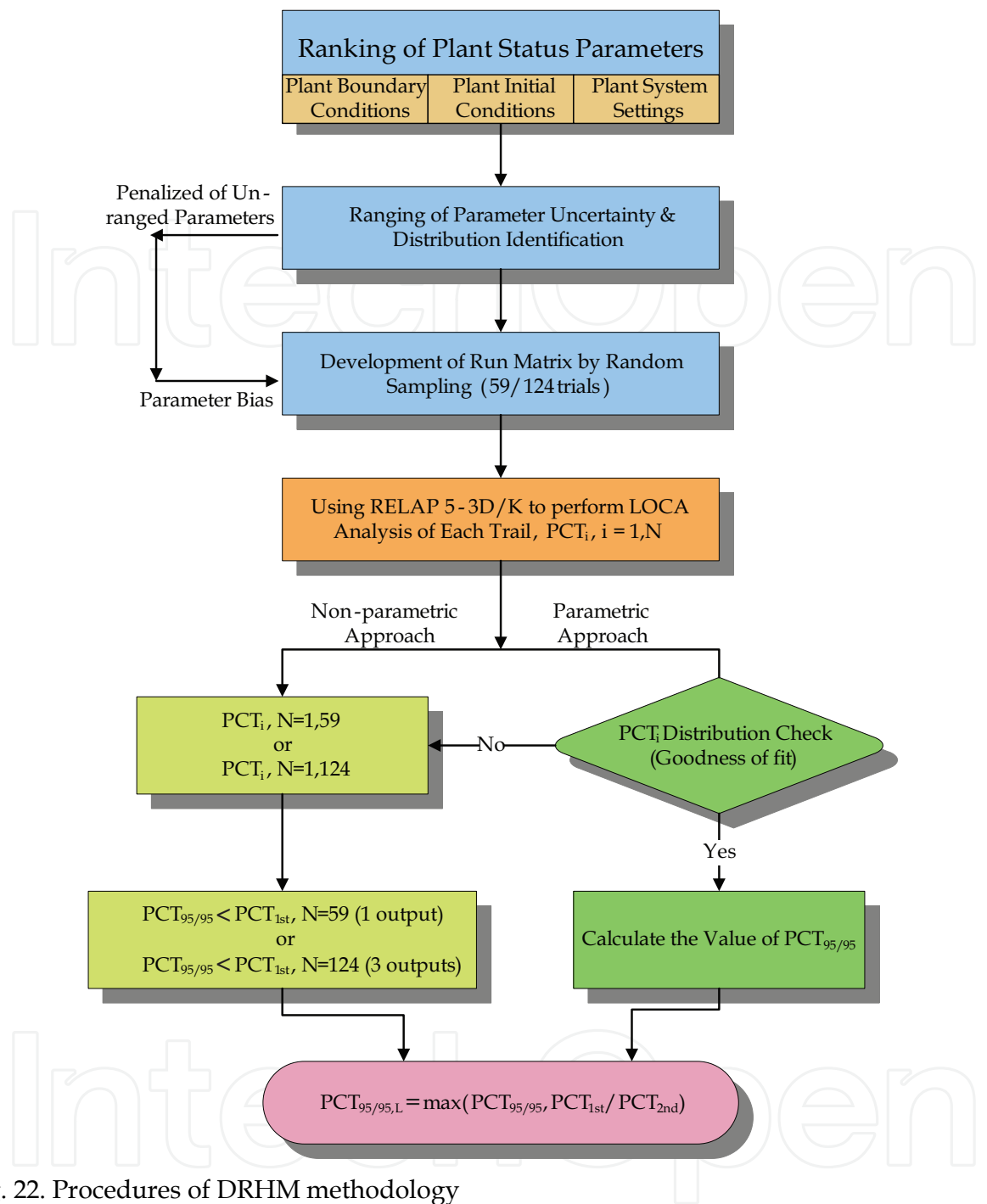
Fig. 22. Procedures of DRHM methodology

elements contribute the total uncertainty of a particular plant status parameter, which involve measurement uncertainty, fabrication uncertainty and normal operational range. For instance, the uncertainties of system pressure and coolant average temperature (T_{avg}) are majorly contributed by measurement uncertainty. While for the uncertainty of the total peaking factor (F_Q), measurement uncertainty, fabrication uncertainty and operational uncertainty are all involved. The associated range of operational uncertainty of F_Q can be determined by the nominal technical specification value (typically 2.274) and statistical upper bounding operating value (typically 2.000). As for the determination of power shape, the traditional bounding shape will be relaxed by sampling realistic operating shapes. Each

operating power shape can be divided into three segments, P_{mid}, P_{bot} and $(1- P_{mid}-P_{bot})$. With the sampling values of $F_{\Delta H}$, F_Q, P_{mid} and P_{bot}, a unique power shape can be defined as shown in Figure 23.
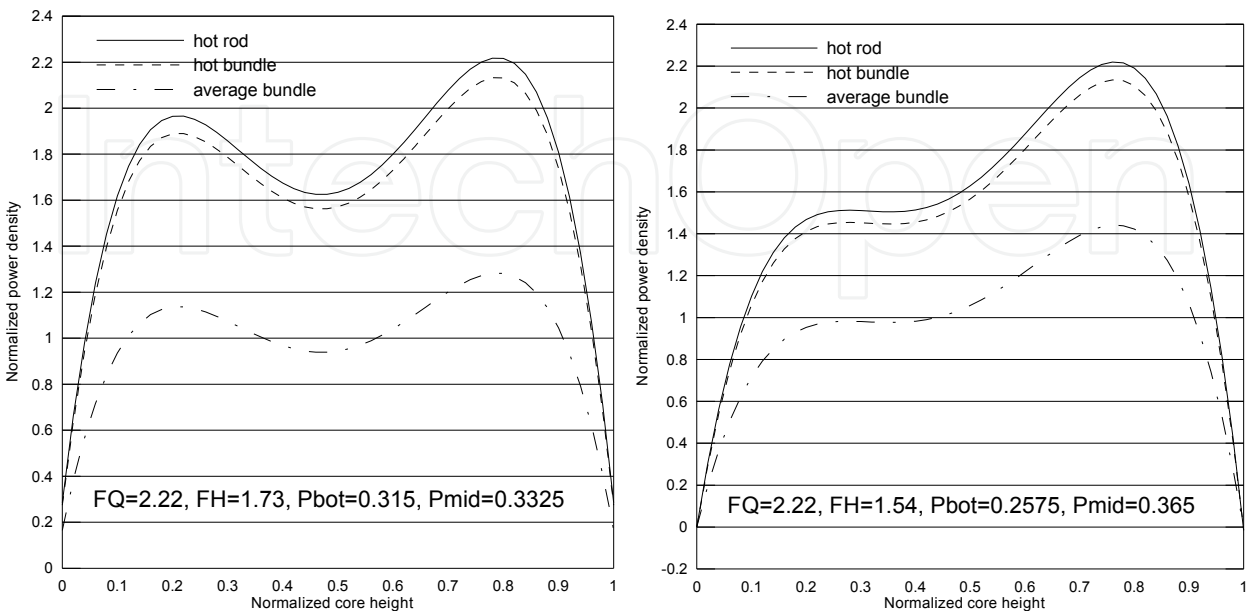

Fig. 23. Sampling of power shapes

(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. Typical parameter samplings of F_Q, P_{rcs}, T_{avg} and P_{acc} are shown in Figure 24. The run matrix needs to consist of trials of 59 sets, 93 sets or 124 sets according to the order statistic method (David and Nagaraja, 1980).
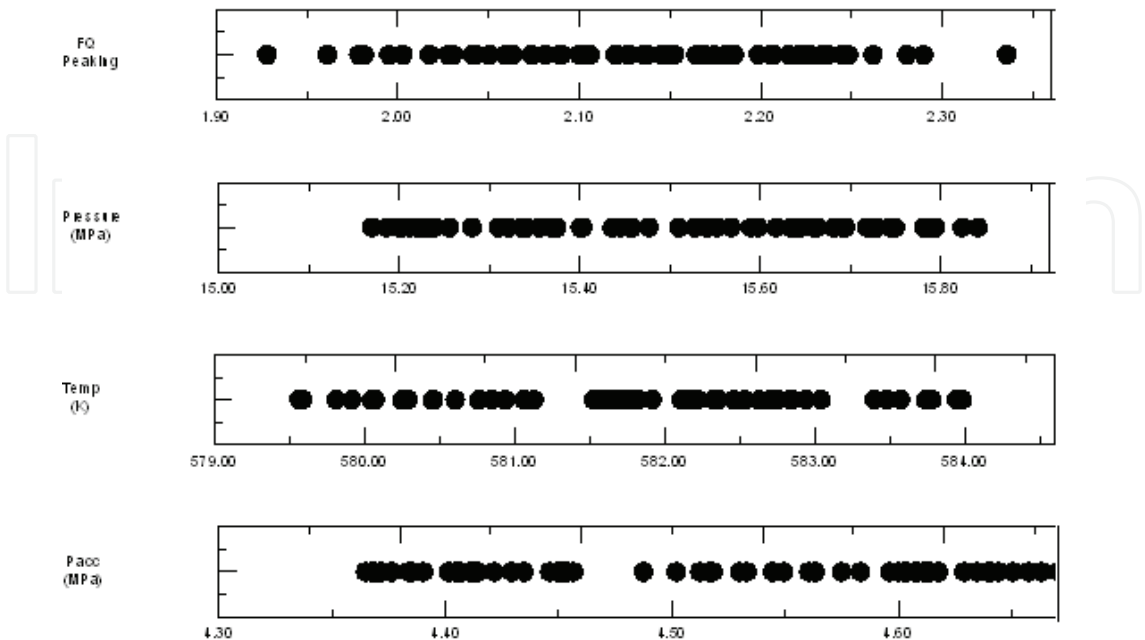

Fig. 24. Typical parameter sampling

(4) Using conservative plant E.M. model to perform LOCA analysis of each trial

Conservative plant E.M. model will be applied to analyze each trial to calculate the PCT of each LOCA event. Regarding the conservative plant E.M. model, requirements of Appendix K for physical models will be satisfied, and a conservative plant specific model will be implemented based on sensitivity studies. Since RELAP5-3D/K is an Appendix K version of RELAP5-3D, it will be adopted to build a plant specific model.

(5) Statistical analysis of calculated figure of merit (PCTs)

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

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 & Nagaraja, 1980) can be applied to calculate the estimator the 95/95 upper tolerance limit.

$$\beta = 1 - \gamma^N \tag{5}$$

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

$$Y_{95/95} \approx Y_{1st}(59) \text{ or } Y_{95/95} \approx Y_{2nd}(93) \text{ or } Y_{95/95} \approx Y_{3rd}(124) \tag{6}$$

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

$$\beta = \sum_{j=0}^{N-P} \frac{N!}{(N-j)!j!} \gamma^j (1-\gamma)^{N-j} \tag{7}$$

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

Parametric approach

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

$$\mu_s = \sum_{i=1}^{n} x_i / n , \quad \sigma_s = \sqrt{\left[\frac{\sum_{i}^{n} x_i^2}{n-1} - \left(\frac{n}{n-1} \right) * \mu_s^2 \right]} \tag{8}$$

If normal distribution can be assumed by goodness-of-fitting test, the μ_p and σ_p under a given confidence level can be expressed as:

$$\mu_p \leq \left[\mu_s + t_\alpha(n-1) * \sigma_s / \sqrt{n} \right] \tag{9}$$

$$\sigma_p^2 \leq \frac{\sigma_s^2(n-1)}{\chi_{1-\alpha}^2(n-1)} \tag{10}$$

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

$$Y_{95/95} = \mu_{p,95\%} + 1.645\sigma_{p,95\%} \tag{11}$$

(6) Determine licensing value of PCT

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

$$PCT_{Licensing} = \max(PCT_{95/95}, PCT_{order}) \tag{12}$$

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

4. Application of DRHM on PWR LBLOCA analysis with RELAP5-3D/K

To demonstrate the benefit of DRHM method for LOCA analysis, uncertainty ranges and distributions of each essential plant parameter identified by Westinghouse (Westinghouse, 2009) are applied to analyze LBLOCA using DRHM method for the Taiwan Maanshan 3-loop PWR plant. The resulting PCT by DRHM method will be compared with the PCT calculated by traditional Appendix K bounding parameter analysis.

In Maanshan DRHM LBLOCA analysis, 59 trails are generated by random sampling of major plant parameters listed in Table 5. The resulting PCT of each trail are shown in Figure 25 and the greatest PCT among 59 sets is 1284.6K. Therefore, the $PCT_{95/95}$ estimated by order statistic method is:

$$PCT_{95/95} \approx PCT_{order} = Max\left[PCT_i, i = 1, 59\right] = 1284.6K \tag{13}$$

Furthermore, the 59 sets of PCT were also arranged into six groups in sequential order for goodness of fitting test by using the Pearson Chi-squares test statistic (Devore, 2004):

$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i - n\hat{p}_i)^2}{n\hat{p}_i} \tag{14}$$

Development of an Appendix K Version of RELAP5-3D and
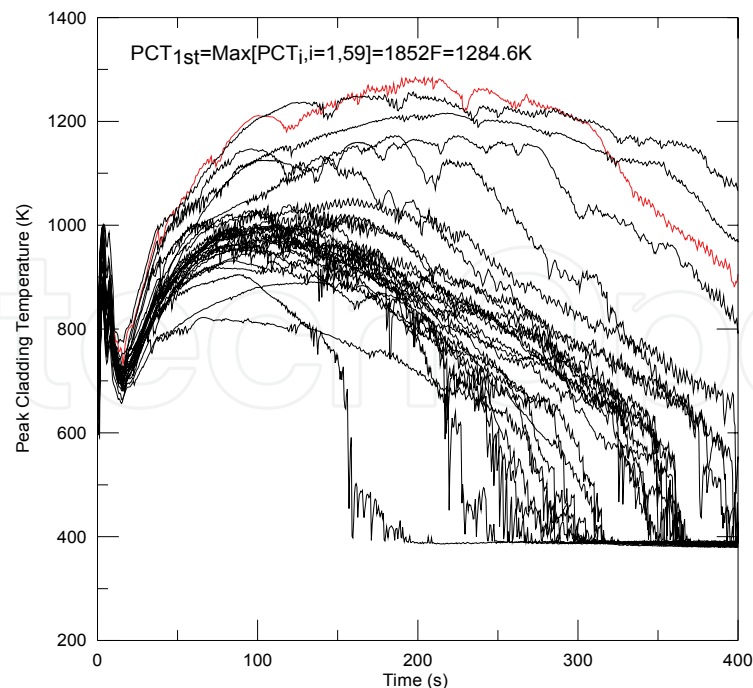Associated Deterministic-Realistic Hybrid Methodology for LOCA Licensing Analysis

63

Fig. 25. Calculated PCT of each trial figure

where n is the total number of samples, n_i is the number of samples in group i and $\hat{p}$ is the probability estimated by integration over group i with standard normal distribution function. The Pearson Chi-squares test statistic will be checked with the Chi-squares critical value, $\chi_\alpha^2(k-r-1)$ where k is the number of group (k=6) and r is the number of unknowns (r=2). A rejection region at (1-α) confidence level will be defined by $\chi_\alpha^2(k-r-1)$ as :

$$\chi^2 \geq \chi_\alpha^2(k-r-1) \tag{15}$$

Therefore, the successful condition of goodness-of-fit test at 95% confidence level will be:

$$\chi^2 < \chi_\alpha^2(k-r-1) = \chi_{0.05}^2(3) = 7.815 \tag{16}$$

Since χ^2 is 4.376 and it is less than the Chi-squares critical value ($\chi_{0.05}^2(3) = 7.815$), therefore the distribution normality can be accepted and the classical parametric approach can be applied to project the μ_p and σ_p base on the μ_s and σ_s under a giver confidence level. Under 95% confidence level the population mean value of PCT can be no greater than:

$$\mu_{p,95\%} \leq \left[\mu_s + t_\alpha(n-1) * \sigma_s / \sqrt{n} \right] = 967.6K \tag{17}$$

and the population standard deviation of PCT can be no greater than:

$$\sigma_{p,95\%}^2 \leq \frac{\sigma_s^2(n-1)}{\chi_{1-\alpha}^2(n-1)} = (185.6K)^2 \tag{18}$$

As a result, the PCT$_{95/95}$ calculated by parametric approach is:

$$PCT_{95/95} = \mu_{p,95\%} + 1.645 * \sigma_{p,95\%} = 1272.9K \tag{19}$$

Comparing PCT$_{95/95}$ (1272.9K) and PCT$_{order}$ (1284.6K), it can be seen that statistical upper bounding values of PCT calculated by both parametric and nonparametric approaches are quite close.

To further demonstrate the benefit of DRHM method, sensitivity studies of major plant parameters were performed to identify the bounding state covering associated parameter uncertainties. In the bounding state analysis, the worse combination of either lower bounds or upper bounds of parameters are investigated. The bounding state was identified to be the upper bounding values of reactor power, F$_Q$, F$_{\Delta H}$, T$_{avg}$, and accumulator temperature and pressure, as well as the lower bounding values of system pressure, ECC temperature and accumulator water volume (Liang, 2010). Results of bounding state analysis were shown in Figure 26, and the PCT of bounding states was identified to be 1385.2K. Resulting PCTs from DRHM method and bounding state analysis were shown in Figure 27. It can be seen that the additional PCT margin generated by statistically combining plant status uncertainty, compared to traditional bounding state analysis, can be as great as 100K. A similar application of DRHM on the LOFT L2-5 based on the same plant status uncertainty was also performed (Zhang et al., 2010), and the resulting PCT analysis is shown in Figure 28. It can be observed that a comparable margin of PCT also was indicated. Furthermore, the standardized regression coefficient (SRC) method was also applied to analyze the importance of each parameter uncertainty of Maanshan plant, and the result is shown in Figure 29. It can be seen that parameter uncertainties of accumulator settings (pressure, liquid volume and temperature), ECC injection temperature, T$_{avg}$ and power shape are relatively important.
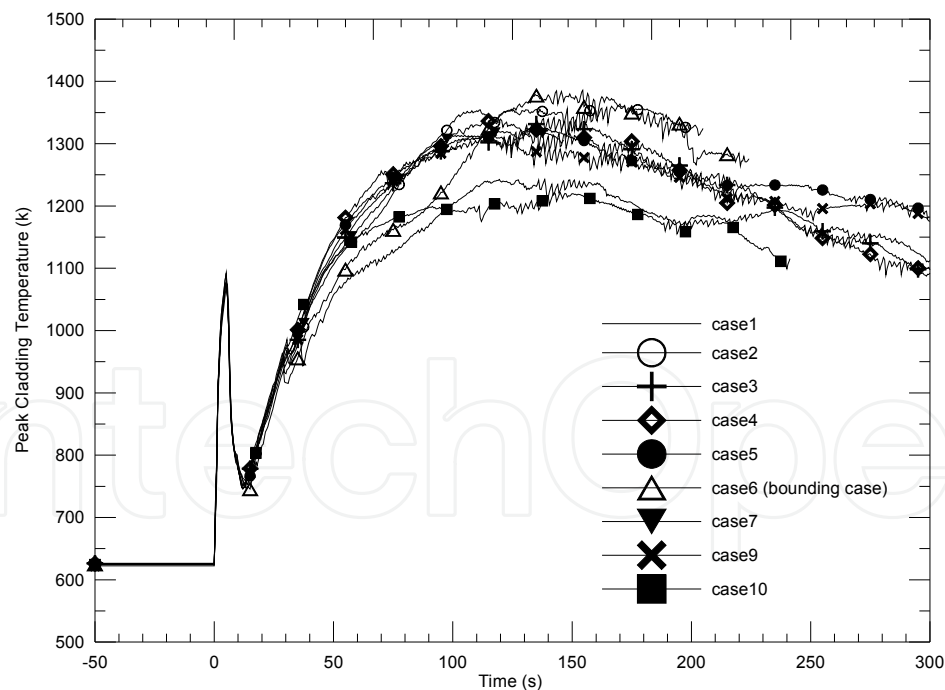
26. Bounding state analysis of PCT

5. Conclusions

Licensing safety analysis can only be performed by approved evaluation models, and E.M. models are composed by two major elements, which involve qualified computational codes

and approved methodology. It is well recognized that B.E. analysis with full-scoped uncertainty quantification can provide significant safety margin than traditional conservative safety analysis, and the margin can be as great as 200K for LOCA analysis. Although a best-estimate LOCA methodology can provide the greatest margin for the PCT evaluation during a LOCA, it generally takes more resources to develop. Instead, implementation of evaluation models required by Appendix K of 10 CFR 50 upon an advanced thermal-hydraulic platform can also gain significant margin on the PCT calculation but with fewer resources. An appendix K version of RELAP5-3D has been successfully developed and through though assessments, the reasonable conservatism of RELAP5-3D/K calculation was clearly demonstrated in whole area of a LOCA event, which covering hydraulics and heat transfer in the phases of blowdown, refill and reflood.
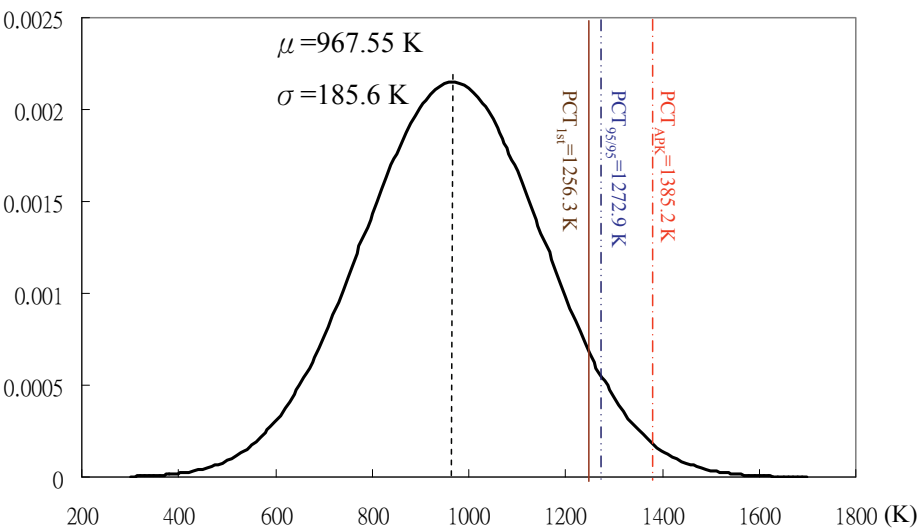

Fig. 27. Comparison of PCTs from both DRHM and bounding appendix K analysis for Maanshan PWR Plant
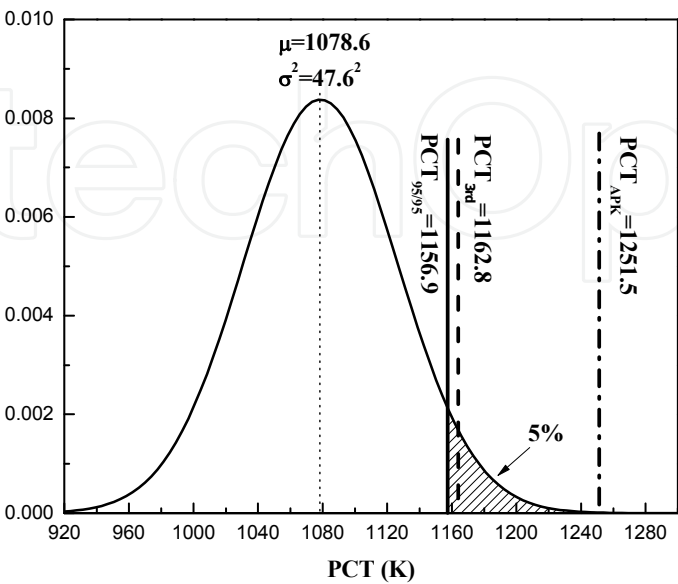

Fig. 28. Comparison of PCTs from both DRHM and bounding state analysis for LOFT L2-5
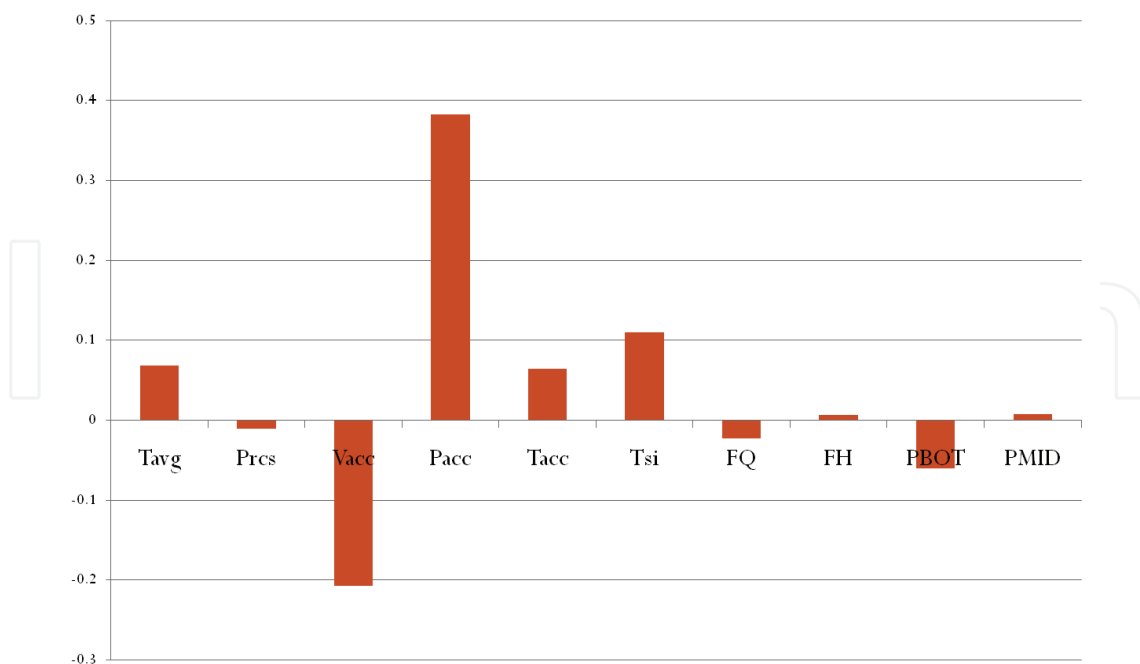
Fig. 29. Importance analysis of plant status parameters

Instead of applying a full scoped BELOCA methodology to cover both model and plant status uncertainties, a deterministic- realistic hybrid methodology (DRHM) was developed to support LOCA licensing analysis. In the DRHM methodology, Appendix K deterministic evaluation models are adopted to ensure model conservatism, while CSAU methodology is applied to quantify the effect of plant status uncertainty on PCT calculation. To ensure the model conservatism, not only physical model should satisfy requirements set forth in the Appendix K of 10 CFR 50, sensitivity studies also need to be performed to ensure a conservative plant modeling. To statistically quantify the effect of plant status uncertainty on PCT, random sampling technique is applied, and both parametric and non-parametric methods are adopted to calculate or estimate the statistical upper bounding value (95/95). When applying the DRHM for LBLOCA analysis, the margin generated can be as great as 80-100K as compared to Appendix K bounding state LOCA analysis.

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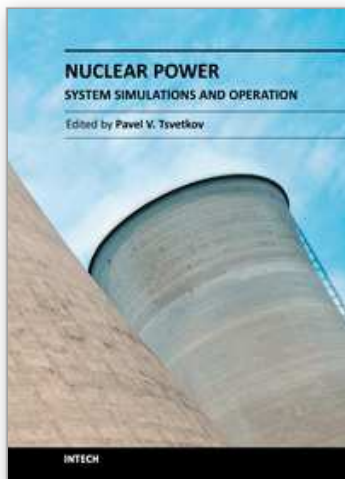
Nuclear Power - System Simulations and Operation

Edited by Dr. Pavel Tsvetkov

At the onset of the 21st century, we are searching for reliable and sustainable energy sources that have a potential to support growing economies developing at accelerated growth rates, technology advances improving quality of life and becoming available to larger and larger populations. The quest for robust sustainable energy supplies meeting the above constraints leads us to the nuclear power technology. Today's nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. Catastrophic earthquake and tsunami events in Japan resulted in the nuclear accident that forced us to rethink our approach to nuclear safety, requirements and facilitated growing interests in designs, which can withstand natural disasters and avoid catastrophic consequences. This book is one in a series of books on nuclear power published by InTech. It consists of ten chapters on system simulations and operational aspects. Our book does not aim at a complete coverage or a broad range. Instead, the included chapters shine light at existing challenges, solutions and approaches. Authors hope to share ideas and findings so that new ideas and directions can potentially be developed focusing on operational characteristics of nuclear power plants. The consistent thread throughout all chapters is the "system-thinking" approach synthesizing provided information and ideas. The book targets everyone with interests in system simulations and nuclear power operational aspects as its potential readership groups - students, researchers and practitioners.

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